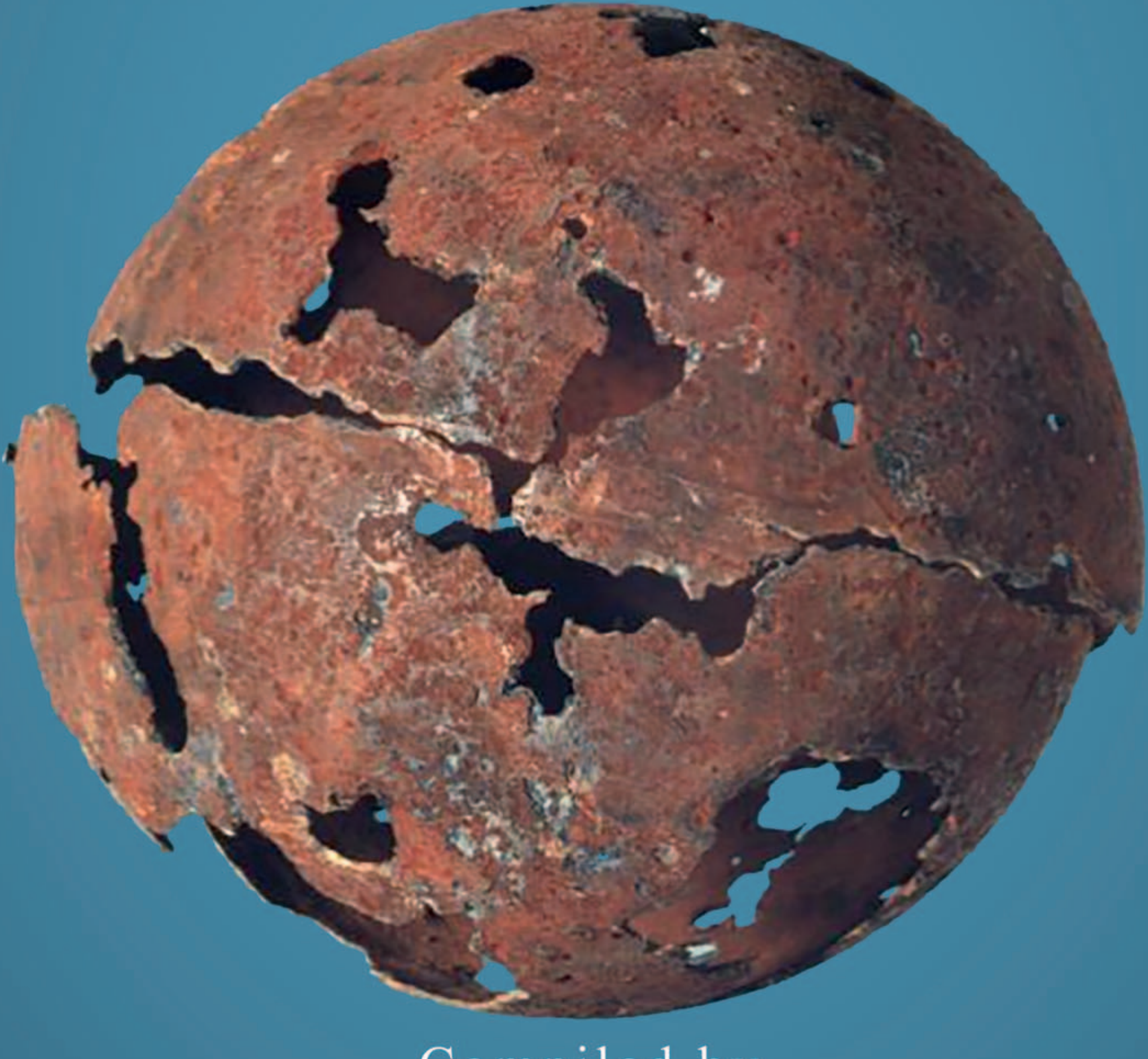
Corrosion Atlas

THIRD, EXPANDED AND REVISED EDITION



Compiled by

Evert D. D. During

Corrosion Atlas

A Collection of Illustrated Case Histories

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Compiled by

Evert D.D. During

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To my wife Erna,
for her love, patience and support.

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FOREWORD

Corrosion is a phenomenon leading to large losses of materials, energy, and money by causing losses of products and production, materials of construction and equipment, and necessitating increased maintenance. This leads to unplanned outages and may even cause serious accidents. Moreover corrosion, due among others to leakage of deleterious products, can also contribute to environmental pollution.

Corrosion can manifest itself in many different forms and fortunately there are also many ways to prevent or combat these. In practice, unfortunately, these remedies are not always applied, for example, because the persons engaged in design, fabrication, maintenance, and application of vehicles, apparatus, machines, and other equipment are not aware of these possibilities. Also, insufficient knowledge may lead to application of corrosion control methods in the wrong way or the wrong situation. Furthermore, obtaining advice from specialists is not always successful as they talk another language and because the details of the operational conditions, including the exact composition of the corrosive environment, are often not or incompletely known to the specialist.

These considerations highlight the need for further, and continuing, education and instruction for those who are engaged in the above-mentioned fields. However, much of the available educational material is unfortunately rather specialized and of too high a scientific level. Thus, it is not of direct use to the people concerned with the solution of corrosion problems they meet in practice. In other cases, it is difficult to use these educational aids for self-study or as a tool in the solution of practical problems.

Having been concerned for many years with corrosion education and instruction and in consulting work in the field of corrosion prevention and control, I therefore take a great pleasure in welcoming the publication of this new (third!) edition of the *Corrosion Atlas*. It is gratifying that the *Atlas* clearly has been so successful that a new edition was necessary. This *Atlas* certainly is of great value in bridging the gap between theory and practice. In this new edition, there are several significant improvements, such as the addition of cross-references between the different case histories, an extension of the Introduction with a clear, more penetrating study of electrochemical corrosion, a chapter on Corrosion Topics and a chapter on corrosion in a number of different water-bearing systems, and a completely new second index on installations, systems, and parts.

This makes this work of increased importance for those who are responsible for the design, fabrication, operation, and maintenance of the extremely varied and often very complicated systems and machinery used in today's technology. They certainly should apply this Atlas extensively in their daily work. The strongly increased number of case histories, with cross-references and new indexes, makes it even more widely applicable than the previous editions. This *Atlas* can therefore be used as an aid in the solution of many practical corrosion problems. It also serves to bring the specialist and the person trying to solve a corrosion problem closer together by presenting a common language, so that misunderstandings are avoided.

Furthermore, the Atlas is an important educational aid for self-study and for special courses. But it can also be profitably used as part of or addition to existing general courses in technical schools and colleges and universities. Its unique, extensive, clear, and beautifully produced illustrative material presents the opportunity to make these courses less abstract and theoretical and so give a much closer link between education and the practice of corrosion prevention and control than usual.

The author of this *Atlas* is to be congratulated on the excellent result of his efforts, which have succeeded in making an already very good book even better. Praise is also due to the organization in which the author has been active for its support of this work, which is of extreme importance for modem technology.

I express my sincere wish that many persons will take advantage of this publication in its new and improved form: in teaching, in self-study, or in trying to solve the practical corrosion problems with they are confronted in their day-to-day work.

Enschede, the Netherlands
March 1997

Paul J. Gellings
Emeritus professor of Inorganic Chemistry and Materials Science,
University of Twente

PREFACE

We are delighted with the relaunch of the *Corrosion Atlas* and the interest you have shown. In recent years, we have seen that curiosity related to corrosion and corrosion phenomena is growing, both in business and education. Although companies in the past mainly focused on the short term, by exchanging installation parts one-on-one, we are now seeing the switch to corrosion prevention and corrosion prediction. A growing number of people are realizing that corrosion can be prevented if there is a better understanding of the materials and the environment in which they are used. Sustainability plays an important role in this trend in terms of the sustainable use of raw materials, preventing degradation and the prevention of damage. By preventing all potential forms of corrosion in the design, the correct materials can be selected. Also, if the production process is modified, it is important to look at the impact of corrosion on the materials used as part of the management of change. Recently, corrosion has increasingly been linked to safety, not only for people but also from the perspective of protecting the environment, within the context of "aging" (an asset management concept). Companies are expected to be aware of the status of their installations, especially when it concerns mostly older ones. Corrosion can have a major impact on the integrity of an installation.

With the understanding that corrosion is more than rusting steel, it is inconceivable just how many materials can be susceptible to corrosion and the variations in the damage pattern. The *Corrosion Atlas* as you will agree with me is a beautiful picture book. It will help you to recognize the ways in which different materials can be affected. When we were still known as Vereniging Krachtwerktuigen, my former colleague Evert During recorded an astounding number of practical examples in this book. After 21 years since the last edition, the name of our company has changed to KWA Bedrijfsadviseurs, but the corrosion processes continue to be the same. The *Corrosion Atlas* is therefore still up to date.

Corrosion is not subject to trends. Carbon steel is still susceptible to oxygen corrosion and stainless steel remains in contact with a chloride-containing medium sensitive to pitting and/or stress corrosion. Materials, such as duplex, copper–nickel alloys, and brass, may also be subject to corrosion under certain conditions, however. In recent years there has been increasing awareness for microbiologically induced corrosion. Evert During has already discussed this in the *Corrosion Atlas* and gives several examples. New analysis techniques and research have provided greater insight into this complicated corrosion mechanism.

I find corrosion an incredibly interesting phenomenon. You can never assume that you fully understand how it works at any given point in time. Each corrosion case always raises the question, why is it going wrong here of all places? Solving corrosion problems is similar to working like Sherlock Holmes: all the pieces of the puzzle need to fit together. After all these years, this continues to be an intriguing process. And even after more than 20 years of working with corrosion, I still find it interesting to browse through the *Corrosion Atlas*. Corrosion control is an enduring area of expertise. Materials will always corrode and we will continue to do our best to minimize or prevent this process. This corrosion picture book helps to form an image of how corrosion looks for a specific material under certain conditions.

Once corrosion has piqued your interest, you will start to see it everywhere. It will never leave you alone. That is why Evert During regularly came to visit us after he retired. He would ask if it was okay if he came to browse our library and literature system. Just to solve a corrosion problem for friends—like many retired corrosion experts who are unable to let go of the profession—embedded in the intriguing process of corrosion and passionate about discovering the cause and finding a solution. When he retired, I had a lamp made for Evert During based on his favorite corrosion object: the stainless steel worm screw "from a gear pump" (case history 04.08.12.02).

Evert During has unfortunately passed away. But I am sure he would have been incredibly delighted and proud if he knew that his *Corrosion Atlas* was republished.

Be amazed by the diverse corrosive phenomena and the beautiful array of forms. My favorites are the powerful "hydrogen damage" on boilers (case history 01.01.20.04), where the steel succumbs to unprecedented forces and the bizarrely erratic pattern created by apparently innocent filiform corrosion (case history 03.20.41.01). I hope this *Corrosion Atlas* picture book brings you hours of pleasure. And may it help you give shape to the direction of corrosion prevention and damage analysis.

Mascha van Hofweegen

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mvh@kwa.nl

ACKNOWLEDGMENTS

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BetzDearbon Inc., Horsham, PA, USA.
Cobra Consultancy, Hazerswoude Dorp, The Netherlands.
Daf Trucks N.V., Eindhoven, The Netherlands.
Dow Benelux N.V., Terneuzen, The Netherlands.
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KEMA, Arnhem, The Netherlands.
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Nalco Chemical Company, Naperville, Illinois, USA.
National Aerospace Laboratory (NLR), Emmeloord, The Netherlands.
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Stork - FDO B.V., Amsterdam, The Netherlands.
TNO, Institute of Industrial Technology, Apeldoom, The Netherlands.
Richard S. Tieseder, Consulting Corrosion Engineer, Oakland, California, USA.

I take this opportunity to offer my sincere thanks to all contributors.

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Last but not least, I owe an acknowledgement to the publishers, Elsevier Science, for their great skill in producing this magnificent Atlas.

Amersfoort, The Netherlands
March 1997

Evert D.D. During
Consulting Corrosion Engineer

USER GUIDE FOR THE CORROSION ATLAS

With reference to the classification, the case history coding is as follows. The first two digits of the code refer to the material of the object attacked, the second two digits refer to the system from which the corroded part originates, the third two digits refer to the phenomenon, and the last two digits refer to the numerical sequence in those instances which several sheets deal with the same subject.

Case histories which are classifiable under different phenomena are shown as a single case in the Atlas, but mentioned under the different phenomena. For instance, “season cracking of brass” is inserted under “stress corrosion cracking” (digits 18), but in the Phenomena Index, it is also mentioned under “Ammonia corrosion” (digits 10).

The description of each case history is summarized on a single sheet, provided with one or more colored macroprints and, in some cases, with a microprint as well.

Items reported are as follows:

Material	The material data available (see main classification). W.-Nr.: Werkstoffnummer (German).
System	Data on the industrial plant, installation, or facility from which the corroded part originates (first subclassification).
Part	Information about the corroded part.
Phenomenon	The type of corrosion or attack to which the case in question is attributable (second subclassification).
Appearance	Description of the appearance of the corrosion or attack.
Time in service	The life span of the corroded part before the corrosion was discovered (the real time in which the corrosion took place may be shorter).
Environment	The definition of the environment (media) with the data relevant to the corrosion process.
Cause	The most probable causes of the corrosion or attack.
Remedy	The advice given or the measures taken in the case in question, often supplemented by alternative options.

Possible ways to use this atlas were as follows:

- Study the corrosion basic (Part I of the introduction) before studying the case histories.
- Study a specified corrosion phenomenon of a specified material in a specified system (installation) with the aid of the classification.
- Study the corrosion phenomena of a specified material by way of the main classification.
- Study a specified corrosion phenomenon of a specified material by way of the phenomena index (the second subclassification).
- Study the corrosion phenomena by system and part based on the applied material, the environment (media), and the appearance by way of the systems index.
- Study a specified corrosion phenomenon or case history mentioned in the introduction (Part II Corrosion Topics or Part III Corrosion in Water-Bearing Systems).
- The cross-references give the possibility for quick comparison with other cases in the same or other systems in different circumstances.

For more information about corrosion, refer to the detailed bibliography.

CLASSIFICATION OF THE CASE HISTORIES*

MAIN CLASSIFICATION: BY MATERIALS

Carbon steels

1. Unprotected carbon steels (non- and low-alloyed steels, cast irons, cast steels)
2. Galvanized steels (hot-dip, Sendzimir, electroplated, sherardized, sprayed, mechanically plated, centrifuge galvanized, duplex protected steels)
3. Carbon steels provided with a coating other than zinc (see 02.) and polymer linings (see 10.)

Stainless steels and nonferrous materials

4. Stainless steels (martensitic, ferritic, austenitic, duplex, special grades)
5. Nickel and cobalt-base alloys
6. Copper and its alloys
7. Aluminum, magnesium, and their alloys
8. Lead, tin, and zinc
9. Noble and reactive metals (silver, gold, titanium, zirconium etc.)
10. Plastics and plastic linings (including synthetic rubber)
11. Concrete and cement mortar linings
12. Coated metals (other than carbon steels)
13. Other materials (natural robber, glass, wood, ceramics)

FIRST SUBCLASSIFICATION: BY SYSTEMS

1. Steam systems (boiler feedwater systems, steam boilers, waste heat boilers, boiling water reactors, steam pipes, and steam using equipment)
2. Steam condensate systems (steam using equipment, condensate pipes, and pumps)
3. Gas turbines
4. Heating systems (central heating systems, hot water heating systems, thermal oil systems)
5. Cold and hot tap water systems (drinking water systems, storage boilers, transport pipes)
6. Cooling water systems (once-through and circulating systems)
7. Cooling systems (with Freon, ammonia, brine mineral oil)
8. Water treatment and sewage treatment plants (for well water, boiler feedwater, and waste water)
9. Air conditioning systems
10. Fire extinguishing systems (tanks, sprinkler pipes, pumps)
11. Process installations (equipment for the extraction, production, treatment, storage, and transport of products and chemicals)
12. Cleaning systems and pickling baths
13. Vacuum and compressed air systems
14. Gas supply systems
15. Electrical and electronic components
16. Civil and structural constructions
17. Street equipment and separating structures
18. Waste and refuse incinerators
19. Aircraft
20. Automotive systems (cars, trucks, and tanks) and trains
21. Ships and marine installations
22. Lubricant systems
23. Gas purification systems (gas scrubbers, absorption filters)
24. Weathering and laboratory test systems
25. Other equipment and installations

SECOND SUBCLASSIFICATION: BY PHENOMENA

1. Oxygen corrosion, including tuberculation
2. Carbonic acid corrosion (also defined as carbon dioxide corrosion and sweet corrosion; including corrosion by aggressive water)
3. Caustic corrosion (including alkalinity corrosion)
4. Acid corrosion (including hydrogen grooving)
5. Sulfide corrosion (not due to sulfate-reducing bacteria; also defined as sour corrosion)
6. High temperature corrosion (carburization, metal dusting, nitriding, oxidation, sulfur corrosion, sulfidation, etc.)
7. Heat flux corrosion
8. Chlorine corrosion
9. Salt corrosion
10. Ammonia corrosion
11. Solder corrosion
12. Halide corrosion (by chloride, bromide, fluoride)
13. Crevice corrosion

14. Galvanic corrosion (couple action, deposition corrosion, reversal of potential, thermogalvanic corrosion)
15. Underdeposit corrosion
16. Selective leaching (dealloying: dealuminification, denickelification, dezincification, and graphitic corrosion)
17. Microbiologically induced corrosion
18. Stress-corrosion cracking (SCC; *trans*- and inter-granular: carbonate/bicarbonate, caustic SCC, environmentally induced cracking, nitrate SCC, polythionic acid SCC, and season cracking)
19. Intergranular corrosion (exfoliation, knife-line attack, sigma-phase embrittlement, and weld decay)
20. Hydrogen damage (high temperature hydrogen attack, hydrogen blistering, hydride embrittlement, hydrogen embrittlement, hydrogen stress cracking)
21. Chelant corrosion
22. Liquid metal embrittlement (including solid and gaseous metal embrittlement)
23. Blooming
24. Atmospheric corrosion (indoors and outdoors)
25. Underinsulation corrosion
26. Stray current corrosion
27. Silica corrosion
28. Fatigue (including corrosion fatigue and thermomechanical fatigue)
29. Ageing
30. Creep, creep embrittlement, and cracking caused by overheating
31. Sandelin phenomenon
32. Erosion (including impingement attack and water hammer)
33. Cavitation damage (including cavitation erosion and cavitation corrosion)
34. Erosion corrosion
35. Fretting (corrosion) and false brinelling
36. Stress cracking (embrittlement) in plastics
37. Diffusion in plastics
38. Material and weld defects (in metals, plastics, and plastic linings)
39. Degradation of plastics
40. Coating failures
41. Filiform corrosion
42. End grain attack
43. Steam blanketing
44. 475°C embrittlement

PHENOMENA INDEX
in Alphabetic Order

Acid Corrosion (04)

By Inorganic Acids

– **Hydrochloric Acid**
of carbon steel 01.01.04.01
of carbon steel 01.01.04.03
of carbon steel 01.01.04.04
of carbon steel 01.01.04.05
of carbon steel 01.01.04.07
of carbon steel 01.01.04.10
of carbon steel 01.04.04.01
of carbon steel 01.06.04.01
of carbon steel 01.11.04.06
of carbon steel 01.11.34.04
of carbon steel 01.12.04.01
of galvanized steel 02.01.04.01
of coated cast iron 03.08.04.01
of stainless steel 04.01.04.01*
of stainless steel 04.11.04.01
of stainless steel 04.11.04.10
of stainless steel 04.11.04.14
of stainless steel 04.11.34.01
of stainless steel 04.12.04.02
of stainless steel 04.12.04.03
of nickel alloy 05.11.04.03
of nickel alloy 05.11.34.02
of copper 06.06.04.01
of admiralty brass 06.06.04.02
of aluminum 07.04.04.01
of aluminum alloy 07.04.04.02
of polytetrafluoroethylene (PTFE) 10.11.04.02
of PTFE-lined steel 10.11.28.01
of glass–fiber–reinforced epoxy 10.11.34.01

– **Phosphoric Acid**
of stainless steel 04.11.04.02
of stainless steel 04.11.04.11*
of stainless steel 04.11.04.16
of stainless steel 04.11.34.04
of nickel alloy 05.11.04.01
of copper 06.05.25.01
of aluminum bronze 06.11.16.02

– **Nitric Acid**
of stainless steel 04.11.04.07*
of stainless steel 04.11.04.08*
of stainless steel 04.11.34.02
of stainless steel 04.12.04.04*

– **Sulfuric Acid**
of carbon steel 01.01.04.02
of carbon steel 01.01.04.08
of carbon steel 01.01.04.09
of carbon steel 01.06.04.02
of carbon steel 01.07.04.01
of carbon steel 01.08.04.01
of carbon steel 01.11.04.01
of carbon steel (hydrogen grooving) 01.11.04.03
of carbon steel 01.11.04.04
of carbon steel 01.11.04.05
of carbon steel 01.11.14.02
of carbon steel 01.11.34.03
of carbon steel 01.11.34.07
of low-alloyed steel 01.24.04.01
of stainless steel 04.08.19.01
of stainless steel 04.08.42.01
of stainless steel 04.11.04.03
of stainless steel 04.11.04.04
of stainless steel 04.11.04.06
of stainless steel 04.11.04.09
of stainless steel 04.11.04.13
of stainless steel 04.11.34.03
of stainless steel 04.12.04.05
of stainless steel 04.24.04.01
of nickel alloy 05.11.04.02
of copper 06.11.34.02
of admiralty brass 06.20.04.01
of bronze 06.11.34.03
of lead 08.11.04.01

– **Sulfurous Acid**
of carbon steel 01.01.04.11

By organic acids

– **Acetic Acid**
of stainless steel 04.11.04.05

– **Citric Acid**
of carbon steel 01.01.04.06

– **Fatty Acids**
of carbon steel 01.11.04.02
of stainless steel 04.08.04.01

– **Formic Acid**
of glass–fiber–reinforced epoxy 10.11.04.01

– **Glycolic Acid**
of carbon steel 01.11.34.06
of stainless steel 04.11.04.15

*Attacked by mixture with other acids.

– **Naphthenic Acid**
  of carbon steel 01.11.34.05
  of carbon steel 01.11.34.08
  of low-alloyed steel 01.11.34.02

– **Sulfamic Acid**
  of stainless steel 04.12.04.01
  of bronze 06.11.04.01

– **Mixture of Organic Acids**
  of stainless steel 04.11.04.05
  of stainless steel 04.11.04.12
  of aluminum alloy 07.07.04.01

Aging (29)
  of carbon steel 01.11.29.01
  of melamine 10.11.29.01
  of polyethylene 10.11.29.02
  of polypropylene (PP) 10.11.29.03
  of natural rubber 13.11.29.01

Aggressive Water Corrosion (02)
  of carbon steel 01.11.02.05
  of galvanized steel 02.05.02.01
  of galvanized steel 02.07.02.01
  of copper 06.05.02.01
  of copper 06.05.02.02
  of aluminum alloy 07.20.02.01

Alkalinity Corrosion
  refer to caustic corrosion

Ammonia Corrosion (10)
  of galvanized steel 02.16.10.01
  of copper 06.02.10.03
  of copper 06.04.10.01
  of copper 06.05.10.01
  of copper 06.13.10.01
  of copper 06.14.18.01
  of brass 06.15.18.01
  of brass 06.25.18.01
  of brass 12.25.18.01
  of admiralty brass 06.02.10.01
  of admiralty brass 06.02.10.02
  of admiralty brass 06.02.28.01
  of admiralty brass 06.06.17.01
  of aluminum brass 06.01.18.01
  of aluminum brass 06.06.18.01
  of aluminum brass 06.11.18.01
  of aluminum brass 06.11.34.01
  of bronze 06.01.10.01
  of bronze 06.07.10.01
  of bronze 06.01.34.01
  of PP 10.11.29.03

Atmospheric Corrosion, Indoors, and Outdoors (24)
  of carbon steel 01.04.28.01
  of carbon steel 01.16.24.02
  of low-alloyed steel 01.11.20.05
  of corten steel 01.16.24.01
  of galvanized steel 02.04.13.01
  of galvanized steel 02.04.24.01
  of galvanized steel 02.05.24.01
  of galvanized steel 02.16.12.01
  of galvanized steel 02.16.24.01
  of galvanized steel 02.16.24.02
  of galvanized steel 02.16.24.03
  of galvanized steel 02.16.24.04
  of galvanized steel 02.16.24.05
  of galvanized steel 02.17.24.01
  of galvanized steel 02.17.24.02
  of galvanized steel 02.17.24.03
  of galvanized steel 02.17.24.04
  of galvanized steel 02.17.24.05
  of galvanized steel 02.17.24.06
  of galvanized steel 02.24.24.01
  of coated steel 03.05.40.03
  of coated steel 03.11.24.01
  of coated steel 03.16.24.01
  of coated steel 03.16.40.01
  of coated steel 03.16.40.02
  of coated steel 03.20.24.01
  of coated steel 03.20.24.02
  of coated steel 03.20.24.03
  of coated steel 03.20.24.04
  of coated steel 03.20.24.05
  of coated steel 03.20.24.06
  of coated steel 03.20.24.07
  of coated steel 03.20.24.08
  of coated steel 03.20.24.09
  of coated steel 03.21.40.08
  of coated steel 03.24.24.01
  of coated steel 03.24.24.02
  of coated steel 03.24.40.02
  of coated steel 03.24.41.01
  of stainless steel 04.01.18.02
  of stainless steel 04.02.18.02
  of stainless steel 04.08.12.04
  of stainless steel 04.11.12.02
  of stainless steel 04.11.12.09
  of stainless steel 04.11.12.11
  of stainless steel 04.11.14.01
  of stainless steel 04.11.17.02
  of stainless steel 04.11.18.07
  of stainless steel 04.16.12.01
  of stainless steel 04.19.12.01
  of stainless steel 04.19.18.01
  of stainless steel 04.22.18.01
  of coated stainless steel 12.11.14.01
  of nickel 05.02.18.01
  of copper 06.05.10.01
  of copper 06.13.10.01
  of brass 06.25.18.01
  of brass 06.15.18.01
  of aluminum alloy 07.07.24.01
  of aluminum alloy 07.09.14.01
  of aluminum alloy 07.16.13.01
  of aluminum alloy 07.16.14.01
  of aluminum alloy 07.19.14.01

of aluminum alloy 07.19.18.01
of aluminum alloy 07.19.19.05
of aluminum alloy 07.20.24.02
of anodized aluminum 07.16.23.01
of anodized aluminum 07.16.24.01
of anodized aluminum 07.16.24.02
of anodized aluminum 07.20.24.01
of anodized aluminum alloy 07.19.13.01
of anodized aluminum alloy 07.19.19.01
of anodized aluminum alloy 07.19.19.02
of anodized aluminum alloy 07.19.19.03
of anodized aluminum alloy 07.19.19.04
of aluminum coating 07.20.24.03
of die-cast zinc alloy 08.20.24.01
of tin 08.25.24.01
of melamine 10.11.29.01
of PP 10.11.29.03
of reinforced concrete 11.16.24.01
of reinforced concrete 11.16.24.02
of reinforced concrete 11.16.24.03
of reinforced concrete 11.16.24.04
of reinforced concrete 11.16.24.05
of silver-plated brass 12.15.24.01
of nickel-plated brass 12.15.24.02
of coated aluminum alloy 12.19.41.01
of copper-nickel chromium coating over die-cast zinc alloy 12.20.24.01
of natural rubber 13.11.29.01

Bimetallic Corrosion

refer to galvanic corrosion

Blooming (23)

of anodized aluminum 07.16.23.01

Bromide Attack

refer to halide corrosion

Carbonate/Bicarbonate Stress Corrosion Cracking

refer to stress corrosion cracking

Carbonic Acid Corrosion, Also Defined as Carbon Dioxide Corrosion and Sweet Corrosion (02)

of carbon steel 01.02.02.01
of carbon steel 01.02.02.02
of carbon steel 01.02.02.03
of carbon steel 01.05.02.01
of carbon steel 01.11.02.01
of carbon steel 01.11.02.02
of carbon steel 01.11.02.03
of carbon steel 01.11.02.04
of carbon steel 01.11.02.06
of carbon steel 01.11.02.07
of galvanized steel 02.02.02.01
of coated steel 03.11.02.01
of coated steel 03.11.02.02
of coated steel 03.11.02.03
of nickel alloy 05.11.02.01
of copper 06.02.02.01
of copper 06.02.02.02
of copper 06.02.34.01
of copper 06.02.34.02
of glass 13.02.02.01

Carburization

refer to high-temperature corrosion

Caustic Corrosion (Including Alkalinity Corrosion) (03)

of carbon steel 01.01.03.01
of carbon steel 01.01.03.02
of carbon steel 01.11.03.01
refer also to caustic stress corrosion cracking
of galvanized steel 02.11.03.01
of copper 06.11.03.01
of aluminum 07.01.03.01
of cast aluminum alloy 07.06.03.01
of aluminum 07.09.03.01
of aluminum 07.11.03.01
of aluminum 07.11.03.02
of glass–fiber–reinforced vinyl ester 10.11.03.01
of glass–fiber–reinforced polyester 10.11.03.02
of glass 13.01.03.01

Caustic Stress Corrosion Cracking

refer to stress corrosion cracking

Cavitation Damage (33)

– Cavitation Erosion

of carbon steel 01.01.33.02
of carbon steel 01.01.33.03
of carbon steel 01.02.33.01
of carbon steel 01.02.33.02
of carbon steel 01.02.33.04
of carbon steel 01.02.33.05
of carbon steel 01.02.33.06
of carbon steel 01.06.33.01
of cast iron 01.01.33.01
of cast iron 01.02.33.03
of cast iron 01.06.33.03
of cast steel 01.04.33.01
of cast steel 01.06.33.04
of stainless steel 04.11.33.01
of copper 06.11.33.01

– Cavitation Corrosion

of carbon steel 01.06.33.02
of cast iron 01.06.33.03
of cast iron 01.06.33.05
of aluminum cast alloy 07.20.33.01
of aluminum cast alloy 07.20.33.02
of titanium 09.08.33.01

– Chelant Corrosion (21)

of carbon steel 01.01.21.01
of carbon steel 01.01.21.02
of carbon steel 01.01.21.03
of carbon steel 01.06.21.01

Chloride Attack
  refer to halide corrosion

Chlorine Corrosion (08)
  of silver 09.11.08.01
  of zirconium 09.11.08.02

Coating Failures (40)
  of alkyd coating 03.05.40.03
  of alkyd coating 03.21.40.08
  of alkyd coating 03.17.40.01
  of alkyd coating 03.24.40.03
  of coal tar coating 03.24.40.01
  of coal tar epoxy coating 03.05.40.02
  of epoxy coating 03.21.40.01
  of epoxy coating 03.21.40.02
  of epoxy coating 03.21.40.03
  of epoxy coating 03.21.40.05
  of epoxy coating 03.21.40.06
  of epoxy coating 03.21.40.07
  of epoxy coating 03.16.40.02
  of epoxy polyamide coating 03.21.40.04
  of epoxy polyamide coating 03.16.40.01
  of epoxy polyamide coating 03.24.40.02
  of phenol formaldehyde resin (baked) 03.01.40.01
  of phenol formaldehyde resin (baked) 03.05.40.01
  of unknown coating (baked) 03.04.40.01
  of unknown coating 03.06.14.01

Cold Hydrogen (Induced) Cracking (HIC)
  refer to hydrogen damage

Corrosion Fatigue
  refer to fatigue

Contact Corrosion
  refer to galvanic corrosion

Couple Action Attack
  refer to galvanic corrosion

Creep, Creep Embrittlement, and Cracking Caused by Overheating (30)
  of carbon steel 01.01.30.01
  of carbon steel 01.01.30.02
  of carbon steel 01.01.30.03
  of carbon steel 01.11.30.02
  of low-alloyed steel 01.11.30.01
  of lead 08.11.30.01
  of polyethylene 10.11.30.01
  of silicon rubber 10.11.30.02

Crevice Corrosion (13)
  of galvanized steel 02.04.13.01
  of galvanized steel 02.20.13.01
  of stainless steel 01.06.14.01
  of stainless steel 04.05.38.01
  of stainless steel 04.06.13.01
  of stainless steel 04.06.13.02
  of stainless steel 04.11.13.01
  of stainless steel 04.11.38.01
  of stainless steel 04.21.13.01
  of nickel alloy 05.11.42.01
  of aluminum alloy 07.16.13.01
  of aluminum alloy 07.19.13.01
  of aluminum alloy 07.25.13.01

Dealloying
  refer to selective leaching

Dealumnification
  refer to selective leaching

Decarburization
  refer to hydrogen damage

Degradation of Plastics (39)
  of ethylene–propylene dimer rubber 10.11.39.01
  of PTFE 10.11.39.02
  of polyvinyl chloride (PVC) 10.11.39.03

Denickelification
  refer to selective leaching

Deposition Corrosion
  refer to galvanic corrosion

Dezincification
  refer to selective leaching

Diffusion in Plastics (37)
  of PTFE 10.02.37.01
  of PTFE 10.11.37.01
  of PTFE 10.11.37.02
  of glass–fiber–reinforced epoxy 10.02.37.02

475°C embrittlement (44)
  of stainless steel 04.11.44.01

Endgrain Attack (42)
  of carbon steel 01.12.42.01
  of stainless steel 04.08.42.01
  of nickel alloy 05.11.42.01

Environmentally Induced Cracking
  refer to stress corrosion cracking

Erosion (Including Impingement Attack and Water Hammer) (32)
  of carbon steel 01.01.32.01
  of carbon steel 01.01.32.04
  of carbon steel 01.01.32.05
  of carbon steel 01.01.32.06
  of carbon steel 01.01.32.07
  of carbon steel 01.11.32.01
  of carbon steel 01.11.32.02
  of carbon steel 01.25.32.01
  of low-alloyed steel 01.01.32.02
  of low-alloyed steel 01.01.32.03
  of stainless steel 04.01.32.01
  of stainless steel 04.01.32.02
  of stainless steel 04.08.12.02
  of stainless steel 04.11.32.01

of stainless steel 04.11.32.02
of stainless steel 04.11.32.03
of stainless steel 04.11.32.04
of nickel alloy 05.11.32.01
of copper 06.01.32.01
of copper 06.01.32.02
of copper 06.02.32.01
of copper 06.04.32.01
of copper 06.05.32.01
of copper 06.05.32.02
of admiralty brass 06.02.32.02
of bronze 06.06.32.01
of lead 08.05.32.01

Erosion Corrosion (34)

of carbon steel 01.01.34.01
of carbon steel 01.01.34.02
of carbon steel 01.01.34.04
of carbon steel 01.01.34.05
of carbon steel 01.01.34.06
of carbon steel 01.01.34.07
of carbon steel 01.01.34.08
of carbon steel 01.02.34.01
of carbon steel 01.02.34.02
of carbon steel 01.06.34.01
of carbon steel 01.11.34.01
of carbon steel 01.11.34.03
of carbon steel 01.11.34.04
of carbon steel 01.11.34.05
of carbon steel 01.11.34.06
of carbon steel 01.11.34.07
of carbon steel 01.11.34.08
of cast iron 01.06.34.02
of low-alloyed steel 01.01.34.03
of low-alloyed steel 01.11.34.02
of stainless steel 04.01.34.01
of stainless steel 04.05.34.01
of stainless steel 04.06.34.01
of stainless steel 04.08.12.02
of stainless steel 04.11.34.01
of stainless steel 04.11.34.02
of stainless steel 04.11.34.03
of stainless steel 04.11.34.04
of stainless steel 04.11.34.05
of stainless steel 04.23.34.01
of nickel alloy 05.11.34.01
of nickel alloy 05.11.34.02
of copper 06.02.34.01
of copper 06.02.34.02
of copper 06.05.34.01
of copper 06.05.34.02
of copper 06.11.34.02
of admiralty brass 06.06.34.03
of aluminum brass 06.11.34.01
of naval brass 06.06.34.01
of bronze 06.01.34.01
of bronze 06.10.34.01
of bronze 06.11.34.03
of bronze 06,11.34.04
of cupronickel 06.06.34.02

– **Sulfidation**

of carbon steel 01.11.06.04
of nickel alloy 05.01.06.01
of nickel alloy 05.03.06.03
of nickel alloy 05.19.06.01

High-temperature Hydrogen Attack

refer to hydrogen damage

Hot Hydrogen (Induced) Cracking (HIC)

refer to hydrogen damage

Hydride Embrittlement

refer to hydrogen damage

Hydrogen Blistering

refer to hydrogen damage

Hydrogen Damage (20)

– **High-temperature Hydrogen Attack (Also Called Decarburization, Methane Embrittlement, Hot Hydrogen-induced Cracking [HIC])**

of carbon steel 01.01.20.02
of carbon steel 01.01.20.03
of carbon steel 01.01.20.04
of carbon steel 01.01.20.05
of carbon steel 01.01.20.06
of carbon steel 01.11.20.01
of carbon steel 01.11.20.02
of carbon steel 01.11.20.03

– **Hydride Embrittlement**

of titanium 09.11.20.01

– **Hydrogen Blistering (Cold HIC)**

of carbon steel 01.11.20.04
of carbon steel 01.23.20.01

– **Hydrogen Embrittlement**

of low-alloyed carbon steel 01.11.20.05
of stainless steel 04.11.20.01

– **Hydrogen Stress Cracking**

of carbon steel 01.01.20.01
of carbon steel 01.01.20.07
of carbon steel 01.11.20.06
of carbon steel 01.11.20.07

Hydrogen Embrittlement

refer to hydrogen damage

Hydrogen Grooving

refer to acid corrosion

Hydrogen Induced Cracking (HIC)

refer to hydrogen damage

Hydrogen Stress Cracking
refer to hydrogen damage

Impingement Attack
refer to erosion

Intergranular Corrosion (19)

– **Exfoliation (layer corrosion)**
of carbon steel 01.16.24.02
of cupronickel 06.01.16.02
of aluminum 99% 07.20.19.01
of aluminum alloy 07.11.19.01
of aluminum alloy 07.19.19.01
of aluminum alloy 07.19.19.02
of aluminum alloy 07.19.19.03
of aluminum alloy 07.19.19.04
of aluminum alloy 07.19.19.05

– **Knife-line Attack**
of stainless steel 04.11.19.04
of stainless steel 04.18.12.01

– **Sigma-phase embrittlement**
of stainless steel 04.11.19.08
of stainless steel 04.11.19.09
of stainless steel 04.12.19.01

– **Weld Decay**
of stainless steel 04.01.19.01
of stainless steel 04.08.19.01
of stainless steel 04.11.19.02
of stainless steel 04.11.19.04
of stainless steel 04.11.19.07
of aluminum alloy 07.23.19.01

– **Other Intergranular Corrosion**
of stainless steel 04.11.19.01
of stainless steel 04.11.19.03
of stainless steel 04.11.19.05
of stainless steel 04.11.19.06
of stainless steel 04.11.19.10
of stainless steel 04.11.19.11
of nickel alloy 05.11.19.01
of nickel alloy 05.12.19.01

Knife-line Attack
refer to intergranular corrosion

Layer Corrosion
refer to exfoliation

Liquid Metal Embrittlement (Including Solid and Gaseous Metal Embrittlement) (22)
of carbon steel 01.01.22.01
of carbon steel 01.01.22.02
of carbon steel 01.11.22.01
of cadmium-plated low-alloyed steel 01.04.22.01
of zinc-coated steel 02.11.22.01
of stainless steel 04.18.22.01

Material and Weld Defects in Metals, Plastics, and Plastic Linings (38)
refer also to weld decay
of stainless steel 04.05.38.01
of stainless steel 04.11.38.01
of stainless steel 04.11.38.02
of aluminum 07.11.18.01
of aluminum 07.11.38.01
of extruded aluminum 07.20.38.01
of perfluoro alkoxy 10.11.38.01
of fluorinated ethylene propylene 10.11.38.02
of PTFE 10.11.38.03
of PP 10.11.38.04

Metal Dusting
refer to high-temperature corrosion

Methane embrittlement
refer to hydrogen damage

Microbiologically Induced Corrosion (17)
of carbon steel 01.05.17.01
of carbon steel 01.06.17.01
of carbon steel 01.06.17.02
of carbon steel 01.06.17.03
of carbon steel 01.10.17.01
of carbon steel 01.11.17.01
of carbon steel 01.21.17.01
of carbon steel 01.21.17.02
of cast iron 01.14.16.01
of bitumen-coated steel 03.08.17.01
of bitumen-coated steel 03.10.17.01
of bitumen-coated steel 03.14.17.02
of tape-wrapped steel 03.14.17.01
of stainless steel 04.05.17.01
of stainless steel 04.05.17.02
of stainless steel 04.08.17.01
of stainless steel 04.11.17.01
of stainless steel 04.11.17.02
of nickel alloy 05.06.17.01
of nickel alloy 05.06.17.02
of admiralty brass 06.06.17.01
of aluminum alloy 07.06.17.01
of aluminum alloy 07.19.17.01
of concrete 11.08.17.01
of reinforced concrete 11.16.17.01

Nitrate Stress Corrosion Cracking
refer to stress corrosion cracking

Nitriding
refer to high-temperature corrosion

Oxidation at High Temperature
refer to high-temperature corrosion

Oxygen Corrosion, Including Tuberculation (01)
of carbon steel 01.01.01.01
of carbon steel 01.01.01.02

of carbon steel 01.01.01.03
of carbon steel 01.01.01.04
of carbon steel 01.01.01.05
of carbon steel 01.01.01.06
of carbon steel 01.01.01.08
of carbon steel 01.01.01.09
of carbon steel 01.01.14.01
of carbon steel 01.02.01.01
of carbon steel 01.02.01.02
of carbon steel 01.02.01.03
of carbon steel 01.04.01.01
of carbon steel 01.04.01.02
of carbon steel 01.04.01.03
of carbon steel 01.04.01.04
of carbon steel 01.05.01.01
of carbon steel 01.05.01.02
of carbon steel 01.06.01.01
of carbon steel 01.06.01.02
of carbon steel 01.10.01.01
of cast steel 01.01.01.07
of galvanized steel 02.02.01.01
of galvanized steel 02.24.01.01
of coated steel 03.11.01.01

Polythionic Acid Stress Corrosion Cracking
refer to stress corrosion cracking

Reversal of Potential
refer to galvanic corrosion

Salt Corrosion (09)
of aluminum 07.09.09.01
of aluminum 07.09.09.02
of aluminum 07.19.09.01

Sandelin Phenomenon (31)
of galvanized steel 02.16.31.01

Season Cracking
refer to stress corrosion cracking

Selective Leaching (Also Called Dealloying) (16)

– **Dealumnification**
of aluminum bronze 06.11.16.02

– **Denickelification**
of cupronickel 06.01.16.02

– **Dezincification**
layer type
of brass 12.15.24.01
of brass 06.04.16.01
of brass 06.20.16.01
of admiralty brass 06.01.16.01
of aluminum–zinc alloy 07.05.16.01
plug type
of brass 06.04.16.02
of brass 06.05.16.01
of brass 06.05.16.02
of brass 06.05.16.03
of brass 06.05.16.04
of brass 06.06.16.01
of brass 06.06.16.02
of brass 06.11.16.01

– **Graphitic Corrosion**
of cast iron 01.01.16.01
of cast iron 01.06.16.01
of cast iron 01.06.16.02
of cast iron 01.14.16.01

Sigma-phase Embrittlement
refer to intergranular corrosion

Silica Corrosion (27)
of carbon steel 01.12.42.01
of galvanized steel 02.04.27.01

Solder Corrosion (11)
of copper 06.06.11.01
of copper 06.15.11.01
of brass 06.05.16.04

Steam Blanketing (43)
of carbon steel 01.01.43.01

Stray-current Corrosion (26)
of carbon steel 01.05.26.01
of coated steel 03.14.26.01
of coated steel 03.14.26.02
of stainless steel 04.05.26.01
of stainless steel 04.11.26.01
of stainless steel 04.12.26.01
of aluminum 07.16.26.01
of lead 08.15.26.01

Stress Cracking (Also Called Embrittlement) in Plastics (36)
of acrylonitrile butadiene styrene 10.06.36.01
of PVC 10.08.36.01
of PP 10.11.36.03
of PP 10.23.36.01
of polyvinylidene fluoride (PVDF) 10.11.36.01
of PVDF 10.11.36.02
of polysulfone 10.11.36.04

Stress Corrosion Cracking (18)

Intergranular

– **Carbonate/Bicarbonate Stress Corrosion Cracking**
of carbon steel 01.05.18.01
of carbon steel 01.11.18.03
– **Caustic Stress Corrosion Cracking**
of carbon steel 01.01.18.02
of carbon steel 01.01.18.03
of carbon steel 01.01.18.05
of carbon steel 01.11.18.01

of carbon steel 01.11.18.04
of stainless steel 04.01.18.03
of stainless steel 04.25.18.01
of nickel alloy 05.01.18.01

– **Environmentally Induced Cracking**
of carbon steel 01.01.18.01

– **Nitrate Stress Corrosion Cracking**
of carbon steel 01.01.18.04
of carbon steel 01.04.18.01
of carbon steel 01.11.18.02
of stainless steel 04.11.18.10

– **Polythionic Acid Stress Corrosion Cracking**
of stainless steel 04.11.18.13
of stainless steel 04.11.18.15

– **Stress Corrosion Cracking**
of carbon steel 01.01.18.06
of nickel alloy 05.02.18.01
of nickel alloy 05.11.18.01
of nickel alloy 05.11.18.02
of aluminum brass 06.06.18.02
of aluminum alloy 07.19.18.01
of aluminum–zinc alloy 07.16.18.01

Transgranular
of stainless steel 04.01.18.01
of stainless steel 04.01.18.02
of stainless steel 04.01.18.04
of stainless steel 04.01.18.05
of stainless steel 04.02.18.01
of stainless steel 04.02.18.02
of stainless steel 04.05.18.01
of stainless steel 04.11.18.01
of stainless steel 04.11.18.02
of stainless steel 04.11.18.03
of stainless steel 04.11.18.04
of stainless steel 04.11.18.05
of stainless steel 04.11.18.06
of stainless steel 04.11.18.07
of stainless steel 04.11.18.08
of stainless steel 04.11.18.09
of stainless steel 04.11.18.11
of stainless steel 04.11.18.12
of stainless steel 04.11.18.14
of stainless steel 04.11.18.16
of stainless steel 04.19.18.01
of stainless steel 04.22.18.01
of copper 06.14.18.01
of brass 06.15.18.01
of brass 06.25.18.01
of aluminum brass 06.02.18.01
of aluminum brass 06.06.17.01
of aluminum brass 06.06.18.01
of aluminum brass 06.06.18.02
of aluminum brass 06.11.18.01
of aluminum brass 06.24.18.01
of chromium-plated brass 12.25.18.01
of aluminum 07.11.18.01

Sulfur Corrosion
refer to high-temperature corrosion

Sulfidation
refer to high temperature

Sulfide Corrosion (05)
of nickel alloy 05.06.17.01
of nickel alloy 05.06.17.02
of nickel alloy 05.11.05.01
of copper 06.05.05.01
of aluminum alloy 07.06.05.01

Tuberculation
refer to oxygen corrosion

Under-deposit Corrosion (15)
of carbon steel 01.04.15.01
of carbon steel 01.05.15.01
of cast iron 01.06.15.01
of galvanized steel 02.08.15.01
of galvanized steel 02.10.15.01
of stainless steel 04.01.15.01
of stainless steel 04.06.15.01
of stainless steel 04.06.15.02
of stainless steel 04.06.15.03
of stainless steel 04.10.15.01
of stainless steel 04.11.12.09
of stainless steel 04.11.15.01
of Monel 05.06.15.01
of nickel alloy 05.06.15.02
of nickel alloy 05.11.15.01
of copper 06.05.15.01
of copper 06.05.15.03
of copper 06.05.15.04
of copper 06.06.15.01
of copper 06.06.15.02
of brass 06.04.16.02
of brass 06.06.16.01
of brass 06.05.16.01
of brass 06.05.16.03
of brass 06.20.16.01
of aluminum brass 06.05.15.02
of aluminum alloy 07.11.15.01

Under-insulation Corrosion (25)
of carbon steel 01.01.25.01
of carbon steel 01.02.25.01
of carbon steel 01.04.25.01
of carbon steel 01.07.25.01
of carbon steel 01.11.18.02
of carbon steel 01.11.25.01
of carbon steel 01.11.25.01
of coated steel 03.11.25.01

of stainless steel	04.01.18.05
of stainless steel	04.11.18.04
of stainless steel	04.11.18.10
of stainless steel	04.11.18.16
of copper	06.05.25.01
of copper	06.11.25.01

Water Hammer
  refer to erosion

Weld Decay
  refer to intergranular corrosion

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Boiler gauge glass	Glass	Uniform attack	13.01.03.01
Boiler water sampling valve	Stainless steel (AISI 316 Ti)	Locally worn	04.01.32.01
Burner deflector	Cronite	Cracking	05.01.06.01
Chimney	Carbon steel	Branched cracks near welds	01.01.18.04
Flue gas heat exchanger	Hot dip galvanized steel	Uniform attack	02.01.04.01
Pressure gauge valve	Bronze	Uniform attack	06.01.10.01
Steam drum	Carbon steel	Intergranular fracture along the weld	01.01.20.07
Water separator	Carbon steel	Horseshoe-shaped attack	01.01.34.05
Tubes			
Economizer tube	Carbon steel	Pitting attack with tubercles	01.01.01.02
Economizer tube	Carbon steel	Cracking	01.01.01.03
Economizer tube	Carbon steel	Gouging under deposits	01.01.04.05
Economizer tube	Carbon steel	External general metal loss	01.01.04.09
Economizer tube	Carbon steel	Intergranular crack	01.01.18.05
Economizer tube	Carbon steel	Locally worn in bend	01.01.34.01
Economizer tube	Carbon steel	Horseshoe-shaped attack	01.01.34.06
Ferrule of tube plate	Incoloy 800 H	Pitting attack with powdery surface	05.01.06.02
Fire tube	Carbon steel	Pitting attack with blisters	01.01.01.04
Fire tube	Carbon steel	Pitting attack with blisters	01.01.01.05
Fire tube	Carbon steel	Uniform attack and cracking	01.01.03.01
Fire tube	Carbon steel	Grooved attack	01.01.04.01
Fire tube	Carbon steel	Grooved attack	01.01.04.04
Fire tube	Carbon steel	Localized uniform corrosion	01.01.04.11
Fire tube	Carbon steel	Cracking	01.01.30.03
Fire tube insert	Carbon steel	Smoothly worn down	01.01.32.07
Fuel element	Zircaloy	Small rings of pitting attack with pustules	09.01.07.01
Superheater tube	Carbon steel	Pitting attack	01.01.01.08
Superheater tube	Carbon steel	External uniform attack	01.01.06.01
Superheater tube	Carbon steel	Circumferential fracture with unbranched transgranular cracks	01.01.28.01
Superheater tube	Carbon steel	Local external wear	01.01.32.06
Superheater tube	Carbon steel	Outer surface partly flattened	01.01.34.03

*Parts in alphabetical order.

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Superheater tube	Stainless steel (AISI 321)	Pock-marked surface	04.01.06.01
Superheater tube	Stainless steel (AISI 304)	Transverse highly branched crack	04.01.18.03
Water header	Carbon steel	External pitting attack to the welds	01.01.04.10
Water tube	Carbon steel	Pitting attack	01.01.01.06
Water tube	Carbon steel	Gouging under deposits	01.01.03.02
Water tube	Carbon steel	Uniform attack	01.01.04.02
Water tube	Carbon steel	Preferential attack to weld	01.01.04.03
Water tube	Carbon steel	Etched, bright metallic	01.01.04.06
Water tube	Carbon steel	Grooved attack to welds	01.01.04.07
Water tube	Carbon steel	External general metal loss	01.01.04.09
Water tube	Carbon steel	Pitting attack under oxide layer	01.01.07.01
Water tube	Carbon steel	Pitting attack under oxide layer	01.01.07.02
Water tube	Carbon steel	Pitting attack under pustules	01.01.07.03
Water tube	Carbon steel	Pitting attack under thick corrosion scale	01.01.07.04
Water tube	Carbon steel	Cracking	01.01.20.01
Water tube	Carbon steel	Brittle rupture, internal gouging	01.01.20.02
Water tube	Carbon steel	Brittle rupture, internal gouging	01.01.20.03
Water tube	Carbon steel	Brittle rupture, internal gouging	01.01.20.04
Water tube	Carbon steel	Brittle rupture, internal gouging	01.01.20.05
Water tube	Carbon steel	Brittle rupture, internal gouging	01.01.20.06
Water tube	Carbon steel	Comet-tail and horseshoe-shaped depressions	01.01.21.02
Water tube	Carbon steel	Smooth rolling attack with islands	01.01.21.03
Water tube	Carbon steel	Intergranular cracking	01.01.22.01
Water tube	Carbon steel	Longitudinal through-wall cracks	01.01.22.02
Water tube	Carbon steel	Ruptured after bulging	01.01.30.01
Water tube	Carbon steel	Bulging	01.01.30.02
Water tube	Carbon steel	Evenly worn	01.01.32.01
Water tube	Carbon steel	External perforation	01.01.32.05
Water tube	Carbon steel	Irregular attack	01.01.43.01
Steam Distribution Systems			
Ball from ball tap	Stainless steel (AISI 413)	Several long straight cracks	04.01.28.01
Condensate drain	Carbon steel	Magnetite deposition	01.01.01.09
Orifice place (insulated)	Stainless steel (AISI 316)	Cracking	04.01.18.05
Steam coil	Stainless steel (W.-Nr. 1.4521)	Pitting attack	04.01.15.01
Steam coil	Stainless steel (AISI 304)	Attacked zone near weld	04.01.19.01
Steam flange	Carbon steel	Locally worn	01.01.32.03
Steam flange	Carbon steel	Locally worn	01.01.32.04
Steam flange	Stainless steel (AISI 304L)	Cracking	04.01.18.01
Steam line	Carbon steel	Cracking	01.01.18.02
Steam line	Carbon steel	Locally eroded	01.01.34.02
Steam valve	Carbon steel	Black deposits on surface	01.01.01.07
Steam valve bolts	Stainless steel (AISI 321)	Fractured	04.01.18.02
Steam valve spring	Inconel X 750	Fractured	05.01.18.01
Thermometer bulb	Carbon steel	Uniformly eroded	01.01.32.02
Steam Using Equipment (Steam Side)			
Ball valve	Stainless steel (AISI 316)	Erosion of ball and valve house	04.01.34.01
Distributor plate	Aluminum	Uniform attack with perforations	07.01.03.01
Heat exchanger tubes	Copper	Deep dents	06.01.33.01
Steam drum wall of potato peeler	Cast stainless steel	Short cracks with corrosion products	04.01.28.02
Steam pipe (wet)	Carbon steel	Pitting and cracks	01.01.18.06
Steam vent pipe	Copper	Roughened surface	06.01.32.02
Turbine blade	Carbon steel	Impingement attack (pitting)	01.01.34.08
Turbine blade	Stainless steel (AISI 410)	Severe pitting at the edges	04.01.04.01
Turbine blade	Stainless steel (AISI 403)	Fine striated grooves	04.01.32.02
02 STEAM CONDENSATE SYSTEMS			
Condensate Return Systems			
Bursting disc	Nickel (>99.5%)	Cracks	
Condensate line	Carbon steel	Pitting attack	
Condensate line	Carbon steel	Pitting attack with corrosion products	

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Condensate line	Carbon steel	Uniform smooth attack	01.02.02.01
Condensate line	Carbon steel	Uniform smooth attack	01.02.02.02
Condensate line (insulated)	Carbon steel	Pitting attack outside	01.02.25.01
Condensate line	Carbon steel	Cracking	01.02.28.01
Condensate line	Carbon steel	Sharp-edged pits	01.02.33.01
Condensate line	Carbon steel	Sharp-edged pits	01.02.33.05
Condensate line	Carbon steel	Uniform attack in bend	01.02.34.01
Condensate line	Hot-dip galvanized steel	Pitting attack	02.02.01.01
Condensate line (underground)	Stainless steel (AISI 316)	Cracking	04.02.18.01
Condensate line	Stainless steel (AISI 304)	Cracking	04.02.18.02
Condensate line	Copper	Uniform smooth attack	06.02.02.01
Condensate line	Copper	Irregular attack	06.02.02.02
Condensate line	Copper	General thinning	06.02.10.03
Condensate line	Copper	Bulging	06.02.32.01
Condensate line	Copper	Pipe wall totally eroded away locally	06.02.34.02
Condensate line	GRE[1]	Blistering	10.02.37.02
Condensate pump impeller	Cast iron	Local wear	01.02.33.03
Condensate valve	Cast iron	Locally attack at connection	01.02.14.02
Steam trap float ball	Carbon steel	Pitting attack	01.02.01.02
Steam trap inspection glass	Glass	Uniform etching	13.02.02.01
Condensate Using Systems			
Extruder cooling pipe	PTFE[2]	Blistering	10.02.37.01
Flue gas heat exchanger	Carbon steel	Pitting attack	01.02.33.01
Steam Using Equipment (Condens Side)			
Air heater header	Carbon steel	Grooved attack at connection	01.02.14.01
Air heater tube	Carbon steel	Uniformly grooved at one side	01.02.02.03
Air heater tube	Carbon steel	Uniform attack	01.02.34.02
Air heater tube	Hot-dip galvanized steel	Uniform attack	02.02.02.01
Boiler heating tube	Copper	Grooved attack	06.02.34.01
Steam cooler tube	Carbon steel	Local pitting attack	01.02.33.02
Steam condenser bolt	Aluminum brass	Brittle fracture	06.02.18.01
Steam condenser tube	Carbon steel	Rough jagged contour of deep overlapping pits free of corrosion products	01.02.33.06
Steam condenser tube	Admiralty brass	General attack with fine grooves	06.02.10.01
Steam condenser tube	Admiralty brass	Severe grooving	06.02.10.02
Steam condenser tube	Admiralty brass	Circumferential crack	06.02.28.01
Steam condenser tube	Admiralty brass	a pattern of erosion spots	06.02.32.02
03 GAS TURBINES			
Blade of stator	Inconel 738 LC	Local attack	05.03.06.01
Vane	Rene 77	Uniform attack	05.03.06.03
Vane (first stage)	Inconel 939	Uniform attack with dark-green corrosion products	05.03.06.02
04 HEATING SYSTEMS (WATER)			
Hot Water Boiler Systems			
Expansion vessel	Hot-dip galvanized steel	Local rust patches outside	02.04.24.01
Expansion vessel	Coated steel	Pitting attack	03.04.40.01
Heat exchanger tube	Copper	Bulging with cracking	06.04.32.01
Hot water line	Hot-dip galvanized steel	Pitting attack with tubercles	02.04.27.01
Fire tube	Carbon steel	Pitting attack	01.04.01.01
Fire tube	Carbon steel	Pits covered with knob-like mounds	01.04.01.04
Flue gas discharge pipe	Aluminum	Severe general attack	07.04.04.01
Flue gas–heated radiant tube	Carbon steel	General corrosion inside	01.04.04.01
Thermometer bulb	Copper	Pitting attack	06.04.10.01
Hot Water Transport Systems			
Hot water line (insulated)	Carbon steel	Uniform attack outside	01.04.25.01
Hot water line	Hot-dip galvanized steel	External: layered corrosion products	02.04.13.01
Hot water line	Copper	Pitting attack	06.04.16.02

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Hot water line	Aluminum	Severe local attack	07.04.14.02
Hot water pump rotor	Carbon steel	Black deposits on surface	01.04.01.02
Hot water valve	Cast steel	Local pitting attack at discharge	01.04.33.01
Hot water valve	Aluminum	Severe general attack	07.04.14.01
Temperature sensor tube	Brass	Covered with a bluish-black coating	06.04.16.01
Hot Water Using Systems			
Hot water heating tube	Carbon steel	Intergranular cracks near welds	01.04.18.01
Hot water heating tube	Hot-dip galvanized steel	Pitting attack outside	02.04.14.01
Hot water heating tube	Aluminum	Uniform attack with picketed surface	07.04.04.02
Radiant pipes	Aluminum	Pitting attack	07.04.12.01
Radiator	Carbon steel	Local attack under deposit	01.04.15.01
Radiator connection hose	PTFE[2]	Blockage by black deposit	01.04.01.03
04 HEATING SYSTEMS (OIL)			
Heating Oil Transport Systems			
Valve bolts	Cadmium-coated carbon steel	Brittle fracture	01.04.22.01
Heating Oil Using Systems			
Heating coil	Carbon steel	Cracking	01.04.28.01
05 COLD AND HOT TAP WATER SYSTEMS			
Cold Tap Water Systems			
Cattle drinking troughs	Hot-dip galvanized steel	Uniform attack	02.05.24.01
Cold water line	Carbon steel	Pitting attack with tuberculation	01.05.01.02
Cold water line	Carbon steel	Severe attack with grooves	01.05.02.01
Cold water line	Carbon steel	Pitting attack with tubercles	01.05.17.01
Cold water line	Carbon steel	Branched intergranular cracks	01.05.18.01
Cold water line	Coated steel	Internal: severe delamination	03.05.40.02
Cold water line	Coated steel	Broken tubercles with rust	03.05.40.03
Cold water line	Stainless steel (AISI 316L)	Pits and cracks	04.05.12.02
Cold water line	Stainless steel (AISI 316L)	Pitting attack with brown nodules	04.05.17.01
Cold water line	Stainless steel (AISI 304L)	Pinholes with red-brown corrosion products	04.05.17.02
Cold water line (weld)	Stainless steel (AISI 316/304)	Severe attack	04.05.34.01
Cold water line	Copper	Pitting attack with tubercles	06.05.02.02
Cold water line (underground)	Copper	Irregular general attack	06.05.05.01
Cold water line	Copper	External irregular blue-green attack	06.05.10.01
Cold water line	Copper	Pitting attack under deposits	06.05.15.01
Cold water line	Copper	Pitting attack under deposits	06.05.15.03
Cold water line	Copper	Severe attack in bend	06.05.34.02
Cold water line	Aluminum brass	Pitting attack under deposits	06.05.15.02
Cold water line	Aluminum zinc alloy	Severe uniform attack	07.06.16.01
Cold water line	Lead	Fractured after bulging	08.05.32.01
Cold water line (underground)	Hot-dip galvanized steel	Grooved attack	02.05.02.01
Cold water line	Hot-dip galvanized steel	Severe attack at connection	02.05.14.05
Level switch	Stainless steel (AISI 304)	Severe attack	04.05.26.01
Tap component	Brass	Pitting attack	06.05.16.02
Tap component	Brass	Pitting attack	06.05.16.04
Hot Tap Water Systems			
Bolt	Stainless steel (AISI 304)	Pitting attack	04.05.12.01
Heat exchanger tube	Copper	Eroded surface	06.05.32.02
Hot water line	Carbon steel	Pitting attack with corrosion nodules	01.05.01.01
Hot water line	Carbon steel	Local attack under deposits	01.05.15.01
Hot water line (underground)	Carbon steel	Severe external attack at one point	01.05.26.01
Hot water line	Hot-dip galvanized steel	Pitting attack	02.05.14.02
Hot water line	Hot-dip galvanized steel	Pitting attack	02.05.14.04
Hot water line	Stainless steel (AISI 316)	Pitting attack in welds	04.05.38.01
Hot water line	Copper	Pitting attack	06.05.02.01
Hot water line	Copper	Pitting attack with tubercles	06.05.02.02
Hot water line	Copper	Pitting attack	06.05.14.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Hot water line	Copper	Pitting attack	06.05.14.02
Hot water line	Copper	Local uniform attack under deposits	06.05.15.04
Hot water line (insulated)	Copper	Severe local attack	06.05.25.01
Hot water line	Copper	Material locally worn away	06.05.32.01
Hot water line	Copper	Attack after irregularities	06.05.33.01
Hot water line	Copper	Attack with flow pattern	06.05.34.01
Hot water line	Brass	Red-colored under deposits	06.05.16.03
Hot water line flange	Aluminum	Severe general attack	07.05.14.01
Storage boiler	Hot-dip galvanized steel	Severe local attack	02.05.14.03
Storage boiler	Coated steel	Pitting attack with blisters	03.05.40.01
Storage boiler electrical heating element	Hot-dip galvanized steel	Severe general attack	02.05.14.06
Storage boiler electrical heating element	Stainless steel (AISI 316)	Cracking	04.05.18.01
Storage boiler heating tube	Hot-dip galvanized steel	Pitting attack	02.05.14.01
Thermometer bulb	Brass	Pitting attack under deposits	06.05.16.01
Whistling kettle	Aluminum	Pitting attack	07.05.14.02
06 COOLING WATER SYSTEMS			
Cooling Water Transport Systems			
Cooling water coil	Stainless steel (AISI 304L)	Pitting attack	04.06.12.03
Cooling water line	Carbon steel	Pitting attack with corrosion nodules	01.06.01.01
Cooling water line	Carbon steel	Heavy pitting attack	01.06.04.02
Cooling water line	Carbon steel	Severe pitting attack and tuberculation	01.06.17.03
Cooling water line	Carbon steel	Local excavation	01.06.34.01
Cooling water line	Hot-dip galvanized steel	Overall attack	02.06.14.02
Cooling water line	Copper	Local attack at solder joints	06.06.11.01
Cooling water line	Brass	Pitting attack with red spots	06.06.16.02
Cooling water line	ABS[3]	Cracking	10.06.36.01
Cooling water line flange	Cast iron	Pitting attack under uniform attack	01.06.15.01
Cooling water line flange	Carbon steel	Local severe attack	01.06.17.01
Cooling water line flange	Carbon steel	Pitting attack	01.06.33.01
Cooling water pump bearing	Cast iron	Uniform attack	01.06.14.02
Cooling water pump impeller	Cast iron	Material locally worn away	01.06.34.02
Cooling water pump impeller	Bronze	Material locally worn away	06.06.32.01
Cooling water reducing pipe	Carbon steel	Material locally worn away	01.06.33.02
Cooling water supply line	Carbon steel	Pitting attack with tuberculation	01.01.01.02
Cooling water supply line (subterranean)	Cast iron	Brittle fracture with external graphitically corroded surface	01.06.16.02
Cooling water valve	Cast iron	Outer edge black colored	01.06.16.01
Cooling water valve	Cast steel	Jagged sponge-like metal loss	01.06.33.04
Cooling water valve and bracket	Carbon steel	Pitting attack	01.06.04.01
Corrosion coupon	Carbon steel	Pitting attack	01.06.17.02
Dosing nozzle	Carbon steel	Severe uniform attack	01.06.21.01
Filter bolts	Sherardized carbon steel	Severe uniform attack	02.06.14.01
Sieve	Stainless steel (AISI 316)	Local attack	04.06.13.02
Heat Exchangers (Including Condensers and Evaporators)			
Condenser tube	Stainless steel (AISI 304)	Severe gouging cooling water side	04.06.34.01
Condenser tube	Carpenter 20	Pitting attack	05.06.17.02
Condenser tube	Copper	Network of shallow ditches	06.06.04.01
Condenser tube	Admiralty brass	Striations in internal surface	06.06.04.02
Condenser tube	Cupronickel (90/10)	Perforation at contact with the steel baffle	06.06.14.01
Condenser tube	Admiralty brass	Longitudinal branched cracks	06.06.17.01
Condenser tube	Cupronickel (90/10)	Irregularly shaped patterns of localized metal loss	06.06.34.04
Evaporator tube	Hot-dip galvanized steel	External: pitting attack	02.06.14.03
Heat exchanger anode	Aluminum	Irregular attack	07.06.14.01
Heat exchanger baffle	Carbon steel	Uniform attack	01.06.14.01
Heat exchanger head	Coated carbon steel	Severe attack	03.06.14.01
Heat exchanger jacket	Stainless steel (AISI 304)	Pitting attack	04.06.15.01
Heat exchanger plate	Stainless steel (AISI 316)	Pitting attack	04.06.13.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Heat exchanger plate	Aluminum	Pitting attack	07.06.05.01
Heat exchanger step	Stainless steel (AISI 316)	Pitting attack	04.06.12.02
Heat exchanger tube	Stainless steel (AISI 304)	Pitting attack	01.06.14.01
Heat exchanger tube	Stainless steel (AISI 430)	Pitting attack	04.06.12.01
Heat exchanger tube	Stainless steel (AISI 316)	Pitting attack under barnacles	04.06.15.02
Heat exchanger tube	Stainless steel (AISI 321)	Pitting attack under deposits	04.06.15.03
Heat exchanger tube	Monel	Pitting attack under deposits	05.06.15.01
Heat exchanger tube	Incoloy 825	Pitting attack under deposits	05.06.15.02
Heat exchanger tube	Copper	Pitting attack	06.06.15.01
Heat exchanger tube	Cupronickel (90/10)	Pitting attack under sludge layer	06.06.15.02
Heat exchanger tube	Copper	Longitudinal crack	06.06.28.01
Heat exchanger tube	Cupronickel (90/10)	Some dents	06.06.34.02
Heat exchanger tube	Admiralty brass	Horseshoe-shaped depressions	06.06.34.03
Heat exchanger tube	Brass	Pitting attack with red spots	06.06.16.01
Heat exchanger tube	Aluminum	Severe pitting attack	07.06.17.01
Heat exchanger tube	Aluminum brass	Cracking	06.06.18.01
Heat exchanger tube	Aluminum brass	Cracking	06.06.18.02
Heat exchanger tube	Naval brass	Irregular attack with flow pattern	06.06.34.01
Heat exchanger tube	Inconel alloy 600	Wide deep pitting attack	05.06.17.01
Other Cooling Water Using Systems			
Diesel-engine cylinder block	Cast iron	Severe local attack	01.06.33.03
Diesel-engine cylinder liner	Cast iron	Jagged, cavernous pits	01.06.33.05
Valve seat of combustion engine	Cast aluminum alloy	Pitting attack	07.06.03.01
07 COOLING SYSTEMS			
Ammonia Systems			
Ammonia evaporator pipe	Continuous hot-dip zinc-coated steel	Uniform attack	02.07.02.01
Ammonia transport line	Carbon steel	Pitting attack under insulation	01.07.25.01
Brine Systems			
Heat exchanger tube	Cunifer (70/30)	Horseshoe-shaped attack	06.07.34.01
Pump impeller	Bronze	Severe local attack	06.07.10.01
Freon Systems			
Condenser tube	Aluminum	Fins totally corroded away	07.07.24.01
Evaporator lamellae	Aluminum	Severe deterioration	07.07.04.01
Freon transport line	Carbon steel	Grooved attack	01.07.14.01
Mineral Oil Systems			
Flue gas tube	Carbon steel	Uniform corrosion to flue gas side	01.07.04.01
08 WATER TREATMENT AND SEWAGE TREATMENT PLANTS			
Water Treatment Plants			
Constructure of ion exchanger	Stainless steel (AISI 308)	Pitting attack at the edge	04.08.42.01
Drainage pipe of an ion exchanger	Stainless steel (AISI 304)	Pitting attack	04.08.12.01
Filter wall	Stainless steel (AISI 304L)	Pinholes with red-brown corrosion products	04.08.17.01
Filter wall	Stainless steel (AISI 304)	Severe corrosion along the weld	04.08.19.01
Regeneration pipe of an ion exchanger	Stainless steel (AISI 316L)	Pitting attack and general corrosion	04.08.12.06
Sewage Treatment Plants and Waste Water Lines (Sewers)			
Aeration tank distributor	Hot-dip galvanized steel	Pitting attack under deposits	02.08.15.01
Aerator tube	Coated steel	Flaked-off coating, pitting	03.08.17.01
Duct and fan housing extraction system	Stainless steel (AISI 304L)	Pitting attack with tubercles	04.08.12.05
Effluent tank heating coil	Titanium	Pitting attack	09.08.33.01
Filter pressure plates	Coated cast iron	Severe general attack	03.08.04.01
Setting tank skimmer	Coated carbon steel	Pitting attack	03.08.14.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Sewer	PVC[4]	Cracking	10.08.36.01
Sewer	Plain concrete	Uniform attack	11.08.17.01
Support construction	Stainless steel (AISI 304)	Pitting attack	04.08.12.04
Tube	Hastelloy B2	Severe crater-line attack	05.08.12.01
Waste water line valve	Stainless steel (AISI 410)	Uniform attack	04.08.04.01
Waste water line flange	Stainless steel (AISI 316)	Pitting attack	04.08.12.03
Waste water pump impeller	Carbon steel	Rough eroded surface	01.08.04.01
Worm of a worm gear pump	Stainless steel	Pitting attack with grooves	04.08.12.02

09 AIR CONDITIONING SYSTEMS

Air duct	Aluminum	Pitting attack	07.09.09.01
Heat exchanger tube fins	Aluminum	Severe deterioration	07.09.14.01
Humidifier drop catch	Aluminum	Uniform attack	07.09.03.01
Plenum floor	Aluminum	Uniform attack	07.09.09.02

10 FIRE EXTINGUISHING SYSTEMS

Extinguisher water line (underground)	Carbon steel	Uniform attack	01.10.01.01
Extinguisher water line	Carbon steel	Local attack	01.10.17.01
Extinguisher water line (underground)	Coated carbon steel	Local attack outside	03.10.17.01
Extinguisher water line (underground)	Stainless steel (AISI 316L)	Pitting outside	04.10.15.01
Sprinkler line (dry)	Hot-dip galvanized steel	Pitting attack	02.10.15.01
Valve	Bronze	Material locally worn away	06.10.34.01

11 PROCESS INSTALLATIONS FOR EXTRACTION, PRODUCTION, TREATMENT, STORAGE, AND TRANSPORT OF PRODUCTS AND CHEMICALS

Attack by Acids (See Also 12: Cleaning Systems and Pickling Baths)

Acetic Acid

Storage vessel	Aluminum	Cracking	07.11.18.01
Transport line	Stainless steel (AISI 316L)	Pitting attack	04.11.12.07

Fluoride Acid

Radiant heat shield	Stainless steel (AISI 304)	Pitting attack	04.11.12.11

Formic Acid

Bellevile washers in a distillation tower	Stainless steel (AISI 316)	Uniform attack	04.11.04.05
Transport line	GRE[1]	Disintegration of reinforcements	10.11.04.01

Glycolic Acid

Packing rings of scrubber	Stainless steel (AISI 430)	Thinning by uniform attack	04.11.04.15
Pump bolt	Carbon steel	Material irregularly eroded	01.11.34.06

Hydrochloric Acid

Ball-cock ball	PFA[6]	Fractured	10.11.38.01
Bellows	Hastelloy C	Cracking	05.11.18.01
Bellows	PTFE[2]	Black brittle layer	10.11.04.02
Mixer tube	Hastelloy C276	Uniform attack	05.11.34.02
Nonreturn valve	Stainless steel (AISI 316)	Severe pitting	04.11.12.08
Nozzle of crude distiller dead end	Carbon steel	Local attack with grooves	01.11.04.06
Nozzle of dip pipe	Hastelloy C	Uniform attack	05.11.04.03
Pump impeller	GRE[1]	Local severe attack with fracturing	10.11.34.01
Strainer of vinyl chloride system	Stainless steel (316 L)	Pitting attack	04.11.04.01
Transport line	PTFE[2]	Blistering	10.11.37.01
Transport line	PTFE[2]	Cracks	10.11.28.01
Well tubing	Stainless steel (AISI 420)	Longitudinal attack	04.11.04.10

Hydrochloric Acid with Fluoride

Equipment of distillation unit	Glass-lined steel	Severe local attack	03.11.12.02
Pipe of distillation unit	Glass	Severe overall attack	13.11.12.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Nitric Acid			
Bolts and nuts	Hastelloy C4	Grooved attack and pitting	05.11.42.01
Condenser tube	Stainless steel (2 RE 51)	Grooved attack and pitting	04.11.19.01
Heating pipe	Stainless steel (W.-Nr. 1.4539)	General roughening	04.11.04.07
Pump impeller	Stainless steel (AISI 316)	Granular surface with cracks	04.11.19.05
Pump impeller	Stainless steel (AISI 304)	Partly eroded	04.11.34.02
Reactor wall	Stainless steel (AISI 316/321)	Local attack near the welds	04.11.19.04
Vessel wall	Stainless steel (AISI 304)	Local attack near the welds	04.11.19.02
Nitric Acid and Sulfuric Acid			
Propeller blade	Stainless steel (AISI 304)	Easily deformable	04.11.04.08
Nitric Acid and Phosphoric Acid			
Reactor vessel wall	Stainless steel (AISI 347)	Local overall corrosion	04.11.04.11
Phosphoric Acid			
Autoclave charge pipe	Stainless steel (AISI 316 L)	Uniform attack	04.11.04.02
Baffle	Stainless steel (904 L)	Severe general attack	04.11.34.04
Butterfly valve	Hastelloy C-22	Pitting and overall attack	05.11.04.01
Conveyor belt chains	Carbon steel	Cracks and rupture	01.11.28.02
Drain line	Stainless steel (AISI 316 L)	Grooves	04.11.04.06
Reactor wall	Aluminum bronze	Red color	06.11.16.02
Polythionic Acid			
Nozzle on a cracking furnace	Stainless steel (AISI 304 H)	Irregular cracking, rough surface	04.11.18.15
Sulfamic Acid			
Pump impeller	Bronze	Uniform attack	06.11.04.01
Sulfuric Acid			
Flange	Carbon steel	Severe local attack	01.11.34.03
Heat exchanger tube	Stainless steel (AISI 316 Ti)	Local uniform attack	04.11.04.03
Heat exchanger tube	Stainless steel (AISI 316 Ti)	Uniform attack	04.11.04.04
Pump impeller	Carpenter 20	Material locally worn away	05.11.19.01
Pump impeller	Bronze (CuSn 10)	Uniform attack with flow pattern	06.11.34.03
Pump impeller	Stainless steel (AISI 317)	Uniformly worn down	04.11.34.03
Pump impeller cap	Stainless steel (AISI 316)	Severe pitting attack	04.11.26.02
Spray plate	Copper	Severe uniform smooth attack	06.11.34.02
Stirrer support	Stainless steel (AISI 304)	Uniformly attacked and eroded	04.11.04.09
Strainer	Hastelloy C22	Severe uniform corrosion	05.11.14.01
Stripping column	Lead	Local attack to leakage	08.11.04.01
Transport line	Carbon steel	Grooved attack	01.11.04.03
Transport line	Carbon steel	Grooved attack	01.11.04.04
Transport line	Carbon steel	Pitting attack	01.11.04.05
Transport line	Carbon steel	Selective leaching of the weld	01.11.04.10
Transport line	Carbon steel	Uniform attack	01.11.14.02
Transport line	Carbon steel	Local uniform attack	01.11.34.07
Transport line	Stainless steel (AISI 304)	Severe general corrosion	04.11.04.13
Transport line	Alloy 20	Numerous small pits	05.11.04.02
Valve	Stainless steel (AISI 316)	Severe uniform attack	04.11.04.06
Valve	Stainless steel (W.-Nr. 1.4539)	Severe uniform attack with cracks	04.11.19.03
Mixture of Organic Acids			
Sample cooler	Stainless steel (AISI 316)	Uniform attack of copper solder	04.11.04.12
Attack by Alkalis			
Caustic Soda			
Discharge pipe gas scrubber	PVDF[7]	Cracking beside the welds	10.11.36.01
Flange	Aluminum	Uniform attack	07.11.03.01
Float ball	Copper	Uniform attack	06.11.03.01
Soda			
Pipe bend transport system	Carbon steel	Local attack	01.11.34.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Pump impeller	Titanium	Attack with flow pattern	09.11.34.01
Strengthener around bellow	Stainless steel (AISI 316)	Pitting attack with cracks	04.11.18.04
Transport line	Carbon steel	Local uniform smooth attack	01.11.03.01
Transport line	Carbon steel	Cracking	01.11.18.01
Transport line	GRVE[8]	Resin layer disappeared	10.11.03.01
Transport line	GRPE[9]	Attack to the polyester at the weld	10.11.03.02
Transport line	PVDF[7]	Cracking	10.11.36.02
Sodium Hypochlorite			
Beer can	Aluminum	Partly corroded away	07.11.03.02
Attack by Atmosphere			
Bolt	Steel (34 Cr Ni Mo 6)	Broken	01.11.20.05
Bolt	Zinc-coated steel	Brittle fracture	02.11.22.01
Bolt	Brass	Red discoloration	06.11.16.01
Bursting disc	Stainless steel (AISI 316)	Pitting under deposits	04.11.12.09
Cutter knife	Coated stainless steel	Rusty	12.11.14.01
Distillation column wall (insulated)	Carbon steel	Local severe attack	01.11.25.02
Electric tracing	Copper	Sheathing melted	06.11.25.01
Heat-exchanger tube end	Stainless steel (AISI 304)	Small pits	04.11.17.02
Pipeline hold-down plate	Melamine	Cracking	10.11.29.01
Sealing sleeve	Natural rubber	Cracking	13.11.29.01
Storage tank	Stainless steel (AISI 304)	Pitting attack	04.11.15.01
Transport line (insulated)	Carbon steel	Irregular general attack	01.11.25.01
Transport line	Coated steel	General attack after the coating flaked off	03.11.24.01
Transport line (insulated)	Coated steel	Severe attack at the base	03.11.25.01
Transport line	Stainless steel (AISI 316)	Local cracking	04.11.18.07
Transport line	Stainless steel (AISI 304)	Pitting attack	04.11.12.02
Transport line	Stainless steel (AISI 316)	Pitting attack	04.11.14.01
Attack by Catalysts			
Ball valve	Stainless steel (AISI 316)	Grooved attack	04.11.32.01
Valve rod	Stainless steel (AISI 410)	Material partly worn away	04.11.32.02
Attack by coke			
Thermocouple	Incoloy 800H	Material wear	05.11.32.01
Attack by Crystals			
Fertilizer Crystals			
Wearing plate	UHMW PE[10]	Cracking	10.11.29.02
Salt Crystals			
Paddle	Stainless steel (AISI 316)	Transverse cracks	04.11.18.12
Attack by Cyanide			
Pump impeller	Tin bronze	Severe local attack	06.11.34.04
Attack by Foods and Allied Products			
Ketchup			
Pump casing	Stainless steel (AISI 316)	Pitting attack	04.11.12.01
Transport line	Stainless steel (AISI 304)	Cracking	04.11.18.06
Margarine			
Control valve	Monel	Grooved attack	05.11.34.01
Perfector tube	Nickel-plated carbon steel	Pitting attack	03.11.12.01
Separator tray	Stainless steel (AISI 304)	Cracking	04.11.18.09
Milk			
Can	Tin-plated steel	Black corrosion patches	03.11.14.02
Pump impeller	Stainless steel (AISI 316)	Material worn away locally	04.11.33.01
Spent Grain			
Transport link	Carbon steel	Worn over entire surface	01.11.32.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Vegetable Oils			
Transport line	Carbon steel	Local uniform attack	01.11.04.02
Attack by Gases and Vapors			
Ammonia			
Cap of extraction system	PP[5]	Fractured	10.11.29.03
Heating coil	Stainless steel (AISI 304L)	Severe overall and annular corrosion	04.11.06.03
Carbon Oxide/Dioxide			
Furnace tube cone	Alloy 800	Local pitting attack	05.11.06.03
Lug of a bracket	Carbon steel	Cracking with fracture	01.11.30.02
Pipe wall bottom	Carbon steel	Terraced attack	01.11.02.07
Chlorine			
Filter holder	PP[5]	Cracking and uniform attack	10.11.36.03
Gas inlet pipe of a reactor	Silver	Uniform attack	09.11.08.01
Heat exchanger tube	Zirconium	Uniform attack	09.11.08.02
Off-gas pipe	PTFE[2]	Cracking	10.11.38.03
Combustion and Flue Gases			
Burner front of a cracking furnace	Stainless steel (AISI 310)	Cracking with plugging	04.11.19.08
Heat exchanger tube	Stainless steel (W.-Nr. 1.4772)	Wall thickness reduction with scale	04.11.06.02
Heat exchanger tube	Lead	Creep rupture	08.11.30.01
Shock tube	Stainless steel (AISI 310)	Brittle fracture	04.11.19.09
Hydrochloric Acid Gas (DRY)			
Safety bellows	Stainless steel (AISI 316)	Uniform attack	04.11.04.14
Hydrogen/Hydrogen Sulfide Mixture			
Cladding of reactor	Stainless steel (AISI 316)	Intergranular cracks	04.11.18.13
Hydrogen/Nitrogen/Ammonia Mixture			
Heat exchanger tube	Carbon steel	Laminar fissuring	01.11.20.01
Inlet Header Pigtails	Carbon steel	Intergranular cracks	01.11.30.01
Natural Gas			
Slotted liner of a gas well	Duplex stainless steel	Material worn away	04.11.32.03
Station pipe	Carbon steel	Local attack	01.11.02.03
Transport line	Carbon steel	Pitting attack	01.11.02.01
Transport line	Carbon steel	Material worn away smooth	01.11.32.02
Well tubing	Carbon steel	Severe local attack	01.11.02.02
Well tubing	Carbon steel	Pitting attack and grooves	01.11.02.04
Nitrogen Gas			
Wall of annealing furnace	Stainless steel (AISI 309)	Uniform attack	04.11.06.01
Off-Gases			
Mist separator wall section	Stainless steel (W.-Nr. 1.4466)	Intergranular cracking	04.11.19.10
Oxygen			
Furnace coil	Thermalloy T66	Uniform attack with cracking	05.11.06.02
Sour Gas			
Overhead Line	Carbon steel	Intergranular cracking near the weld	01.11.18.03
Zinc Vapors			
Chain in zinc recuperation furnace	Carbon steel	Flaking-off scale formation	01.11.22.01
Attack by Hydrocarbons			
Ammonium Carbamate			
Condenser hold-down plate	Duplex stainless steel	Selective attack to the austenitic phase	04.11.19.06

SYSTEMS AND PARTS*	**MATERIALS**	**APPEARANCE**	**CASE HISTORIES**
Condenser pipe	Titanium	Cracking and uniform attack	09.11.20.01
Dip pipe of ammonia stripper	Stainless steel (AISI 316 L)	Completely corroded away	04.11.19.11
Benzaldehyde			
Reactor pipe	PTFE lining[2]	Blistering	10.11.37.02
Benzene			
Storage tank	Stainless steel (AISI 304)	Pitting attack	04.11.12.03
Butylene			
Transfer pipe	Carbon steel	Pitting attack	01.11.06.01
Crude Oil			
Heat exchanger expansion bellows	Incoloy 825	Pitting attack under deposits	05.11.15.01
Storage tank	Carbon steel	Grooved attack near weld	01.11.02.05
Well tubing	Coated steel	Local attack	03.11.02.02
Crude Oil Distillates			
Process pipe	Carbon steel	Brittle fracture	01.11.29.01
Ethanol Amine			
Line from reboiler	Stainless steel (AISI 316)	Material locally worn away	04.11.34.05
Hydrocarbons (Not Defined)			
Furnace tube distillation unit	Carbon steel	Coke deposition, reduction wall thickness	01.11.06.10
Radiant coil cracking furnace	Nickel alloy ASTM HP 40	Bulging with cracking	05.11.06.01
Hydrocarbons with Ammonia and Cyanide			
Condenser pipe	Aluminum brass	Transverse cracking	06.11.18.01
Condenser pipe	Aluminum brass	Attack with flow pattern	06.11.34.01
Sparger of reactor	Carbon steel	Cracking near weld	01.11.06.03
Hydrocarbon with Caustic Soda			
Scrubber off-gas line	Carbon steel	Cracking near the weld	01.11.18.04
Hydrocarbons with Halides or Hydrochloric Acid			
Deaerator adaptor	Stainless steel (AISI 321)	Attack with flow pattern	04.11.34.01
Demister material	Stainless steel (AISI 304)	Pitting attack	04.11.12.06
Heat exchanger tube	Stainless steel (various)	Pitting attack	04.11.12.05
Plug-cock plug	FEP[11]	Local damage	10.11.38.02
Rundown pipeline	Carbon steel	Grooved etching	01.11.34.04
Transport line	Stainless steel (AISI 304)	Cracking	04.11.18.02
Transport line	Stainless steel (AISI 316)	Cracking	04.11.18.03
Transport line	HDPE[12]	Cracking	10.11.30.01
Tray clamp	Carbon steel	General attack	01.11.14.01
Wall of alkylation plant	Carbon steel	Blistering	01.11.20.04
Hydrocarbons with Hydrogen			
Ballast plate of platformer	Carbon steel	Blistering	01.11.20.03
Furnace pipe of desulfurization plant	Carbon steel	Cracking near the weld	01.11.20.02
Heater tube	Carbon steel	Pitting attack without deposits	01.11.06.02
Hydrocarbons with Naphthenic Acid			
Furnace tube of distillation unit	Carbon steel	Pitting attack and uniform attack	01.11.34.02
Vapor line of distillation unit	Carbon steel	Pitting attack	01.11.34.05
Hydrocarbons with Sulfur Compounds			
Effluent line of distillation column	Carbon steel	Fractured after reduction of wall thickness	01.11.06.06
Heat exchanger tube desulfurization	Carbon steel	Local reduction of wall thickness	01.11.06.05

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Plant			
Outlet header of overhead condenser	Carbon steel	Stepwise transgranular cracking	01.11.20.07
Process pipe distillation unit	Carbon steel	Uniform attack	01.11.06.08
Reactor test block of desulfurization Plant	Carbon steel	Uniform attack	01.11.06.09
Sidestream line	Carbon steel	General attack	01.11.34.08
Transport line	Carbon steel	Uniform attack	01.11.06.07
Tube sheet of waste heat boiler	Carbon steel	General corrosion	01.11.06.04
Methyl Isobutyl Ketone			
Filter holder	PSU[13]	Cracking	10.11.36.04
Mixture of Chloroform and Carbon Tetrachloride			
Flange seal	EPDM[14]	Swollen and cracks	10.11.39.01
Mixture of Methanol, Acetone, Ketones			
Sealing O-ring	Silicon rubber	Cracking	10.11.30.02
Mixture of Organic Product with Alcohols			
Heat exchanger tube	Copper	Material partly worn away	06.11.33.01
Naphtha			
Furnace pipe	Stainless steel (AISI 310)	Cracking	04.11.28.01
Platformer pipe	Carbon steel	Cracking	01.11.28.01
Organic Solvents			
Stamper	PVC[4]	Degradation	10.11.39.03
Styrene			
Agitator shaft guide block	PTFE[2]	Swelling	10.11.39.02
Attack by Kieselguhr			
Tank bottom near air inlet valve	Stainless steel (AISI 304)	Uniform eroded surface	04.11.32.04
Attack by Salt Solutions			
Centrifuge drum	Duplex stainless steel	Pinholes	04.11.12.04
Injection section of dosing line	Stainless steel (AISI 316 L)	Perforating crack	04.11.18.11
Flange of reactor	Stainless steel (AISI 316 L)	Severe uniform attack	04.11.13.01
Pipe flange	Stainless steel (AISI 308/304)	Pitting attack (intergranular corrosion)	04.11.19.07
Attack by Sulfide			
Guide roller for plastic film	Hastelloy B	Pitting attack	05.11.05.01
Attack by Temperature			
Epicote centrifuge bowl	Stainless steel (duplex)	cracks	04.11.44.01
Attack by Textile Dyes			
Guide bar in textile steamer	Stainless steel (AISI 304)	Cracking	04.11.18.05
Attack by Soil			
Talk bottom	Aluminum	Pitting attack	07.11.15.01
Attack by Water			
Brew Water			
Tank wall	Stainless steel (AISI 304 L)	Small cracks	04.11.18.14
T-piece at brew water tank	Stainless steel (AISI 304 L)	Cavity in weld	04.11.38.02
Cooling Water			
Cooling water/steam delivery line	Carbon steel	Low-branched cracks	01.11.28.03
Food can	Tin-plated steel	Rust spots	03.11.14.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Wall of reactor	Stainless steel cladding (AISI 316 on carbon steel)	Cracking	04.11.18.10
Disposal and Waste Water			
Heat exchanger tube	Inconel 625	Cracking	05.11.18.02
Reactor tube	Nickel 200	Pitting attack and general attack	05.11.02.01
Reducer	Stainless steel (AISI 316)	Pitting attack	04.11.12.10
Station pipe	Coated carbon steel	Local attack near weld	03.11.01.01
Station pipe	Coated carbon steel	Local attack	03.11.02.01
Transport line	Coated carbon steel	Pitting attack near weld	03.11.02.03
Formation Water			
Oil-well casing	Coated carbon steel	External casing corrosion of the mesa type	01.11.02.06
Ground Water			
Storage tank bottom plate	Carbon steel	External local attack	01.11.17.01
Storage tank bottom plate	Aluminum	Local layered swelling	07.11.19.01
Mine Water			
Suction and discharge valve guides of pump	Stainless steel (martensitic)	Crumbling	04.11.20.01
Process Water			
Mixer blade	Stainless steel (AISI 316)	Cracks and rupture	04.11.28.02
Plate of paper mill strainer	Stainless steel (AISI 316)	Pitting attack under deposits	04.11.17.01
Shaft of mixing device	Stainless steel (AISI 316 L)	Cracks with ductile fracture	04.11.28.03
Rain Water			
Autoclave jacket (insulated)	Carbon steel	Cracking	01.11.18.02
Column wall of distillation plant (insulated)	Carbon steel	Local attack outside	01.11.25.02
Tap Water			
Pipeline	Duplex stainless steel	Selective attack of the weld zone	04.11.38.01
Process line (insulated)	Stainless steel (AISI 316)	Cracking	04.11.18.16
Transport line	Stainless steel (AISI 304)	Cracking	04.11.18.01
12 CLEANING SYSTEMS AND PICKLING BATHS			
Ball bearings	Carbon steel	Pitting attack	01.12.42.01
Ball valve	Stainless steel (AISI 304)	Pitting attack	04.12.04.02
Butterfly valve	Cast stainless steel (AISI 316Nb)	Overall attack	04.12.19.01
Caustic pump	Carbon steel	Overall shallow pitting attack	01.12.04.01
Conductivity electrodes	Stainless steel (AISI 304)	Completely dissolved	04.12.26.01
Conveyor plate milk storage system	Continuous hot-dip zinc-coated steel	Uniform attack	02.12.03.01
Fixtures of spray system	Stainless steel (AISI 316)	General attack	04.12.04.03
Heating pipe	Stainless steel (904 L)	Uniform attack	04.12.04.05
Pipe	Incoloy 800 H	Very rough surface	05.12.19.01
Pipe from cleaning circuits	Stainless steel (AISI 304)	Uniform attack	04.12.04.01
Spray nozzles	Stainless steel (AISI 303/304)	General attack	04.12.04.04
13 VACUUM AND COMPRESSED AIR SYSTEMS			
Rejection water pipe of vacuum pump	Copper	External uniform attack, blue colored	06.13.10.01
14 GAS SUPPLY SYSTEMS			
Coupling with indoor piping	Cast iron	Local attack	01.14.14.01
Transport line	Cast iron	Local attack with black color	01.14.16.01
Transport line	Taped steel	Local attack	03.14.17.01
Transport line	Coated steel	Local attack	03.14.26.01
Transport line	Coated steel	Local attack with holes	03.14.26.02
Transport line	Coated steel	Localized attack	03.14.17.02
Transport line	Copper	Local attack	06.14.14.02
Transport line	Copper	Cracking	06.14.18.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
15 ELECTRICAL AND ELECTRONIC COMPONENTS			
Battery cable	Copper	Blue copper corrosion products	06.15.11.01
Electrical switch	Silver-plated brass	Severe attack with blue corrosion products	12.15.24.01
Jacket of an underground cable	Lead	Pitting attack	08.15.26.01
Lamp cap	Brass	Cracking	06.15.18.01
Mirror heating element	Nickel-plated brass	Heavily corroded with blue corrosion products	12.15.24.02
16 CIVIL AND STRUCTURAL CONSTRUCTIONS			
Bridges, Motor Ways, and Tunnels			
Boulevard separation	Reinforced concrete	Decayed structure with uniform attack of the reinforcement	11.16.24.05
Bridge girder	Carbon steel	Layered corrosion	01.16.24.02
Bridge structure	Coated steel	Rusting on edges, bolts etc.	03.16.40.01
Bridge structure	Coated steel	General rust penetration	03.16.40.02
Coastal road post	Reinforced concrete	Local wearing away of the concrete with uniform corrosion of the reinforcement	11.16.24.04
Crash barrier	Painted steel	Flaked-off coating with under-rusting	03.16.24.01
Foot bridge steps	Reinforced concrete	Flaked-off cement, gravel visible	11.16.24.02
Gate railings	Hot-dip galvanized steel	Pitting attack	02.16.12.01
Tunnel wall	Reinforced concrete	Pitting attack	11.16.12.01
Buildings (Excluding Factories)			
Balcony railing	COR-TEN steel	Filthiness of the concrete structure with rust from the railing	01.16.24.01
Facade element of the window frame	Aluminum alloy	Pitting attack underneath rubber strip seal	07.16.13.01
Facade panels	Reinforced concrete	Detached pieces	11.16.24.03
Gallery slab	Reinforced concrete	Uniform, rust layer	11.16.24.01
Grooved floor element	Reinforced concrete	Cracking with rebar corrosion	11.16.12.02
Inner wall	Stainless steel (AISI 304)	Brown patches	04.16.12.01
Outer wall	Aluminum	Pitting attack	07.16.24.02
Roof cover	Aluminum	Pitting attack	07.16.26.02
Roof support	Hot-dip galvanized steel	Local attack under deposits	02.16.12.02
Structural beams	Hot-dip galvanized steel	Gray-veined appearance	02.16.31.01
Weld in structure	Hot-dip galvanized steel	Selective attack of the weld	02.16.24.03
Window sill	Aluminum	White bloom on the surface	07.16.23.01
Glasshouse Structures			
Attachment strips	Electroplated steel	Uniform attack	02.16.24.02
Beam	Continuous hot-dip zinc-coated steel	Uniform attack	02.16.24.04
Industrial Structures and Factories			
Door frame with hinge	Aluminum	Uniform attack on contact surface	07.16.14.01
Grating floor	Hot-dip galvanized steel	Brown rust spots	02.16.24.01
Platform bolt with nut	Sherardized steel	Rusted at our side	02.16.24.05
Roofing	Aluminum	Uniform attack	07.16.24.01
Roof truss	Aluminum zinc alloy	Cracking	07.16.18.01
Various			
Cattle shed support	Hot-dip galvanized steel	Irregular pitting attack	02.16.10.01
Jet screen	COR-TEN steel	Filthiness of the concrete structure with rust from the screen	01.16.24.01
Manure storage pit	Reinforced concrete	Concrete cover dissolved	11.16.17.01
Swimming pool floor	Aluminum	Pitting attack	07.16.12.01
17 STREET EQUIPMENT AND SEPARATING STRUCTURES			
Street Equipment			
Highway sign	Coated steel	General large checking	03.17.40.01
Lamp post	Hot-dip galvanized steel	Brown corrosion products	02.17.24.02
Letter box support	Hot-dip galvanized steel	Brown corrosion products	02.17.24.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Traffic bollard	Hot-dip galvanized steel	Uniformly corroded	02.17.24.04
Waste-bin strips	Zinc electroplated steel	Uniformly corroded	02.17.24.05
Separating Structures			
Barbed wire	Zinc electroplated steel	Rust formation	02.17.24.03
Barrier alongside a road	Hot-dip galvanized steel	Uniform corrosion	02.17.24.06
Fence posts	Hot-dip galvanized steel	Uniformly corroded	02.17.24.04
Wire netting	Zinc electroplated steel	Rust formation	02.17.24.03
18 WASTE AND REFUSE INCINERATORS			
Grid	22% chromium steel	Copper-colored surface attack	04.18.22.01
Inspection hatch	Stainless steel (AISI 316)	Pitting attack	04.18.12.03
Sludge incinerator stack	Stainless steel (AISI 316 Ti)	Pitting attack and razor-sharp attack alongside the weld	04.18.12.01
Stack cyclone	Stainless steel (AISI 316 Ti)	Irregular uniform attack with pitting	04.18.12.02
19 AIRCRAFT			
Compressor blade	Stainless steel (17-4 PH)	Small pinholes	04.19.12.01
Elevator panel	Aluminum alloy	Severe attack in lap joint	07.19.13.01
Fairing (wing fuselage)	Aluminum alloy	Partly corroded away	07.19.19.04
Fitting of helicopter	Aluminum alloy	Layered attack	07.19.19.02
Fuel tank hatch	Aluminum alloy	Pitting attack	07.19.17.01
Lever pin of compressor vane system	Stainless steel (Nitronic 60)	Transgranular fracture	04.19.17.01
Longeron in fuselage	Aluminum alloy	Partly corroded away	07.19.19.03
Outboard rib	Aluminum alloy	Layered attack around the bush hole	07.19.19.05
Side stay bracket	Aluminum alloy	Layered attack around the bush hole	07.19.14.01
Side stay bracket	Aluminum alloy	Through crack	07.19.18.01
Steering wheel	Cast magnesium	General attack	07.19.09.01
Tail plane	Aluminum	Layered corrosion	07.19.19.01
Turbine vane	Cobalt alloy	Pitting attack	05.19.06.01
Wheel housing	Coated aluminum	Thread-like filaments under the coating	12.19.41.01
Window post	Aluminum alloy	Surface flaw	07.19.28.01
20 AUTOMOTIVE SYSTEMS AND TRAINS			
Air horn	Coated die-cast zinc alloy	Coating blistered, zinc alloy corroded	12.20.24.01
Cab front panel	Coated steel	Rusting of spot welded seams	03.20.24.05
Cooling pipe	Extruded aluminum	Thinning with horseshoe pattern	07.20.34.01
Cooling pipe	Extruded aluminum	Line pitting attack	07.20.38.01
Door	Coated steel	Rust bleeding from seam	03.20.24.08
Door handle	Coated die-cast zinc alloy	Coating blistered, zinc alloy corroded	12.20.24.01
Door hinge	Coated steel	Rust bleeding from overlap	03.20.24.09
Door lock	Die-cast zinc alloy	Blocking by corrosion products	08.20.24.01
Door surroundings	Coated steel	Rust on damaged part	03.20.24.03
Exterior mirror	Aluminum coating on glass	Dull nonrelecting surface	07.20.24.03
Fuel tank	Aluminum alloy	Layered corrosion	07.20.19.02
Hose pillar of radiator	Brass	Color fading from yellow to red	06.20.16.01
Hydraulic lift cylinder	Zinc electroplated steel	Overall attack	02.20.13.01
Induction wheel	Brass	Severe pitting	06.20.04.01
Lid of engine cooling block	Aluminum cast alloy	Pitting and overall corrosion	07.20.02.01
Lid of water heat exchanger	Aluminum cast alloy	Severe corrosion near brass tap	07.20.14.01
Light reflector	Varnished steel	Hair-like filaments	02.20.41.01
Mounting panel	Aluminum alloy	White and red corrosion products	07.20.24.02
Oil reservoir	Aluminum	Layered corrosion	07.20.19.01
Rain gutter	Coated steel	Edge corrosion	03.20.24.01
Seam sill box	Coated steel	Rust bleeding from seam	03.20.24.02
Stabilizer	Coated steel	Stone chipping with rust	03.20.24.07
Support bulkhead	Coated steel	Rust in seams	03.20.24.06
Support fuel tank	Coated steel	Rust on welds, screws, edges	03.20.24.04
Thermostat housing	Aluminum cast alloy	Sharp-edged pits and holes	07.20.33.02
Water-cooler lid	Aluminum cast alloy	Flow patter with pitting	07.20.33.01
Wagon wall	Aluminum	Pitting attack	07.20.24.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
21 SHIPS AND MARINE INSTALLATIONS			
Bilge water pipe	Carbon steel	Pitting attack and wall thinning	01.21.17.01
Bottom plate of bilge compartment	Carbon steel	Pitting attack	01.21.17.02
Chain link	Carbon steel	Fractured with pitting attack	01.21.28.01
Fore deck	Coated steel	General soft, dusty surface	03.21.40.02
Gutter on offshore installation	Coated steel	Cracking of coating	03.21.40.01
Seawater ballast tank	Coated steel	Blistering	03.21.40.03
Seawater ballast tank	Coated steel	Blisters and rust	03.21.40.05
Seawater ballast tank	Coated steel	Rusty pinpoint area	03.21.40.06
Seawater ballast tank	Coated steel	Small rusty tubercles	03.21.40.07
Ship's hull	Coated steel	Scaling and peeling	03.21.40.07
Ship's hull	Coated steel	General rusting and coating breakdown	03.21.40.08
Ship's shell	Carbon steel	Pitting attack	01.21.12.01
Sleeve of a ship's propeller shaft seal	Stainless steel (W.-Nr. 1.4464)	Severe pitting attack	04.21.13.01
Sonar system cover	Brass	Local attack	06.21.14.01
22 LUBRICANT SYSTEMS			
Bearing ring	Chromium steel with Babbitt metal	Babbitt metal crumbled out	12.22.35.01
Oil pipes	Stainless steel (AISI 304)	Cracking	04.22.18.01
Roller bearing	Stainless steel (chromium)	Small pieces broken out	04.22.35.01
23 GAS PURIFICATION SYSTEMS			
Activated charcoal filter wall	Stainless steel (AISI 304)	Pitting attack	04.23.14.01
Activated charcoal thermometer bulb	Hastelloy B2	Pitting attack	05.23.14.01
Pump shaft	Stainless steel (AISI 410)	Severe local attack	04.23.34.01
Scrubbing tower discharge pipe	Aluminum	Severe attack beside the weld	07.23.19.01
Scrubbing tower supporting grid	PP[5]	Cracking	10.23.36.01
Scrubbing tower wall	Carbon steel	Cavities in the steel	01.23.20.01
Suction pipe CO_2 scrubber	Stainless steel (AISI 304L)	Pitting attack	04.23.12.01
24 WEATHERING AND LABORATORY TESTS			
In Contact With Water			
Test plates	Various galvanized steel	More or less corroded	02.24.01.01
Test plates	Aluminum alloy	General corrosion	07.24.12.01
Test plates	Zinc electroplated steel	Surface uniformly corroded	02.24.12.01
In Contact With Sulfuric Acid			
Test plates	Carbon steel	Severe corrosion	01.24.04.01
Test plates	Stainless steel (AISI 316)	Severe attack at the cutting edges	04.24.04.01
In Marine–Industrial Atmosphere			
Test plates	Hot-dip galvanized steel and duplex-coated steel	Attack on zinc layer	02.24.24.01
Test plates	Galvalume-coated steel	Local attack	03.24.24.01
Test plates	Hot-dip aluminized steel and sprayed aluminum coating on steel	Pitting attack	03.24.24.02
Test plate	Coated steel	General large checking in alligator pattern	03.24.40.01
Test plate	Coated steel	Rusting at scribe and edges blistering	03.24.40.02
Test plate	Coated steel	Coating is pulling away	03.24.40.03
In Indoor Atmosphere			
Test plates	Carbon steel with an ethyl cellulose-based coating	Thread-like filaments under coating	03.24.41.01
Stress-Relieved Annealing Test (SIS 117101)			
Condenser pipe	Aluminum brass	Numerous parallel longitudinal cracks	06.24.18.01
25 OTHER EQUIPMENT AND INSTALLATIONS			
Impeller of grit-blasting machine	Carbon steel	Grooved attack	01.25.32.01
Pipes of church organ	Tin	Gray spots and locally fractured	08.25.24.01

SYSTEMS AND PARTS*	MATERIALS	APPEARANCE	CASE HISTORIES
Rod in store	Brass	Cracking	06.25.18.01
Sheet material	Aluminum	Stripe-like discolorations	07.25.13.01
Test autoclave wall	Stainless steel (316L)	Cracking	04.25.18.01
Threaded end shower system	Chromium-plated brass	Pitting attack with cracking	12.25.18.01
Wire end with nipple	Carbon steel	Corrosive attack and fracture	01.25.14.01

EXPLANATION ABBREVIATIONS OF PLASTICS

1	GRE	Glass–fiber–reinforced epoxy
2	PTFE	Polytetrafluoroethylene
3	ABS	Acrylonitrile butadiene styrene
4	PVC	Polyvinyl chloride
5	PP	Polypropylene
6	PFA	Perfluoroalkoxy
7	PVDF	Polyvinylidene fluoride
8	GRVE	Glass–fiber–reinforced vinyl ester
9	GRPE	Glass–fiber–reinforced polyester
10	UHMWPE	Ultra-high molecular weight polyethylene
11	FEP	Fluorinated ethylene propylene
12	HDPE	High-density polyethylene
13	PSU	Polysulfone
14	EPDM	Ethylene–propylene dimer rubber

INTRODUCTION

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PART I: GENERAL ASPECTS OF CORROSION, CORROSION CONTROL, AND CORROSION PREVENTION

1. DEFINITION OF CORROSION

The generally accepted definition of corrosion reads as follows:

Corrosion is the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material or its properties.

Attack, decay, or becoming unserviceable by physical, mechanical, or biological causes are therefore excluded. Examples of such phenomena are superheating, wear, erosion, cavitation, swelling of plastics, decay of wood, and so on. On the other hand, corrosion is considered as including combined forms of attack in which the simultaneous occurrence of corrosion by chemical or electrochemical attack and the effect of the other previously mentioned causes leads to an item becoming unserviceable at an above-normal rate. Examples of these phenomena are stress corrosion, erosion corrosion, and corrosion fatigue.

In principle, there are two basic forms of corrosion:

- Electrochemical corrosion or wet corrosion.
- Chemical attack or dry corrosion.

Electrochemical corrosion results from reaction between a metal surface and an ion-conducting environment. Such corrosion can occur if the metal comes into contact with an electrolyte for transport of electric current. Most cases of electrochemical corrosion occur in aqueous environments such as natural waters, atmospheric moisture and rain, wet soil, as well as man-made solutions such as boiler water, cooling water, chemical solutions, and so on.

Corrosion is also possible under dry conditions, namely at high temperatures in gaseous environments, molten salts, or liquid metals. Dry corrosion reactions are direct chemical reactions between a metal and the medium. The corrosion in hot gases is referred to as high-temperature corrosion. Although the environment is nonconductive, this form of corrosion can also be regarded as electrochemical, by which the ionic processes are restricted to the surface of the metal and the corrosion product layers.

In molten salt corrosion, the mechanisms of deterioration are more varied than in aqueous corrosion, but there are many similarities. Liquid–metal corrosion differs fundamentally from aqueous and molten salt corrosion in that the medium is in a nonionized state.

2. THE CONSEQUENCES OF CORROSION

Technical Consequences

Corrosion shortens the lifetime of production assets and transport systems by causing their premature failure, which is sometimes accompanied by accidents. Particularly in the case of a phenomenon such as stress corrosion cracking, this can occur very unexpectedly because here only a very slight material loss leads to severe weakening of the structure.

Another technical consequence of corrosion is disturbance of the proper performance of machinery and equipment, for example, by solid corrosion products becoming lodged between moving parts and blocking them. This can lead to unexpected malfunctions particularly in noncontinuously moving components (e.g., valves).

Another important aspect is the occurrence of leakage, for example, resulting from perforation of a material by pitting corrosion, which as its name indicates is very local and is capable of causing severe consequences even with slight material loss. Besides the loss of product, in certain cases, unacceptable environmental pollution may be caused.

The final items to be mentioned in this brief synopsis of technical consequences are contamination of, for example, process media or foods by dissolved or solid corrosion products.

Economic Consequences

Corrosion is of great importance in economic terms because virtually all measures taken to combat corrosion itself or its consequences entail additional costs. In many cases, normal unalloyed steel could be used on the basis of fabrication or strength considerations alone, were it not that the rapid attack to the steel made its application impossible under the given conditions. However, almost all other materials are more expensive than unalloyed steel. Also, other forms of corrosion control, such as dosing inhibitors, coating the metal with paint, plastics, or other coatings, and cathodic protection, involve increased costs by comparison with a situation in which no corrosion would occur.

In assessing the costs of corrosion, a distinction should be drawn between the direct and indirect costs. Direct costs relate to the costs of inspection and maintenance, the application of protection methods, the premature replacement of structures, and the application of more expensive materials of construction. Indirect costs refer in the first place to loss of production caused by shutting down installations during repair or maintenance. Then there is the loss of product by leakages and the loss of useful effect, for example, by reduced heat transfer due to pipes coated with corrosion products or blockages caused by corrosion products. Contamination of products, leading to their becoming unserviceable or losing value, may also be a major source of economic losses. The indirect costs caused by corrosion may also be regarded as those of overdesign: unfamiliarity with rates of corrosion occurring in practice, insufficient confidence in control measures, or the application of unnecessarily large safety margins often leads to the selection of much thicker or more expensive material than is strictly necessary for constructional reasons. The loss of interest caused by higher investments in corrosion control is also counted as an indirect cost.

To summarize, the costs of corrosion consist of the following:

- Direct corrosion costs
  - Capital: replacement of buildings, installations, and machinery;
  - Design and control: materials selection, corrosion allowances, special treatments, control agents, maintenance, repair;
- Indirect corrosion costs
  - Depreciation and interest losses;
  - Product and production loss, technical support;
  - Additional reserves, insurance.

British and American surveys have shown that the overall—direct plus indirect—costs caused by corrosion amount to approximately 4.5% of Gross National Product. That represents about $500 per annum per capita of the population of the industrialized countries. Roughly 15%–35% of this cost, depending on the line of industry, can be saved by better corrosion prevention and corrosion control.

Social Consequences

There is also a social aspect to corrosion. In recent years, there has been an increasingly growing realization that the world's reserves of energy and raw materials are not infinite. Corrosion results in the loss of large volumes of material every year. Thus, it is estimated that about 10% of the world's steel output, that is approximately 5×10^7 tons per annum, is made for the purpose of replacing corroded steel. In considering this figure, we should remember that, once corroded away, the metal has been completed lost and is no longer available as scrap. Because the use of scrap greatly reduces the amount of energy consumed in manufacturing steel, it will be clear that corrosion leads to additional consumption of energy. Corrosion control is therefore one of the routes toward energy and raw materials conservation. Finally, these consequences include much graver losses—incalculable in economic terms—of health and even life caused by the failure of equipment (explosions) or means of transport (aircraft) due to structural degradation caused by corrosion. Effective corrosion prevention may therefore contribute toward the limitation of economic, social, and personal loss.

3. THE THEORY OF ELECTROCHEMICAL CORROSION

As is generally known, most metals occur naturally in ores. In their relevant natural conditions, these metal oxides and sulfides exist in a thermodynamically fairly stable state.

By adding large quantities of energy, the metal manufacturing industry ultimately converts them into useful materials of construction.

Corrosion amounts in effect to nothing else than the reversion of these metals to their lowest energy state, namely ores (rust), in accordance with the laws of thermodynamics.

Oxidation and Reduction

The commonest form of corrosion (in terms of tons of metal subject to it) is electrochemical corrosion, which can occur, for example, in aqueous solutions, in the atmosphere, and in the soil. Here, the actual corrosion reaction is invariably the anodic or oxidation reaction, whereby a metal dissolves while releasing electrons as ions, for example:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}$$

or is converted into a solid compound, such as

$$2\mathrm{A1} + 3\mathrm{H_2O} \rightarrow \mathrm{A1_2O_3} + 6\mathrm{H}^{+} + 6\mathrm{e}$$

Such a reaction, however, can only proceed continuously if the electrons formed are removed by a cathodic or reduction reaction, such as the formation of hydrogen:

$$2\mathrm{H}^{+} + 2\mathrm{e} \rightarrow \mathrm{H_2}$$

which proceeds in acid solutions; or oxygen reduction:

$$\mathrm{O_2} + 2\mathrm{H_2O} + 4\mathrm{e} \rightarrow 4\mathrm{OH}^{-}$$

which occurs above all in neutral solutions.

The site where the metal is oxidized is called the anode, and the site where a component of the medium is reduced is called the cathode (see Fig. 1). Negative charge (electrons) is taken up at the cathode, which therefore becomes negative, while electrons are discharged at the anode, which therefore reacts positively.

In the case of corrosion in a neutral medium, as soon as the solubility product of the iron and hydroxyl ions is exceeded, a deposit forms, and the various rust-forming reactions proceed depending on the corrosive environment.

In the case of electrochemical corrosion, therefore, both the oxidation reactions and reduction reactions are essential. It will be clear that both reactions keep one another in equilibrium. In other words, if we are able to curb either reaction we automatically reduce the corrosion can be removed from a neutral aqueous system, no corrosion will occur. However, if the water contains an additional quantity of oxidant, the corrosion will increase.

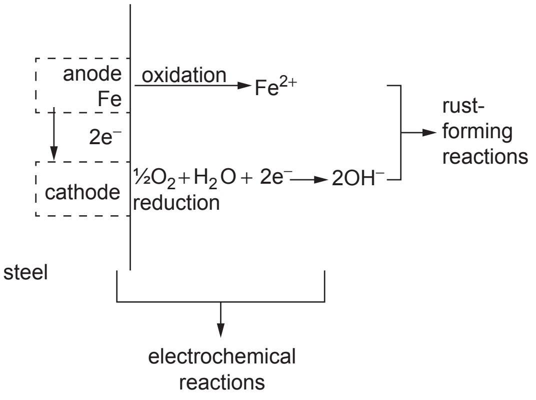

Figure 1 Schematic representation of the electrochemical reactions of steel corrosion.

In the case of acid corrosion, hydrogen formation occurs as reduction reaction, as indicated previously. Generally, no rust-forming reactions will follow because the resultant products are fairly well soluble in acid. Acid corrosion, however, can be considerably intensified by the presence of oxidants (e.g., oxygen). This effect is schematically represented in Fig. 2.

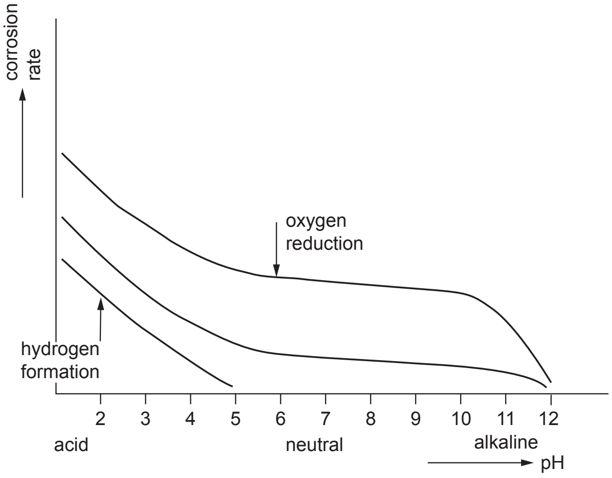

Figure 2 Schematic representation of the rate of steel corrosion as a function of pH and dissolved oxygen.

Oxygen reduction and hydrogen formation are the two most common reduction reactions. However, reduction of oxidizing metal ions, such as Fe_3^+ and reduction of oxidizing anions, such as NO_3^-, can also cause a considerable increase in corrosion.

Polarization and Depolarization

If the reaction of one of the electrodes is blocked by accumulation of reaction products, a state of polarization exists, and the corrosion process will stop. The corrosion will only resume upon depolarization of the anode or cathode. Besides this concentration polarization, there are also other forms of polarization. Examples of concentration polarization are as follows:

- The previously mentioned deposition of corrosion products on the anode, for example, ferrous oxide. This layer may be entrained or dissolved by strong flow or reduced pH: depolarization.
- Hydrogen gas formation at the cathode in an acid environment, also mentioned previously. Supply of oxygen removes the hydrogen film by reaction to water. Here too, flow can entrain the hydrogen bubbles: depolarization.

The Corrosion Potential

The corrosion potential or cell potential is formed by the coupling of two half-cells, as illustrated in Fig. 3.

The left-hand half-cell contains a copper plate in a solution with 1 mol/L Cu^{2+} at 25°C (standard conditions). The same applies in the half-cell with the zinc plate. If the plates are not coupled, a half-cell potential is formed (= electrode potential: plate potential relative to a reference electrode).

The following equilibria are set:

$$Cu \leftrightarrows Cu^{2+} + 2e \; E^\circ = +0.377 \text{ V relative to NHE}^*$$
$$Zn \leftrightarrows Zn^{2+} + 2e \; E^\circ = -0.763 \text{ V relative to NHE}^*$$

NHE, normal hydrogen electrode.

Table 1 lists the standard potentials (at 25°C) of a number of important electrochemical reactions:

When the two metals of Fig. 3 are coupled, a current will flow, and the corrosion potential will be set. For this system, the following applies:

$$E = E^\circ_{Cu/Cu^{2+}} - E^\circ_{Zn/Zn^{2+}} = 0.337 \text{ V} - -0.763 \text{ V} = 1.1 \text{ V}$$

The corrosion potential (cell potential) is therefore the sum of the two electrode potentials (=half-cell potentials).

Table 1 Standard Oxidation/Reduction (Redox) Potentials at 25°C, Measured Relative to NHE

Au	→ $Au^{3+} + 3e$	+1.498
$O_2 + 4H^+ + 4e$	→ $2H_2O$	+1.229
Pt	→ $Pt^{2+} + 2e$	+1.2
Pd	→ $Pd^{2+} + 2e$	+0.987
Ag	→ $Ag^+ = e$	+0.799
Hg	→ $Hg^{2+} + 2e$	+0.788
$Fe^{3+} + e$	→ $Fe^{2+} + 0.771$	
$O_2 + 2H_2O + 4e$	→ $4OH^-$	+0.401
Cu	→ $Cu^{2+} + 2e$	+0.337
$Sn^{4+} + 2e$	→ $Sn^{2+} + 0.15$	
$2H^+ + 2e$	→ H_2	0.000
Pb	→ $Pb^{2+} + 2e$	−0.126
Sn	→ $Sn^{2+} + 2e$	−0.136
Ni	→ $Ni^{2+} + 2e$	−0.250
Co	→ $Co^{2+} + 2e$	−0.277
Cd	→ $Cd^{2+} + 2e$	−0.403
Fe	→ $Fe^{2+} + 2e$	−0.440
Cr	→ $Cr^{3+} + 3e$	−0.744
Zn	→ $Zn^{2+} + 2e$	−0.763
Al	→ $Al^{3+} + 3e$	−1.662
Mg	→ $Mg^{2+} + 2e$	−2.363
Na	→ $Na^+ + e$	−2.714
K	→ $K^+ + e$	−2.925

NHE, normal hydrogen electrode.

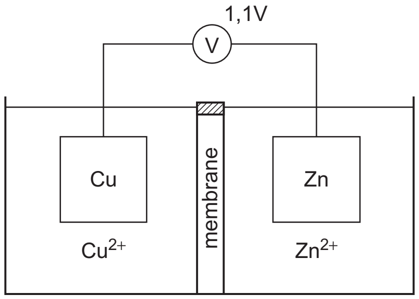

Figure 3 Coupling of two half-cells.

Determination of the current direction shows that when zinc is coupled to copper the zinc dissolves and the copper is deposited:

$$Zn \rightarrow Zn^{2+} + 2e$$
$$Cu^{2+} + 2e \rightarrow Cu \downarrow$$

This yields an important rule in corrosion theory:

In any electrochemical reaction, the half-cell with the lower potential is oxidized, and the half-cell with the higher potential is reduced.

This rule makes it possible to predict what will happen if different metals are coupled together or metals are placed in a solution. The previously mentioned iron in hydrochloric acid dissolves on account of the half-cell potential of Fe/Fe^{2+} being lower than that of H/H^{+}.

Therefore, whether a metal will corrode depends primarily on the driving force of the overall reaction, as:

$$Fe + 2H^{+} \rightarrow Fe^{2+} + H_2$$

This can be expressed as electrical voltages or potentials of the subreactions which together give the overall reaction. Such a reaction is therefore possible when the equilibrium potential of the anodic reaction is lower than that of the cathodic reaction. These equilibrium potentials can be determined with reference to the standard potentials and Nernst's formula.

In situations which deviate from "normal conditions," Nernst's formula can be used to calculate the electrode potential for any reaction, as follows:

$$E = E^{\circ} + \frac{RT}{nF} \ln \frac{[Ox]}{[Red]}$$

where

E : electrode potential
E° : standard electrode potential
R : gas constant
T : temperature in °K
F : Faraday number
n : number of reacting electrons per atom
$\frac{[Ox]}{[Red]}$: concentration (activity) of oxidants and reductants.

It has been discussed previously how two reactions occur in an electrolyte during corrosion to one and the same material (see Fig. 1). The corrodent material is therefore a multiple electrode. The electric potential difference resulting from the two reactions determines the absolute corrosion potential. This cannot be measured as such.

A relative corrosion potential (E_{corr}) can be measured in practice in relation to a reference electrode (stable electrode potential) by means of a voltmeter with a high input impedance. Such a reference electrode is the hydrogen electrode having a defined potential of 0 V.

The corrosion potential is strongly affected by the oxidizing/reducing character of the electrolyte. More oxidizing conditions will result in a higher corrosion potential. However, the corrosion rate cannot be directly derived from this. In most cases, it is possible to state whether the corrosion rate will increase or diminish.

The E/pH Diagram (Pourbaix Diagram)

It appears from the previously mentioned that both the pH and the oxidizing/reducing character of the corrosive medium are important factors determining whether or not metals corrode and also the value of the corrosion potential. M. Pourbaix was the first to represent both variables in an E/pH diagram. Fig. 4 is the simplified E/pH diagram for the iron–water system at 25°C.

From this diagram, it can be seen that below a pH of approximately 9, iron will spontaneously tend to dissolve according to the reaction equation:

$$Fe + 2H^{+} \rightarrow Fe^{2+} + H_2 \uparrow$$

because the equilibrium potential of the reaction $Fe \rightarrow Fe^{2+} + 2e$ (line 1) is below that of the reaction $2H^{+} + 2e \rightarrow H_2$ (line b).

These diagrams enable us to predict

- the spontaneous direction of a reaction;
- the composition of the corrosion products;
- the effect of changes in the medium on the corrosion sensitivity.

The uninterrupted lines indicate the stability ranges for Fe and its corrosion products (Fe^{2+}, Fe^{3+}, $Fe(OH)_2$, and $Fe(OH)_3$). At the same time, this indicates the immunity, corrosion, and passivity ranges.

In the case of a neutral solution (e.g., pH = 7), depending on the corrosion potential, all these three ranges may be involved. Under normal conditions, the corrosion potential will lie in the corrosion range, and the iron will corrode. Strictly speaking, on the basis of this situation, there are three possibilities for reducing the corrosion (see the arrows in Fig. 4).

- The corrosion potential can be reduced into the immunity range (iron stable). This can be done, for example, by impressing a negative voltage (cathodic protection);

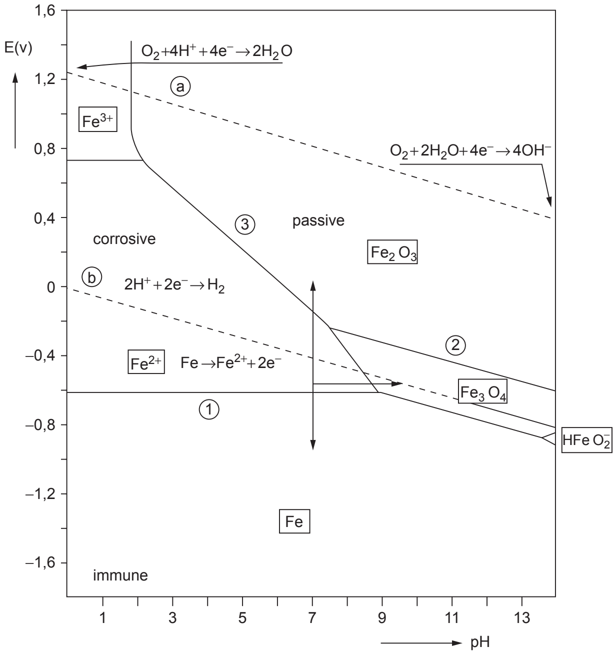

Figure 4 Simplified E/pH diagram of iron in aqueous solution.

- The corrosion potential can be raised into the passivity range. This can be done by impressing a positive voltage or dosing an oxidizing component to the medium which will combine with steel to form a passivating layer;
- Finally, the pH can be increased, so that a passivating iron oxide film (Fe_3O_4) will be formed.

The effectiveness of the previously mentioned methods can vary considerably. Especially in the last two methods, the effectiveness is mainly determined by the protective nature of the passive layers formed. The Pourbaix diagrams are unable to allow for this.

Today, E/pH diagrams are available for many metals and corrosive media at various temperatures. However, these diagrams have only limited validity in combination with the corrosion potential. They only indicate which components are thermodynamically stable in which ranges and whether or not a driving force exists for the electrochemical reactions. They do not refer to the rate at which these reactions proceed.

Corrosion Rate and Polarization Diagrams

A second determining factor for the occurrence of corrosion is the rate of the corrosion reaction. Even if the reaction is possible according to the previously -mentioned thermodynamic criterion, as a rule, problems will only occur if the rate of that reaction is sufficiently high. In electrochemical corrosion, the rate is generally expressed, by means of Faraday's law, as a current density I_{corr} t.

$$I_{corr}t = \frac{nFw}{M}$$

where I_{corr} is expressed in amps, t is the time in seconds for which the current has flowed, nF is the number of coulombs (C) required to convert 1 mole of metal to corrosion product, where n is the number of electrons involved in the metal dissociation reaction, and F is the Faraday constant (96,480 C/mol; M is the molecular weight of the metal in grams; and w is the mass of corroded metal in grams).

The rate of a corrosion reaction depends on various factors, such as the nature of the reactions proceeding, the concentration and supply of the reagents, and the form of the corrosion products. Corrosion rates are often represented in polarization diagrams, in which the current densities of the reactions occurring are plotted against the potential.

$$\begin{aligned} \text{At } E_{corr} \quad I_{ox} &= I_{red} \\ I_{ox} + I_{red} &= 0. \\ I_{corr} = I_{ox} &= I_{red} \end{aligned}$$

where E_{corr} is the corrosion potential, I_{ox} is the oxidation current, I_{red} is the reduction current, I_{corr} is the corrosion current.

Because the net current flow is zero, the corrosion current cannot be measured directly.

If the corroding electrode, however, is taken out of this equilibrium state, a net current will begin to flow. Using a potentiostat, an electrode can be raised to any desired potential, and the associated current measured. The two-electrode system used for corrosion potential measurement is then enlarged into a three-electrode system. The third electrode is needed to allow the current to pass through the corroding electrode. In this way, a potential/current correlation can be found; this is also known as the polarization curve or I/E curve.

If a positive potential is established in relation to E_{corr}, the oxidation current will exceed the reduction current ($I_{ox} > I_{red}$). Conversely, if a negative potential is established, the reduction current will prevail ($I_{red} > I_{ox}$). The principle of the polarization curve is shown in Fig. 5.

The algebraic sum of I_{ox} and I_{red} is measured. At sufficiently high polarization (more than ±50 mV), only an oxidation current or reduction current is measured. The current/voltage correlation is linear in the vicinity of the corrosion potential, and further away it is logarithmic. If, at the same time, the reduction current and oxidation current are placed at the same side of the potential axis, the I/E curve appears as shown in Fig. 6. This is a typical polarization curve as measured in *active* corrosion; for example, iron in hydrochloric acid. The corrosion current at the corrosion potential can be determined

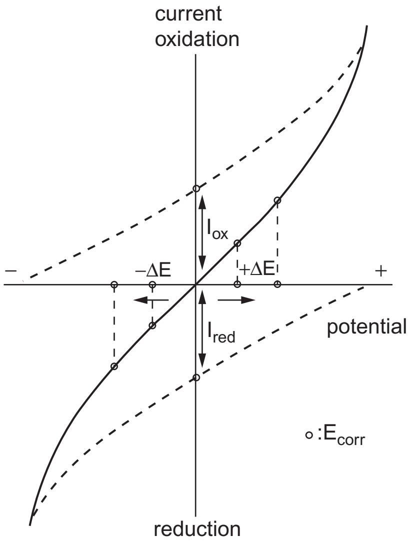

Figure 5 Schematic representation of the polarization curve.

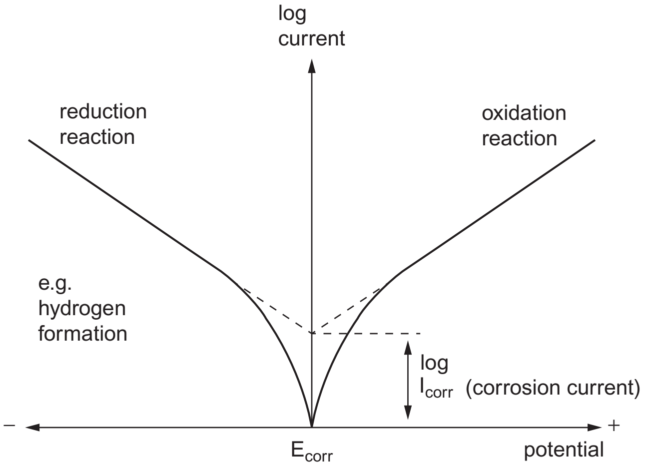

Figure 6 Polarization curve for corrosion in an acid environment.

by extrapolating the logarithmic parts (Tafel slopes). So a method is now available for subsequently deriving the *corrosion rate*. For corrosion in acid, as illustrated in Fig. 6, the transfer of charged particles at the metal/acid interface is the step which determines that rate.

Corrosion in a neutral environment is often determined by the reduction of oxygen, the reacting oxygen being transported to the interface by diffusion. Here, it is the transport of the reagents (oxidants) to the interface which is the step determining the corrosion rate. This results in a polarization curve as illustrated in Fig. 7.

This means that the quantity of dissolved oxygen is more important for the level of the corrosion current than the type of metal. In general, the effect of oxidants on the corrosion rate has already been indicated (see Fig. 2). Fig. 8 illustrates how this affects the polarization curve for corrosion in an acid environment in the presence of, for example, Fe^{3+}.

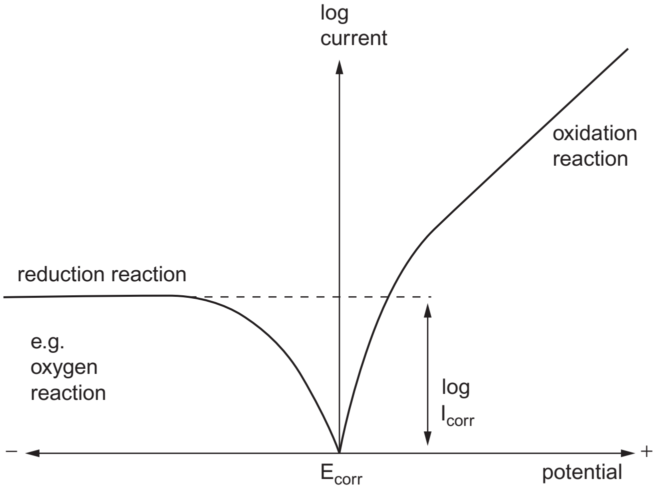

Figure 7 Polarization curve for corrosion in a neutral environment.

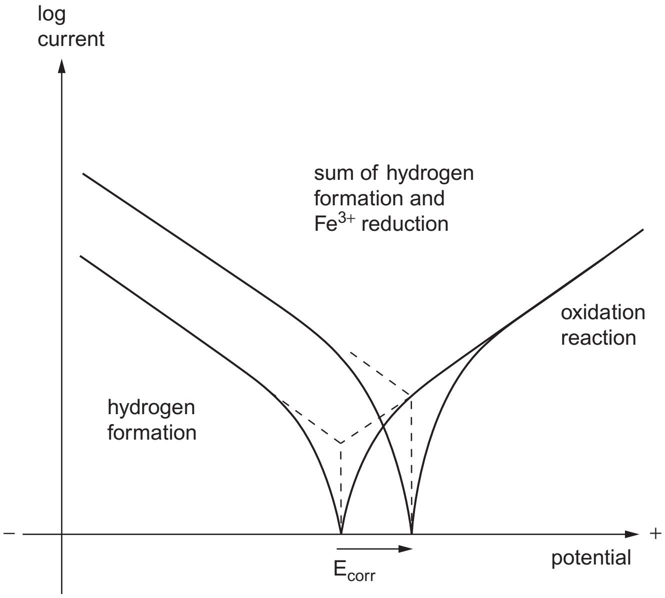

Figure 8 Effect of a second oxidant on the polarization curve.

A cathodic polarization curve on a higher level (the sum of both reduction reactions) raises the corrosion rate and also raises the corrosion potential.

Where the corrosion products form a dense and adhesive layer (such as on zinc, aluminum, and stainless steel), after initial formation of the layer, the corrosion process will come to a virtual standstill.

The metal is then said to be passive. A Pourbaix diagram will also show whether this is possible in principle.

We see, for example, from Fig. 4 that iron can be passive in a range between lines 2 and 3, that is to say at sufficiently high potential and not excessively low pH.

Closing Remarks

Electrochemical reactions are primarily responsible for the process of corrosion. It is a fundamental requirement that both reduction reactions and oxidation reactions take place.

Besides the effect of oxidants as discussed here, other factors such as temperature, rate of movement of the electrolyte, and electrolyte conductivity also play an important role. The influence of these variables can be studied by recording polarization curves. In addition, Pourbaix diagrams often yield highly valuable information. Corrosion is therefore not a mystery but a process that is generally observable and therefore controllable.

4. FORMS OF ELECTROCHEMICAL CORROSION

The classification of electrochemical corrosion into various forms is somewhat arbitrary. The commonest classification is that, according to Fontana and Green, into eight forms of corrosion:

1. Uniform or general corrosion
2. Galvanic or bimetallic corrosion
3. Crevice corrosion
4. Pitting corrosion
5. Intergranular corrosion
6. Selective leaching or dealloying
7. Impact corrosion (erosion corrosion, impingement corrosion, cavitation corrosion, and fretting corrosion)
8. Stress corrosion cracking (including corrosion fatigue)

Besides the forms in which they occur, this section will also deal briefly with the mechanisms of the various corrosion phenomena. For more details and preventive measures, reference is made to Part II, Corrosion Topics, and Part III, Corrosion in Water-Bearing Systems.

Uniform Corrosion

Uniform corrosion, also known as general corrosion, takes place evenly over the entire surface of the metal. This is because the anodic and cathodic reactions are uniformly divided over the surface (Fig. 9).

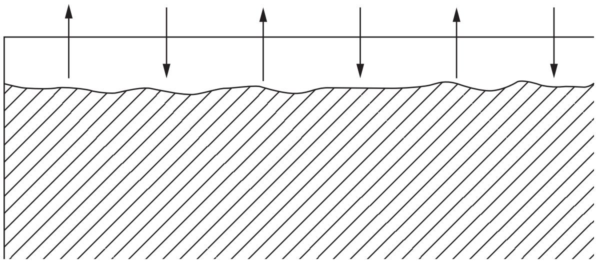

Figure 9 Uniform corrosion.

Uniform corrosion is the commonest—and in terms of weight most important—form of corrosion.

As a result of its regular character and usually well definable rate, lifetime predictions can be made to within reasonable limits of accuracy. Accordingly, general corrosion does not present any particular technical problems, and application of a “corrosion allowance” is possible.

Localized Corrosion

In all other cases, the attack is more localized as a result of the presence of heterogeneous situations. The essence of localized corrosion is that fixed anodic sites on the surface can be indicated where the oxidation reaction dominates, surrounded by a cathodic zone where the reduction reaction takes place.

Localized corrosion is far more treacherous in nature and far less readily predictable and controllable, and it is moreover capable of leading to unexpected damage with disastrous consequences.

Fig. 10 illustrates the difference between uniform (A) and localized (B) corrosion. In the first case, the anodic and cathodic partial currents are homogeneously dispersed over the surface. In the second case, the oxidation reaction is localized. In both cases, the charge of the oxidation process is equal to the charge of the reduction process, calculated over the entire surface.

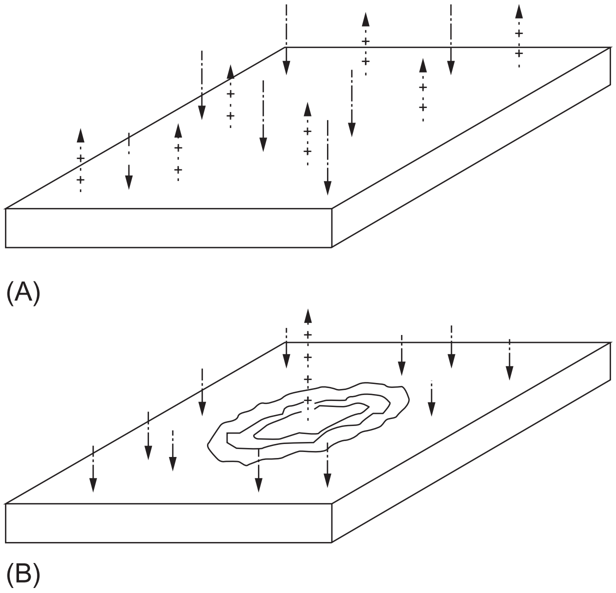

Figure 10 Difference between uniform (A) and localized (B) corrosion.

Galvanic Corrosion

The coupling of two metals with different potentials in a conductive electrolyte solution results in accelerated attack to the anodic metal and reduced attack (so protection) to the cathodic metal. This form of galvanic corrosion is also known as contact or bimetallic corrosion (Fig. 11).

In galvanic corrosion, the entire metal surface becomes anodic due to contact with another more noble metal. At the anode (the non-noble metal), the following reaction takes place to the bivalent metal M:

$$M \rightarrow M^{2+} + 2e$$

At the (noble) cathode, in aerated, neutral, or alkaline media, oxygen reduction will take place according to the following reaction:

$$O_2 + 2H_2O + 2e \rightarrow 2OH^-$$

In certain cases, especially in acid media or in the absence of oxygen, the cathodic reaction can continue, releasing hydrogen:

$$2H_3O^+ + 2e \rightarrow 2H_2O + H_2$$

or, in a neutral medium:

$$2H_2O^+ + 2e \rightarrow 2OH^- + H_2$$

Galvanic corrosion is a very common phenomenon, often in unexpected places. An initial indication of whether galvanic corrosion may occur can be obtained by making use of the previously mentioned half-cell potentials. In practice, however, this entails considerable risks because the standard half-cell potentials are generally determined under quite different conditions to those prevailing in practice.

The combination of the two metals will assume a potential which lies somewhere between the individual corrosion potentials. For the noble metal—with the more negative corrosion potential—this means an increase in potential, leading to a higher corrosion rate of the metal. The reverse applies to the active (less noble) metal. Depending on factors such as geometry and electrical conductivity of the solution, the extra attack will occur near the contact surface or it will be more widespread over the surface. Besides depending on the electrochemical characteristic of the metals, the intensity of the extra attack depends particularly on the area ratio between the more noble to the more active metal. Above all, a small active surface area has an adverse effect first, because of the relatively large potential increase caused by the (large) noble

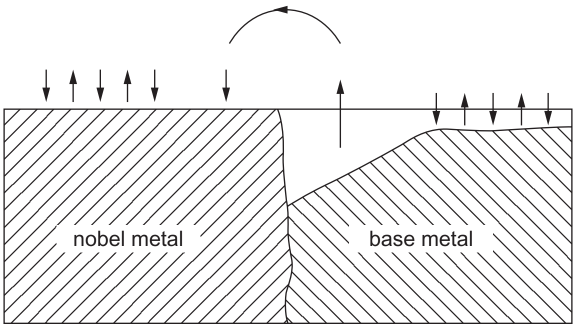

Figure 11 Galvanic or bimetallic corrosion.

surface area, and second, because the extra corrosion current now has to be supplied by a small surface area. This therefore means a high current density of the anodic reaction, and hence a high corrosion rate.

Another form of galvanic corrosion is the pitting galvanic corrosion caused by the deposition of noble metals or metal oxides on less noble metal, which is also known as deposition corrosion (corrosion due to cathodic contamination of the anode).

Crevice Corrosion

Crevice corrosion is a common form of corrosion to which active–passive metals are particularly sensitive. Crevice corrosion is generally observed where small amounts of standing electrolyte solution occur, for example, between flanges, bolts, nuts, and so on (Fig. 12).

Crevice corrosion can also occur underneath corrosion products and other deposits and is then known as under-deposit corrosion. The presence of chloride ions is highly conducive to crevice corrosion. The crevice must be wide enough to admit moisture and narrow enough to ensure a standing medium.

The mechanism is represented as follows:

Take, for example, two metal plates (M), which are riveted together and are located in aerated seawater (pH = 7).

The overall reaction consists of the dissolving of metal M and the reduction of oxygen to hydroxide ions:

oxidation $M \rightarrow M^{+} + e$

reduction $O_2 + 2H_2O + 4e \rightarrow 4OH^-$

Initially, these reactions occur over the entire surface area, also inside the crevice (Fig. 13). After some time, the oxygen inside the crevice will have been consumed due to the absence of flow. The dissolution process of metal M, however, continues inside the crevice (Fig. 14).

This results in a positively charged solution through which chloride ions migrate into the crevice. The metal chloride concentration inside the crevice is increased as a result. These metal chlorides hydrolyze in water, forming an insoluble hydroxide and an acid:

$$M^{+}CL^{-} + H_2O \rightarrow MOH\downarrow + H^{+}Cl^{-}$$

Crevice corrosion is therefore an autocatalytic process.

For reasons unknown, chloride and hydrogen ions accelerate the dissolving rate of most metals and alloys.

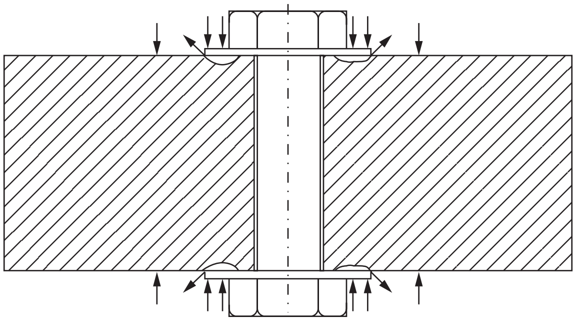

Figure 12 Crevice corrosion.

In view of the role played by the difference in aeration in this form of corrosion, whereby the crevice (or the sludge-covered part) becomes anodic relative to the aerated part outside the crevice (or deposit), it is also referred to as differential aeration cell corrosion (also known as corrosion by oxygen concentration cells).

Pitting Corrosion

Pitting corrosion is a dangerous form of localized corrosion, capable of causing holes to occur in the metal. Pitting corrosion is often difficult to observe because of the small diameters of the pits and because they are often covered with corrosion products (Fig. 15).

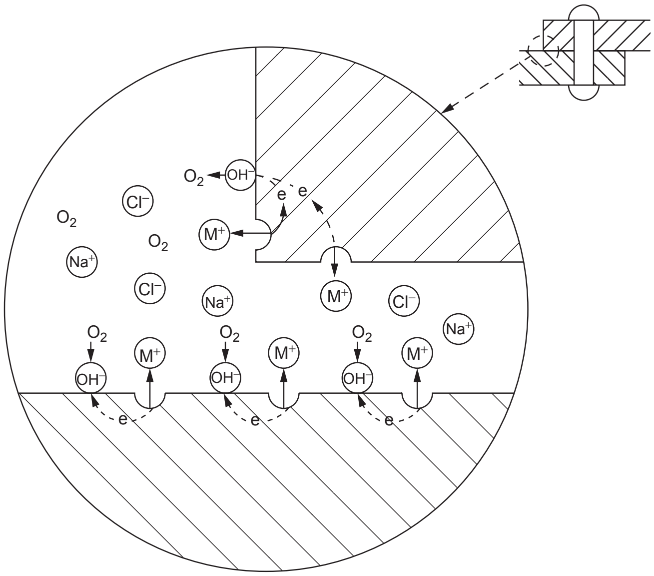

Figure 13 The initial phase of crevice corrosion.

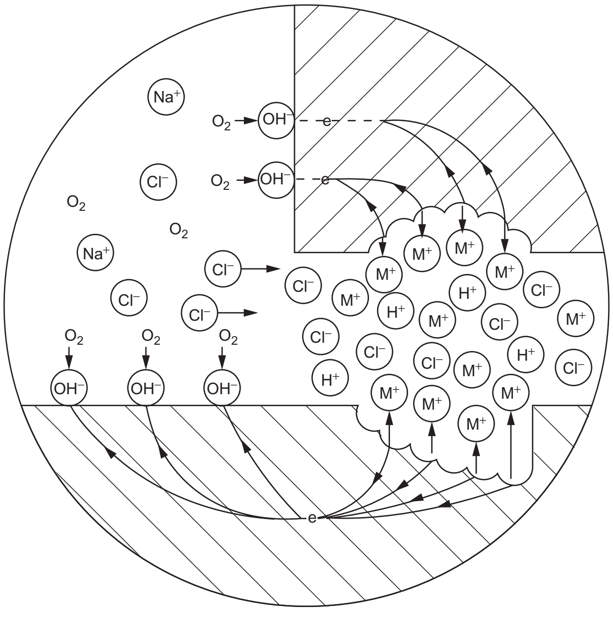

Figure 14 A later stage of crevice corrosion.

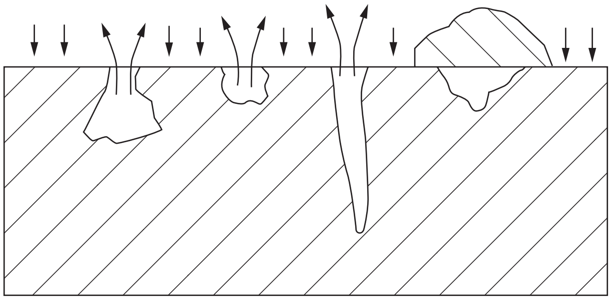

Figure 15 Pitting corrosion.

Pitting corrosion is often difficult to simulate in laboratory tests because of the long incubation times it involves. In practice, perforations in the metal often occur totally unexpectedly. Two types of pitting corrosion can be distinguished, namely:

- pitting caused by halides (generally chloride pitting of stainless steel) and
- pitting of carbon steel caused by oxygen attack

Chloride pitting is also an autocatalytic process in which conditions arise which have a stimulating effect on the process. This process is schematically represented in Fig. 16.

Inside the pit, the metal M dissolves allowing chloride ions to migrate to the positive charge in the pit. The resultant metal chloride hydrolyzes, forming an insoluble hydroxide and hydrochloric acid.

Outside the pit, oxygen reacts to hydroxide. These reactions are the same as those discussed for crevice corrosion. In effect, crevice corrosion is a special form of pitting.

As the mechanism indicates, chloride-containing media have a highly pitting effect. A familiar example is brackish water and seawater, which is often used as coolant and causes much damage. Other halide ions also display pitting tendency. Increasing the flow rate reduces the level of attack by pitting corrosion. Especially, stainless steels and other passivating metals such as nickel, titanium, and aluminum are sensitive to pitting corrosion due to halide ions. These ions penetrate into the protective oxide skin, and they also impede the recovery of damaged sites in that skin. The passive layer is susceptible to damage by a variety of causes (chemical or mechanical) so that the metal becomes locally active. This results in the formation of a galvanic cell with a large passive cathodic surface and a small active anodic surface. The presence of chloride ions can prevent repassivation of the damaged sites, allowing pitting to occur.

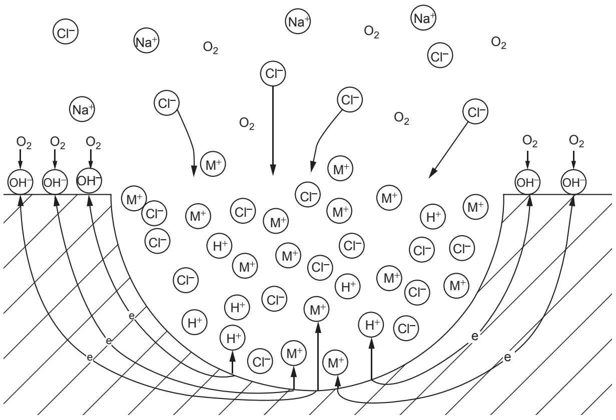

Figure 16 Autocatalytic process in chloride pitting.

The mechanism of oxygen attack to carbon steel is shown in Fig. 17. Local small differences in structure at the steel surface due to minor differences in carbon content, heat treatment, or mechanical deformation allow small anodic and cathodic sites and hence uniform corrosion to occur.

In a neutral to slightly alkaline oxygen-rich medium, the following reactions occur:

At the anode,

- oxidation: $Fe \rightarrow Fe^{2+} +$

At the cathode,

- hydrogen formation: $H^+ + e \rightarrow H$
- depolarization: $H + H + \frac{1}{2}O_2 \rightarrow H_2O$
- oxygen reduction: $\frac{1}{2}O_2 + H_2O + 2e \rightarrow 2OH^-$ hydroxide formation over the entire steel surface:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$\text{further oxidation}: 2Fe(OH)_2 + \frac{1}{2}O_2 + H_2O \rightarrow 2Fe(OH)_3 \downarrow$$

This can further react through FeOOH to Fe_2O_3. Ultimately, a layer of rust forms on the steel (Fig. 18), consisting of a whitish-green/black layer of hydrated ferrous oxide ($FeO{\cdot}nH_2O = Fe(OH)_2$) and a reddish-brown layer of hydrated ferric oxide ($Fe_2O_3{\cdot}nH_2O = Fe(OH)_3$) at the waterside. In between, a transitional area may form consisting of a black magnetic layer of hydrated ferroferrite ($Fe_3O_4{\cdot}nH_2O$), magnetite.

The rust layer, formed of poorly soluble Fe compounds, reduces the diffusion of O_2 to the Fe surface and hence the corrosion rate.

Ultimately, regions will form underneath the rust layer where oxygen is no longer present. This represents the beginning of a new form of corrosion by the development of oxygen concentration cells. This is accompanied by the formation of rust nodules, also known as tubercles, below

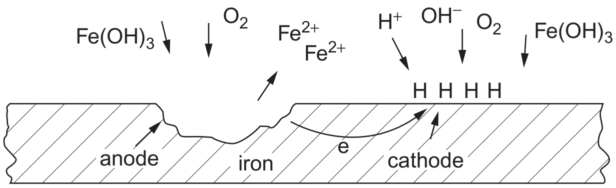

Figure 17 The mechanism of oxygen attack.

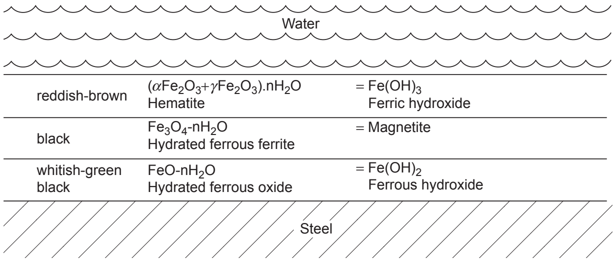

Figure 18 Build-up of the rust layer on steel in oxygen-rich water.

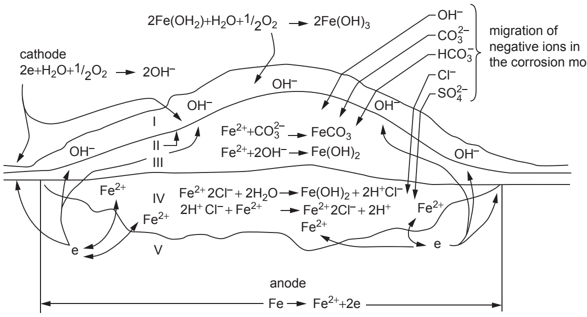

Figure 19 Reaction mechanisms in the development of a corrosion nodule (tubercle).

which there is pitting corrosion to the steel (see Fig. 19). Besides OH^- ions, CO_3^{2-}, Cl^-, and SO_3^{2-} ions also migrate through the tubercle to the positive anode surface, further intensifying the corrosion. These rust nodules tend to form especially in aerated water systems, such as in cooling water circuits, but also in heating systems and steam condensate systems in the case of insufficient oxygen scavenging or deaeration. Although this in effect represents a new corrosion phenomenon ("tuberculation"), this form of pitting is generally regarded as oxygen pitting. The corrosion nodules are not formed in the case of high flow rates or low pH values ($pH < 4$ in strong acids, and pH 5–6 in weak acids, e.g., carbonic acid in condensate lines). In those cases, the corrosion products are either entrained or dissolved.

The tubercle consists of the following:

1. A friable outer crust, consisting of ferric hydroxide (hematite), carbonates, silicates, other deposits, settled particles, and dirt.
2. A brittle black inner skin of ferrous ferrite (magnetite) which reacts as cathode.
3. The friable tubercle core, mainly consisting of ferrous hydroxide and iron carbonate in addition to chlorides, sulfates, and phosphates.
4. A liquid-filled cavity underneath the detached core, caused by the prevailing acid conditions and preventing deposition of oxides and hydroxides.
5. The corroded anodic surface where the iron enters into solution.

Intergranular Corrosion

All metals are built up of small crystals or grains, the surface of one grain being adjacent to that of another grain and thereby forming grain boundaries. Under certain conditions, small areas near the grain boundaries can become much more reactive (because they are more anodic) than the bulk of the grains. The corrosion is able to penetrate metal via the grain boundaries, and it is therefore known as intergranular (also intercrystalline) corrosion (Fig. 20).

Intergranular corrosion can lead to reduction of the strength of constructions by the formation of a structure in which grains have disappeared.

Intergranular corrosion may result from various causes. A well-known example is the occurrence of weld decay in stainless steel in which the attack occurs in a zone at about 5 mm along the weld (refer Part II, Chapter 13).

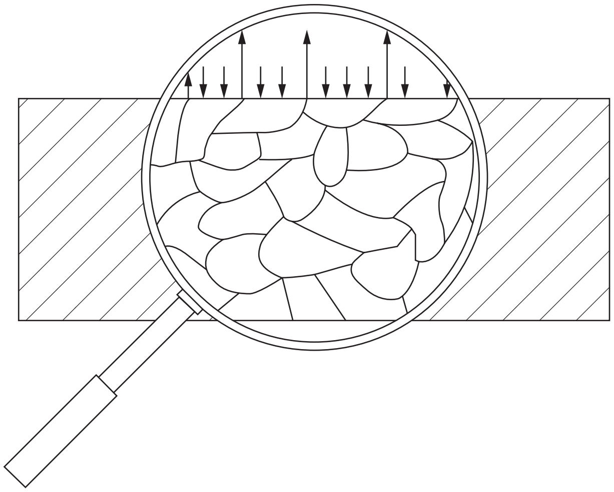

Figure 20 Intergranular corrosion.

Selective Leaching (Dealloying)

Selective leaching is the selective removal of a particular element from an alloy due to the occurrence of corrosion. In many cases, this corrosion is not visible to the naked eye although perforation or fracture may nevertheless occur due to the reduced strength. In this process, the most active component of an alloy will selectively enter into solution, while the rest remains as a porous and mechanically highly weakened mass (Fig. 21).

The best-known example is dezincification of brass, which occurs especially under deposits of dirt. There are two forms of dezincification:

- uniform (layer-type dezincification);
- localized (plug-type dezincification).

The latter form is the most severe. It gives rise to conical pits filled with porous pure copper. Besides the previously mentioned mechanism, another mechanism is reported, namely that the entire alloy enters into solution after which

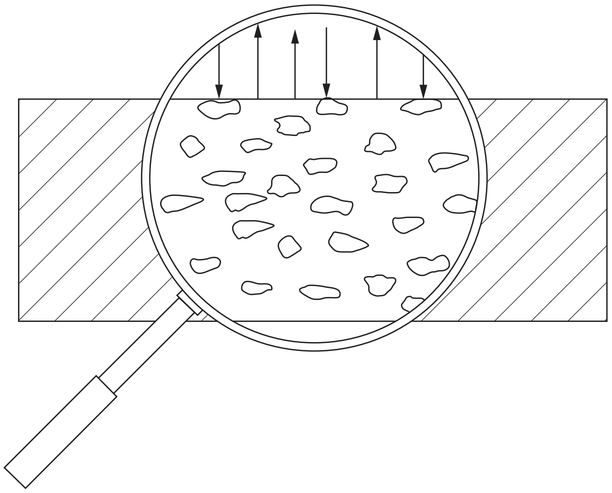

Figure 21 Selective leaching or dealloying.

the CU^{2+} ions are expelled from the solution by zinc from the alloy. The Cu^{2+} ions then deposit as porous copper.

Graphitization (also known as spongiosis) of cast iron, in which the iron dissolves and the graphite remains leaving the cast iron as soft as butter, is also a form of selective leaching.

Impact Corrosion

There are different forms of impact corrosion, namely:

Erosion Corrosion

Erosion corrosion consists of the acceleration of or increase in attack to a metal by differences in the velocity of a corrosive fluid and the metal surface. In general, this velocity is high, and often effects of mechanical wear and abrasion are involved. Erosion corrosion results from violent turbulence at a particular site due to a disruption in the flow pattern, for example, in a pipe downstream of a constriction or an obstacle or in a bend.

The metal is removed from the surface in the form of dissolved ions or dimensionally stable corrosion products which are mechanically worn from the metal surface. Erosion corrosion can easily occur in the case of soft metals or where a protective layer on the metal surface is damaged. Erosion corrosion invariably occurs in the form of intensified general corrosion.

Solid particles or air bubbles in liquids are particularly destructive in the erosion corrosion process. Erosion corrosion can generally be recognized from a distinct flow pattern in the form of smooth pits, grooves, waves, or gullies (Figs. 22–24).

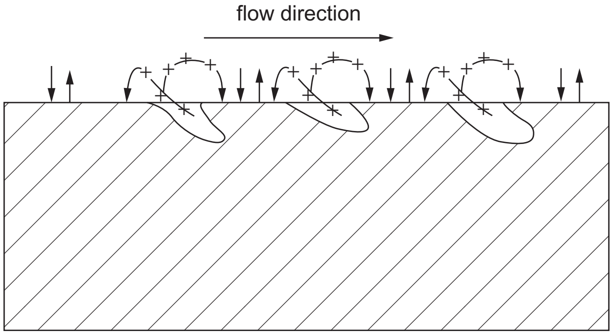

Figure 22 Localized erosion corrosion, attack in a distinct flow pattern.

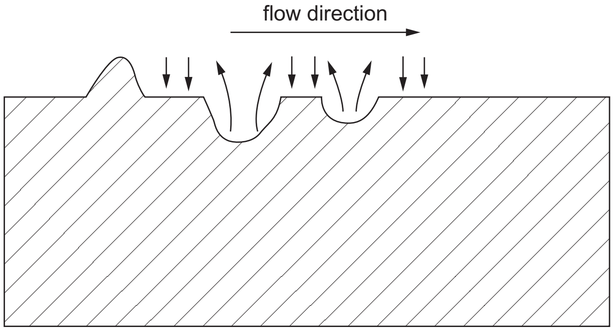

Figure 23 Localized erosion corrosion, attack downstream of irregularity.

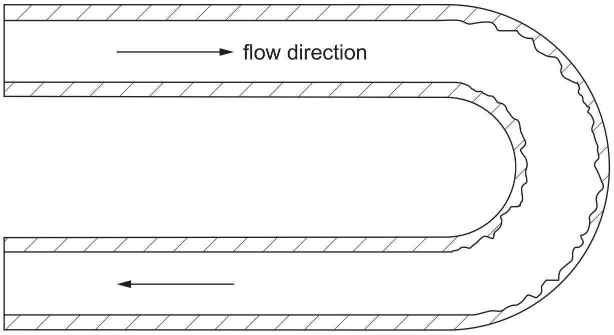

Figure 24 Erosion corrosion, localized grooved attack.

Impingement Corrosion

This is in effect a particular form of erosion corrosion. It can occur, for example, where wet steam is changed in direction by a bend or in a condenser (where it collides against the condenser tubes). The impact of entrained water droplets causes locally severe erosion corrosion in the form of pitting in the case of perpendicular collision or grooves in the case of collision parallel to the surface.

Cavitation Corrosion

This is a particular form of corrosion caused by the formation and implosion of gas bubbles in a liquid close to a metal surface. It can damage a protective film, leading to surface attack (see Part II, Chapter 1).

Fretting Corrosion

Fretting corrosion is the form of attack which occurs when two surfaces are in mutual contact and, while nominally at rest, are nevertheless subject to small periodical movements (Fig. 25). It manifests itself in pits surrounded by powdery corrosion products. Fretting corrosion is affected by the amplitude of slip, frequency of vibration, and loading of the two surfaces.

There are two theories on the mechanism of fretting corrosion. The first theory assumes the formation of microwelds at the contact points, which the vibrations cause to break off. According to the second theory, frictional heat causes an oxide layer to form, which subsequently decomposes.

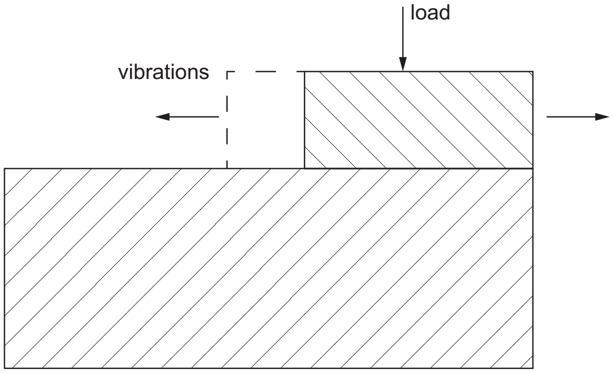

Figure 25 Fretting corrosion.

Stress Corrosion Cracking and Corrosion Fatigue

There are two forms of corrosion in which cracks form in the metal, penetrating inward more or less perpendicular to the surface. This involves an interaction between the metal, its environment, and a mechanical load. Stress corrosion cracking is caused by a constant tensile strain acting at the surface. This corrosion is clearly recognizable by the branched cracking pattern. Stress corrosion occurs in both intergranular and transgranular form (Fig. 26).

The best-known examples are caustic stress corrosion cracking in carbon steel, ammonia stress corrosion (season cracking) in copper alloys, and chloride stress corrosion cracking in stainless steel.

There are many possible mechanisms, chief among which are

- stress adsorption

  This weakens the bonds and allows further cracking of the material due to adsorption of certain substances by stressed bonds at the crack tip.

- The film rupture/metal solution mechanism

Under mechanical load, a protective film in a scratch can rupture and allow a very small anodic area to form, which rapidly dissolves because the rest of the passive metal acts as cathode.

Sensitivity to this corrosion form depends on the repassivation rate relative to the dissolving rate.

In corrosion fatigue, the load is cyclic instead of static (Fig. 27). The fatigue resistance is reduced due to a corrosive medium. Upon fracturing, the fracture surface splits into two parts, namely one with a rough surface (the brittle end fracture) and a smooth part covered with corrosion products. In the case of pure fatigue, that is, without corrosion, the latter part is shiny.

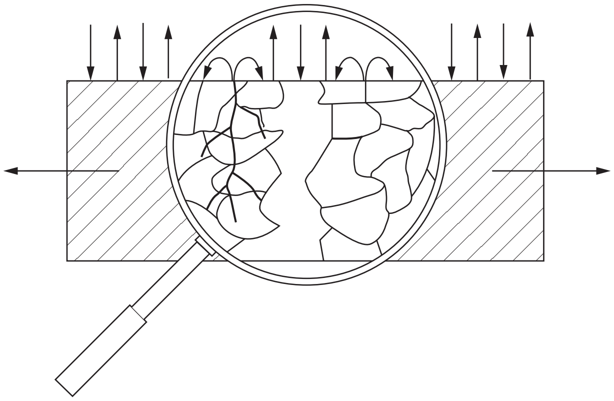

Figure 26 Stress corrosion cracking, left transgranular, right intergranular.

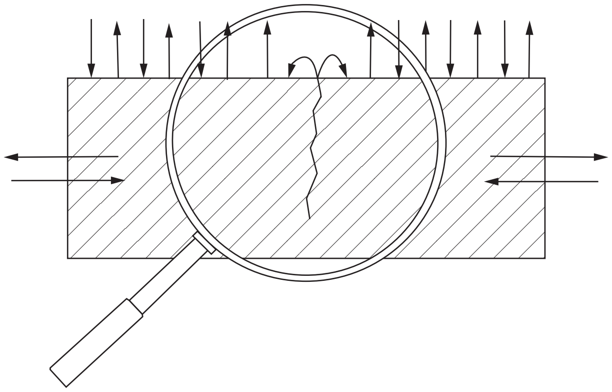

Figure 27 Corrosion fatigue.

In contrast to stress corrosion, corrosion fatigue is not accompanied by branched cracking. Cracking is unbranched and mostly transgranular. Apart from the environment, the cyclic frequency plays an important role in corrosion fatigue (low frequencies are accompanied by more intensive corrosion and therefore tend to accelerate this form of corrosion).

5. FAILURE ANALYSIS AND DIAGNOSIS

A certain systematic approach should be observed in hunting the causes of corrosion. For this purpose, a number of stages can be distinguished, as indicated in the following. The procedure may be simplified, depending entirely on the nature and scale of the problem. The overall result should be a report in which recommendations are made as to how the corrosion can be prevented in future. Sometimes the measures to be taken will demand a high investment, and it will not be possible to implement them at short notice. In such a case, recommendations should be made for both short-term and long-term measures.

Systematics for diagnosing the causes of corrosion:

- Gather data on the corroded part (the system)
  - type of construction (description, drawing, sketch) and purpose;
  - composition of material (type code of metal or alloy);
  - any pretreatment and/or surface treatment (coatings);
  - contact with other metals.
- Gather data on the corroded surface by means of inspection
  - appearance (pitting, uniform, cracking, flow pattern, depth, etc.) to be recorded by visual report, photographs, drawings, and so on;
  - corrosion products present on the surface (chemical analysis);
  - other deposits present on the surface, originating from elsewhere or from the medium (chemical analysis);
  - appearance of coating (intact, pitting, blistering, peeling off, under-rusting, etc.).
- Recording the operating conditions
  - nature of environment (gas, liquid, solid, or mixture);
  - composition of environment (chemical analysis, aggressiveness in relation to the present material, contaminations), constant, or variable (average, minimum/maximum);
  - physical data (temperature, pressure, flow velocity);
  - mechanical aspects: load (static/dynamic, magnitude, tensile/pressure, frequency of load fluctuations);
  - operation (continuous, intermittent, standard/non-standard conditions, repairs, maintenance, inspections).
- Supplementary data
  - age, time to failure of the corroded part;
  - damage occurred before, measures taken (which checks?);
  - is the corrosion specific or more general in the plant or the system?
  - what checks on surface treatment (coatings)?

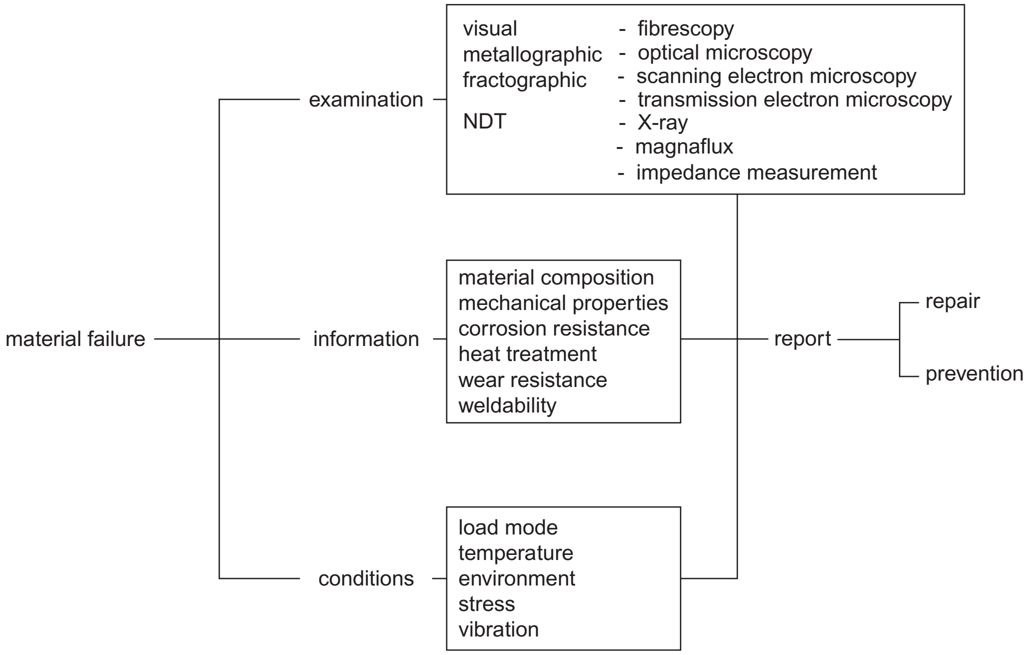

Figure 28 Operating procedure in case of a failure.

- Additional examination
  - material, identification by chemical analysis and mechanical testing, nondestructive testing;
  - corrosion appearance: simple microscopic examination, with application of replica technique;
  - cause of corrosion: metallographic examination, scanning electron microscopy, X-ray diffraction, and so on;
  - corrosion measurements on-site and/or long-term tests and electrochemical analysis in the laboratory;
  - literature search.
- Reporting
  - analysis of the results and statement of the diagnosis;
  - conclusions and recommendations for short-term and long-term measures (to be drawn up in consultation with the user and taking into account the scale of damage).

A summary of the operating procedure in case of a failure is given in Fig. 28.

6. CORROSION CONTROL

For control of the corrosion, a selection may be made from among the following measures:

1. *Choice of a different material.* Application of another more corrosion-resistant material. However, the choice of material is determined not only by the corrosion resistance but also by the mechanical properties and economic considerations.
2. *Design modifications.* By adapting the design, treatment, and construction, the part of the system can be rendered less vulnerable to corrosion.
3. *Application of coatings*. In this way, material can be separated from the environment (metallic, inorganic nonmetallic, or organic coatings to be applied after appropriate pretreatment).
4. *Change of environment,* for example,
   - removal of oxygen and/or raising the pH
   - dosing of inhibitors

   in combination with appropriate checks: change/control of temperature, flow velocity, stray currents.
5. *Intervention in the reactions*, in particular with electrochemical methods such as cathodic protection (with sacrificial anodes or with inert anodes with impressed current) and anodic protection (e.g., to stainless steel).
6. *Changing the procedures.* Introduction or modification of procedures for start-up, shut-down, operation, and stoppage; recommendation concerning inspection, corrosion monitoring, maintenance.

The analysis and diagnosis of failures as discussed in Section 5 is required in the case of corrosion occurring in use. The corrosion problems are solved by the troubleshooting method. It is, of course, far better not to allow matters to reach that stage and initiate the corrosion control much earlier, namely at the design stage of the system. This is known as corrosion prevention.

7. CORROSION PREVENTION AT THE DESIGN STAGE

General

Many cases of corrosion damage are attributable to errors made in the design stage or during the construction of plants or components.

These errors are often caused by

- lack of communication between those concerned;
- lack of knowledge about corrosion and materials;
- lack of or substandard specifications (inspection requirements).

A large number of criteria play a role in the material selection process, for example, process data, application, type of equipment (pump, line, vessel, heat exchanger, reactor, furnace, etc.), constructional possibilities, availability, costs, safety, environment, maintenance philosophy, service life, official code requirements and so on.

In the course of corrosion-conscious design, attention will also have to focus on: design, installation and siting of the item concerned, the prevention of stagnant conditions, crevices, disruptions in flow pattern, undesirable combinations of dissimilar metals, and the effect of joining techniques. The definitive choice of material should be optimized for the present application, in other words, the lowest cost material in terms of effectiveness and safety. It will be clear that the knowledge relating to the previously mentioned criteria covers a range of different disciplines.

A good design with a view to the prevention of corrosion/material failures can only be accomplished following close consultation between the designers (process engineers, equipment engineers), constructors (manufacturers, welding experts), and the materials experts (corrosion, material, and coating specialists etc.).

If any one of these disciplines is found to be lacking or in the case of insufficient specialized knowledge on the matter, efforts will have to be made to supplement this, for example, with the services of external experts. It is important not to rely solely on the supplier's recommendations, but independent consultants should be approached.

Recommended consultation process for the design of a new installation.

The procedure to be followed is broadly as follows:

- The *designers* (process engineers) define the process parameters, such as composition, nature of the substances, temperature, and pressure. It is also very important that they should indicate what may happen during start-up and shutdown or what might happen in the event of a runaway reaction. The presence of trace elements is very important, especially their concentration and whereabouts. These parameters should not be determined on the basis of input/output, but a serious effort should be made to define the process conditions for each piece of equipment or component.
- On the basis of the previously mentioned criteria, the *materials specialist* will specify suitable materials. In doing so, it is important that he should indicate the reasons for making a given (provisional) choice (e.g., literature references, results of corrosion tests, economic considerations, etc.). It is also his task to indicate any risks that may be associated with the choice of a given material and what alternatives there are. At the same time, he should consult with corrosion control specialists to assess the possibilities of using low-cost material provided with a coating and/or cathodic protection or correlated to the dosing of corrosion inhibitor.
- The *constructors* will assess whether the above provisional choice of material could lead to constructional problems; they should also bear in mind availability and costs.

All three disciplines, on the part of both the supplier and the principal, will assess the provisional selection of materials. Their comments will then be reviewed by the materials specialist(s), who will then submit the definitive selection to the others for approval. Finally, in the service stage, it is of the utmost importance that any changes in process operation or start-up procedure are first discussed with the materials expert.

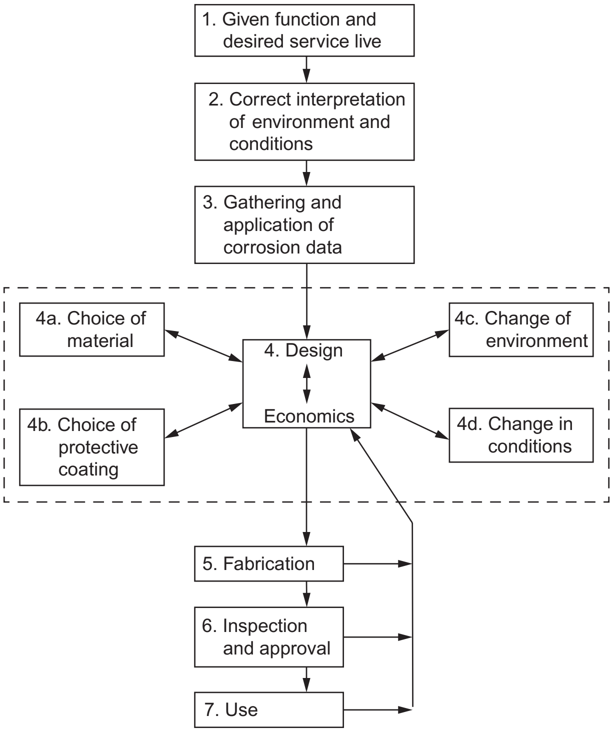

Figure 29 Design scheme.

In practice, it is by no means uncommon, in spite of a sound design on the basis of the original conditions, for such changes to result in catastrophic failures.

Fig. 29 indicates the general aspects of corrosion control and prevention in the various stages, with the necessary feedbacks. It goes without saying that proper consultation with a corrosion specialist remains of the greatest importance.

In practice, unfortunately, we see all too often that corrosion control is only thought of when the design is already cut and dried. This means that, by then, it is virtually never possible to obtain a solution which is optimal from the corrosion angle. That can only be done by integrating corrosion control in the form of corrosion prevention as a basic part of the design process.

Factors Influencing Selection of Materials and Corrosion Resistance

When a material has to be chosen for a given application, that choice depends on a large number of factors apart from corrosion resistance. Fig. 30 illustrates in schematic form a number of the most important of those factors.

However, the corrosion resistance itself depends in turn on a number of factors, the most important of which are schematically illustrated in Fig. 31.

The figure immediately makes it clear that corrosion resistance is not a true material property, in contrast to, for example, strength. First of all, there is the influence of the environment.

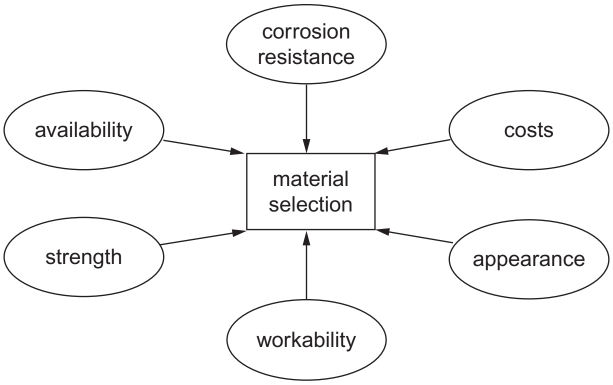

Figure 30 Factors influencing material selection.

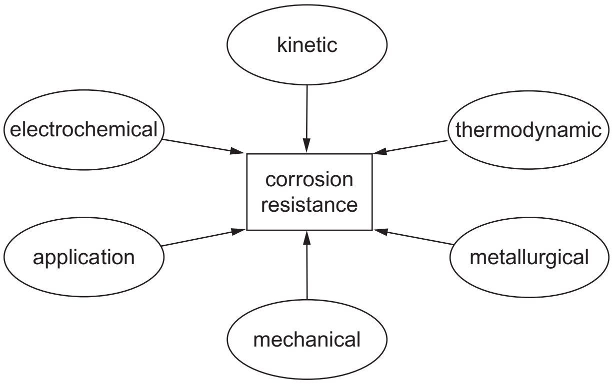

Figure 31 Factors which affect the corrosion resistance.

A metal may be corrosion resistant in a certain environment, whereas the opposite may apply in another environment. Think, for example, of aluminum, which is highly resistant in many aqueous solutions but which will corrode rapidly in a dilute soda solution. Another example is stainless steel AISI 316 (18% Cr, 10% Ni, 2% Mo), which is often reported to be more corrosion resistant than AISI 304 (18% Cr, 8% Ni), and 316 is accordingly selected in preference to 304 for safety reasons. However, in nitric acid and in a number of other acids and oxidizing solutions, 316 is clearly less corrosion resistant than 304.

Furthermore, the decision as to whether a material is suitable or unsuitable is also co-determined by the application and the service life desired. However, even though the service life of the equipment itself may be sufficient, its corrosion resistance may nevertheless be too low, for example, if the corrosion products lead to unacceptable contamination of the product itself or upset the process. For instance, enzymatic and microbiological reactions are sometimes upset by traces of copper ions in the solution as low as 1–5 ppm.

Design Rules

In conclusion, a number of design rules are mentioned to assist the designer because here again the old adage applies that prevention is generally much better and cheaper than cure.

1. Welded connections, provided they are properly made, are generally preferable to riveted or screwed connections, which can often lead to crevice corrosion.
2. Tanks, reactor vessels, and so on should be so designed that they are easy to empty and clean.
3. The design should allow for simple, efficient, and low-cost maintenance and inspection.
4. Ensure that components (e.g., pumps, outlet pipes, etc.) expected to be liable to corrosion are simple and rapid to exchange.
5. Avoid mechanical stresses (to prevent stress corrosion).
6. Avoid sharp bends and constrictions in piping (to prevent erosion corrosion).
7. Avoid contact between dissimilar metals (to prevent contact corrosion).
8. Avoid strong local heating because corrosion generally increases rapidly with temperature, and occasionally evaporation occurs leading to increased concentrations.
9. Wherever possible attempt to avoid contact with aggressive substances.
10. The most general rule is that heterogeneity should be avoided (local stress concentrations, temperature differences, sites where moisture and dirt can accumulate, etc.).

It is of utmost importance that corrosion control should be borne in mind throughout the entire design process and not only thought of toward the end when the design itself has virtually been finalized. By then, optimized corrosion control is generally no longer possible.

The pursuit of optimized corrosion resistance must be an integrated part of the design process.

PART II: CORROSION TOPICS

The various forms of corrosion have already been discussed in Part I, Chapter 4. This second part of the introduction takes a look at 13 common corrosion phenomena in alphabetical order, with reference to the Case Histories as reported in the Atlas. The specific measures which can be taken to prevent these corrosion phenomena from occurring are also discussed.

1. CAVITATION DAMAGE

Cavitation is the process whereby pressure variations in a liquid can in a short period of time cause countless small cavities to form and then implode. The cavities fill with liquid vapor and the gases present in the liquid. In effect, the liquid will begin to boil locally due to the pressure reduction to below the vapor pressure. Just as in the boiling process, the occurrence of cavitation requires the presence of nuclei in the form of contaminants or air bubbles, often entrapped in crevices or grooves in the solid surface.

As soon as the pressure rises back above the vapor pressure, the vapor bubbles will implode causing high-pressure shock waves with pressures up to 400 MPa, sufficient to damage any metal (Fig. 1).

A second theory which has gained ground recently is that, as the bubbles implode, microjets occur and cause pits on colliding with the metal surface (Fig. 2).

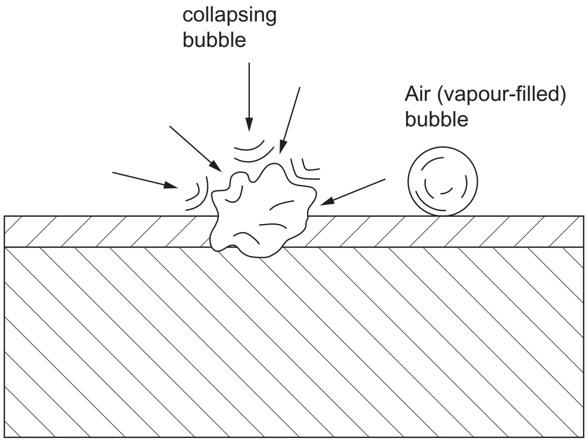

Figure 1 Cavitation damage: imploding bubbles. From Pludek, Design and corrosion control. Reproduced with permission.

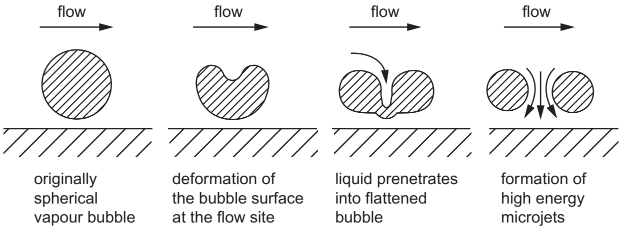

Figure 2 Cavitation damage: microjets.

This form of cavitation damage is known as cavitation erosion, and sometimes it can occur within as little as a few minutes. The eroded metal particles are entrained with the liquid flow, forming a potential source of pure erosion elsewhere in the system. The attack pattern of cavitation erosion sometimes resembles that of oxygen pitting and sometimes that of acid attack. The resultant craters, however, have irregular and sharp edges and a rough internal surface. At an advanced stage, the surface assumes a sponge-like appearance (honeycomb structure).

Cavitation can also be limited to damage to a metal's oxide skin, thereby accelerating the corrosion rate. This is known as cavitation corrosion.

Apart from damaging the metal surface, cavitation can also generate noise, varying from a rustle or the sound of stones striking metal to loud bangs exceeding 100 dB. The vibrations caused by the shock waves can lead to fatigue phenomena, detachment of anchorages, and mechanical fracture. In addition, the formation of bubbles can result in diminished capacity of valves and pumps.

Occurrence

Sites liable to sudden pressure drop are in principle sensitive to cavitation.

Cavitation can occur immediately downstream from valves and orifice plates etc. in a liquid stream (01.04.33.01 and 01.06.33.01/02/04). As it passes such a constriction, the liquid flow velocity increases and, in accordance with the law of the conservation of energy, the static pressure decreases. If this pressure falls below the vapor pressure (saturation pressure) of the liquid, vapor bubbles will form only to implode after the pressure increases as the velocity decreases. Where these implosions occur at the metal surface, they will result in erosion (Fig. 3).

Cavitation can also cause damage to pump impellers if the pressure falls locally to below the vapor pressure in turbulent zones due to too low a supply pressure. The damage is then caused by the vapor bubbles imploding at the delivery side of the impeller (01.01.33.01, 01.02.33.03, 04.11.33.01). This phenomenon is also known at the rear of ship propellers and in hydraulic turbines and also in boiler blow-down lines (01.01.33.03).

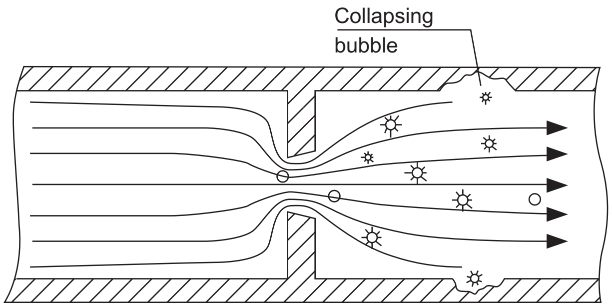

Figure 3 The implosion of vapor bubbles.

In steam-heated equipment and condensate lines, the implosion of vapor bubbles in relatively colder condensate can cause cavitation erosion (01.02.33.01/02/04/05).

Finally, cavitation can also occur as a result of vibration (01.02.33.06 and 01.06.33.05).

Prevention

Like corrosion itself, cavitation can best be controlled by taking measures in the design stage:

- Prevent strong turbulence and pressure variations by appropriate dimensioning.
- Use multistage valves so that the pressure drop is staged.
- Specify smooth finish.
- Use cavitation-resistant materials: cast iron, brass, and aluminum are more sensitive to cavitation than carbon steel. Stainless steels and cupronickel alloys, on the other hand, are less sensitive. Most cavitation-resistant of all are Stellite alloys, while aluminum brass is also fairly cavitation resistant. Both stainless steel and Stellite are used for lining cavitation-sensitive fittings. Of the nonmetals, rubber in the form of neoprene and other elastomers such as polyurethane, being fairly cavitation-resistant coatings, are candidates. Nylon also has good properties in this respect.

In the service stage, the following measures may also be taken if appropriate:

- Maintain sufficient pressure in the entire system; for example, sufficient supply pressure to pumps may also be ensured by means of a bypass with overflow valve from the delivery to the suction side.
- Reduce vibration transfer.
- Prevent ingress of dispersed air.
- Inject or generate larger air or gas bubbles to buffer the implosions in order to limit cavitation damage.
- If corrosion is also involved (cavitation corrosion), cathodic protection and the dosing of corrosion inhibitors may be successful.

2. EROSION CORROSION

Erosion corrosion is a process that occurs regularly in liquids-bearing systems. Even at slight corrosiveness of the medium, the damage can develop strongly within a short period due to synergy between corrosion and—often local—high liquid velocity.

The mechanism of erosion corrosion has already been considered in part I, Chapter 4. Metals which are capable of forming a relatively thick layer of protective corrosion products, such as carbon steel, are more sensitive to erosion corrosion than the conventional passive metals such as stainless steel and titanium. This is because the oxide skins of the latter metals are far thinner and possess a larger adhesion to the metal surface. In addition, soft metals such as copper and certain copper alloys are of course extra sensitive to erosion.

Occurrence

The measure in which erosion corrosion occurs is in fact dependent on two factors: the velocity and corrosiveness of the medium. A high-velocity reinforces the turbulence of the liquid film along the wall and hence the erosion. In this context, obstructions in the flow can also cause turbulence and local erosion corrosion damage. T-pieces, bends, elbow pipes, inlet ends of heat exchanger pipes, pumps, and valves are examples of sensitive sites, as are sites following abrupt diameter transitions, root fusions, inserted pipe ends, and local deposits (Fig. 4). On the other hand, depending on the metal and medium, below a given velocity, no erosion corrosion will occur.

With regard to the corrosiveness of the medium, it may be stated that even a slight degree of corrosiveness combined with sufficient turbulence may give rise to damage. The risk of damage is increased by the presence of solid particles (e.g., sand) or gas bubbles in the liquid. Droplets in a gas stream (e.g., wet steam) can cause damage in the form of pits or grooves, for example, to the outer side of coils: this is known as impingement. Lastly, temperature is also a factor: the higher the temperature, the higher the corrosion rate.

Depending on the type of metal, the aggressiveness of the medium and the turbulence occurring, erosion corrosion can manifest itself in widely varying forms:

Uniform Attack

Uniform attack occurs at high flow velocities but also in aggressive media. The surface can be *smooth* (01.01.34.01, 01.11.34.02/03/07, 05.11.34.02, 06.01.34.01, 06.11.34.02) or *rough* (01.02.34.02, 01.11.34.08, 04.11.34.01, 06.02.34.02).

The same uniform attack is obtained if solid particles are present in the liquid:
smooth (04.11.34.03) or
rough (04.11.34.02/04 and 06.11.34.03), or if particles are present in a gas (01.01.34.02) or if bubbles are present in a liquid (01.06.34.01/02).

Local Attack

Local attack occurs in the case of more local turbulence. That can be in the form following form:
horseshoes (01.01.34.05/06/07, 06.05.34.01, 06.06.34.01/03 and 07.20.20.34.01), or

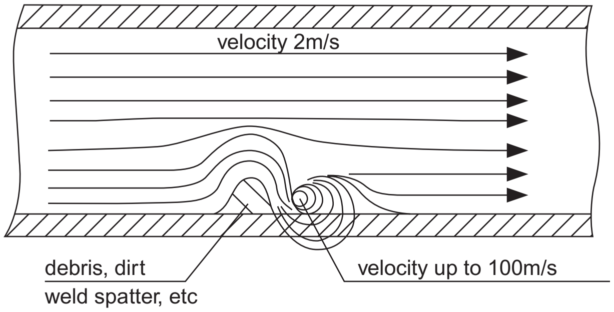

Figure 4 Erosion corrosion downstream from deposits. From Landrum, Fundamentals of designing for corrosion control. Reproduced with permission.

bites (01.02.34.01, 01.11.34.01/06, 04.11.34.05 and 04.23.34.01), or
grooves (01.01.34.04, 01.11.34.04, 04.05.34.01, 04.08.12.02, 05.11.34.01, 06.02.34.01 and 06.10.34.01), or
gouging or dents after deposits (04.06.34.01, 06.06.34.02/04), or
pits (01.01.34.02/08).

All these forms of attack will always be oriented in the flow direction. If the eroded surface is still free of deposits and corrosion products, the erosion corrosion is of recent occurrence.

However, it is not always possible to conclude the basis of the appearance if whether it is a case of erosion corrosion or pure erosion. That is mostly dependent on the local circumstances such as the composition of the medium. Therefore, it is recommended in practice also to consult the case histories mentioned under erosion (see the Phenomena Index).

Prevention

Because there are many factors that can contribute toward erosion corrosion, there are many different measures eligible for controlling this problem. Nine of these are discussed in the following:

- *Reduce velocity and turbulence*
  Because erosion corrosion is directly correlated with velocity and turbulence, the reduction of these is the first consideration. In many cases, that means design modifications, such as:
  - enlarge line diameters and curvature radii of bends;
  - prevent abrupt changes in flow direction and ensure effective streamlining in pipework and equipment;
  - remove or reduce obstructions in the flow;
  - improve the pattern of distribution, for example, by placing baffles in heat exchanger inlets;
  - apply flat aerodynamic or hydrodynamic surfaces and avoid rough surfaces.
- *Apply tough alloys*
  The following list of materials rates in sequence of increasing resistance of erosion corrosion: copper, brass, aluminum brass, cupronickel, carbon steel, chromium steel, stainless steel, and titanium. Stellite alloys, in particular, are exceptionally resistant to erosion.
- *Reduce the quantity of air and solid particles in liquids*
  This can be done, for example, by incorporating automatic deaerators and filters in the circuit. By introducing drains and steam/water separators, the number of liquid droplets in a gas stream (e.g., compressed air or steam) can be limited.
- *Prevent contamination*
  Note that low liquid velocities allow contaminants to deposit. This danger is also present during shutdown periods. Clean regularly.
- *Use protective materials at critical sites*
  Use thick-walled material at vulnerable sites or install interchangeable wearing plates. Protect coil inlets of heat exchangers with abrasion-resistant inserts or ferrules of stainless steel or ceramic material.
- *Reduce the corrosiveness of the medium*
  If corrosion can be prevented, no erosion corrosion will occur. Although there are not many means to this end, a few measures may nevertheless be considered:
  - reduce or remove corrosive ions (e.g., Cl^-) or dissolved gases (e.g., O_2, CO_2, H_2S);
  - lower the temperature
  - improve the pH setting.
- *Dose corrosion inhibitors*
  Dosing with ferrosulfate protects copper alloys, for example, against erosion corrosion in seawater, although it must be borne in mind that these measures are fairly expensive and often environmentally detrimental.
- *Use abrasion-resistant coatings or linings*
  The advantage of this measure is that it eliminates the need for high-cost alloys.
- *Apply cathodic protection*
  This method has only limited use for the internal protection of pipes; only the first 100–150 mm can be protected.

3. EXFOLIATION CORROSION

Exfoliation is a form of corrosion which proceeds laterally from the point of initiation, parallel to the metal surface. Expansion of the resultant voluminous insoluble corrosion products creates a layered swelling appearance that resembles a book which has first been soaked in water and then dried again. Corrosion products are alternated by uncorroded layers.

Ultimately, exfoliation occurs. Above all, aluminum alloys are sensitive to this form of corrosion. Exfoliation proceeds along the grain boundaries so that it is a form of intergranular corrosion (Fig. 5).

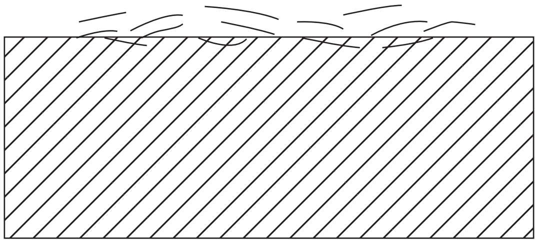

Figure 5 Exfoliation corrosion.

Occurrence

Exfoliation occurs particularly in alloys in which an extended crystal structure has formed parallel to the surface during the fabrication process (e.g., cold forming). This corrosion is promoted by an unfavorable distribution of precipitates along the grain boundaries during the solidification process. Exfoliation corrosion occurs particularly in a slightly acid aggressive atmosphere or moist soil and where aluminum is used in combination with a more noble metal (galvanic corrosion).

Also, particularly extruded aluminum products of the 2000 series (copper–magnesium alloys), the 7000 series (zinc–copper–magnesium alloys) and certain cold-worked products of the 5000 series (magnesium–manganese and chromium alloys) are extremely sensitive to it.

Cupronickel alloys, notably 70Cu-30Ni and 80Cu-20Ni alloys, are sensitive to exfoliation.

The wide-scale use of aluminum alloys in the aircraft industry has yielded a number of cases of practical experience with exfoliation of aluminum (07.19.19.01/02/03/04/05). However, this form of corrosion also occurs in the automotive industry (07.20.19.01/02) and aluminum storage tanks.

Examples of exfoliation in other alloys are 01.16.24.02 and 06.01.16.02.

Prevention

Heat treatment can improve exfoliation resistance in aluminum alloys because it improves the distribution of the precipitates.

Another possibility is to use more resistant materials. Aluminum alloys 1100, 3003, and 5052, for example, are more resistant. The same applies for the cupronickel alloys 90Cu-10Ni and Monel (70Ni-30Cu). Addition of 4%–5% iron and manganese also renders cupronickel alloys less sensitive to exfoliation.

4. FATIGUE AND CORROSION FATIGUE

Metal exposed to *cyclical loading* tends to crack: this phenomenon is known as *metal fatigue* (refer to Part I, Chapter 4). This cracking, which ultimately leads to fracture, occurs after a large number of cycles at a stress below the limit of elasticity. Before fracture occurs, the material exhibits cracking (01.11.28.01, 04.01.28.01, and 07.19.28.01). The fracture plane is characterized by a smooth and shiny part alongside a part with a rough surface, the latter resulting from the brittle fracture which occurs when the limit of elasticity is reached in the remaining material (04.11.28.03).

Corrosion fatigue occurs when there is a combination of corrosion and fatigue, and it can be defined as the reduction of fatigue resistance by the effect of a corrosive medium. In this case, a shiny part of the fracture plane is absent because the plane is covered with corrosion products (01.01.28.01, 01.21.28.01, 04.11.28.02). However, corrosion products need not necessarily be present in the crack, while equally, they may accumulate in a pure fatigue crack. Corrosion fatigue should not be confused with *stress corrosion cracking*. The distinction between the two is based on the nature of the load on the metal. In the case of stress corrosion cracking, there is a *static load*. The crack resulting from corrosion fatigue in carbon steel is generally transgranular and is unbranched or sparsely branched.

In aluminum and copper alloys, however, cracking is often intergranular (06.06.28.01). In case of alternating high and low temperatures, also causing stresses, the occurrence of thermomechanical fatigue is possible (01.02.28.01, 01.04.28.01, 01.11.28.03, 04.01.28.02, and 04.11.28.01).

Influencing Factors

Installations

Corrosion fatigue only attacks installations which can be exposed to cyclical loads. These include, for example, certain components of aircraft, drilling platforms, boilers and steam turbines, above-ground telephone cables, conveyor lines, rotating machine parts, and internal valve springs. Corrosion fatigue can therefore occur industrywide.

Stresses

It is self-evident that the growth rate of a corrosion fatigue crack increases with the level of the alternating tensile/pressure load. Whereas the frequency of the alternating load plays no role in ordinary fatigue, it is nevertheless very important in corrosion fatigue. At low frequencies, the more prolonged contact between the crack surface and the electrolyte leads to an increased effect of the corrosion on the crack growth rate. The higher the frequency, the slower corrosion fatigue cracks will grow.

Environment

A corrosive medium will promote both crack initiation and crack growth rate in corrosion fatigue. Almost all fatigue cracks originate at the bottom of pits. Especially oxygen- and chloride-containing environments are conducive to this form of corrosion. Aircraft which are operated on regular *trans*-ocean flights and are exposed to the saline maritime atmosphere in the process will therefore sooner experience corrosion fatigue than aircraft flying continental routes. As a general rule, as chemical activity of the medium increases, the metal's resistance to corrosion fatigue decreases. Temperature increases will also accelerate crack growth.

Metal Composition

Although the addition of small amounts of Cr and Ni to steel increases both its general corrosion resistance and tensile strength, nevertheless unalloyed steel can be less sensitive to corrosion fatigue. Of course, the electrode potential of the metal in the medium concerned and, above all, its resistance to pitting corrosion play an important role.

Although in ordinary fatigue, crack initiation is impeded by a high tensile strength, this does not apply to corrosion fatigue because in this case, it is the corrosion that initiates cracking. Moreover, once initiated in a metal, a crack will propagate faster with rising tensile strength.

Prevention

- *Use more resistant materials*: copper and copper alloys are generally speaking more resistant to corrosion fatigue than carbon steel and aluminum
- *Improve ductility and impact strength*
- *Improve the design*, so as to reduce the stress and number of stress cycles. Avoid abrupt changes in diameter and sharp angles. Use butt welds instead of fillet welds in view

of the latter's greater sensitivity to corrosion fatigue. Avoid internal stresses. Enlarge the dimensions, mass, or strength of critical components.
- *Ensure a sufficiently flexible construction* in order to absorb excessive stresses due to thermal expansion, vibrations, shocks, and load and pressure variations. Avoid vibrations.
- *Avoid rough surface finishes and sharp edges, as these can initiate corrosion fatigue.*
- *Increase fatigue resistance* by stress relief annealing or by shot peening, hammering, rolling, and so on in order to create pressure stresses. Corrosion fatigue resistance can also be improved by means of nitriding and carburizing.
- *Increase corrosion resistance* by applying coatings and/or cathodic protection or reduce the corrosiveness of the medium, for example, by means of corrosion inhibitors.

5. FILIFORM CORROSION

Filiform corrosion is an omnidirectional thread-(hair-, worm-) shaped attack to a metal underneath the coating, which cracks open locally due to the formation of corrosion products. This attack occurs underneath lacquer, varnish, and paint coatings especially on steel (e.g., coated steel cans), aluminum (e.g., in the building sector, in the past commonly in aircraft [12.19.41.01], and sometimes in aluminum packaging foil) and magnesium. Filiform corrosion can also occur underneath polyurethane, linseed oil, various alkyd resins, ureum resins, and epoxy springs.

In aircraft, this corrosion occurs particularly when many hours are flown in hot countries, in patrol aircraft flying low above the sea, aircraft making many transoceanic flights, or standing on coastal airfields. This is caused by the elevated atmospheric salt concentration levels. Besides outside atmosphere, filiform corrosion can also occur in humid indoor atmosphere (03.20.41.01 and 03.24.41.01).

Apart from causing a less than aesthetic appearance, filiform corrosion is not normally disastrous because of the limited depth of attack. An exception to this is aluminum packaging foil, which can corrode through entirely, leaving the packaged goods no longer air-tight and moisture-free. In other cases, filiform attack to coating can lead to further corrosion of the metal.

Mechanism

Although researchers disagree as to the exact mechanism, there is a strong suspicion that its occurrence is fairly directed correlated with coating procedures which are incompatible with what has become accepted practice in recent years. Improper cleaning, use of contaminated rinsing agents, failure to check the conversion coating bath for proper strength, and accumulation of impurities all contribute toward operational failure both in the form of filiform corrosion and other forms of top coat exfoliation.

It is suspected that coating defects, mechanical damage of the coating, or moisture diffusing through semipermeable lacquers are the driving forces behind this corrosion. They are thought to be capable of forming oxygen concentration cells. Occurrence of this corrosion is conditional on the presence of a moist (relative humidity 60%–95%), oxygen-containing atmosphere at a temperature of 20–35°C. The "head of the worm" reacts acid (pH 1–4) and attacks the metal. Acid contaminants in the atmosphere, such as chloride, sulfate, sulfide, nitrogen oxides, and carbon dioxides, intensify the corrosion.

The width of the "threads" can vary from 0.05 to 0.3 mm (average 0.2 mm), while the propagating rate over the surface is somewhere between 0.01 and 0.85 mm/day (average 0.2–0.4 mm/day). The depth of the attack to the metal is not severe, but it may rise to 15 μm. These figures depend of course on the metal, the coating type, the relative humidity, and the corrosiveness of the environment.

Prevention

In order to control this corrosion, the user should observe the following points:
- ensure optimized pretreatment of the metal surface to diminish the risk of coating defects;
- galvanizing the metal prior to coating or treating it with zinc or chromate primers greatly increases corrosion resistance;
- duplex coating systems make the metal less sensitive to filiform corrosion;
- maintain the level of relative humidity below 60%. However, this applies only in the case of long-term indoor storage;
- check whether a more resistant uncoated metal could be selected: for example, copper, stainless steel, or titanium.

6. GALVANIC CORROSION

Two hundred years ago, Luigi Galvani and Alessandro Volta discovered the phenomenon known as galvanic corrosion, also referred to as contact corrosion or bimetallic corrosion. Where electrical contact exists between dissimilar metals which are moreover in contact with the same conductive environment (electrolyte), the less noble metal (anode) will be attacked. The other metal, the cathode, is protected by this. This is the principle of cathodic protection of metals.

In practice, when selecting materials for installations, the rules for the application of dissimilar metals are regularly ignored, so that galvanic corrosion is a common corrosion phenomenon.

For the mechanism of galvanic corrosion, refer to Part I, Chapter 4.

Conditions for the Occurrence of Galvanic Corrosion

Galvanic corrosion can occur if the following conditions are met:
- *An electrolyte is in contact with both metals.* This electrolyte need not always be aggressive toward each metal. It may

take the form of a quantity of liquid in which both metals are submerged, but equally a condensed film or a moist solid, such as soil, salt deposits, or corrosion products, can act as an electrolyte.
- *An electrical connection exists between the two metals.* Generally, this does not mean direct physical contact between the metals. That is unnecessary as long as current can somehow pass from one metal to the other. The connection itself need not necessarily be submerged in the electrolyte.
- *A sufficient potential difference exists between the two metals*, so that a galvanic current of some significance will occur.
- *The ability of any of the cathodic reactions listed in Part I, Chapter 3 to proceed* on the more noble of the two metals. In most practical situations, this amounts to the consumption of dissolved oxygen.

Factors That Can Affect the Rate of Galvanic Corrosion

The corrosion behavior of a bimetallic couple is determined by the corrosion potential of each metal individually in the electrolyte present. On that basis, galvanic series have been compiled in which metals and metal alloys are classified from noble to non-noble in a given environment, generally seawater. Interpretation of these galvanic series, however, requires some caution. The extent of the potential difference in no way affects the rate at which the reactions will proceed because it also depends on a number of other factors, such as:
- polarization effect;
- composition of the electrolyte;
- aeration and flow rate;
- surface area ratio.

The Polarization Effect

By polarization is understood any phenomenon that impedes or totally blocks the outward migration of metal ions from the anode or of electrons from the cathode. Examples are the deposition of zinc hydroxide on a zinc anode and the formation of a passivating oxide skin on stainless steel or titanium acting as a cathode. Adsorption of hydrogen causes polarization of the cathode. The commonest form of polarization is concentration polarization, which results from an elevated metal ion concentration at the anode or increased OH concentration (pH increase) on the cathode. The latter increase can lead to hardness deposition, whereby the corrosion is additionally inhibited (by the formation of a protective chalky-rust film). In cases of galvanic coupling, the polarization of the reduction reaction at the cathode is dominant.

The Electrolyte

The composition of the electrolyte greatly affects the rate of galvanic corrosion. High conductivity tends to promote it, while a low pH stimulates hydrogen formation at the cathode. In pure (distilled or demineralized) water, bimetallic corrosion is seldom a problem. Also, the size of the affected zone depends on the conductivity of the solution. In the vicinity of the interface of the two metals, the effect of galvanic corrosion is generally most severe. As the distance from this point increases, the severity of the attack decreases. In solutions with low conductivity, the corrosion remains limited to a sharp groove at the interface (01.02.14.01).

Aeration and Flow Rate

In galvanic corrosion, the cathodic reaction generally consists of the reduction of dissolved oxygen. Just like corrosion of a single metal, contact corrosion is therefore partly dependent on the rate at which oxygen can reach the metal surface from the bulk of the electrolyte. This diffusion (and hence the corrosion) is accelerated by an increased flow velocity, which causes an intensified supply of oxygen-containing electrolyte. In neutral electrolytes, both single metal corrosion and bimetallic corrosion can often be suppressed by means of oxygen removal. Under such anaerobic conditions, however, cathodic depolarization and therefore corrosion can occur by the action of sulfate-reducing bacteria (SRB; see Chapter 9: Microbiologically Induced Corrosion).

On certain metals and alloys, flow velocity has another effect which is clearly visible especially in seawater. This effect can act in two directions: at increasing flow velocities, copper and cupronickel become less noble and corrode more, whereas materials such as stainless steels become more noble and therefore corrode less. The explanation is that the latter materials become passive in well-aerated and flowing solutions, making them more resistant to corrosion. Aluminum, stainless steel, and titanium have a stable oxide skin and tend to polarize.

In flowing aerated solutions, the oxide film becomes thicker, so that the galvanic corrosion of the coupled metal will decrease still further. In copper and noble metals such as platinum and silver, the naturally formed oxide layer is much thinner. It is rapidly reduced to metal, at which it acts as an efficient cathode without polarization and thereby promotes galvanic corrosion.

The Surface Area Ratio

On the basis of the fact that the total anode current must always equal the total cathode current, the current density at the anode will be inversely proportional to the surface area ratio to the cathode (see Table 1). A very small anode will therefore corrode much faster than one that is much larger relative to the cathode. This surface area effect is particularly important when the conductivity of the electrolyte is high. Only if the rate of cathodic reduction is determining for the corrosion rate, for example, due to limited oxygen supply at the cathode, this effect will not be observed.

Unfavorable surface area ratios are present especially in the case of fasteners and connections, such as soldered and welded seams or rivets. For that reason, these must always have the same (or slightly higher) polarity as the plate or pipe they unite.

Table 1

CORROSION OF GALVANIC COUPLES IN SEA WATER AT 40–80 F (4–27°C)

● UNFAVORABLE – normal deterioration of either material may be increased moderately or severely.
× UNCERTAIN – direction and/or magnitude of effect on normal behavior may vary, depending on circumstances.
○ COMPATIBLE – deterioration of either material is normally within tolerable limits.

S – Exposed area of the metal under consideration is small compared with the area of the metal with which it is coupled.
E – Exposed area of the metal under consideration is approximately equal to that of the metal with which it is coupled.
L – Exposed area of the metal under consideration is large compared with that of the metal with which it is coupled.

METAL CONSIDERED	COUPLED WITH →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1 Magnesium Alloys	S	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	▨	●	×	●	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
2 Zinc	S	●	▨	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	▨	×	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	▨	○	○	○	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
3 Beryllium	S	×	○	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	×	▨	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	×	▨	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
4 Aluminum Alloys	S	●	○	×	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	×	×	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	▨	×	×	×	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	×	●	●	●	×	●	×	×	×	●
5 Cadmium	S	×	○	×	×	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	×	×	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	●	▨	○	○	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
6 Mild Steel, Wrought Iron	S	●	○	●	×	○	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	▨	○	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	●	●	▨	○	○	○	○	○	○	○	○	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	●
7 Cast Iron, Flake or Ductile	S	●	○	●	×	○	○	▨	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	○	▨	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	●	●	●	▨	●	○	×	×	×	×	×	●	×	×	×	●	×	×	×	×	×	×	×	×	○	○	○	○	×
8 Low Alloy High Strength Steel	S	●	○	●	×	○	○	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	×	×	▨	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	●	●	●	×	▨	○	○	○	○	○	○	●	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	●
9 Austenitic Cast Irons, Types 1 & 2	S	●	○	●	×	○	○	○	○	▨	●	●	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	●	●	●	●	●	×
	E	●	●	●	●	●	●	×	×	▨	●	●	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	×	●	●	●	●	×
	L	●	●	●	●	●	●	●	●	▨	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	×
10 Naval Br (CA464), Yel. Br. (CA268), AlBr (CA687), Red Br (CA230, Adm'ty Br (CA443), Mn Bronze	S	●	●	●	●	●	○	×	○	○	▨	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	●	●	●	●	▨	×	×	×	×	●	×	×	×	●	×	×	×	×	×	×	●	●	●	×	×	×	●
	L	●	●	●	●	●	●	●	●	●	▨	×	×	×	×	●	×	×	×	●	×	×	×	×	×	×	×	●	○	×	○	○	●
11 Tin	S	●	●	●	●	●	○	×	○	○	×	▨	×	×	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	●	●	●	●	×	▨	×	×	×	●	×	×	×	●	×	×	×	×	×	×	●	●	×	×	×	×	●
	L	●	●	●	●	●	●	●	●	●	×	▨	×	×	×	●	×	×	×	●	×	×	×	×	×	×	×	●	○	×	×	○	●
12 Copper (CA102, 110), Si Bronze (CA655)	S	●	●	●	●	●	○	×	○	○	×	×	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	●	●	●	●	×	×	▨	×	×	●	×	×	×	●	●	×	×	×	●	×	●	●	×	×	×	×	●
	L	●	●	●	●	●	●	●	●	●	●	×	▨	×	×	●	×	×	×	●	×	×	×	×	×	×	×	●	○	●	●	○	●
13 Lead Tin Solder	S	●	●	●	●	●	○	×	○	○	×	×	×	▨	●	●	×	×	×	●	×	×	×	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	●	●	●	●	×	×	×	▨	×	●	×	○	○	●	×	○	○	×	×	×	●	●	●	●	×	×	●
	L	●	●	●	●	●	●	●	●	●	●	×	●	▨	×	●	●	×	×	●	×	×	×	×	×	×	×	●	○	○	○	○	●
14 Tin Bronze (G&M)	S	●	●	●	●	●	○	×	○	○	×	×	×	×	▨	●	×	×	×	●	×	×	×	×	●	×	●	●	●	×	×	×	●
	E	●	●	●	●	●	●	●	●	●	×	×	×	×	▨	●	○	○	○	●	×	×	×	×	●	×	×	●	○	×	○	○	●
	L	●	●	●	●	●	●	●	●	●	●	×	●	●	▨	●	×	×	×	●	×	○	○	×	×	×	×	●	○	×	○	○	●
15 Stainless Steel, 12 14% Cr (AISI Types 410, 416)	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	L	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Continued

Table 1—cont'd

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
16	Nickel Silver (CA 732, 735, 745, 752, 764 770, 794)	S	●	●	●	●	●	○	×	○	○	×	×	×	●	×	●	▨	×	×	●	×	●	●	●	●	×	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	×	○	●	▨	○	○	●	○	×	×	×	×	×	×	●	×	●	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	▨	○	○	●	○	○	○	○	×	○	×	●	○	×	○	○	●
17	90/10 Copper-Nickel (CA706)	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	○	▨	○	●	○	●	×	×	×	●	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	○	○	●	○	▨	○	●	○	○	○	○	×	×	×	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	×	▨	○	●	○	○	○	○	×	○	○	●	○	○	○	○	●
18	80/20 Copper-Nickel (CA 710)	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	○	○	▨	●	○	●	×	×	×	●	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	●	●	●	○	○	▨	●	○	○	○	○	×	×	×	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	×	○	▨	●	○	○	○	○	×	○	○	●	○	○	○	○	●
19	Stainless Steel, 16-18% Cr (AISI Type 430)	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●	●	●	●	●	●	●	●	●
20	Lead	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	○	○	○	●	▨	○	○	×	×	×	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	×	×	×	●	×	×	●	○	○	○	●	▨	○	○	×	×	×	●	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	×	●	●	●	×	×	●	×	○	○	●	▨	○	○	×	×	×	×	●	○	×	○	○	●
21	70/30 Copper Nickel (CA715)	S	●	●	●	●	●	○	×	○	○	×	×	×	×	○	●	○	○	○	●	○	▨	○	●	×	×	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	○	×	●	×	○	○	●	○	▨	○	×	×	×	×	●	×	×	○	○	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	●	●	●	●	○	▨	○	○	×	○	○	●	○	○	○	○	●
22	Nickel-Aluminum-Bronze	S	●	●	●	●	●	○	×	○	○	×	×	×	×	○	●	○	○	○	●	○	○	▨	●	×	×	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	○	×	●	×	○	○	●	○	○	▨	×	×	×	×	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	●	×	×	●	○	○	▨	○	×	○	○	●	○	○	○	○	●
23	Nickel Alloy 600	S	●	●	●	×	●	○	×	○	○	×	×	×	×	×	●	○	○	○	●	×	○	○	▨	×	×	●	●	●	×	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	×	×	●	×	○	○	●	×	×	×	▨	×	×	×	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	●	×	●	●	×	×	●	×	●	●	▨	×	×	○	●	○	×	○	○	●
24	Silver Braze Alloys	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	×	×	×	●	×	×	×	×	▨	×	●	●	×	×	×	×	●
		E	●	●	●	●	●	●	●	●	●	×	×	●	×	●	●	×	×	×	●	×	×	×	×	▨	×	×	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	×	×	●	×	×	×	×	▨	×	×	●	×	×	×	×	●
25	Nickel	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	○	○	○	●	×	○	○	×	×	▨	●	●	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	●	×	×	×	×	×	●	×	×	×	●	×	×	×	×	×	▨	×	●	×	×	×	×	●
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26	Silver	S	●	●	●	●	●	○	×	○	○	×	×	×	×	×	●	×	○	○	●	×	○	○	○	×	×	▨	●	×	×	×	×	●
		E	●	●	●	●	●	●	●	●	●	●	●	●	●	×	●	×	×	×	●	●	×	×	×	×	×	▨	●	×	×	×	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	×	×	×	×	●
27	Stainless Steel, 18 Cr, 8 Ni (AISI Types 302, 304, 321, 347)	S	●	●	●	×	●	○	×	○	○	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●
		E	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	▨	●	●	●	●	●
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28	Nickel Alloys 400 and K 500	S	●	●	●	●	●	○	○	○	○	○	○	○	○	○	●	○	○	○	●	○	○	○	○	×	○	×	×	▨	×	×	×	●
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29	Stainless Steel, 18 Cr, 12 Ni-Mo (AISI Types 316, 317)	S	●	●	●	×	●	○	○	○	○	×	×	●	○	×	●	×	○	○	●	×	○	○	×	×	○	×	●	×	▨	×	×	●
		E	●	●	●	●	●	●	●	●	○	×	×	×	●	×	●	●	×	×	●	×	×	×	×	×	×	×	●	×	▨	×	×	●
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30	Stainless Alloy 20, Nickel Alloy 825	S	●	●	●	×	●	○	○	○	○	●	×	●	○	○	●	○	○	○	●	○	○	○	○	×	○	×	●	×	×	▨	×	●
		E	●	●	●	●	●	●	●	●	○	×	×	×	×	○	●	×	×	×	●	×	○	×	×	×	×	×	●	×	×	▨	×	●
		L	●	●	●	●	●	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	●	●	●	×	●	×	●	×	×	▨	×	●
31	Titanium, Nickel Alloys C, C 276, 625	S	●	●	●	×	●	○	○	○	○	○	○	○	○	○	●	○	○	○	●	○	○	○	○	×	○	×	●	×	×	×	▨	×
		E	●	●	●	●	●	×	×	×	○	×	×	×	×	○	●	×	×	×	●	×	○	×	×	×	×	×	●	×	×	×	▨	×
		I	●	●	●	●	●	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	●	●	●	×	●	×	●	×	×	×	▨	×
32	Graphite, Graphitized Cast Iron	S	●	●	●	●	●	●	×	●	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	×	▨
		E	●	●	●	●	●	●	●	●	×	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	×	▨
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Source: Galvanic Corrosion Indicator, International Nickel Co.

At the same time, it is important not to exaggerate this, as in Case History 06.21.14.01, in spite of the favorable surface area ratio, the large potential difference between the two alloys in conjunction with the high conductivity of the seawater caused severe bimetallic corrosion within 1 year. Discontinuities (cracks or pinholes) in cathodic coatings such as magnetite (mill scale) or copper plating on steel also expose extremely small anodic surfaces (06.05.14.01).

This is also the case where the coating of a metal which is in contact with a more noble metal exhibits pores or other defects, and severe local corrosion will occur (03.05.40.01, 03.06.14.01, 03.08.14.01, and 03.11.14.02).

Forms of Galvanic Corrosion

Contact Corrosion

The most familiar is contact corrosion, which occurs when two dissimilar metals are directly coupled (01.01.14.01, 01.02.14.02, 01.06.14.01, 01.11.14.01/02, 02.05.14.03, 02.06.14.01, 07.04.14.01/02, 07.05.14.01/02, 07.09.14.01).

But contact between activated charcoal and stainless steel and other alloys can also cause galvanic contact corrosion (04.23.14.01 and 05.23.14.01).

Deposition Corrosion

Less familiar but no less dangerous is the galvanic corrosion caused by cathodic contamination of the anode, whereby the deposition of more noble metals or metal oxides on the anodic metal leads to local cell formation. This attack is known as deposition corrosion, not to be confused with under-deposit corrosion which is discussed in Part I, Chapter 4 and in Chapter 10 of this part.

As the result of a displacement reaction (non-noble metal ions displace the noble metal ions from the solution), dissolved corrosion products are able to deposit on a less noble metal in the same solution. In this way, local but intensive bimetallic corrosion cells are formed on the surface.

This phenomenon is frequently observed in circulating water systems incorporating, in addition to copper, other metals such as steel, galvanized steel, or aluminum. Even if the dissimilar metals have been electrically separated by means of isolation flanges, galvanic corrosion cannot be avoided. Copper ions will deposit on galvanized steel and cause severe localized pitting (02.05.14.04, 02.06.14.02/03) or on stainless steel (04.01.14.01). The application of aluminum and steel in a single system leads to similar problems (07.04.12.01).

Other examples of this deposition corrosion are pitting attack to copper by carbon particles (e.g., originating from lubricants 06.05.14.02) or by deposition of iron rust particles originating from upstream steel linework (06.05.15.01. and 06.06.15.01).

Reversal of Potential

At temperatures above 60°C, the potential of galvanized steel may reverse, so that the zinc becomes more noble than the bare steel, and the steel enters into intensified anodic solution in pores of the zinc layer (02.04.14.01, 02.05.14.01/02/06). Besides temperature, occurrence of this problem also depends on the water composition. For instance, reversal of potential is promoted by oxygen, hydrogen carbonate, and nitrate but inhibited by sulfate, chloride, silicate, and calcium.

Thermogalvanic Corrosion

When a metal is subjected to a thermal gradient by uneven heating or dissipation of heat, this has a similar effect on the metal as galvanic corrosion. The metal is differentially polarized, and anodic and cathodic areas are formed, causing preferential attack at the hot area (see Fig. 6 and Case History 06.06.14.01).

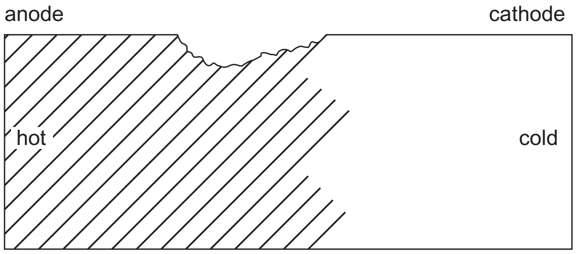

Figure 6 Thermogalvanic corrosion. From Pludek, Design and corrosion control. Reproduced with permission.

Prevention

The prevention of galvanic corrosion is primarily a matter that must be dealt with in the design stage. Depending on the conditions, the following measures can be considered:

- Avoid if possible bimetallic connections between dissimilar metals, which can form a corrosion potential or select combinations of metals with potentials which are as close together as possible.
- Provide bimetallic connections with a complete dielectric isolation (isolation flanges, sleeves, and gaskets made of impermeable plastic or rubber). If this is impracticable, apply the surface area ratio rule and make sure that the anodic surface is much larger than the cathodic surface (see Table 1).
- If appropriate, use readily replaceable anodic components or make them thicker. Soldered or welded connections are to be preferred to threaded connections in the anodic part.
- Use the appropriate welding and soldering metals (no less noble than the material to be joined).
- Modify the relative position of various metals or modify the direction of flow in order to prevent cathodic contamination of an anodic surface (in the case of recirculating systems, this is obviously not applicable).

In the service stage, the following measures can also be taken:

- If possible, prevent aeration of the electrolyte.
- Dose corrosion inhibitors (e.g., copper inhibitors).
- Apply cathodic protection of the anodic metal using sacrificial anodes or inert anodes with impressed voltage. In the case recirculating water systems, inert anodes are preferred to sacrificial anodes in order to prevent sludge accumulation and contamination of the system.
- Apply a coating to the cathode or to both poles. Do not coat the anode alone: if the cathode is left bare, there is a greatly increased risk of severe local galvanic corrosion (pitting) through pores and defects in the coating. It is also possible to apply a metallic coating of the same metal as the anode to the cathodic surface; for example, an aluminum coating on steel which is in contact with aluminum. Coating the anode alone is only possible in combination with cathodic protection.
- Avoid local temperature differences caused by uneven heating or cooling. Avoid the formation of cold or hot spots, for example, due to discontinuities in insulation or coating.

7. HIGH-TEMPERATURE CORROSION

High-temperature corrosion refers to the reaction of metals with gases at a temperature so high that no water is present. For this reason, the term “dry corrosion” is sometimes used (refer to the definition of corrosion in Part I). Under atmospheric conditions, therefore, this temperature limit lies at 100°C. In practice, however, high-temperature corrosion will only occur at far higher temperatures (>200°C), depending inter alia on the metal concerned.

High-temperature corrosion of metals occurs in hot dry gases, such as air, sulfur dioxide, hydrogen sulfide, hydrogen, and dry steam.

The commonest corrosion phenomena of high-temperature corrosion will be treated in alphabetical sequence, as follows:
carburization, including metal dusting;
nitriding;
high-temperature oxidation;
sulfidation, including hot corrosion and sulfur corrosion.

Carburization

Carburization is, of course, the reverse of decarburization, a feature of high-temperature hydrogen attack. This phenomenon is also related to high-temperature corrosion, but it is treated under hydrogen damage (see next chapter). Apart from being a form of high-temperature corrosion, carburization is also a process which is deliberately applied for the hardening of low-alloyed steel. Absorption of carbon at the steel surface yields a steel that responds better to heat treatment and possesses a higher surface hardness, so that frictional resistance increases without sacrificing the toughness of the base material.

Besides this desired external carburization, the phenomenon can also appear in an undesired way. At high temperatures, the carbon will detach from the surface and, under conducive conditions, diffuse further into the metal. In certain metals, this may give rise to attack. In the case of chromium-containing alloys, such as stainless steel, progressive carburization can lead to reduced resistance against oxidation and sulfidation arising from chromium depletion by the separation of chromium carbides at the grain boundaries.

The resultant intergranular attack accompanying carburization causes cracks in the alloy, which of course impair its mechanical properties. In effect, this process may be compared with the causes of weld decay (see Chapter 13). Carburization can occur in gases containing carbon monoxide or hydrocarbons, such as methane, propane, and so on. It may cause uniform attack (04.11.06.01) or bulging with cracking (05.11.06.01). An example of a chemical reaction which may occur during carburization is $2CO \leftrightarrows C + CO_2$, the C standing for carbon dissolved in the metal.

The proportion of chromium in an alloy greatly affects the alloy’s sensitivity to carburization. Alloys with less than 12% chromium are extremely sensitive, while alloys containing over 20% chromium are more resistant. Small additions of alloying elements, such as silicium, niobium, tungsten, and titanium, are highly beneficial to carburization resistance.

Metal Dusting

Metal dusting is a special form of carburization, which occurs in low-alloyed steels, chromium steels, austenitic stainless steels, and nickel and cobalt alloys in the temperature range between 450°C and 800°C. The materials disintegrate into a powdery mixture of carbon, metal particles, and sometimes metal oxides and carbides. These corrosion products are readily removed in a gas stream, leaving grooves and pits in the metal surface (01.11.06.01/02, 05.01.06.02, and 05.11.06.03).

Metal dusting is invariably preceded by internal carburization, whereby the chromium is bonded. Subsequently, the remaining Fe or Fe–Ni matrix reacts to form the unstable carbide M_3C, which disintegrates into metal particles and carbon. The M stands for metal (i.e., in this case, Fe and Ni). Resistance to metal dusting depends solely on the ability to form a stable Cr_2O_3 skin. High-chromium ferritic steels are therefore very resistant, while ferritic steels containing 12%–13% Cr are more sensitive to this attack. Because of their low chromium-diffusing ability, austenitic steels are very sensitive, especially the alloys with 30% Ni (Alloy 800 and AC 66).

Nitriding

Just like carburization, nitriding is used as a surface-hardening process for low-alloyed steels. This process takes place by contacting the steel at high temperature (but below 538°C) with ammonia or other nitrogen compounds. Decomposition of ammonia yields active (atomic) nitrogen, which results in the formation of nitrides by diffusing into the metal. This desired nitriding process, however, can also lead to undesired side effects. If the nitrogen diffusion is insufficient, a brittle and insufficiently protective nitride skin will be formed, reducing the corrosion resistance in aqueous environments. In addition, this may lead to diminishing toughness.

Direct attack is possible in the case of extended heating in a nitrogen-containing gas stream at high temperature. In these conditions, nitriding is a form of high-temperature corrosion (01.11.06.03, 04.11.06.03, and 05.03.06.01/02).

Metals such as iron, chromium, aluminum, and titanium readily form nitrides, and these are therefore unserviceable in the case of a high nitriding potential. Nickel and copper, on the other hand, do not form stable nitrides at high temperature and are therefore fairly resistant to nitriding. High nickel–chromium alloys (50%–80% nickel) possess the highest resistance.

High-Temperature Oxidation

In high-temperature oxidation, a metal oxide skin (or scale) forms on the metal (which is why this phenomenon is also referred to as external oxidation) (Fig. 7).

In the case of iron, various oxide layers may form one on top of the other, in outward sequence: FeO, Fe_3O_4, and F_2O_3. Because this corrosion generally proceeds in a linear way, the built-up oxide skin will not provide any protection against further corrosion by oxygen ion diffusion. Oxidation can occur in boilers, namely on the flue-gas side of superheater

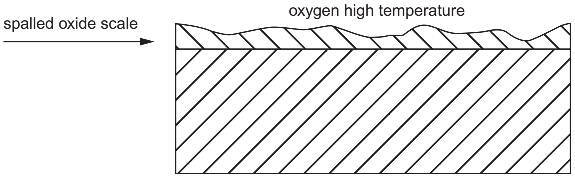

Figure 7 High-temperature corrosion by oxidation.

tubes (01.01.06.01 and 04.01.06.01) in distillation units (01.11.06.10) but also in furnaces (04.11.06.02, 05.11.06.02) and at turbine vanes (05.03.06.02).

Addition of certain proportions of alloying elements, such as chromium or aluminum, can enhance the oxidation resistance of metals by forming a protective oxide layer. These alloys, however, may be sensitive to internal oxidation. The oxides are then formed below the metal surface (possibly along the grain boundaries). In that case, the alloying elements are more reactive than the base material. Although these internal oxides increase the hardness and strength of the material, for high-temperature applications, the alloy nevertheless becomes excessively subject to embrittlement. Moreover, the formation of Cr_2O_3 or $A1_2O_3$ precipitates below the metal surface means that these elements are no longer available for improving the quality of the external oxide layer, the precise purpose of their addition.

Sulfidation

In the case of a sufficiently high partial pressure (concentration) of sulfur compounds in a gaseous environment, sulfides will be formed instead of oxides. Sulfidation, or oxidation by sulfur, is in general a considerably more severely destructive form of high-temperature corrosion than oxidation by oxygen. This is because a sulfide scale will sooner tend to crack and spall than an oxide scale. The melting points of metal sulfides are as a rule lower than those of metal oxides. Once a melt has formed, the corrosion rate will increase drastically due to the faster movement of the ions. This means that the maximum service temperature of a metal or alloy is determined by the melting point of the metal-sulfide eutectic.

The mechanism of sulfidation is similar to that of oxidation. By the same token, the same alloying elements can be used to increase resistance to sulfidation attack. Under certain conditions, however, the sulfur can penetrate through the protective $A1_2O_3$ and Cr_2O_3 oxide scales and form sulfides in the alloy, usually at the crystal boundaries (internal sulfidation) and subsequently lead to accelerated attack.

The form in which the sulfur is present affects the rate of attack. Gaseous sulfur may be present as sulfur vapor, SO_2, SO_3, H_2S, and as organic sulfides. If oxygen is also present, as in the case of SO_2 or SO_3, a mixed sulfur oxide scale will often form which offers more protection than the pure sulfide scale which is formed in the case of H_2S, organic sulfur compounds and sulfur vapor. For protection against sulfidation, coatings containing aluminum or chromium are also used. Like oxidation, sulfidation can cause attack on the flue gas side in boilers (01.11.06.04 and 05.01.06.01) and also in turbines (05.19.06.01).

Hot Corrosion

The term hot corrosion is generally used to describe an accelerated attack to the blades of gas turbines. Two types of hot corrosion are distinguished here, namely,
type I: high-temperature hot corrosion
type II: low-temperature hot corrosion

Sulfidation is involved in both cases.

Type I hot corrosion occurs in the metal temperature range of 850–950°C. This form of attack is conditional on the presence of a layer of liquid sodium sulfate on the blade surface (05.03.06.03). Solid or gaseous sodium sulfate in itself does not cause corrosion. The temperature range in which sodium sulfate liquefies is influenced by the following:

- Pressure: the higher the pressure, the higher the boiling point. In modern high-pressure turbines, there is therefore a greater risk of sulfidation;
- Contaminants in the sodium sulfate melt: contaminants such as common salt but also oxides of vanadium, molybdenum, and tungsten reduce the dew point;
- The concentration of common salt in the air intake: a high common salt concentration will result in both a reduced dew point and a raised boiling point.

The corrosion process proceeds as follows:

Both sulfur and oxygen are released from the layer of liquid sodium sulfate. The oxygen converts the protective chromium oxide skin into a nonprotective chromate skin. The sulfur diffuses inward rapidly and forms chromium sulfides. These are later converted into oxides by the oxygen, which diffuses at a slower rate. The sulfur is then released and diffuses further into the material, where it again forms new sulfides.

Type I (high-temperature hot corrosion) is characterized by the following:

- Uniform attack.
- A zone with sulfides at the corrosion front.
- The sulfur is not consumed and therefore acts as a catalyst.

To control high-temperature hot corrosion, the following measures can be taken:

- Installation of filters in the air stream to trap particles, for example, sulfates and chlorides;
- Use of low-sulfur and low-sodium fuel;
- Doping the fuel with an additive to convert vanadium pentoxide into a harmless vanadate;
- Application of higher-grade, more appropriate alloys;
- Application of coatings, for example, Al–Cr diffusion coatings.

Type II (low-temperature hot corrosion) occurs in the metal temperature range from 650 to 700°C, well below the melting point of Na_2SO_4 (884°C). This form of corrosion is characterized by the following:

- A pitting appearance;
- The absence of a zone with sulfides at the corrosion front;
- In this case, the sulfur is consumed.

The pitting is caused by the formation of low-melting mixtures of Na_2SO_4 and cobalt sulfate ($CoSO_4$), a corrosion product of the reaction of the blade casing surface with SO_3 in the combustion gas. The melting point of the Na_2SO_4–$CoSO_4$ eutectic is 540°C. Unlike type I, in type II, the partial pressure of SO_3 in the gas is critical for the reactions taking place.

Cobalt-free nickel-base alloys (and coatings) are more resistant to type II hot corrosion than cobalt-base alloys. Resistance to this form of corrosion increases with rising chromium content of the alloy or coating.

Sulfur Corrosion

Sulfur corrosion, also called sulfidic corrosion or high-temperature sulfur corrosion, is in fact a form of sulfidation at lower temperatures, between 260°C and 540°C. It occurs in carbon steel and low-alloyed steel in contact with sulfur-containing hydrocarbons. The sulfur content of crude oils varies from practically nil to levels as high as 7% by weight. The main corrosive sulfur compounds in oil processing are hydrogen sulfide and mercaptans, which may be present as such or be formed by decomposition of other sulfur compounds during distillation.

The relative corrosivity of sulfur compounds generally increases with temperature and reaches its maximum between 375 and 425°C. Depending on the process particulars, corrosion occurs in the form of uniform thinning (01.11.06.05/06/07/08/09), localized attack or erosion corrosion. Maximum rates up to 10 mm/year have been experienced in high-velocity areas.

Corrosion control depends almost entirely on the formation of protective metal sulfide scales that exhibit parabolic growth behavior. In general, nickel and nickel-rich alloys are rapidly attacked by sulfur compounds at elevated temperature, while chromium-containing steels provide excellent corrosion resistance (as does aluminum). The combination of hydrogen sulfide and hydrogen can be particularly corrosive, and as a rule, austenitic stainless steels are required for effective corrosion control.

8. HYDROGEN DAMAGE

The term hydrogen damage covers a number of corrosion phenomena in which hydrogen plays the key role. The main forms of hydrogen damage are discussed with reference to their mechanism, appearance, and the conditions (environment) in which the attack occurs. The following forms are discussed in the following, in alphabetical order:

high-temperature hydrogen attack;
hydride embrittlement;
hydrogen blistering;
hydrogen embrittlement;
hydrogen stress cracking.

All these forms of hydrogen damage result from diffusion of atomic hydrogen into the metal. The atomic hydrogen may originate from corrosion processes or from hot gas mixtures.

High-Temperature Hydrogen Attack

High-temperature hydrogen attack is also referred to as hot hydrogen attack or decarburization. The latter term is the reverse of carburization, as discussed in the preceding chapter. It occurs in carbon and low-alloyed steels exposed for an extended period to hydrogen under high pressure and at high temperature (>220°C). Diffusion occurs of atomic hydrogen formed in corrosion processes or by dissociation of molecular hydrogen in a gas stream at the steel surface. At grain boundaries, crystal imperfections, inclusions, discontinuities, and other defects, the atomic hydrogen reacts with the dissolved carbon or with the metal carbides, forming methane:

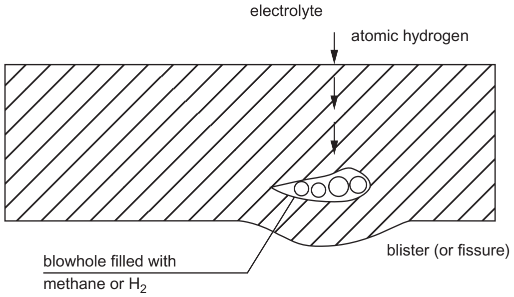

Figure 8 Hydrogen damage by hydrogen blistering or by decarburization. From Pludek, Design and corrosion control. Reproduced with permission.

$$8H + C + Fe_3C \rightarrow 2CH_4 + 3Fe.$$

Because of the pressure build-up of the methane in the steel, this results in the formation of intergranular cracks, fissures, and blisters, often extending to the surface of the steel (Fig. 8).

Outwardly, this form of hydrogen damage sometimes indeed greatly resembles the low-temperature blistering discussed further in the following. The decarburization occurring moreover weakens the steel. This process is also known as methane gas embrittlement.

At sufficiently high temperatures (>540°C), decarburization can also occur at the steel surface, by diffusion of the dissolved carbon to the surface, where methane is then formed with the atomic hydrogen present. In that case, the hydrogen damage causes general decarburization at the surface instead of blistering or cracking in the metal. Microscopically, the decarburization is clearly visible as tiny intergranular cracks parallel to the surface.

Occurrence

In metal, decarburization occurs particularly in areas where stresses are present, for example, near welds. In boilers, decarburization can occur as a result of caustic or acid corrosion (01.01.20.02/03/04/05/06). In addition, this form of damage also occurs in refinery equipment where steel is in contact with hydrogen gas under high pressure and temperature (01.11.20.01/02/03).

Prevention

To prevent hot hydrogen attack, the first step is to select steel containing sufficient chromium and molybdenum. By forming carbides with the carbon, these metals enhance the steel's resistance to hydrogen. In selecting the material, use may be made of the Nelson Graphs issued by the American Petroleum Institute (API Publication 941). These graphs show the correlation between alloy composition, temperature, and partial hydrogen pressure with reference to the occurrence of this attack. At combinations of higher temperatures and partial pressures of H_2, the successive materials of choice are carbon steel, 0.5 Mo steel, 1 Cr–0.5 Mo steel, 2 Cr–0.5 Mo steel, and 2.25 Cr–1 Mo steel. It will be clear from the previously mentioned that stainless steels with a chromium content of 12% and above and in particular austenitic stainless steels are immune to the occurrence of methane embrittlement. However, because hydrogen diffusion nevertheless occurs in these steels, this may still result in hot hydrogen attack to carbon steel with stainless-steel cladding.

Hydride Embrittlement

Hydride embrittlement refers to the degradation of metals such as magnesium, tantalium, niobium, vanadium, zirconium, titanium, and their alloys in a hydrogen-containing environment.

The hydrogen may originate from welding work without adequate protection with regard to the environment, a heat treatment, corrosion processes, or a casting operation without a controlled atmosphere. The damage is caused by the formation of a brittle metal hydride (MHx), which precipitates in the metal where it attacks the mechanical properties and initiates cracking.

Material stresses accelerate the formation of hydride. As a result, hydride precipitation will continually recur in the stress field at the crack tip, and the crack will continue to penetrate further until the fracture is complete (stress-induced hydride embrittlement).

Occurrence

In titanium, hydride formation occurs by absorption of hydrogen originating from corrosion processes (09.11.20.01) or from hydrogen-containing gas. If more than 150 ppm hydrogen is absorbed, a brittle titanium hydride phase will precipitate. Particularly where the normally present protective oxide skin has been damaged by friction or chemical reduction, the hydrogen absorption by titanium will increase dramatically. Also, the presence of surface contaminants and temperatures above 70°C promote hydrogen absorption.

Prevention

Hydride formation can be minimized by building a thick protective oxide film by means of anodizing or thermo-oxidative treatments. Pickling in a mixture of nitric acid and hydrogen, fluoride is applied to remove iron contamination. Cathodic coupling (with consequent H_2 formation) with other metals must of course be avoided.

Hydrogen Blistering

This form of hydrogen attack, also known as cold hydrogen attack, occurs particularly in low-strength steels, where atomic hydrogen (H) originating from corrosion processes diffuses into the steel at ambient temperature. This diffusion then comes to a standstill, similar to high-temperature hydrogen attack, at contaminations and defects in the steel, where the atomic hydrogen is converted into molecular hydrogen (H_2).

This formation of molecular hydrogen is characteristic of hydrogen blistering. The larger hydrogen molecules prevent further diffusion so that the hydrogen gas begins to accumulate locally (Fig. 8). The rising pressure deforms the steel, causing blisters which erode the strength of the structure and lead to its ultimate failure.

The severity of hydrogen blistering depends on the severity of the corrosion as a source of hydrogen, but even at low corrosion rates, sufficient hydrogen can be formed to cause considerable damage. However, it is a slow process which can be effectively monitored by periodical nondestructive testing, permitting measures to be taken in good time to prevent disastrous failures.

Certain substances, such as sulfides and phosphorous and arsenic compounds, are capable of preventing the recombination of atomic hydrogen to molecular hydrogen at the steel surface and thereby promote the diffusion process.

Occurrence

Blistering occurs particularly in steel:

- exposed to acid vapors or effluents containing H_2S, CO_2, or cyanide, as commonly encountered in oil and gas production and in the petrochemical industry (01.11.20.04, 01.23.20.01);
- exposed to pickling liquids used to clean the steel surface;
- exposed to electrolysis (during electroplating);
- serving as cathode in a cathodic protection system.

Hydrogen blistering can also occur in aluminum.

Prevention

Hydrogen blistering can basically be prevented by means of the following measures:

- process modifications to ensure that either the formation of the previously mentioned acid components is suppressed very largely if not entirely, or that those components are removed (e.g., washed out in a scrubber at an early stage);
- dosing of corrosion inhibitors to the medium;
- removal of the “poisons” (sulfides, arsenic compounds, cyanides, and phosphorous compounds) from the medium;
- use of “purer” steel, without inclusions capable of causing hydrogen accumulation;
- coating the steel (if feasible from the constructional and process operation points of view) or cladding it with stainless steel or Alloy 400.

Hydrogen Embrittlement

Here too, atomic hydrogen diffuses into the metal matrix. In this case, however, this leads to sudden fracture because the penetrated hydrogen embrittles the metal. The hydrogen may originate from corrosion processes, pickling liquids, electroplating, and cathodic protection. Because no reactions occur in the metal, the atomic hydrogen which has diffused into the metal can be expelled by heating the metal. The process is therefore reversible, and the toughness of the metal is totally restored. The previously mentioned forms of hydrogen damage in which reactions do occur are also known by the term hydrogen reaction embrittlement.

Occurrence

Hydrogen embrittlement can occur after a very small quantity of hydrogen has been absorbed from the medium. It occurs not only in carbon steel (01.11.20.05; the hardened grade with HRC ≥ 22 is particularly sensitive) but also in austenitic stainless steel (04.11.20.01) and nickel alloys. In steel, hydrogen embrittlement occurs most severely at ambient temperature either in the form of delayed failure or as slow strain rate embrittlement. The embrittlement is caused as cracks are initiated by the combination of residual stresses (e.g., as a result of hardening the steel) and hydrogen diffusion. It may also occur due to the presence of notches, in which case the material subject to the greatest stress, immediately under the deepest point of the notch, is of course most sensitive.

Prevention

Hydrogen embrittlement can be prevented by the following:

- selecting a different inhibitor (also during pickling), so that the corrosion rate decreases;
- changing the plating conditions (adjusting the choice of bath and current intensity);
- annealing the metal at 200°C, whereby the hydrogen is expelled, and the metal reverts to its original state;
- using different alloys. Metals with the highest tensile strength are most subject to hydrogen embrittlement. On the other hand, alloying elements such as Ni and Mo increase resistance to this form of corrosion;
- for welding purposes, using electrodes with a low hydrogen content and working under dry conditions.

Hydrogen Stress Cracking

Hydrogen stress cracking may be described as brittle fracturing of a tough alloy under constant strain in a hydrogen-containing environment. For that reason, it is sometimes known as “hydrogen-assisted stress corrosion cracking” and “static fatigue.” In this kind of situation, fracture often occurs at a strain below the yield point of the metal. For many steels, there is a threshold strain below which no hydrogen stress corrosion occurs. This limit depends on the material strength and the specific hydrogen-containing environment. In general, this threshold strain decreases as the yield point (elastic limit) and tensile strength increase.

The cracking mechanism is determined by the volatility of the hydrogen, the strength of the metal, the microstructure resulting from the heat treatment, the imposed strain, and the temperature.

In contrast to the highly branched cracks which characterizes normal stress corrosion cracking, this form of damage is generally recognizable from the sharply defined single cracks.

Occurrence

Hydrogen stress corrosion occurs at ambient temperature and above all in highly stressed parts made of high-strength steels (such as bolts and compressor fans). However, it also occurs in carbon–steel components with hard welds. Precisely, in high-pressure processes requiring high-strength materials, the welds are much harder than the base material, and cross-cracking occurs in the welds due to hydrogen stress corrosion. Stainless steels and certain other metals are also sensitive to hydrogen stress corrosion.

This phenomenon occurs in steam boilers (01.01.20.01/07) as well as in equipment in the petrochemical industry (01.11.20.06/07).

H_2S acts as a catalyst on the corrosion rate and hydrogen absorption,but it is not directly involved in the cracking mechanism. As a rule of thumb, it is sometimes assumed that at least 50 ppm H_2S must be present in the environment. In fact, so-called sulfide (assisted) stress cracking is a special form of hydrogen stress corrosion. Especially in the petroleum industry, an acid H_2S-containing medium is a cause of sulfide stress corrosion. Here, the cracks contain sulfide corrosion products.

Prevention

Ensuring an appropriate metallurgical condition of the steel is the most effective way of preventing hydrogen stress corrosion. This means that the hardness of the welds must be limited to 200 HB (including the HAZ), corresponding with a tensile strength of 620 MPa. In addition, applying a heat treatment to the welds (up to 620°C) will reduce the risk of hydrogen stress corrosion. API Publication 942 gives guidelines for the prevention of hydrogen stress corrosion in oil refining and the petrochemical industry.

9. MICROBIOLOGICALLY INDUCED CORROSION

Microbial corrosion is one of the commonest forms of corrosion in water-bearing systems, especially in cooling water systems. At the same time, it is also one of the most complex and least-known processes. Besides water-bearing systems, this corrosion also occurs in other places, for example, at the bottom of oil storage tanks. In the aqueous phase present there, anaerobic bacteria in particular can develop by feeding on the oil (or gasoline) as source of nutrient. Frequently, microbiological corrosion is misinterpreted and thought to be due to a different cause. In that case, inappropriate measures may be taken, so that the intended result is not achieved.

MIC is caused by a large number of bacteria, end generally leads to rapid pitting attack. It can occur in carbon steel, cast iron, copper and copper alloys, stainless steel, nickel and certain nickel alloys, aluminum, and concrete.

Corrosion Phenomena

Three corrosion processes are distinguished, namely:

1. *Cathodic depolarization*
   The bacteria absorb the hydrogen formed at the cathode into their metabolism, thereby activating the galvanic cell (see Part I, Chapter 3).
2. *Attack by products of metabolism*
   The bacterial metabolism produces aggressive substances, for example, sulfides, sulfuric acid, nitric acid, or organic acids, which attack metal (or concrete).
3. *Formation of electrochemical cells*
   These form underneath deposits as differences arise in aeration, salt concentration, pH, and so on. This is the largest and most widespread form of microbiological corrosion.

Besides these three forms of direct corrosion of metals, two further effects should be mentioned which are capable of promoting corrosion in general as a result of bacterial growth, namely:

- decomposition of corrosion inhibitors (nitrite, amines) by oxidation;
- degradation of coatings by their use as a nutrient or by the metabolism products formed.

The following factors influence the aggressiveness of corrosive bacteria: temperature, organic carbon and nitrogen concentration levels, flow velocity, oxygen and ammonia content, water treatment applied, pH, and other influences many of which are still unknown.

The bacteria are divided into two groups, anaerobic and aerobic, which are active in oxygen-deficient environments and oxygen-rich environments, respectively.

Of the many forms of microbiological corrosion, the following will be discussed:

- Corrosion of carbon steel by SRB.
- Corrosion of stainless steel by iron bacteria.
- Corrosion of concrete by sulfur bacteria.

Corrosion of Carbon Steel by SRB

Occurrence

The best known of the SRB is Desulfovibrio. SRBs are found in most soils. Their growth is of course dependent on the presence of sulfate or sulfite. They can occur in anaerobic water but also under locally anaerobic conditions such as in corrosion products or underneath deposits. They can withstand temperatures up to approximately 80°C and are active in the pH range of 5–9. They often cause pitting corrosion, for example, in:

- “dead” (containing standing water) lines in tap water systems (01.05.17.01);
- “wet” sprinkler lines (01.10.17.01);
- conveyor lines for unaerated well water (01.06.17.01);
- cooling water systems underneath deposits (01.06.17.02/03);
- underground pipes or tanks (01.14.16.01, 01.11.17.01);
- fuel tanks;
- ships’ hulls.

A bitumen coating is no guarantee to avoid this corrosion (03.08.17.01, 03.10.17.01, 03.14.17.01/02). Aluminum alloys are also sensitive to microbiological attack (07.06.17.01). Even stainless steel (04.11.17.01/02) and nickel-base alloys are not resistant to SRBs (04.11.17.01/02 and 05.06.17.01/02).

Mechanism

The mechanism is schematically shown in Fig. 9.

The corrosion begins with a redox reaction between iron and water:

Anodic reaction:

$$4\mathrm{Fe} \rightarrow 4\mathrm{Fe}^{2+} + 8\mathrm{e}$$

Dissociation of water:

$$8\mathrm{H_2O} \rightarrow 8\mathrm{OH}^- + 8\mathrm{H}^+$$

Cathodic reaction:

$$8\mathrm{H}^+ + 8\mathrm{e} \rightarrow 8\mathrm{H}$$

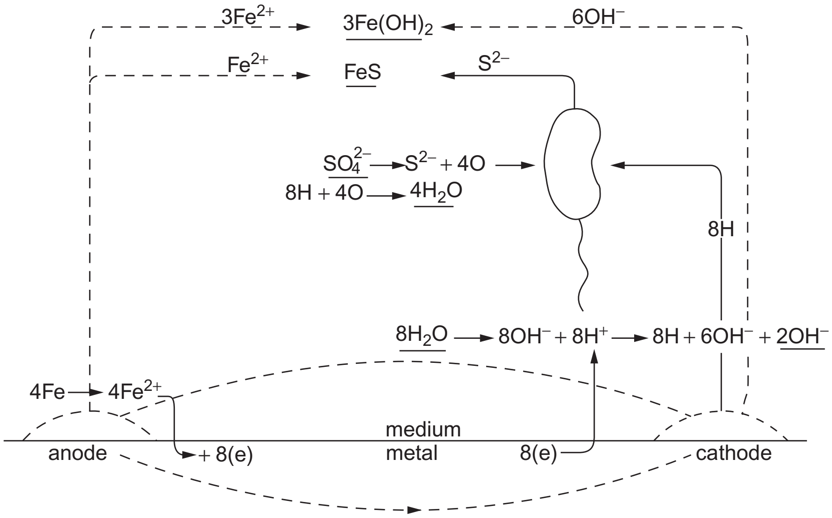

Figure 9 Anaerobic corrosion by sulfate-reducing bacteria.

Bacteria use the hydrogen formed in order to reduce sulfate:

Bacteriological activity:

- conversion of sulfate: $SO_4^{2-} \rightarrow S^{2-} + 4O$
- cathodic depolarization: $8H + 4O \rightarrow 4H_2$

Whereupon S^{2-} and OH^- together with Fe^{2+} form a deposit of corrosion products:

$$Fe^{2+} + S^{2-} \rightarrow FeS$$

$$3Fe^{2+} + 6OH^- \rightarrow 3Fe(OH)_2$$

Overall reaction:

$$3Fe + SO_4^{2-} + 4H_2O \rightarrow 3Fe(OH)_2 + FeS + 2OH^-$$

The iron sulfide formed reacts cathodically toward iron and therefore further activates the galvanic cell.

Detection: When freshly corroded surfaces are exposed to hydrochloric acid, the rotten-egg odor of hydrogen sulfide is easily detected. More sensitive spot tests using sodium azide are often successful in detecting metal sulfides at very low concentrations on surfaces.

Another well-known anaerobic bacteria is the acetifying Clostridia species (01.21.17.01/02). Bacterial attack in fuel tanks is also a well-known phenomenon (07.19.17.01).

Prevention and Control

MIC-free construction with carbon steel can be practiced in various ways:

- Avoid dead angles in the design, which should also provide for ease of maintenance.
- Eliminate possible sources of organic contamination.
- Use bioresistant coatings (coal tar, asphalt) or bioresistant synthetic plastics (with Cu^{2+}, Cr^{3+}, or Zn^{2+}).
- Counteract the bacteria by ensuring good aeration (e.g., by embedding underground systems in gravel).

Once a system shows signs of MIC attack, direct control measures must be resorted to:

- regular cleaning of the system;
- the controlled dosing of biocides and dispersants in cooling systems, combined with close monitoring for bacterial growth;
- modify the environment conditions (e.g., dewater oil, alter temperature or pH);
- apply ultraviolet disinfection (although its effectiveness remains unclear);
- apply cathodic protection.

Corrosion of Stainless Steel by Iron Bacteria

Iron bacteria are a genus of aerobic bacteria; the best-known species are Gallionella ferruginea and Leptotrix ochracea. They are found, for example, in steel pipes, and their presence is virtually always accompanied by the presence of flakes and thick deposits of iron oxides. They are capable of utilizing the energy released from the oxidation of Fe^{2+} to Fe^{3+}, which allows them to grow autotrophically.

Appearance

If Gallionella colonies deposit on stainless steel, the corrosion displays the following appearance:

- the corrosion initiates preferentially on the weld seam and those parts of the HAZ nearest the weld;
- attacked areas are covered with brown nodules which often spread perpendicularly to the weld seam in the direction of water flow;
- the attack remains limited to the round welds; that is, it appears on the assembly welds but not on the longitudinal manufacture welds;
- perforation at the surface of the attacked material is very small and not readily visible. However, very characteristic is the presence of a markedly larger cavity below the penetration. Often, a tunnel will have formed below the surface, which may lead to leakage in the HAZ; generally welding material residues can be demonstrated in it;
- in spite of the use of "L" grade stainless steel, intergranular corrosion is found at the sites of attack, in cold, nonaggressive water;
- depending on the conditions, the perforation rate is 0.5–1.5 mm/month.

Occurrence

Biocorrosion problems occur most commonly in new systems when they are first wetted. If a problem occurs in an older system, that will virtually always be a result of changes such as a new water source or a different water quality, new materials of construction (e.g., due to repair), new operating procedures (e.g., allowing water to stand during a shutdown whereas previously it was drained off), or new operating conditions (especially temperature).

Microbiological corrosion of the weld seams in stainless steel occurs in particular in stagnant water remaining in stainless steel equipment after pressure testing, but also in the case of iron-containing cooling water or tap water (04.05.17.01/02, 04.08.17.01).

Mechanism

In a neutral aerated system, the iron bacteria convert the bivalent iron into trivalent oxides and hydroxides as a by-product of their metabolism, as follows:

$$3Fe^{2+} + \frac{1}{2}O_2 + (2 + x)\, H_2O \rightarrow Fe_2O_3\ xH_2O + 4H^+$$

If these ions occur in the water, they are used in the conversion processes. Otherwise, iron ions from the metal surface are consumed.

In cases of corrosion by Gallionella bacteria, the deposited corrosion products (i.e., the metabolism products of those bacteria) have been observed to contain high levels of chlorides. Preferential attack of the delta ferrite in the weld metal has also been observed. This preferential attack of the ferrite phase is characteristic of corrosion by ferric chloride ($FeCl_3$) and dilute HCl: typically compounds produced by Gallionella.

Precisely, how the various corrosion and biological reactions are interlinked, however, remains an open question.

The following mechanism may be imagined:

- Colonization of iron and manganese bacteria on the weld bead, so that an oxygen concentration cell forms.
- Dissolving of iron underneath the deposit.
- Attraction of chlorides from the aqueous environment.
- Oxidation by the bacteria of iron (bivalent) to iron (trivalent) and formation of a strongly aggressive and acid chloride solution, which ultimately causes pitting.

Prevention

The following measures may be considered for the prevention of this corrosion:

- In the case of pressure testing not followed by taking the component into immediate service, it is advisable to use demineralized water or steam condensate and to dry the equipment as rapidly as possible after testing;
- if contaminated water has to be used failing any alternative, biocides should be added or the water heated to above 70°C, the contact time should be minimized, and the system should be thoroughly cleaned and dried;
- if well water is used, make sure there is an efficient deferrizing unit;
- use resistant materials, for example, plastics.

Corrosion of Concrete by Sulfur Bacteria

Sulfur bacteria are also aerobic bacteria, the best-known of which is Thiobacillus thiooxidans. They are capable of oxidizing elemental sulfur, in addition to sulfur compounds such as sulfide and thiosulfates, into sulfuric acid. This acid attacks steel and other materials such as concrete and cement These bacterial activities are often preceded by the formation of H_2S by SRB under anaerobic conditions.

This process occurs particularly in concrete sewer pipes and in sewage purification plants.

Mechanism

The mechanism is schematically shown in Fig. 10.

- Below the water level, micro-organisms attach to the sewer wall and form a biological skin: the slime layer.
- Oxygen from the sewage can only penetrate the slime layer to a limited depth because it is rapidly consumed by aerobic bacteria in the decomposition of organic matter. Deeper in the slime layer, SRB can oxidize organic matter (represented here as C) with sulfate instead of oxygen, as follows:

$$SO_4^{2-} + 2C \rightarrow S^{2-} + 2CO_2$$

- The sulfide formed diffuses from the slime layer to the sewage. It remains in solution as HS or H_2S, unless the sewage still contains oxygen, which causes oxidation to SO_4^{2-}.
- In the case of oxygen-lean water, the H_2S escapes from the sewage to the sewer atmosphere above. Especially, in the case of turbulent flow conditions, a large amount of H_2S can be released.

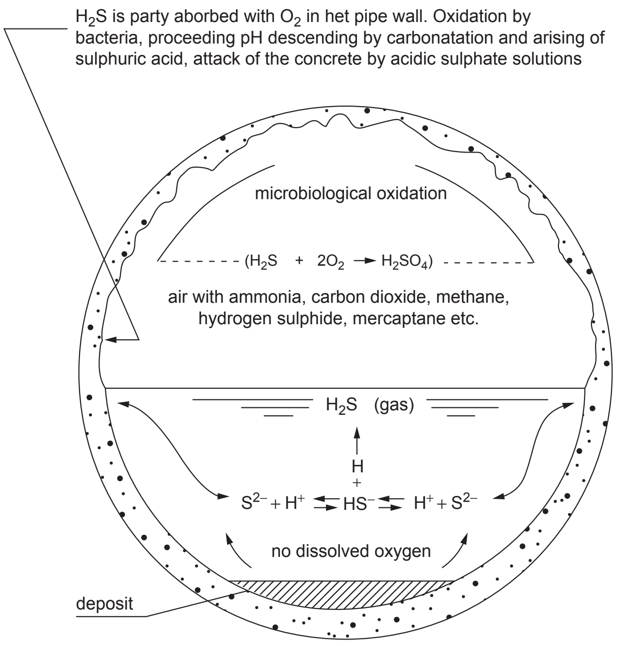

Figure 10 Attack of concrete sewer pipe by sulfur bacteria.

- The inner wall of the sewer pipe above the water level is usually moist due to condensation. Released H_2S gas dissolves in the condensation moisture, and under the aerobic conditions prevailing there, sulfur-oxidizing bacteria can convert it into sulfuric acid:

$$H_2S + 2O_2 \rightarrow H_2SO_4$$

- The resultant strongly acid environment causes the cement steel to dissolve from the concrete:

$$CaCO_3 + Ca(OH)_2 + 2H_2SO_4$$
$$\rightarrow CaSO_4 \cdot 2H_2O + CaSO_4 + H_2CO_3$$

Under favorable conditions, this biogenic sulfuric acid attack can cause the wall thickness to decrease by several millimeters each year (11.08.17.01 and 11.16.17.01). Conducive factors are stagnant water discharge where sewers are laid at irregular heights or in the case of (temporary) overdimensioning and the rising temperature of sewage in recent decades.

Prevention

MIC in concrete can be controlled with the following measures:

- ensure sufficient free fall so that sewage does not stand in the sewer for long periods;
- ensure sufficient ventilation in the sewerage system so that H_2S is removed;
- use higher-density concrete with additional cover (sacrificial layer);
- apply an acid-resistant coating, for example, an epoxy-based two-component system (pay special attention to good adhesion);
- apply a combination of acid-resistant potassium silicate-base concrete and an elastic coating (also very suitable for repairs).

These sulfur bacteria are sometimes also found at the top of tubercles in steel pipes. Just as in concrete corrosion, there is a symbiotic relationship between the Thiobacillus and the SRB. Under the anaerobic conditions in the tubercle, the latter convert sulfate into sulfide, while in the aerobic environment, at the top of the tubercle, the Thiobacillus reoxidizes the sulfide to sulfate. Indirectly, this promotes the corrosion by intensifying the sulfate-reducing bacterial activity deep in the tubercle.

Identification of MIC

Identifying microbiological corrosion is usually not a simple matter, as this phenomenon occurs simultaneously with others, such as electrochemical corrosion, sludge deposition, and formation of biological slime. However, any form of microbiologically induced corrosion (MIC) can be recognized from the following:

- the morphology of the attack;
- the composition and distribution of the corrosion products and of the deposits present;
- the microbiological analysis;
- the environment specifications.

It is emphasized that all four factors must be compatible with the diagnosis of microbiological corrosion. The presence of potentially corrosive bacteria or other organisms alone is no evidence of corrosion having been caused by these organisms. The diagnosis must not be based on overwhelming evidence, but on total consistency of all the evidence.

10. PITTING AND CREVICE CORROSION OF STAINLESS STEEL

Although its name suggests otherwise, stainless steel is frequently affected by corrosion. The cause is generally ignorance among users, who use this material regardless wherever carbon steel fails. This regularly leads to disappointment when corrosion nevertheless occurs, often to a more serious degree than in the case of normal steel.

Stainless steels are iron-based alloys with at least 13% chromium. Because a protective chromium oxide skin forms on the surface of these steels, they are corrosion resistant. They are then passive stainless steels. However, if this chromium oxide skin is damaged or absent, the stainless steels are nevertheless active and sensitive to corrosion, and inter alia pitting and crevice corrosion can occur.

Pitting

Halogenides, such as chlorides, bromides, and fluorides, can damage stainless steel by penetrating the passive oxide layer at weak sites and moreover impede the recovery of mechanical or chemical damage. A galvanic cell forms, consisting of a small anode at the center of a large cathodic surface (see Galvanic Corrosion in Chapter 6). The presence of molybdenum as in AISI 316 increases the pitting resistance.

Crevice Corrosion

Crevice corrosion is caused by the presence of differential aeration cells, which are formed by differences in oxygen concentrations in the conducting liquid inside and outside a crevice or underneath and alongside a deposit. In the latter case, the phenomenon is known as under-deposit corrosion. As soon as any corrosion occurs, the small amount of oxygen in the crevice or under the deposit is rapidly consumed. The result is an anaerobic environment in which the stainless steel becomes locally active due to the attack to the chromium oxide skin. Just as in pitting, a galvanic cell is formed with the still passivated material outside the crevice acting as cathode and the activated material inside the crevice as anode.

The reaction mechanism of pitting and crevice corrosion is comprehensively discussed in Chapter 4 of Part I. The formation of HCl causes rapid propagation of pitting, which often initiates cracking.

Driving Factors

Both pitting and crevice corrosion require an oxidizing environment; the presence of oxygen in the electrolyte is sufficient, but other oxidants such as free chlorine, oxidizing acids, and metal ions such as iron and copper ions promote pitting and crevice corrosion. Of course, chloride content plays an important role. These forms of corrosion are furthermore promoted by reduced pH (<8) and increased temperature. Crevice corrosion develops readily especially under nonconductive materials such as asbestos, rubber (gaskets), glass, and teflon. Welding without shield gas and failure to passivate after grinding or pickling are conducive to the formation of an active surface which is sensitive to chloride pitting.

In addition, the surface structure plays an important role. Inclusions of manganese sulfide can form active anode spots which may be a point of attack for chlorides and thereby cause pitting in the form of endgrain attack (see Fig. 11).

Practical Examples

The Corrosion Atlas contains a large number of Case Histories describing pitting and crevice corrosion of stainless steel under a range of different conditions.

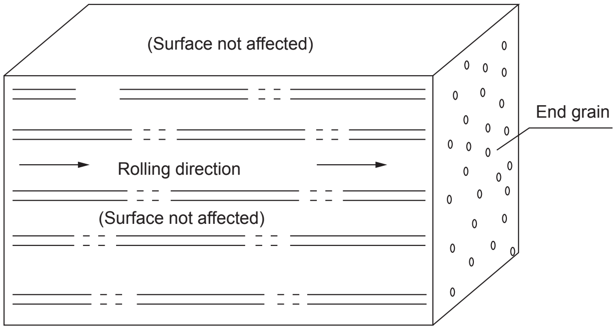

Figure 11 Schematic of a stainless steel plate showing long lines of inclusion and stringers. From Landrum, Fundamentals of designing for corrosion control. Reproduced with permission.

Typical examples of pitting are as follows:

Pitting caused by high chloride content in combination with low pH: AISI 304: 04.08.12.01 and in spite of the presence of molybdenum in AISI 316: 04.05.12.02, 04.08.12.02/03/06 and 04.11.12.08.

The influence of Mo on the pitting resistance is clear to see in 04.05.12.01 and 04.11.12.03.

In the case of fouling, AISI 316 is not resistant to seawater: 04.06.12.02.

Poor postweld treatment decreases the pitting resistance: 04.06.12.03.

Chromium steel has a lower resistance to chloride than the austenitic stainless steels: 04.06.12.01, but duplex stainless steels can be attacked by chloride as well: 04.11.12.04/05.

Chloride-containing foods can attack AISI 304 and 316 as well: 04.11.12.02/01. Chloride in the atmosphere can attack AS 304: 04.08.12.04/05, 04.11.12.06, and AISI 316: 04.11.12.09.

AISI 316 can be attacked by chloride-containing flue-gases: 04.18.12.01/02/03.

Typical examples of crevice and under-deposit corrosion are as follows:

In crevices caused by construction: 01.06.14.01, 04.06.13.1, 04.11.13.01 and 04.21.13.01. Underneath seal: 04.06.13.02, as a result of poor weldments: 04.05.38.1 and 04.11.38.01, under copper deposition: 04.01.14.1 and under deposits: 04.01.15.01, 04.06.15.01/02/03, 04.10.15.01, 04.11.12.09 and 04.11.15.01.

Examples of end grain attack in stainless steel are given in 04.08.42.01 and in nickel alloy in 05.11.42.01.

Testing

Potentiodynamic and potentiostatic testing can determine the sensitivity of a given stainless steel grade in a specific medium. In both laboratory tests, the breakdown potential is determined in a chloride solution; this is also known as the pitting potential. By raising the temperature incrementally, the laboratory assistant can determine the breakdown temperature above which pitting occurs in a given solution at a given potential; this value is known as the critical pitting temperature.

As a rule of thumb, pitting resistance can be expressed in terms of the pitting resistance equivalent (PRE). This index can be calculated on the basis of the chromium, molybdenum, and nitrogen contents, in the following equation:

$$1 \times \mathrm{Cr}\% + 3.3 \times \mathrm{Mo}\% + 30 \times \mathrm{N}\%$$

A PRE index above 38 guarantees adequate pitting resistance for the commonest practical cases.

The Prevention of Pitting and Crevice Corrosion in Stainless Steel

In the design *stage*,

- avoid crevices in the structure (*do not use riveted* joints);
- ensure effective tank drainage and appropriate dimensioning of line work, so that no deposits remain behind;
- use pitting-resistant alloys for preference.

In the construction *stage*,

- close existing crevices by means of welding or applying compound;
- ensure good workmanship: even root fusion, GMA (MIG), or GTA (TIG) welding with shield gas, appropriate postweld treatment;
- make sure all gaskets are in good repair, and bolts are properly tightened.

In the service stage,

- prevent contamination of the stainless steel surface by, for example, filtering the medium or improved water conditioning; if necessary, initiate regular cleaning;
- if possible, reduce the chloride content and increase the pH;
- avoid using hydrochloric acid to clean stainless systems if any alternative is possible;
- dose corrosion inhibitors;
- apply cathodic protection, if appropriatly combined with a coating.

11. SELECTIVE LEACHING

Selective leaching, also referred to as dealloying and parting, is a collective term for a number of different phenomena which are characterized in that a single element of the alloy is selectively dissolved. Dezincification, denickelification, dealuminfication, decobaltification, and decarburization are all examples of this. However, graphitic corrosion of cast iron is also a form of selective leaching. Because the element which is removed is always anodic relative to the alloy itself, dealloying also bears some resemblance to galvanic corrosion. The damage caused by selective leaching is very treacherous.

Although the color of the attacked surface may change, otherwise no externally observable changes in the form of pits, cracks, or grooves occur. The shape and dimensions also remain completely intact. However, the attacked metal becomes lighter in weight and porous and loses its original mechanical properties; it becomes highly brittle and has a very low tensile strength.

Dezincification

Dezincification occurs above all in brass containing more than 20% zinc, known as yellow brass. Brass containing less than 15% zinc, also known as red brass, is insensitive to dezincification.

The mechanism of dezincification is discussed in Part I. In most cases, dezincification is visible to the naked eye, in the form of local reddish coloring by the remaining copper. Here, two forms of dezincification are differentiated: layered or uniform dezincification and more localized or plug dezincification (refer to the Phenomena Index). Layered dezincification occurs mainly in higher zinc alloys, and plug dezincification tends to occur in brass grades with a lower zinc content. Sometimes brass affected by plug dezincification is covered with a brownish-white, zinc-rich corrosion product. In general, plug dezincification is promoted by higher temperatures and a high pH, while layered dezincification tends to occur at ambient temperature and in a neutral to slightly acid environment.

Driving Factors

There are a number of factors which can promote dezincification:

- if deposits are present on the brass surface (06.04.16.02, 06.05.16.01/03) or at crevices in the structure allowing differential aeration cells to form;
- certain water compositions such as mildly aggressive water (06.05.16.02), water with a high or low pH (06.06.16.02), and water with a high chloride content (06.01.16.01, 06.20.16.01);
- if heat transfer occurs;
- high water temperature;
- stagnant flow (06.06.16.01);
- if brass acts as anode in galvanic corrosion (06.04.16.01, 06.11.16.01);
- if tensile stresses are present (dezincification often precedes the occurrence of stress corrosion in brass).

Prevention

Dezincification can be prevented by:

- appropriate selection of material. Use brass with at least 85% copper (red brass). Yellow brass can be inhibited by alloying with 1% tin (admiralty brass) and small quantities of arsenic, antimony, or phosphorous. Inhibited aluminum brass is also eligible. In corrosive media, bronze, aluminum bronze, cupronickel, Monel, and sometimes stainless steel may possibly be used.
- ensure a clean surface by maintaining adequate flow and cleaning the surface periodically. In addition, appropriate water treatment is required to prevent corrosion products, biological contamination, or hardness sludge from depositing on the surface.
- avoid the use of brass in the case of:
  - high water temperatures (>70°C);
  - water with a low bicarbonate content and a high chloride content:

    $$\frac{ppm\ Cl^-}{ppm\ HCO_3^-} > 1$$

  - crevices in the structure.
- dose corrosion inhibitors. Film-forming products (such as tolyltrazole) are particularly effective in controlling corrosion of brass;
- apply cathodic protection;
- remove brass fittings if the circuits of which they form part have to be cleaned with an acid or caustic solution;
- in aqueous systems with brass fittings, ensure effective conditioning (pH, chloride).

Graphitic Corrosion

In gray cast iron, graphite is embedded in the iron matrix in the form of flakes. The problem is that under certain conditions this embedment is not stable. For example, the iron may enter into selective solution, leaving behind a porous mass of graphite and rust.

The driving force behind this phenomenon is galvanic corrosion. It is able to occur because graphite is highly cathodic relative to iron. As a result, small galvanic couples can form in the microstructure which, when in contact with a sufficiently aggressive environment, can result in galvanic corrosion.

Causes

As a general rule, graphitization occurs preferentially in relatively only slightly corrosive media, such as soft water, water with a slightly acid pH, and brackish water. Graphitization can occur in cooling water (01.06.16.01) but also in deaerated demineralized water (01.01.16.01). However, aggressive soils can also cause graphitization (01.06.16.02). In underground cast iron pipes, external graphitization can occur due to MIC because if sulfate is present in the soil SRB are capable of initiating graphite corrosion (01.14.16.01). Finally, stray currents can also cause graphitization of underground pipes. Because of their highly noble character, graphitized components may give rise to galvanic corrosion of less noble material.

External Characteristics

The problem is that graphitization is a slow corrosion process which often manifests itself only after many years. Although the mechanical properties of cast iron degrade severely, it may be some time before serious damage occurs, particularly if sufficient structural support is present, shock loads are absent, and internal pressure remains low. Because there is no change in shape and dimensions, graphitization is moreover difficult to recognize visually, although a color change occurs from gray to black, which is readily visible at the brittle fracture surface in particular. The soft material notches easily at the affected sites. Also, graphitized cast iron feels somewhat greasy, and in the absence of a pen, it is suitable—at a stretch—to write with. Furthermore, the affected cast iron produces a dull noise when struck with a hammer, instead of a healthy clear metallic sound.

Of course, under certain conditions, the graphitized metal is sensitive to erosion and cavitation, resulting in grooves or pits. In that case, special care is called for, because such an appearance can mask the occurrence of graphitization. In such cases, metallographic examination can determine whether graphitization is present.

Prevention

Graphitization can be prevented by the following:

- The use of more resistant material.
  Material selection is of course very important in preventing the graphitization of gray cast iron. Consideration may be given to the use of nodular cast iron, which is less sensitive—but not totally immune—to graphitization. Although this form of selective leaching is almost invariably seen in gray

cast iron, cases of graphitization have also been recorded in nodular cast iron. In view of the material structure, that is not particularly strange because in this case, the graphite is embedded in the matrix material in the form of tiny spheres. White cast iron, corrosion-resistant chromium, nickel, or silicium-containing cast iron are examples of materials which are insensitive to selective leaching. Like cast steel, austenitic cast iron is also immune. In addition, modem synthetics (plastics) are often a useful alternative.

- Modification of the environment.
  Sometimes the aggressiveness of the environment can be reduced by increasing the pH (01.01.16.01) or reducing the chloride content. Using sweet cooling water instead of brackish water is an example of this. Furthermore, cast iron should not be allowed to come into contact with sulfate-containing soil or other material.
- Use of coatings
  Coatings which insulate cast iron from its environment are a potential remedy. Commercially, this option is often the most attractive of all. Damage to coatings while the line is being laid and during subsequent compaction of the soil must of course be avoided. If necessary, corrosion prevention by means of coatings may be supplemented with cathodic protection.

12. STRESS CORROSION CRACKING

Stress corrosion cracking may be defined as a cracking process that requires the simultaneous action of a corrodent and sustained tensile stress.

The cracking may be both intergranular and transgranular, depending on the combinations of material and environment.

Tensile stresses can occur as a result of

- fabrication, machining, or assembly, in which case they are residual stresses.
- service, for example, internal or external pressure, load, unequal expansion on heating, and so on, in which case they are operating stresses.

Stress corrosion occurs specifically in certain metals in certain solutions, as indicated in Table 2.

Various plastics are also subject to cracking when stresses occur in a corrosive environment. In that case, the attack is known as stress cracking.

Examples of various stress corrosion cracking phenomena are reported in the Case Histories (third digits: 18). Of the most important of these, the following are discussed in the following:

- caustic stress corrosion cracking in carbon steel;
- chloride stress corrosion cracking in stainless steel;
- ammonia stress corrosion cracking in copper alloys;
- stress cracking in plastics.

Caustic Stress Corrosion Cracking of Carbon Steel

This form of corrosion, which is still frequently called by its obsolete name "caustic embrittlement," is a form of intergranular stress corrosion (where the cracks travel along the crystal boundaries). It occurs in steel subjected to mechanical tensile stresses in contact with hot concentrated caustic solutions.

Table 2 Alloy-Environment Systems Susceptible to Stress Corrosion Cracking

Alloy	Environment
Carbon steel (non- and low-alloyed)	Carbonates and bicarbonates (reversion to caustic)
	Caustic
	Nitrate
	Mixture of nitric and sulfuric acid
	Mixture of magnesium chloride and sodium fluoride
	Hydrogen (attack)
	Cyanide
	Anhydrous ammonia (liquid)
	$CO/CO_2/H_2O$ mixtures
Austenitic stainless steel	Organic and inorganic chlorides
	Acidic hydrogen sulfide
	Caustic
	Sulfurous and polythionic acids
	Nitrates
	Hydroxide
	Seawater
Nickel-base alloys	Caustic above 316°C (above 50%)
	(Alloys 200,400, and 600) mercurous nitrate (alloy 400)
	Mercury (alloy 400)
	Hydrofluoric acid and oxygen (alloy 400)
	fluosilicic acid (alloy 400)
Copper-base alloys	Amines (break down to ammonia)
	Dilute ammonia (including humid ammonia atmosphere) ammonium hydroxide
	Mercury
	Sulfur dioxide
Aluminum alloys	Seawater
Titanium	Organic chlorides above 290°C
	Hydrogen embrittlement
	Methanol
	Seawater (sodium chloride)
	Nitrogen tetroxide
Tantalum	Hydrogen embrittlement

Occurrence

The best-known example of this corrosion is the "caustic embrittlement," which formerly occurred in boilers provided with riveted connections. High caustic concentrations occurred in the crevices of the riveted connection due to local excessive evaporation, causing concentration of the alkaline boiler water (in other words, comparable with under-deposit caustic formation, see Part III, Chapter 1). In the latter case, uniform corrosion can also occur, as a precursor of hydrogen damage (see Part III and Chapter 8 of this part). This form of attack can also occur in water-tube boilers (01.01.18.05). In the case of steam contaminated with alkaline boiler water or caustic, caustic stress corrosion cracking may occur in the steam line (01.01.18.02). Caustic conveyor lines may also be sensitive to this corrosion (01.11.18.01). Incidentally, caustic stress corrosion cracking can also occur in stainless steel and nickel alloys (04.01.18.03, 04.25.18.01, and 05.01.18.01).

Prevention

In most cases, this amounts to:

- prevention or reduction of tensile stresses;
- prevention of caustic contamination;
- prevention of crevices in structures where high caustic concentrations can occur due to evaporation;
- prevention of process temperatures above 40°C.

Chloride Stress Corrosion Cracking of Stainless Steel

Of the stainless steels, only austenitic stainless steels are sensitive to this form of corrosion. In this case, the cracking is transgranular (straight through the crystals).

This form of corrosion occurs only if the following three conditions are met:

- the presence of tensile stresses due to residual stresses or operating stresses;
- the presence of chloride and oxygen in the medium;
- a temperature of at least 60°C; below this temperature, no stress corrosion is generally found in austenitic steel (with the exception of strongly acid environments).

The level of the stress, the level of the chloride content and the temperature, and the composition of the alloy together determine the rate at which stress corrosion cracks develop; this may vary from several minutes to several years. The rate depends mainly on the incubation time, after which the material will crack fairly suddenly. The cracking rate is of the order of several millimeters per hour. It is impossible to weld a stress corrosion crack because the crack proceeds faster than the welder can weld. A stress corrosion crack can initiate from the bottom of a pit.

Occurrence

Chloride stress corrosion cracking can occur in a variety of installations where the previously mentioned conditions are met, for example:

- in the case of chloride-containing atmospheres (04.01.18.02, 04.02.18.02 and 04.19.18.01);
- in the case of chloride-containing water (04.02.18.01, 04.11.18.01/14);
- in the case of chloride-containing products (04.11.18.04/05/06/09/11/12);
- in the case of chloride-containing text marker or tape (04.11.18.07, 04.22.18.01);
- in consequence of local heating (04.05.18.01 and 04.11.18.02).

One very common cause of stress corrosion is the so-called evaporation effects of salt water on the outside of a hotline. The water may, for example, enter between the insulation and the stainless steel by leaking from a flanged or soldered connection or in the form of rainwater through the insulation, chloride-containing, or otherwise (04.01.18.04/05, 04.11.18.16). Local lack of insulation may result in stress corrosion cracking on the inner wall of a line (04.11.18.03). This form of stress corrosion cracking can also occur under chloride containing seals (04.01.18.01 and 04.11.18.08).

Prevention

Chloride stress corrosion cracking of stainless steel can be prevented by:

- prevention of high mechanical stresses in machining, fabrication, and assembly;
- elimination of stresses by stress relief annealing to 850–1150°C, followed by even and above all rapid cooling in order to avoid residual stresses caused by uneven cooling and chromium carbide formation (refer to Chapter 13);
- shot-peening, a process which builds up small compressive stresses on the surface by blasting it with glass beads;
- reduction of the chloride content, use of chloride-free insulation, and a weather barrier;
- maintain low process temperatures (less than 60°C);
- providing lines with an external protection of paint, coating, or foil (not PVC) against the effects of evaporation;
- application of cathodic protection in general, and in the case of lines insulated with aluminum foil beneath the insulation;
- application of an alloy with better resistance to stress corrosion (duplex steel or alloys with more than 25% nickel).

Ammonia Stress Corrosion Cracking in Copper Alloys

Stress corrosion of brass is also known as “season cracking” because this form of corrosion was first observed in brass cartridge cases during the Boer War in South Africa (ca.1900), during the wet season. Ammonia gas from the marshes made the cartridges useless because they cracked. This form of corrosion only occurs when both tensile stresses (originating from applied or residual stresses) and a humid ammonia-containing atmosphere are present.

Occurrence

Examples of ammonia sources are:

- decay processes releasing ammonia into the atmosphere (06.06.17.01 and 06.15.18.01);
- use of ammonia-containing detergents;
- leaking sewer pipes;
- use of ammonia-containing fluxes in welding;
- an ammonia refrigeration system (06.06.18.01);
- ammonia-containing fertilizers (06.25.18.01);
- use of ammonia-containing or ammonia-forming chemicals to treat boiler feedwater (06.02.18.01);
- dosing of ammonia as neutralizing agent (06.11.18.01).

Some copper types are also sensitive to ammonia stress corrosion cracking (06.14.18.01). This stress corrosion occurs principally in α-brass and is usually intergranular. Sensitivity to ammonia stress corrosion cracking can be tested by the stress-relief annealing test according to SIS 117101 (06.24.18.01).

Prevention

Stress corrosion cracking in copper alloys can be prevented by:

- stress-free construction;
- thermal stress relief (specific times and temperatures depend on alloy composition, severity of deformation, prevailing stresses, and the size of the load being heated: 30 min to 1 h, from 150 to 425°C);
- use of brass with less than 20% zinc;
- preventing the formation of ammonia;
- avoiding contact between ammonia and the copper alloy by coating it or encasing it in a plastic pipe;
- use of ammonia-free solders.

Stress Cracking in Plastics

Because chemical reactions with substances from the environment do not occur in plastics, the term stress corrosion cracking is not applicable here. The damage mechanism is also not comparable with the stress corrosion which occurs in metals. In plastics, cracking of mechanically loaded materials is accelerated by the simultaneous action of chemicals. The medium can penetrate into the crack and generate a swelling pressure at the crack tip, thereby raising the notch stress. Many plastics are susceptible to the occurrence of stress cracking, for example:

	Case Histories
• acrylonitrile butadiene styrene by organic solvents	10.06.36.01
• polyvinyl chloride (PVC) by softening agent	10.08.36.01
• polyvinylidene fluoride by caustic	10.11.36.01/02
• polypropylene by chlorine	10.11.36.03 and 10.23.36.01
• polysulfone by methyl isobutyl ketone	10.1136.04

13. WELD DECAY AND KNIFE-LINE ATTACK IN STAINLESS STEEL

Weld Decay

Weld decay in stainless steel generally refers to the intergranular corrosion which occurs at about 5 mm distance from the weld seam in the heat-affected zone. It is caused because, during the welding process, the HAZ traverses the temperature range from 425 to 815°C. In this process, separation of chromium carbide occurs at the grain boundaries. The chromium in stainless steel then bonds with the carbon to form chromium carbide. The result of this is that, in particular, the material of the grains in a thin surface layer is severely depleted of chromium and hence loses its corrosion resistance; the material is locally sensitized (for examples, refer to the phenomena index).

This intergranular corrosion, which occurs not only as a result of welding but also of other heat treatments, can lead to perforation of the material or to mechanical failure of the structure, although at first sight, there appears to be nothing wrong.

Knife-Line Attack

However, there is another, less familiar, form of weld decay, which is referred to as knife-line attack. This is also a matter of chromium depletion by the formation of chromium carbides, but in this case, specifically in titanium- or niobium-stabilized stainless steel. Initially, during the process of welding stabilized stainless steel, no chromium carbide is formed in the weld decay zone because the carbon is bonded to titanium or niobium. In the heated zone immediately adjacent to the weld, where a temperature of ≥1225°C is reached, however, all the carbides (i.e., also titanium and niobium carbide) enter into solution and remain dissolved during rapid cooling. The carbon in that zone is therefore no longer bonded after the welding operation. In the event of a subsequent heat treatment (e.g., multilayer welding or stress relief annealing), this zone will therefore indeed be sensitive to weld decay by chromium carbide formation (for examples, refer to the phenomena index, No. 04.11.19.04 illustrates a rare combination of weld decay and knife-line attack).

Prevention

Weld decay can be prevented by:

- making a weld in thin layers under constant cooling, so that the heat input is limited (this is not feasible for large welds). Use the appropriate weld electrodes and materials (either with an extra low carbon content or stabilized).
- Postannealing at between 1020°C and 1150°C, whereby all the carbides redissolve and chromium and carbon are redistributed over the alloy. This must of course be followed by rapid cooling. Incidentally, this method is only used very rarely because the entire structure needs to be heated, which may be accompanied by deformations, and sufficiently rapid cooling is virtually impossible in the case of large structures.
- Use low-carbon stainless steel (<0.03%) so that carbide separation occurs less readily (e.g., AISI 304L or 316L).
- Use titanium- or niobium-stabilized stainless steel (e.g., AISI 316 Ti, 321 or 347), in which all the carbon is bonded as carbide to titanium or niobium, so that chromium carbides can no longer form.
- Quench the steel after stress relief annealing.

Knife-line attack can be prevented by heating the weld to 1065°C, whereby the chromium carbide dissolves, and titanium or niobium carbide is reformed. The material will then be restabilized.

PART III: CORROSION IN WATER-BEARING SYSTEMS

1. CORROSION IN BOILER SYSTEMS

Steam supply systems continue to be associated with a large number of corrosion phenomena resulting in a high cost due to unscheduled maintenance, energy loss, and unforeseen stagnation in the steam supply. Often this leads to loss of production.

This chapter considers the corrosion phenomena occurring in each part of a steam supply system, namely:

- the feedwater system
- the boilers themselves, both on water-side and flue-gas side
- the steam system
- the condensate system

Corrosion in Feedwater Systems

Oxygen Corrosion in Line Work and Deaerator

The commonest corrosion problem in the feedwater system is oxygen corrosion caused by a malfunctioning deaerator. This can lead to pitting, both in the deaerator itself and in the feedwater line to the boiler (01.01.01.01) and in feedwater preheaters if present Application of a coating in the feedwater system is not always a successful remedy (03.01.40.01). It is accompanied by the following reaction, in which the pits are covered with reddish-brown nodules of iron rust or hematite (Fe_2O_3):

$$2Fe + H_2O + O_2 \rightarrow Fe_2O_3 + H_2\uparrow$$

Besides causing corrosion in the feedwater system, poorly deaerated feedwater can also lead to corrosion in the boiler and in the condensate system, and therefore the cause of the malfunction in the deaerator must be traced and remedied as soon as possible.

Possible causes are:

- Errors in the deaerator design.
- Incorrect setting of the deaerator.
- Contamination and/or corrosion of components during service or a change in the load.
- Recirculation of high-pressure condensate which expands in the deaerator.

In order to avoid these disruptive situations and to enable the necessary measures to be taken at an early stage, periodical inspections of the deaerator are essential. An annual internal inspection for contamination, corrosion, atomizer operation, and so on is also very desirable.

Cavitation Erosion, Erosion Corrosion, and Graphitization of Impellers

Impellers of condensate and boiler feedwater pumps are also ready prey to corrosion. Here, three types of damage can be distinguished. If the supply pressure is too low, cavitation erosion can occur (01.01.33.01). If an aggressive feedwater composition is accompanied by a high flow velocity, the impeller material concerned may exhibit erosion corrosion (06.01.34.01 en 01.01.34.04). Sometimes graphitization of cast iron impellers occurs. In that case, the alkalinity of the feedwater is too low, so that the iron dissolves and the carbon remains (01.01.16.01).

Selective Leaching

Besides the previously mentioned graphitization of impellers, other forms of selective leaching can occur in feedwater systems, such as dezincification of feedwater pump components made of admiralty brass and denickelification of feedwater heaters made of cupronickel (06.01.16.01/02).

Cracking in Deaerators

Residual stresses from welding, together with fatigue due to vibrations and oxygen corrosion, may cause cracking in the vicinity of welds in deaerators (01.01.18.01). Especially in high-pressure deaerators (>0.4 MPa), this may lead to disastrous failure. However, low-pressure deaerators (<0.15 MPa) can also be rejected due to cracking. Stress-free annealing of the welds offers virtually complete protection against cracking.

Water-Side Corrosion in Boilers

Oxygen Corrosion

Oxygen corrosion remains a frequent problem in boilers. It can be caused by insufficient deaeration of the feedwater in the operational stage or by poor preservation during periods of shutdown. The mechanism of oxygen corrosion is fairly simple. In the absence of oxygen and temperatures above 120°C, water reacts with iron, forming magnetite (according to the Schickor reaction). This black iron oxide (Fe_3O_4) forms a protective skin on the metal surface:

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4\ H_2\uparrow$$

The magnetite skin prevents further corrosion. However, if regular supplies of oxygen occur at a later stage, this layer is broken down and converted into a nonprotective layer of hematite ($Fe_2\ O_3$):

$$4Fe_3O_4 + O_2 \rightarrow 6\ Fe_2O_3$$

During operation, the economizer is most sensitive to oxygen corrosion (01.01.01.02/03), but fire tubes can also be attacked (01.01.01.05). During shutdown, this form of corrosion occurs on the fire tubes of fire-tube boilers (01.01.01.04) and in the water tubes and drums of water-tube boilers (01.01.01.06/08). Control of this corrosion obviously requires an efficient deaerator. Other suitable measures are additional deaeration by dosing an oxygen scavenger (see also Corrosion in Condensate Systems) and improving the preservation method.

Caustic Corrosion

Corrosion in boilers is often due to an incorrect pH setting. Both an excessively high and an excessively low pH may be the source of the problem. In boilers, caustic corrosion is above all a consequence of extreme concentration of the boiler water underneath scale deposits or in crevices (01.01.03.01/02). Initially, the protective magnetite skin dissolves as follows:

$$4NaOH + Fe_3O_4 \rightarrow 2NaFeO_2 + Na_2FeO_2 + 2H_2O$$

Next, caustic and water react directly with the steel as follows:

$$Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2 \uparrow$$

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2 \uparrow$$

Another consequence of highly alkaline boiler water may be caustic stress corrosion cracking, leading to cracking (01.01.18.05, 04.01.18.02, and Part II, Chapter 12).

Acid Corrosion

Acid corrosion in boilers can be caused by magnesium chloride–containing cooling water entering the condensate system. This can take place, for example, via a seawater-cooled condenser of a power plant. If such acid-forming salts occur in high local concentrations, small quantities of hydrochloric acid are formed by hydrolysis:

$$MgCl_2 + 2H_2O \rightarrow Mg(OH)_2 \downarrow + 2HCl$$

Other chloride-containing contaminants can also produce hydrochloric acid by decomposition under certain conditions.

Even if the bulk of the boiler water reacts alkaline, the acid need not necessarily be neutralized immediately. This is because porous deposits, crevices, or poor boiler water circulation may prevent thorough mixing of the water. This enables local sharp decreases in pH. The hydrochloric acid then attacks the steel as follows:

$$Fe + 2HCl \rightarrow Fe\ Cl_2 + H_2 \uparrow \ (01.01.04.05)$$

In fire-tube boilers, a similar type of acid corrosion sometimes occurs if dosing of sodium bisulfite is adopted for the chemical bonding of oxygen. Particularly, when this is applied not in addition to but instead of thermal deaeration, there will usually be an extremely high sulfate concentration in the boiler water. Presumably, under such conditions, acid is formed by hydrolysis (01.01.04.11).

Other sources of acid contamination of boiler water are the entrainment of regeneration acid with the makeup water or of acid or acid-forming products with the condensate.

Finally, acid corrosion can also occur when chemical cleaning treatments of boilers are poorly performed or poorly inspected (01.01.04.01/04/06/07).

Hydrogen Attack

Both acid attack and caustic attack of steel initially cause the formation of atomic hydrogen. Hydrogen damage may result (see Part II, Chapter 8). The atomic hydrogen diffuses into the steel and reacts with iron carbide, with formation of methane (01.01.20.02/03/04/05/06/07).

The pH can be controlled by means of appropriate boiler water conditioning and daily testing of the feedwater and boiler water composition, which will prevent this form of corrosion.

Erosion Corrosion

In boilers, erosion corrosion occurs particularly in evaporator tubes if excessive steam formation leads to excessively high water velocity. In an over-dimensioned economizer, undesirable steam formation can occur in the economizer tubes. This leads to erosion corrosion particularly in the bends (01.01.34.01/06). Turbulence can cause erosion corrosion at other sites in the boiler. Research carried out by KEMA Nederland B.V. in Arnhem, Holland, has shown that a causal relationship exists between the contents of copper, chromium, molybdenum and carbon, and the erosion corrosion resistance of carbon steel in water–steam systems. This is specified as the G_{KEMA} value, which can be calculated as follows:

$$G_{KEMA} = 90 - 160.\ Cu - 115.\ Cr - 40.\ Mo + 35.\ C$$

Erosion corrosion resistant material for water–steam systems should have a G_{KEMA} value of at most 80.

Chelant Corrosion

Chelant corrosion is a risk if complex binders are dosed as part of the boiler-water conditioning procedure. For example, dosing with sodium ethyl diamine tetra-acetic acid (Na-EDTA) can cause the steel to be attacked as follows:

$$Fe_3O_4 + Fe + 8H + 4CH \rightarrow 4Fe\,(II)\,CH + 4H_2O$$

(CH = chelate molecules)

This chelant corrosion produces a typically uniform corrosion picture without specific characteristics. If the flow velocity is sufficiently high, there may be a wavy surface with areas of damage resembling comet-tails and horseshoes. Oxygen is a strong promoter of the formation of chelant corrosion. The risk is also increased by overdosing and local concentration of the complex binder. It is quite clear that these conditioners must be dosed with particular care. In order to prevent chelant corrosion, the levels of complex binder and oxygen in the feedwater must be carefully checked. Practice has shown that this form of corrosion occurs in the steam drum and downcomers but also in the feedwater line (01.01.21.01/02/03). Because places with a large heat flux are extra sensitive, hot spots in the boiler should be avoided.

Heat-Flux Corrosion

A number of different corrosion processes can be strongly accelerated at sites where there is a high heat flux; logically, this is called heat-flux corrosion (01.01.04.05, 01.01.07.01/02/03/04, 01.01.20.04/05, and 09.01.07.01).

Liquid Metal Embrittlement

During welding or high-temperature operation, copper-containing deposits in boilers can lead to cracking as a result of liquid metal embrittlement. This is caused by molten copper penetrating into the steel along austenite grain boundaries, causing intergranular cracking and failure of the pipes (01.01.22.01/02).

Prior to overhaul, any copper deposit present should be removed by chemical cleaning, incorporating a copper removal step in order to prevent copper plating.

Steam Blanketing

Obliquely rising water tubes, for example, at the bottom of water tube boilers, are particularly sensitive to damage by thermal stresses. Here, the protective oxide skin of magnetite (Fe_3O_4) can sometimes be so badly damaged that leakage results.

For example, circulation upsets or strong radiation may cause an intensive boiling process in these tubes, whereby steam bubbles remain attached to the heated upper side of the tube and form a local steam blanket. This results in a local sharp decrease in cooling, and enhanced oxidation takes place (formation of magnetite). If the steam blanket is expelled by load fluctuations (caused by changed circulation), the cooling will temporarily recover, and the formed oxide can flake off.

This steam blanketing can cause substantial loss of wall thickness in a comparatively short time (0.01.43.01). In the case of concentration of salts underneath the steam film, steam blanketing can also cause acid and caustic corrosion and even lead to hydrogen damage (see Part II, Chapter 8).

Steam blanketing can be prevented either by reducing the heat load at these sites, that is by applying thermal insulation or by structurally improving the circulation in the tubes concerned. In addition, appropriate water treatment should be applied in order to prevent the formation of circulation-impeding deposits.

Corrosion by Overheating

Steel in a boiler can become overheated. This may be caused by excessive radiation from the furnace or insufficient cooling. Cooling may be impeded by deposits in the evaporator section or superheater causing blockages. The overheating causes the steel to lose strength, and it begins to creep and bulge, which results in cracking (01.01.30.01/02). This phenomenon occurs frequently in boilers. In itself, this is not strictly corrosion, but the high steel temperature will cause the oxidation process to accelerate, thereby forming an undesirably thick oxide skin. When the pipe wall cools (during shutdown), the over-thick oxide skin will be subjected to stress and spall off. In a following operational period, locally strong oxide growth will recur. If this cycle is repeated a number of times, the lifetime of the tubes may be substantially reduced. If this phenomenon occurs in the final superheater, the hard oxide particles entrained with the steam can cause erosion of the steam-consuming equipment (e.g., the turbine blades).

Overheating can be prevented by correcting an unbalanced heat distribution, improving the cooling, or by applying different steel grades capable of withstanding higher temperatures. Thermally insulating and blocking deposits can play an important role in overheating. The formation of deposits can be prevented by effective boiler-water treatment together with appropriate monitoring.

Fire-Side Corrosion in Boilers

Irrespective of the fuel—coal, oil, or gas—combustion products are present in the boiler in all three phases: solid, liquid, and gaseous. As they cool while traveling to the stack (the combustion gas temperature varies from approximately 1650°C in the flame to 120°C or less in the stack), gaseous products can condense to a liquid or even solidify. The combustion products seldom remain as oxides but generally react among themselves. This may form new compounds and complexes with lower melting temperatures, and these can therefore create problems in the form of fire-side corrosion.

The boiler wall, flue-gas coolers and the walls of the superheater tubes, and the economizer tubes are the most sensitive areas in this respect, in that cooling takes place rapidly because the surfaces are relatively cold compared with the temperature of the flue gases.

Oil-Ash and Coal-Ash Corrosion

Aggressive slag can form when coal and oil are fired. The risk is largest if the oil contains high levels of vanadium, sodium, or sulfur (or a combination of these). The molten slag depositing on the superheater tubes may lead to oil-ash or coal-ash corrosion, a form of high-temperature corrosion (see Part II, Chapter 7).

In oil-ash corrosion, the vanadium and sodium compounds present in the oil are oxidized in the flame to form vanadium pentoxide (V_2O_5) and sodium oxide (Na_2O). Because the sodium oxide acts as binder, the ash particles can adhere to the metal surface. Subsequently, vanadium pentoxide and sodium oxide react on the metal surface, forming a liquid eutectic. The composition of this varies depending on the vanadium–sodium ratio in the oil. The resultant melt penetrates through the magnetite, after which the underlying steel is exposed to rapid oxidation, with the vanadium pentoxide acting as catalyst. The presence of other heavy metals such as tungsten and niobium also accelerates this oxidation process. In the case of coal-ash corrosion, complex alkali sulfates are formed at the metal/deposit interface. The accelerated oxidation of the steel leads to a reduction in wall thickness and therefore to loss of tensile strength. Ultimately, damage occurs in the form of creep cracking (01.01.06.01) or pitting (04.01.06.01).

The oxidation occurs at temperatures between 600°C and 800°C. The presence of steam-side deposits in the superheater will increase the metal temperature, considerably increasing the risk of these melts forming.

Prevention

This high-temperature corrosion can be prevented by:

- adding an oil additive. Good experience has been gained with the addition of magnesium compounds (where vanadium content is not excessive). This results in the formation of a magnesium–vanadium complex ($3MgO.V_2O_5$) with a high melting temperature;
- firing the boiler with less excess air, thereby slowing down the formation of vanadium pentoxide;
- keeping the temperatures of the air-heater below 600°C;
- applying periodic chemical treatments to the superheater, thereby preventing the build-up of internal temperature-increasing deposits;
- switching to a different, vanadium-free fuel.

Dew-Point Corrosion

A notorious phenomenon in fire-side corrosion is acid attack of cold boiler surfaces by acid, known as dew-point corrosion.

A differentiation is made between dew-point corrosion during service, also known as "cold-end corrosion," and dew-point corrosion during idle periods.

Dew-Point Corrosion During Service

The temperature can fall below the dew-point in the economizer, the air-heater, and the stack. The most familiar example is sulfuric acid attack associated with the firing of sulfur-containing oil (01.01.04.08).

Sulfuric acid is formed by the reaction between water vapor and sulfur trioxide. Upon contact of the flue-gases with relatively cold surfaces below the dew-point, the steel is attacked by the condensed sulfuric acid. The dew-point depends on the concentrations of water vapor and sulfur trioxide present in the flue gases and varies from 116 to 166 °C or higher. The attack proceeds as follows:

$$H_2SO_4 + Fe \rightarrow FeSO_4 + H_2 \uparrow$$

Prevention

Sulfuric acid corrosion can be prevented by:

- keeping the air excess below 5%, thereby minimizing the quantity of sulfur trioxide;
- designing the boiler in such a way that low metal temperatures (below the dew-point of sulfuric acid) cannot occur;
- using oil additives as a chemical solution;
- using fuels with a low sulfur content and a low moisture content.

This cold-end corrosion can also occur in waste combustion boilers by the formation of hydrochloric acid during the combustion of chloride-containing plastics (01.01.04.03/10). Nitrogen oxides containing exhaust gases from gas-fired boilers can cause nitrate stress corrosion cracking to the carbon steel chimney (01.01.18.04).

Besides originating from the fuels, the acid components present in the flue gases can also originate from contaminants present in the combustion air (02.01.04.01). It will be clear that these forms of dew-point corrosion can easily be prevented by not allowing the temperature to fall excessively during service and/or by preventing contamination of the combustion air.

Dew-Point Corrosion During Idle Periods

Besides during service, dew-point corrosion can also occur during periods when the boiler is idle. During cooling, condensation occurs on the fire-side surface, reacting with the sulfur-containing deposits to form sulfuric acid which then attacks the boiler steel (01.01.04.02/09). The corrosion occurs particularly at the outside of the economizer tubes and at any places where acid sulfur-containing deposits are present.

Prevention

Dew-point corrosion during idle periods can be prevented by:

- Specifying fuels with a low sulfur content;
- Water-jetting the corrosion-sensitive parts immediately after shutdown, followed by neutralization of the surface using lime water;
- Keeping the boiler dry on the fireside by
  - maintaining the temperature of the boiler water, for example, by means of a heat exchanger and a boiler in service, or
  - placing troughs with unslaked lime in the furnace, or
  - more sophisticated, circulating dried air.

Erosion and Erosion Corrosion

Besides fire-side corrosion, boilers are also subject to fire-side erosion. Possible causes may be:

- Incorrect setting and operation of the soot-blowers.
- A steam jet from a leaking nearby tube.
- The presence of fly-ash.
- An inappropriate boiler design.

Soot-Blowers

Properly adjusted soot-blowers remove the soot from between the tubes of superheaters. In practice, they are frequently found to be directed at the tube surface. Condensed water droplets, possibly with entrained fly-ash particles, have an abrasive effect and cause accelerated oxidation of the steel. Malfunctioning soot-blowers can also cause erosion problems. Generally, there is a grooved corrosion picture, with a clear flow pattern. This can ultimately lead to loss of wall thickness and fracturing of the tube (01.01.34.03).

To prevent soot-blowers causing erosion problems, the position of the nozzles and the blow direction must be periodically inspected. Use of superheated steam or effective water separation in the steam line can prevent the presence of water droplets in the steam. If these measures are ineffective, tube life can be extended by enlarging the wall thickness at sensitive places. The best procedures for this purpose are metal coating, buttering, and plasma spraying.

Leaking Tubes

The steam jet leaving a leaking tube can cause considerable erosion damage in its immediate vicinity. In this way, a single leak can result in a series of multiple leakages (01.01.32.05).

In principle, this may occur anywhere in the boiler, but particularly tubes with the highest steam pressure (superheater tubes) tend to be affected by this problem. Prevention of water-side corrosion can prevent the occurrence of pipe leakages and the consequent erosion by steam jets.

Fly-Ash

Fly-ash can also cause erosion, in particularly in combination with high flue-gas velocities. The most sensitive areas are the economizer, the superheater, and the roof furnace tubes and also any area where canalization or strong turbulence occurs. Fly-ash erosion occurs particularly in boilers which are fired with excess fuel, that is, to say with deficient air. Also, boilers fired with fuel contaminated with sand and dirt show a damage picture which is identical to fly-ash erosion (01.01.32.06/07).

Design Errors

Design errors in boilers can reinforce erosion damage. In fluidized bed boilers, the sand bed can erode the lower part of the furnace tubes if the brickwork is not constructed high enough (01.01.32.01).

Corrosion in Steam Systems

In general, few corrosion problems occur in the steam lines and on the steam side in steam consumers. The main problems encountered are erosion corrosion and caustic stress corrosion cracking. However, due to the high pressures in the steam system, these problems can lead to serious failures if the lines rupture.

Erosion (Corrosion)

Erosion (corrosion) can be caused by the presence of water droplets or solid particles in the steam. Water droplets can consist of entrained boiler-water resulting from malfunctioning steam/water separation or by boiler foaming due to contamination of the feedwater by organic materials (01.01.34.02 and 06.01.32.02). Water droplets originating from the injection cooling of superheated steam can also cause erosion (01.01.32.02). Finally, water droplets can form by condensation in the steam line (01.01.32.04 and 06.02.32.02). Particularly, turbine blades are sensitive to erosion, both due to the presence of water droplets (01.01.34.08 and 04.01.32.02) and solid particles in die steam. The latter may originate from the boiler, for example, as detached magnetite particles from superheater tubes but also from a new steam line which has been insufficiently blown through with steam prior to being taken into operation. This impingement attack can also occur at the steam side of heat exchangers (06.01.32.01).

Prevention

Erosion problems in the steam system can be prevented by the following measures:

- improve the steam–water separation if necessary. Measuring the steam conductivity will give a good indication of separator performance;
- prevent excessive concentration of the boiler water and make sure that organic materials cannot contaminate the condensate. This will prevent carryover and foaming of the boiler water. The best way of checking condensate quality is also by conductivity measurement because an organic contamination is virtually always accompanied by an inorganic contamination;
- provide long steam lines with sufficient drain points. For example, fit a steam trap in a drainage line of a low-lying part of the steam line;
- avoid injecting excess water. This can be done by correct adjustment of the injection cooling (thermometer bulbs should not be located immediately downstream from the injection point);
- prevent magnetite from flaking off in the superheater tubes by reducing the superheater temperature or using special high-temperature alloys. If necessary, replace the superheater or apply periodical chemical cleaning treatments;
- in the case of new construction, select the appropriate material for the turbine blades. These are usually made of chromium steel. However, cobalt alloys, titanium, and other erosion-resistant metals are increasingly gaining ground.

Caustic Stress Corrosion Cracking

Caustic stress corrosion cracking is the second problem that can cause damage in steam lines, particularly in the vicinity of welds. Formerly, it was known by the obsolete term “caustic embrittlement“ (for further information, see Part II, Chapter 12). It occurs if the steam is contaminated with alkaline water, for example, with boiler water due to carryover or by leakage of an attemperator (05.01.18.01) or with alkaline injection water. The latter can occur, for example, where recycled condensate used for injection purposes has been contaminated with a caustic substance during the process operation (01.01.18.2).

Contamination of steam with boiler water and contamination of injection water with alkaline products can best be monitored by means of the previously mentioned continuous conductivity measurement procedure. For injection cooling, it is safe practice to use fully demineralized water with a conductivity of ≤0.02 mS/m.

Acid Corrosion

Besides caustic corrosion, steam contaminated with boiler water can also result in acid corrosion, for example, of turbine blades, resulting from hydrolysis of the entrained chlorides and sulfates (04.01.04.01).

Excessive Magnetite Formation

Another undesirable but less disastrous phenomenon can occur in the case of insufficiently deaerated feedwater. In this situation, excessive magnetite can form in the steam line. Because this can cause blockage of steam control valves, sieves, and condenser drains, care should always be taken to ensure proper deaeration (01.01.01.07/09).

Corrosion in Condensate Systems

Corrosion in condensate systems can result in damage in a number of different ways.

The main cause of corrosion in condensate systems is the presence of oxygen and/or carbon dioxide in the condensate. Other causes are cavitation, erosion corrosion, and ammonia corrosion.

Leakage of condensate lines or damage to steam consumers will sometimes occur within only a few months after installation. Corrosion in the lines, however, can also lead to contamination of the boiler water with iron oxide sludge, and in certain cases, process chemicals may even leak into the condensate.

Oxygen Corrosion

The occurrence of oxygen corrosion obviously depends on the presence of oxygen. This gas can enter the system due to defective feedwater deaeration. If a vacuum occurs in condensate lines during idle periods, atmospheric air can also be drawn in. The temperature inside the condensate system is relatively low. Therefore, a protective magnetite skin (Fe_3O_4) will not generally form, as it does in the steam lines and in the boiler itself. In the condensate system, the oxygen will tend to react with the steel as follows:

$$2Fe + O_2 + 4H^+ \rightarrow 2Fe^{2+} + 2H_2O$$

Depending on the flow velocity and pH of the condensate, the dissolved iron is entrained with the flow or it will precipitate locally as Fe_2O_3. Almost invariably, there is a pitting corrosion picture (01.02.01.01/03). The presence of salts in the condensates, for example, because boiler water is entrained with the steam or because of inleakage of cooling water or tap water, will considerably accelerate the rate of corrosion.

Prevention

For the prevention of oxygen corrosion, the following measures can be considered:

- Ensure there is an efficient deaerator and perform regular checks (at least once every year) of the residual oxygen content.
- Consider dosing an oxygen scavenger following thermal deaeration. This is advisable especially in the case of boilers operating at pressures of 4 MPa and higher. Choose between hydrazine hydrate 24% or organic oxygen scavengers, depending on local conditions. These chemicals are dosed into the deaerated feedwater or directly into the condensate. For lower pressures, sodium (bi)sulfite is a suitable oxygen scavenger, but it may only be dosed into the boiler feedwater.
- If possible, condensate lines should be laid at free fall, so that during night-time and/or weekend shutdowns on condensate can remain in them. If this is impossible, the condensate system should at any rate be provided with drainage points to enable draining during idle periods. In the absence of condensate, air ingress will be much less able to cause corrosion.
- Prevent aeration of the condensate on its way to the boiler house by avoiding the use of open condensate tanks.
- If aeration of the condensate cannot be prevented, a film-forming amine may be dosed into the steam. This will form a fatty, water-repellent film on the steel, providing protection against corrosion.

Carbonic Acid Corrosion

The occurrence of carbonic acid corrosion depends on the quantity of bound carbon dioxide in the deaerated feedwater. This amount is defined by the amount of bicarbonate in the makeup water, the water treatment method, and the condensate/makeup water ratio. This form of corrosion occurs only where a cation exchanger is used in the sodium cycle. Carbonic acid corrosion cannot occur if the makeup water is demineralized or dealkalized.

Mechanism

Where a cation exchanger is used in the sodium cycle (generally called a softener) for the preparation of the makeup water, sodium bicarbonate is formed from the temporary hardness ($Ca(HCO_3)_2$). When the makeup water is heated in the deaerator (and later in the boiler), this bicarbonate will decompose into carbonate, carbon dioxide, and water, as follows:

$$2\ HCO_3^- \rightarrow CO_3^{2-} + CO_2 + H_2O$$

The carbon dioxide released in the deaerator in this way and the carbon dioxide already present in the makeup water and the recycled condensate are also removed during the deaeration process. In the boiler, the carbonate will separate partially—between 60% and 80%, depending on the boiler pressure—into carbon dioxide and alkali, as follows:

$$CO_3^{2-} + H_2O \leftrightarrows CO_2 + 2\ OH^-$$

Clearly, the more bicarbonate there is in the make-up water, the more carbon dioxide will form. However, the more condensate that is recycled, and therefore the less makeup water that is needed, the lower the bicarbonate concentration in the feedwater becomes.

As the steam condenses, CO_2 dissolves in the condensate. The resultant carbonic acid then dissociates as follows:

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^-$$

Formation of H^+ ions causes the pH of the condensate to fall to between 4 and 6, thereby causing attack to the steel as follows:

$$2H^+ + 2\ HCO_3^- + Fe \rightarrow Fe(HCO_3)_2 + H_2 \uparrow$$

Carbon acid corrosion leads to uniform attack to the steel in the case of horizontal, incompletely filled lines in the form of a gully (01.02.02.01/02). Air heater pipes are particularly sensitive to this form of corrosion (01.02.02.3).

Particularly in hospital clinics, there is a tendency to install copper condensate lines for constructional reasons. However, copper is also attacked by carbonic acid if oxygen is present at the same time. The corrosion appearance may be both uniform and irregular (06.02.02.01/02). Galvanized steel is also not resistant to oxygen and/or carbonic acid corrosion (02.02.01.01 and 02.02.02.01).

Prevention

Suitable preventive measures against carbonic acid corrosion are:

- Maximize condensate recycling (this also saves water and energy).
- Apply alkalinity reduction to the makeup water. For this purpose, ion exchangers are used to remove the bicarbonate ions from the water. Besides this partial desalting, more complete desalting could also be applied by means of demineralization and/or reverse osmosis.
- Dose ammonia or neutralizing amines into the feedwater in order to neutralize CO_2. Filming amine dosing also protects against carbonic acid corrosion. For reasons of public hygiene (in food manufacturing or where steam is used for air humidification), the use of chemicals in this way is not always permitted. Refer to the guidelines of the United States Federal Drug Administration.
- Construct the condensate system from stainless steel AISI 304 (in the case of impure steam, 316 is preferable in view of its better chloride resistance), which is resistant to both oxygen and carbonic acid corrosion. Especially in small systems, this may be the most economic solution.

Cavitation Erosion

Cavitation erosion in condensate systems occurs particularly in condensate lines when steam bubbles enter relatively cold condensate where they implode. Steam bubbles may originate from a leaking steam trap; these traps should therefore be properly monitored for leakage (01.02.33.01). However, steam bubbles can also form when high-pressure condensate is passed into a low-pressure condensate line (01.02.33.05). This problem can be avoided by returning the high-pressure condensate and low-pressure condensate separately to the boiler house. It is also possible to incorporate an expansion tank in the condensate system so that the high-pressure condensate has room to expand.

Cavitation erosion also occurs frequently in condensate and boiler feedwater pumps due to insufficient static pressure at the suction side of the pump. The cause may be that the condensate tank or the deaerator, respectively, is positioned too low (01.02.33.03). Moreover, a large number of bends or too small a diameter will cause excessive resistance in the suction lines, allowing the pressure on the suction side to become too low. Finally, cavitation erosion can also occur in condenser tubes due to vibrations (01.02.33.06).

Erosion Corrosion

Erosion corrosion is also a frequent problem in condensate lines and steam consumers, particularly where there is a combination of high velocity, turbulence, and corrosivity of the condensate.

The danger of this damage is that it can occur sooner than expected. This is because the velocity in condensate lines can increase if the quantity of “vapor steam” which forms during the pressure drop (expansion) across the steam trap has been disregarded for dimensioning purposes. Moreover, the condensate need only be mildly aggressive. A carbon dioxide content of 20 ppm is sufficient.

Erosion corrosion occurs particularly in bends, and copper lines are especially sensitive to it (01.02.34.01/02 and 06.02.34.01/02). To prevent this damage, it is of course important for the condensate line to be appropriately dimensioned. Carbonic acid corrosion can be controlled by dosing a neutralizing amine, which will also prevent the occurrence of erosion corrosion.

Ammonia Corrosion

Given the simultaneous presence of oxygen and ammonia, ammonia corrosion can occur at pH values >9.0 in the form of uniform or grooved attack to, for example, copper condenser tubes (06.02.10.01/02/03). In contact with brass, ammonia can lead to stress corrosion cracking (06.02.18.01).

In many cases, the presence of ammonia is predictable, for example, when it is dosed or due to decomposition of chemicals such as hydrazine and neutralizing amines. However, sometimes ammonia corrosion can occur unexpectedly because it may be naturally present in the makeup water, for example, if use is made of a private supply of well water (06.01.10.01).

If copper or copper alloys are incorporated in the condensate system, ammonia (or products which can form ammonia through decomposition) must therefore not be dosed. Alternatively, the components concerned should be constructed from an ammonia-resistant material, such as carbon steel or stainless steel.

Galvanic Corrosion

If the condensate is sufficiently conductive due to contamination with boiler water or cooling water or due to an excessive carbon dioxide concentration, galvanic corrosion may occur in combinations of dissimilar metals (01.02.14.01/02).

2. CORROSION IN WARM AND HOT WATER HEATING SYSTEMS

Water heating systems may be differentiated into:

- Water heating systems in the sense of the familiar central heating systems, operating at a maximum temperature of 110°C, mostly 90°C out and 70°C return.

  These are usually applied exclusively for space heating purposes and sometimes also for making hot tap water by means of water heaters etc.

- Hot water heating systems operating at temperatures above 110°C (130–180°C), used exclusively in industry or offices and hospitals and so on for process heating, steam production by tube exchangers, hot tap water making, heating factory halls, and heat source for central heating systems.

The corrosion problems occur most commonly in hot water systems, in large-scale central heating systems of offices and hospitals, locations where much new construction is practiced and in district and town heating systems featuring zone circuits and for the heating of major industrial complexes. The smaller-sized central heating systems used for individual homes or blocks generally do not suffer any corrosion problems because the makeup of these systems is virtually nil.

The main cause of corrosion in this type of systems is the presence of oxygen in the water.

Oxygen Corrosion

Oxygen corrosion causes a pitting corrosion picture. These pits are often covered with brown nodules, filled with black iron oxide, Fe_3O_4, also known as magnetite (01.04.01.01/04).

Mechanism

The corrosion reactions are:

at the anode: $Fe \rightarrow Fe^{2+} + 2e$

at the cathode: $O_2 + 2H_2O + 4e \rightarrow 4OH^-$

and then: $Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + H_2\uparrow + 2H_2O$$

Sources of oxygen may be:

- The fill water, particularly if the system is drained at regular intervals for the purpose of phased new construction, reconstruction, or repair.
- The supply water, particularly if it has to be added at regular intervals.
- Diffusion of atmospheric oxygen through gaskets, membranes, plastic hoses as used in floor heating systems, and plastic hose connections.

Deposition of Magnetite

Supply of oxygen may not only lead to leakage via the pitting corrosion, but it may also result in blockages caused by magnetite. Particularly, small-diameter hose connections with small orifices, which are commonly used in, for example, induction units, are sensitive to this problem. This magnetic iron rust is also capable of causing pump failures due to its abrasive effect on the bearings and in in-line pumps due to deposits in the magnetic field around the rotor and pump shaft (01.04.01.02/03).

Excessive magnetite formation may furthermore impede the efficient operation of control valves. Lastly, the formation of hydrogen gas may cause an irritating noise in the system and lead to blockage of the uppermost sections. Blockage also occurs as a result of poor deaeration.

Deposit Corrosion

Accumulation of sludge originating from deposited hardness or corrosion products may cause corrosion of the material underlying the sludge layer due to formation of differential aeration elements. This under-deposit corrosion commonly occurs where frequent makeup is practiced, which also introduces oxygen into the system. It appears at places characterized by low flow, such as in the lower part of radiators, where the sludge can settle (01.04.15.01).

The formation of deposits can also lead to dezincification of brass (06.04.16.01/02).

A totally different consequence of sludge formation in central heating systems is noise in the system. This is caused because the poor heat discharge causes boiling of the water film which is present in the boiler underneath a sludge layer. The steam bubbles penetrate through the sludge and implode in the less hot water. These implosions are accompanied by bangs which are audible throughout the building and may cause the central heating boiler and line work to thump and shake. In such cases, the sludge has to be removed from the boiler, either by mechanical or chemical means.

Galvanic Corrosion

If oxygen is present in addition to a combination of dissimilar metals, there is a risk of galvanic corrosion in water heating systems (07.04.14.01/02). Application of galvanized steel in such systems is out of the question in view of the risk of reversal of potential, which causes pitting of galvanized steel (02.04.14.01 and Part II, Chapter 6).

Corrosion by Chemicals

Inappropriate or improperly monitored dosing of chemicals in these systems may sometimes cause severe corrosion (01.04.18.01, 02.04.27.01, 06.04.10.01, and 07.04.12.01).

Cavitation Erosion

In hot water systems, there is a risk of cavitation occurring should the system pressure be equal to or only marginally higher than the saturation pressure associated with the hot water temperature. Even slight resistance in the system, caused by, for example, valves, will allow steam bubbles to form and then implode, thereby causing cavitation erosion (01.04.33.1).

Fire-Side Corrosion

As in steam systems, contamination of the combustion air may also cause fire-side corrosion in water heating systems (01.04.04.01 and 07.04.04.01).

Corrosion Prevention

Corrosion prevention may be realized:

- By constructive measures.
- By makeup treatment.
- By water conditioning.

By Constructive Measures

Corrosion in water heating systems must be primarily prevented by means of purely constructive measures, for example:

- Appropriate dimensioning and construction of expansion and overflow vessels.
- Applying a “nitrogen cushion” in these vessels.
- Application of sectional valves.
- Use of metallic gaskets, and only using plastic hose connections which are provided with an impermeable barrier (such as aluminum foil).
- Preventing the occurrence of vacuum by maintaining sufficient pressure right up to the topmost parts of the system.
- Appropriate construction of zone circuits with adequate facilities for the prevention of corrosion from outside sources.

By Makeup Treatment

Suitable measures are:

- Water softening, which is at any rate essential in hot water systems and sometimes, depending on the water consumption, for warm water systems as well.
- Alternatively demineralization, which is specifically used in the case of large-scale district heating systems.
- Deaeration of the fill water and makeup water, if appropriate under vacuum.

By Water Conditioning

Suitable measures for this purpose are:

- Dosing of oxygen scavengers.
- pH control (pH 10–10.5).
- Dosing of corrosion inhibitors.
- Sidestream demineralization.
- Sidestream filtration.

3. CORROSION IN COOLING WATER SYSTEMS

Types of Systems

According to the volume of heat to be discharged and the stage in the process, these are classified either as main or secondary cooling systems.

For main cooling systems, tube heat exchangers are generally used, in which the water flows through the tubes. In secondary systems, plate-type coolers are used in addition to tube heat exchangers.

According to their design, main cooling systems may de-differentiated into once-through and recirculating systems:

Once-Through Cooling Water Systems

These are systems in which surface water (from the sea, rivers, lakes, and canals) or well water passes through the cooling system once and is then discharged to open water or the sewer or is reused for other purposes (Fig. 1).

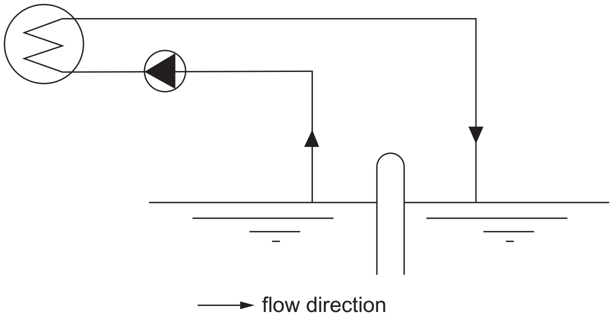

Figure 1 Open once-through cooling system.

Open (Evaporative) Recirculating Cooling Water Systems With Cooling Tower

These are systems in which the water is recirculated, and the absorbed heat is transferred to the atmosphere by means of evaporation. Water losses due to evaporation, splash, and discharge have to be made up by means of mains water or purified well water or surface water (Fig. 2).

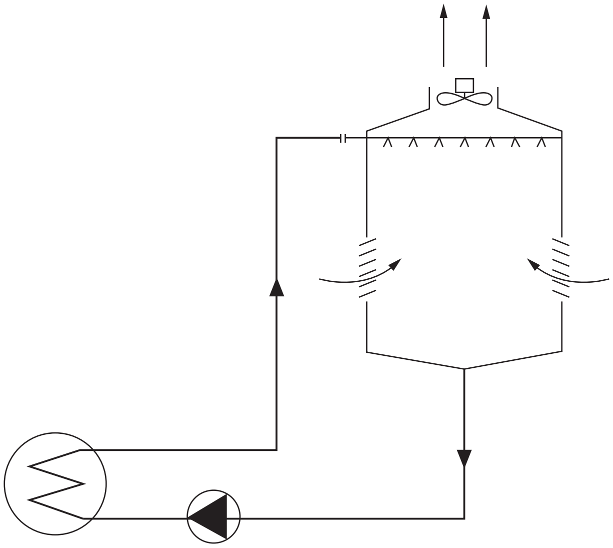

Figure 2 Open recirculating cooling system with cooling tower.

Secondary cooling systems generally consist of open (evaporative) or closed (nonevaporating) recirculation systems. In these systems, the cooling is indirect: to cold water; to the atmosphere; or by means of a cooling unit. If the system incorporates, an open vessel serving as a circulation trough and/or to allow for expansion, enabling the absorption of oxygen and carbonic acid; it is known as an open system (Fig. 3).

If such a vessel is separated from the atmosphere, for example, by a membrane, it is known as a closed system (Fig. 4).

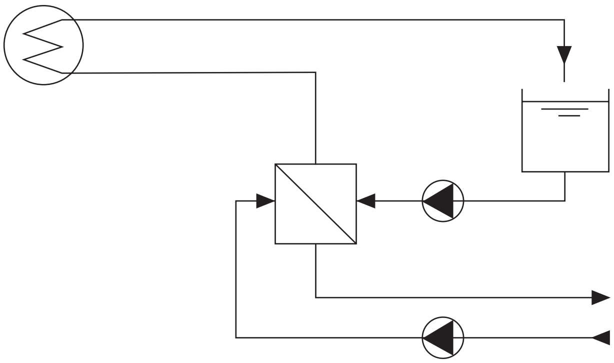

Figure 3 Open recirculating cooling system with indirect cooling.

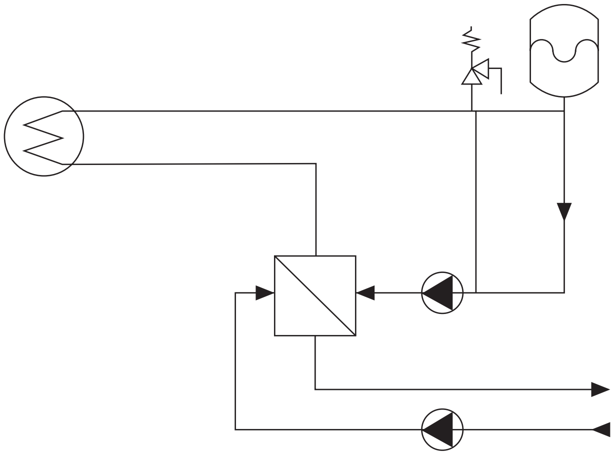

Figure 4 Closed recirculating cooling system with indirect cooling.

Clearly, from the viewpoint of corrosion, a closed system is preferable in the case of secondary cooling. This will permit optimized water conditioning to be maintained without problems. Open circulating systems with or without a cooling tower and once-through systems require great attention in terms of corrosion control.

Corrosion Problems in Cooling Water Systems

The following problems may be encountered:

Oxygen Corrosion

In the presence of unprotected steel components, oxygen corrosion is the principal cause of corrosion due to the intensive aeration of the circulating water. It occurs particularly where inhibitor dosing is absent, insufficient, or ineffective and also where the protective coating is damaged. This results in pitting attack covered with wart-shaped corrosion products (see Part I, Chapter 4: Pitting Corrosion, and 01.06.01.01/02).

Under-Deposit Corrosion

Deposits may consist of bioorganisms, sludge particles, hardness salts, or corrosion products. The deposit enables differential aeration elements to form, leading to local attack (see Part I, Chapter 4 and Part II, Chapter 10). The corrosion is usually of the pitting type (01.06.15.01). Under-deposit corrosion occurs not only in carbon steel, but it may also be a problem in stainless steel (04.06.15.01/02/03), nickel alloys (05.06.15.01/02), and copper alloys (06.06.15.01/02). In brass, *dezincification* may occur underneath deposits.

Microbiologically Induced Corrosion

Under anaerobic conditions, inter alia SRB may develop (see Part II, Chapter 9), with the formation of sulfide that attacks metal (01.06.17.01/02/03, 05.06.17.01/02, and 07.06.17.01).

Even without substantial deposition, sulfide can cause corrosion in unaerated systems, by affecting the material's protective oxide skin (07.06.05.01).

Corrosion by Too High or Too Low pH

Poor water conditioning (usually due to ineffective monitoring) or product leakages may allow the pH of the cooling water to reach values for which the material concerned is not intended, leading to attack (01.06.04.01/02, 06.06.16.02, and 07.06.03.01). Contamination of the cooling water with atmospheric sulfur dioxide can lead to the formation of sulfuric acid. Contamination with ammonia from leaking ammonia condensers can lead to the formation of nitric acid as a result of bacterial conversion.

Acid corrosion in cooling systems can also occur during chemical cleaning (06.06.04.01/02).

Corrosion by Excessive Chloride Content

If the system is designed for sweet water but is operated with brackish water or if excessive salt concentration occurs in circulating systems due to insufficient discharge, there is a severely elevated risk of corrosion (04.06.12.01/02 and 06.06.16.01). Graphitization of gray cast iron may also occur (01.06.16.01).

Erosion Corrosion

This type of corrosion (see Part II, Chapter 2) may be caused by the presence of air bubbles (01.06.34.01/02) or fine sand particles in the cooling water (e.g., seawater). Also, vortices in pipe inlets and turbulence inside the pipes due to excessive velocities are capable of causing erosion corrosion. Particularly, systems with admiralty brass or aluminum brass pipes cooled with brackish water or seawater are sensitive to this (06.06.34.01/03). Such vortices may also occur downstream from irregularities (e.g., deposits) on the pipe wall (04.06.34.01, 06.06.34.02/04).

Cavitation (Erosion and Corrosion)

Cavitation owing to the formation and collapse of vapor bubbles is a phenomenon that also occurs in cooling water systems (01.06.33.01/02/03/04/05).

Galvanic Corrosion

Galvanic corrosion (see Part II, Chapter 6) may occur if the leap in potential between two adjacent materials is too large (01.06.14.01 and 02.06.14.01) or in the case of deposition of more noble metals or metal oxides (02.06.14.02/03). In the case of damage to a coating applied to the anodic material, intensified galvanic corrosion may occur (03.06.14.01) unless cathodic protection is also applied.

Crevice Corrosion

This type of corrosion (see Part I, Chapter 4 and Part II, Chapter 10) can occur in crevices of certain materials such as stainless steel (04.06.13.01/02).

Stress Corrosion Cracking

In cooling systems, the attack known as season cracking in copper alloys is caused by ammonia originating from biodecomposition (06.06.17.01) or by product leakage (06.06.18.01; see Part II, Chapter 12).

Corrosion Prevention and Corrosion Control in Cooling Water Systems

The measures for corrosion prevention may be classified as follows:

- by material selection.
- by design.
- by makeup treatment and water conditioning.
- by maintenance.

By Material Selection

The choice of material depends on the quality of the cooling water, the nature of the medium to be cooled, the scheduled lifetime of the cooling system, and the effects of leakage.

In *seawater-cooled* condensers for power plants, titanium is currently the material of choice for tubing. High Cr and Mo stainless steel may also perform well but has not yet been widely applied in practice. Cupronickel and aluminum brass are also in principle suitable as materials for seawater cooling systems, but they demand much more care and maintenance, and the risk of unexpected leakage is greater.

For *river-water* once-through cooling systems, circulation cooling and for closed cooling systems with water velocities up to 1.8 m/s, brass is a good option. Aluminum brass is generally capable of withstanding speeds up to 2.0 m/s, assuming the water contains no erosive material.

For still higher velocities, cupronickel alloys or stainless steel should be chosen. For smaller cooling systems, alternatives are available in the form of galvanized or coated steel. For galvanized steel and also for aluminum, the pH of the cooling water must remain below 8.5.

If coated tubing is not used, the choice of plate material depends on the tube material to be used. This also applies in the case of headers. If constructed of steel, they are coated: in the case of river water cooling generally a plastic lining and in the case of seawater cooling a rubber lining. Extra corrosion protection is then needed in the form of cathodic protection generally with sacrificial anodes. Otherwise, any damage to the protective coating could lead to severe local attack.

Environmental requirements relating to the discharge of copper and other metal ions to the cooling water will become increasingly important in the selection of materials.

For transmission lines, the choice lies between plastic, stainless steel, and coated or galvanized steel.

By Design

When designing a cooler, questions to bear in mind include the following:

- The through-flow pattern: Do all the tubes carry the same amount of water, is turbulence not excessive and are there no dead angles (in view of erosion corrosion and sludge deposits).
- Is the cooler easy to inspect (hatches).
- Is proper drainage possible during standstill.
- Are facilities needed for conditioning or cleaning purposes.

By Makeup Treatment and Water Conditioning

This will be considered system by system.

In the case of once-through systems, the scope for conditioning is limited due to the large flow and also in view of environmental implications. Measures to consider are:

- *Filtration* through drum or belt sieves to remove coarse contaminants capable of blocking the tubes.
- In the case of brass-tubed condensers, dosing of *iron sulfate* solution (continuously or batchwise) to build a protective skin on the tubing.
- Dosing of *chlorine* in the form of chlorine bleach or chlorine gas to counteract bacterial and algae growth on the tube wall. In view of the harmful environmental effects due to the formation of toxic organochlorine compounds, overdosing must be avoided.
- Periodically or continuously *cleaning* the tubes to remove deposits of sludge, oxides, and algae. For this purpose, systems have been developed based on sponge-rubber spheres or brushes. Carborundum-coated spheres also enable harder deposits to be removed.

For smaller systems, the following measures are also suitable:

- *Filtration* through fine sieves or cartridge filters, enabling the removal of minor impurities (not always economic).
- *Deferrizing* in the case of well water in order to prevent excessive iron oxide deposition and anaerobic conditions (sulfide formation). The use of well water for cooling purposes is no longer strictly justifiable unless it is reused for other purposes.
- Adjusting the pH by dosing *alkaline or lime* in order to control possible aggressiveness of the water.

In open recirculating systems with one or more cooling tower, attention is required for both makeup treatment and conditioning. Suitable measures may be:

- *Softening*, *dealkalizing*, *or demineralization* of the makeup water in order to minimize the system hardness or salt concentration or to maintain them at the appropriate level where certain inhibitors are dosed.
- In the case of makeup with well water *deferrizing* and hence aeration of the makeup water.
- Dosing *corrosion inhibitors* to the system. There is a wide range of these to choose from silicate, polyphosphate, phosphonate, trisodiumphosphate, copper inhibitors, and so on. Phosphates are normally used in combination with dispersants.
- Dosing *hardness stabilizers* and dispersants in order to keep sludge and hardness salts in suspension or solution.

Well-known products are polyol esters, polycarbonic acids, polyphosphates, and other polyelectrolytes such as polyacrylate.

- Dosing *chlorine* in the form of chlorine bleach or chlorine gas to control biological growth. Suitable alternatives to chlorine are organic biocides, which often act more effectively and selectively.
- Dosing *sulfuric acid* in case of high concentration in order to control the deposition of hardness compounds by converting the bicarbonate into sulfate (dealkalization).

Care must be taken not to exceed the solubility product of calcium sulfate and to avoid attack to any concrete that may be present in the system.

- Deliberately maintain a given *hardness* content in the cooling water in order to maintain a thin protective hardness layer on the surface to be cooled (known as equilibrium water). However, this is only valid within a given temperature range (see Chapter 4).
- Periodic *cleaning* of the cooling system and specifically the cooling tubes in order to remove sludge, algae, too thick hardness deposits and any corrosion products.

In open and closed recirculation systems with indirect cooling, as used in secondary cooling systems, there is a wide range of choice of corrosion inhibitors for conditioning the cooling water:

- benzoates
- copper inhibitors (which react with chlorine):
  - mercaptobenzothiazole
  - benzotriazole
  - tolyltriazole
- lignin derivatives
- molybdate
- nitrite
- organic inhibitors:
  - acrylate
  - sulfonated copolymers
  - sarcosinates
- emulsifiable oils
- silicates (both ortho- and poly-)
- zinc
- chromate

Many of these inhibitors or mixtures thereof are available under commercial brand names. To ensure an appropriate choice, it is good practice to take professional advice. Because of environmental requirements, some of these products are subject to a total or partial discharge ban. A known problem is the toxicity of chromate, which happens to be a very effective inhibitor. When it is used, no discharges whatsoever from the system are permitted (including repairs).

Thorough evaluation of the effectiveness and environmental impact of these inhibitors is desirable in view of the relatively high expense associated with their application.

Simple conditioning is possible if the system is charged with demineralized water. Then, an optimized pH setting is sufficient to ensure good corrosion protection. It is also relatively simple to monitor.

In the case of an open system, however, the pH will decline due to CO_2 absorption. In that case, conditioning by means of a buffering system, for example, soda/hydrogen carbonate, is advisable. If copper is present in the system, a copper inhibitor needs to be dosed as well.

By Maintenance

When performing maintenance on cooling systems, the following items need special attention:

- *Preservation measures* to be taken during period of shutdown and maintenance. If the cooler is charged, flush regularly, in the case of salt water daily. Drained salt-water cooling systems should be flushed with sweet water.
- Regular *inspection* of sites sensitive to contamination and corrosion and cleaning if necessary.

If *erosion corrosion* is seen at the tube inlet side, consider application of cathodic protection with sacrificial anodes or the installation of inserts.

- Possibly replace sacrificial anodes.
- If corrosion is diagnosed or suspected, perform nondestructive testing (e.g., by eddy current).
- Check whether the phenomena observed require modifications in operation, design, choice of materials, or conditioning.
- Before and after any modifications, establish the corrosivity by means of one or more of the following methods:
  - coupons
  - resistance or polarization probes
  - test coolers
  - measuring the water quality and the Langelier index (see Chapter 4)
- If contaminations occur due to deposition of suspended matter, it may be useful to apply a sidestream filter.
- Thorough recording of experience gained and measures taken.

4. CORROSION IN COLD AND HOT TAP WATER SYSTEMS

In tap water systems, corrosion affects not only reliability of the system but also the quality of the potable water and the process water.

Tap water systems may be classified into cold tap water systems and hot tap water systems.

Materials used in public cold tap water distribution systems are cast iron, steel, galvanized steel, asbestos cement, concrete, PVC, polyethylene, copper, lead, and brass.

The quality of the potable water, which is designed to minimize the release of metal compounds and the formation of harmful deposits, virtually eliminates corrosion in domestic potable water systems. Moreover, pipes made of plastics are being increasingly used.

In cold tap water systems, corrosion therefore remains limited to industrial systems producing an in-house supply of process water.

In hot tap water systems, on the other hand, corrosion frequently occurs even when mains water is used. In these systems, water is heated to 40–70°C and then transported to the various consumers. It is used for process water, for cleaning purposes, in kitchens, and for sanitation purposes.

The tap water is heated in storage boilers or counter-flow units by means of steam or water from a hot water or central heating system. With the exception of domestic systems, the hot tap water is usually recirculated continuously by the system, so that hot water is immediately available from each drainage point.

Galvanic Corrosion

Galvanic corrosion (discussed in Part I, Chapter 4 and Part II, Chapter 6) is the commonest form of corrosion in these systems. The following forms of galvanic corrosion are differentiated:

Couple action (contact corrosion), for example:

- By the coupling of galvanized steel to copper or copper alloys (02.05.14.03/05).
- By the coupling of aluminum to stainless steel (07.05.14.01/02).

Deposition corrosion (deposition of more noble material) for example:

In hot tap water systems:

- By the deposition of copper on galvanized steel (02.05.14.04).
- By the deposition of graphite on copper (06.05.14.02).

Reversal of potential (of galvanized steel above 60°C) in hot tap water systems (02.05.14.01/02/06).

Prevention

Galvanic corrosion can be prevented by:

- Appropriate choice of material in the design stage and by observing the correct sequence of metals in order to prevent deposition corrosion, although this will not be of much use in a recirculating system.
- Application of cathodic protection with inert anodes with impressed current (e.g., in storage boilers).
- Not using galvanized steel above 60°C.

Oxygen and Carbonic Acid Corrosion

In oxygen-containing water with sufficient temporary hardness, a protective layer of iron carbonate will gradually form on steel, which serves to protect against corrosion. This is caused by the wall alkalinity due to the cathodic reaction whereby OH^- ions are formed (see Part I, Chapter 3). The presence of oxygen in mildly aggressive water, in which the formation of a protective chalk rust layer is not possible, may lead to pitting in untreated steel (01.05.01.01/02).

The level of aggressiveness of the water is determined not only by the amount of hydrogen carbonate (temporary hardness) but also by the pH and the salt content of the water. In the case of highly aggressive water, the process is in effect attack by carbonic acid, leading to a uniform corrosion (01.05.02.01). Increasing the tap water temperature decreases the aggressiveness, so that hot tap water is generally less aggressive than cold.

The level of aggressiveness as well as the water's tendency to form calcium deposits is defined by the position of the calcium-carbonic acid equilibrium:

$$Ca(HCO_3)_2 \leftrightarrows CaCO_3 \downarrow + \; CO_2 \uparrow + H_2O$$

and can be expressed in the Langelier Saturation Index (LSI) and the Ryznar Stability Index (RSI).

The theoretically derived LSI is defined as: LSI = pH − pHs, where pH is the actual measured value in the water, and pHs is the pH of saturation calculated from the expression:

$$pHS = \left(pK_2^{'} - pK_{sp}^{'}\right) + pCa + pAlk$$

where $K_2^{'}$ is the apparent second dissociation constant of H_2CO_3, $K_{sp}^{'}$ is the apparent solubility product of $CaCO_3$, pCa is −log 10 [Ca^{2+}] in moles per liter, and pAlk = −log 10 [total alkalinity] in equivalents per liter.

The RSI is an empirical expression: $RSI = 2pH - pH$, where pH and pHs have the same meaning as previously described. Interpretations of LSI and RSI valves are listed in Table 1:

Water that has been softened for certain applications by means of a cation exchanger is in principle also aggressive and may attack copper as well as steel.

Prevention

This type of corrosion should primarily be controlled by means of water treatment, that is, by raising the *pH* of the water or by *hardening* the water. This may be done by dosing caustic or lime or by filtration over semicombusted dolomite, preceded, or otherwise by carbonic acid expulsion in order to save on the cost of chemicals. This also applies for copper-aggressive water.

Table 1 Predictions of Water Characteristics by LSI and RSI

LSI	RSI	Tendency of Water
2.0	<4	Heavy scale forming, nonaggressive
0.5	5.0–6.0	Slightly scale forming, moderately aggressive
0	6–6.5	Balanced or at $CaCO_3$ saturation[a]
−0.5	6.5–7	Nonscaling, slightly aggressive[a]
−2.0	>8	Undersaturated, very aggressive[a]

LSI, Langelier Saturation Index; *RSI*, Ryznar Stability Index.

[a] Pitting corrosion by oxygen attack is possible.

Should softening be essential in order to prevent calcium scale formation, for example, in hot tap water storage boilers, partial softening may be considered. In this procedure, the water softener is fitted with a bypass.

If water treatment is ineffective, it will be necessary to switch to the use of more corrosion-resistant material.

Under-Deposit Corrosion

The formation of deposits allows oxygen concentration cells to form, so that the surface below the deposit becomes anodic relative to the clean surface. These deposits may consist of hardness salts due to pressure reduction in pumped-up groundwater or by temperature increase or from corrosion products resulting from inappropriate material selection. If sacrificial anodes (e.g., of aluminum) are used in hot water storage heaters, aluminum oxide may deposit in the downstream pipes (01.05.15.01).

Where deposits form on brass, dezincification may occur (06.05.16.01/03).

Prevention

The formation of deposits should be prevented by means of:

- appropriate water treatment (e.g., [partial] softening, efficient deferrizers);
- proper material selection to prevent the formation of corrosion products;
- application of inert instead of sacrificial anodes.

Sulfide Corrosion

Where a plant or institution has its own (well-)water supply, sulfide corrosion may occur due to the presence of SRB in the system in the case of anaerobic well water or underneath deposits under otherwise aerobic conditions.

However, SRB can also develop and cause corrosion in noncirculated sections of the system (see Case History 01.05.17.01).

Prevention

This form of corrosion can be controlled by *aeration* of the well water, expelling the H_2O and making the water aerobic.

If deferrizing is practiced, aeration will take place at the same time and iron oxide deposits are also prevented. Standing water should be avoided as far as possible.

Erosion (Corrosion) and Cavitation Erosion

Attack to copper piping by erosion (corrosion) or cavitation erosion is fairly common in hot tap water systems. Either the water velocity is excessive or local strong turbulence occurs (01.05.32.02, 06.05.33.01, and 06.05.34.01). In the case of continuous flow as in recirculation systems, the maximum allowable water velocity is 0.8 m/s at 70°C. The presence of air bubbles in the water may contribute toward the occurrence of erosion (corrosion; 06.05.32.01 and 06.05.34.02).

However, erosion corrosion can also occur in stainless steel conveyor lines, for example, at the welds (04.05.34.01).

Prevention

An important point to bear in mind here is appropriate *dimensioning* of the system. At the same time, sharp bends or sudden constrictions or enlargements should be avoided. Another item of attention is material selection, for example, using stainless steel, which is more erosion-resistant, rather than copper. Finally, the pH of the water is a factor because it determines the solubility of the oxide.

Other Corrosion Causes

Errors during soldering (06.05.16.04), contamination of the copper with graphite (06.05.14.02) and use of inappropriate copper grades (06.05.15.03) may cause corrosive behavior in copper. Water treatment can be of little help here.

Pitting corrosion occurs incidentally in copper piping of cold and hot tap water systems due to the composition of the water, which is then said to be copper-aggressive water (06.05.02.01/02 and 06.05.16.02).

Prevention

- When soldering, use of approved solders is recommended.
- Refrain from using graphite as a lubricant or in gaskets.
- Oxygen-containing copper (ETP copper) is particularly sensitive to pitting attack beneath deposits. This grade should therefore not be used.

Pitting by copper-aggressive water can sometimes be controlled by dosing chemicals to harden the water or by admixing other hard water. Alternatively, application of more corrosion-resistant piping (such as plastic) may be considered.

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GLOSSARY OF TERMS USED IN THIS WORK

Alkalinity reduction	(Part) removal of the carbonate and bicarbonate alkalinity from water, mostly by ion exchangers.
Anaerobic	Free of air or uncombined oxygen.
Anode	Electrode at which anodic reaction predominates.
Anodic protection	Electrochemical protection by increasing the corrosion potential to a value corresponding to the passive state. *Note*: This technique needs very little current flow, but it leads to intensified corrosion in case of power breakdown.
Anodic reaction	Electrode reaction equivalent to a transfer of positive charge from the electronic to the ionic conductor. *Note*: An anodic reaction is an oxidation process. $Me \rightarrow Me^{n+} + ne^-$.
Atmospheric corrosion	Corrosion with the earth's atmosphere at ambient temperature as the corrosive environment.
Attemperator	A heat exchanger in which the superheated steam is cooled by boiler water at the outside.
Bimetallic corrosion	Contact corrosion (deprecated): galvanic corrosion, where the electrodes are formed by dissimilar metals or other electronic conductors.
Blooming	Corrosion of anodized aluminium by acid residues due to insufficient rinsing.
Boiler feedwater	Mixture of steam condensate and make-up water.
Carbonation of concrete	The attack of concrete by carbon dioxide. The calcium hydroxide is transformed to calcium bicarbonate that is flushed by water.
Carbonic acid corrosion	Corrosion by water that has become aggressive by dissolved carbon dioxide $\left(CO_2 + H_2O \rightarrow H_2CO_3 \leftrightarrows CO_3^{2-} + 2H^+\right)$ (see also sweet corrosion). *Note*: This corrosion causes uniform attack in condensate return lines.
Carburization	The absorption of carbon into a metal surface at high temperatures, by which carbides are formed as a result of which the metal becomes brittle. *Note*: Distinguish from the term carburizing as used in metallurgy.
Cathode	Electrode at which cathodic reaction predominates.
Cathodic protection	Electrochemical protection by decreasing the corrosion potential (see galvanic protection and impressed current protection).
Cathodic reaction	Electrode reaction equivalent to a transfer of negative charge from the electronic to the ionic conductor. *Note*: A cathodic reaction is a reduction process: $Ox + ne^- \rightarrow red$.
Caustic embrittlement	An obsolete term for caustic SCC.
Caustic SSC	That form of SCC occurring in carbon steel exposed to alkaline solutions.
Cavitation damage	Damage of a material associated with collapse of cavities (or vapor bubbles) in the liquid at a solid–liquid interface, in the high-pressure regions of a unit. *Note*: Damage being worse at the outlet side of pumps or across control valves or orifice plates. Minimum internal pressure within the unit must always be greater than the "bubble point" of the liquid to avoid this type of attack.
Cavitation corrosion	A process involving conjoint corrosion and cavitation. *Note*: Cavitation corrosion may occur, e.g., in rotary pumps and on ships' propellers.
Cavitation erosion	Cavitation damage as such, not involving corrosion.
Chelant corrosion	Corrosion by a chelating agent.
Cold-end corrosion	Dew-point corrosion during service. Most problems caused by cold-end corrosion occur in relatively low-temperature boiler components such as the economizer, air preheater, induced-draft fan, flue-gas scrubbers, and stack.
Concentration corrosion cell	Corrosion cell in which the potential difference arises from a difference in concentration of the corrosive agent(s) near its electrodes.
Contact corrosion	Synonym for bimetallic corrosion (galvanic corrosion).

Corrosion	Physicochemical interaction between a metal and its environment which results in changes in the properties of the metal and which may often lead to impairment of the function of the metal, the environment, or the technical system, of which these form a part. *Note*: This interaction is usually of an electrochemical nature.
Corrosion cell	Short-circuited galvanic cell in a corrosion system, the corroding metal forming one of its electrodes (see galvanic cell).
Corrosion fatigue	A process involving conjoint corrosion and alternating straining of the metal. *Note*: Corrosion fatigue may occur when a metal is subjected to cyclic straining in a corrosive environment. Corrosion fatigue may lead to cracking.
Couple action attack	See galvanic corrosion.
Creep	The continuous plastic elongation of a metal under an applied stress.
Creep (-rupture) embrittlement	Embrittlement under creep conditions of, e.g., aluminum alloys and steel, resulting in abnormally low rupture ductility.
Crevice corrosion	Corrosion associated with, and taking place in, or immediately around, a narrow aperture or clearance. *Note*: The formation of a differential aeration cell is the cause of this corrosion.
Deaerator	A mostly horizontal tank in which the boiler feedwater is freed of dissolved oxygen (and other gases) by intensive contact with fresh steam, according to the laws of Henry and Raoult.
Dealkalization	See alkalinity reduction
Dealkalizing	See alkalinity reduction
Dealloying	The selective corrosion (removal) of a metallic constituent from an alloy, usually in the form of ions (e.g., dezincification). *Note*: This corrosion is also known as parting or selective leaching.
Dealumnification	Corrosion in which aluminium is selectively leached from aluminium-containing alloys. See also dealloying and selective leaching.
Decarburization	See high-temperature hydrogen attack.
Demineralization	Removal of all the dissolved mineral matter from the water by ion exchangers.
Denickelification	Corrosion in which nickel is selectively leached from nickel-containing alloys. See also dealloying and selective leaching.
Deposition corrosion	Galvanic corrosion by plating out of a more noble metal or metal oxide on a less noble metal (e.g., copper on zinc or aluminum).
Dew-point corrosion	Dew-point corrosion will occur in boilers wherever the temperature of metal drops below the sulfuric acid (or hydrochloric acid) dew point of the flue gas during service (= cold-end corrosion) or during idle periods, where surfaces can be covered with acid-forming deposits.
Dezincification	Selective corrosion of brass resulting in preferential removal of zinc. Dezincification is a form of dealloying. *Note*: This corrosion causes mechanically weak copper-rich areas in the form of plugs or layers; sometimes both zinc and copper corrode, but copper is redeposited.
Differential aeration cell	Corrosion cell, in which the potential difference arises from a difference in the concentration of oxygen near its electrodes. *Note*: The location with the lowest oxygen content, e.g., in a crevice or underneath deposit, becomes anodic and will be attacked.
Economizer	A heat exchanger, placed in the flue gases, for heat recovery by the boiler feedwater.
Electrolyte	An ionic conductor, usually in aqueous solution.
Electroplating	Electrodeposition of a thin adherent layer of a metal or alloy on an object serving as a cathode. *Note*: This process is also known as electrogalvanizing.
Embrittlement	Severe loss of ductility of a metal (or alloy).
475 °C embrittlement	An embrittlement phenomenon occurring in ferritic stainless steels containing 12% or more chromium after long-term exposure to temperatures between 400°C and 540°C.
End grain	The surface of the metal which is cut perpendicular to the direction of rolling.
End grain attack	Selective corrosion of the end grain. During the rolling of steel, nonmetallic inclusions are rolled out and elongated into long “stringers” all in the direction of rolling. When the end grain is exposed to a strong corrodent, such as boiling nitric endgrain attack starts at areas where stringers are exposed on sheet or plate ends and can aggressively proceed down into the steel. Austenitic stainless steels but carbon steels as well may be susceptible to endgrain attack.

Environment	The surroundings or conditions (physical, chemical, and mechanical) in which a material exists.
Environmental (environmentally induced) cracking	Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor. Environmental cracking is a general term that includes corrosion fatigue, high-temperature hydrogen attack, hydrogen blistering, hydrogen embrittlement, liquid metal embrittlement (LME), solid metal embrittlement, SCC, and sulfide stress cracking.
Epitactical oxide	Oxide growing on the original metal surface.
Erosion	Deterioration of a surface by the abrasive action of solid particles in a liquid or gas, gas bubbles in a liquid, liquid droplets in a gas, or due to (local) high flow velocities.
Erosion corrosion	A process involving conjoint corrosion and erosion. *Note*: The corrosion products are continuously removed by erosion, as a result of which the corrosion is accelerated.
Exfoliation	A thick layer-like growth of loose corrosion products (see Layer corrosion). *Note*: Exfoliation is generally oriented in the direction of rolling, extrusion, or principal deformation.
False brinelling	Damage caused by vibration between metal parts.
Fatigue	A process leading to fracture resulting from repeated stress cycles well below the normal tensile strength. Such failures start as tiny cracks which grow to cause total failure.
$FeCl_2$ value	The $FeCl_2$ value is a specification of carbon steel for acid-corrosion resistance in evaporators (heat-flux corrosion may cause low pH gouging). At a certain critical chloride concentration, magnetite loses its protection. The critical ferrous chloride concentration of carbon steel can be calculated from the elements C, Si, Cr, Mo, and Mn ($FeCl_{2crit} = 270.0C + 125.Si + 120.Cr + 75.Mo + 70.Mn - 65$). Acid-corrosion resistant material for evaporators should have a $FeCl_{2cril}$ value of minimum 35 mmol $FeCl_2$.
Filiform corrosion	Corrosion that occurs under some coatings in the form of hairs or filaments progressing across the metal surface.
Fretting corrosion	A process involving conjoint corrosion and oscillatory slip between two surfaces in contact. *Note*: Fretting corrosion may occur, e.g., at mechanical joints in vibrating structures.
Galvanic cell	Combination of different electrodes connected in series with an ionic conductor. *Note*: The galvanic cell is an electrochemical of electrical current and will produce current when the electrodes are connected by an external conductor.
Galvanic corrosion	Corrosion due to the action of a corrosion cell. *Note*: The term has often been restricted to the action of bimetallic corrosion cells, for example, bimetallic corrosion.
Galvanic protection	Electrochemical protection in which the protecting current is obtained from a corrosion cell formed by connecting an auxiliary electrode to the metal to be protected.
Galvanizing (hot dip)	Coating of iron and steel with zinc using a bath of molten zinc.
General corrosion	Corrosion proceeding at almost the same rate over the whole surface of the metal exposed to the corrosive environment. *Note*: This corrosion is also known as overall or uniform corrosion.
G_{kema} value	G_{kema} is the KEMA specification of carbon steel for erosion-corrosion resistance in water-steam systems. G_{kema} can be calculated from the elements Cu, Cr, Mo, and C in the carbon steel ($G_{kema} = 90 - 160 \cdot Cu - 115 \cdot Cr - 40 \cdot Mo + 35 \cdot C$). Erosion–corrosion resistant material for water-steam systems should have a maximum G_{kema} value of 80.
Grain	A portion of a solid metal in which the atoms are arranged in an orderly pattern. The irregular junction of two adjacent grains is known as the grain boundary.
Graphitic corrosion	Selective corrosion of grey cast iron, resulting in preferential removal of metallic constituents, leaving graphite. Graphitic corrosion is a form of dealloying. *Note*: This corrosion is also known as graphitization but term recommended because of its use in metallurgy.

Heat-affected zone	Refers to the area adjacent to a weld where the thermal cycle has caused microstructural changes which generally affect corrosion behavior.
Heat-flux corrosion	Corrosion in economizer or evaporator tubes due to a local strong heat flux. It may result in departure from nucleate boiling which may cause local high concentrations of acid, alkali, or chloride, resulting in low or high pH gouging or chloride pitting.
Hot corrosion	A form of sulfidation of gas-turbine blades in the metal temperature range from 650° to 950°C
High-temperature corrosion	The reaction of metals with gases at a temperature so high that no water is present (mostly >200°C). Carburization, high-temperature oxidation, high-temperature hydrogen attack, sulfidation, and nitriding are forms of high-temperature corrosion.
High-temperature hydrogen attack	The occurrence of cracks or fissures owing to pressure build-up by methane gas, formed by the reaction of atomic hydrogen diffused into the steel above roughly 260°C and metal carbides or dissolved carbon. *Note*: This corrosion is also known as decarburization or methane embrittlement.
Hydride embrittlement	Embrittlement due to the precipitation of metal hydride phases formed by the diffusion of hydrogen into the metals magnesium, zirconium, titanium, niobium, vanadium, and tantalum.
Hydrogen blistering	The formation of blisters on or below a metal surface from excessive internal hydrogen pressure. *Note*: Hydrogen may be formed during cleaning, plating, corrosion, and so forth. The atomic hydrogen diffuses into the steel. The diffusion stops at contaminations in the steel, where atomic hydrogen is converted into molecular hydrogen. Pressure build-up then causes the steel to fracture.
Hydrogen damage	A general term for the embrittlement, cracking, blistering, and hydride formation that can occur when hydrogen is present in some metals.
Hydrogen embrittlement	A process resulting in a decrease of the toughness or ductility of a metal due to absorption of hydrogen. *Note*: Hydrogen embrittlement often accompanies hydrogen formation, e.g., by corrosion or electrolysis, and may lead to cracking.
Hydrogen-induced cracking (HIC)	An alternative term for high-temperature hydrogen attack (hot HIC) and for hydrogen blistering (cold HIC).
Hydrogen grooving	A high local attack in the form of grooving in carbon steel used for strong sulfuric acid. The corrosion takes place when strong acid is not moving, by disturbing the ferrous sulfate layer as a result of the steady passage of hydrogen bubbles, evolved in the corrosion of steel in sulfuric acid on a preferred path. The normal steady state of low corrosion (0.1–0.5 mm/year at ambient temperatures) will be disrupted, and grooving will result with high local corrosion rates of 3 mm/year or more.
Hydrogen stress cracking	A brittle fracture of a tough alloy under constant strain in a hydrogen-containing environment (other terms: hydrogen-assisted SCC and static fatigue). It occurs at ambient temperature.
Impingement attack	Localized erosion corrosion caused by turbulence or impinging flow at certain points.
Impressed current protection	Electrochemical protection in which the protecting current is supplied by an external source of electric energy.
Inhibitor	Chemical substance which decreases the corrosion rate when present in the corrosion concentration, without significantly changing the concentration of any other corrosive agent. *Note*: A corrosion inhibitor is generally effective in a small concentration. In commercial applications, additives are sometimes named as inhibitors.
Intergranular corrosion	Corrosion in or adjacent to the grain boundaries of a metal.
Knife-line attack	Corrosion resulting in a narrow slit in or adjacent to the filler/parent boundary of a welded or brazed joint. *Note*: This corrosion is a form of weld decay sometimes observed on stabilized stainless steel.

Langelier index	The Langelier index (Li) or saturation index in a theoretically derived quantity for the judgement of corrosive or scaling qualities of water. The index is deduced from the real pH, and the calculated saturation pH (pHs) of the water: Li = pH – pHs and is interpreted as follows: Li tendency of the water ≥ +2.0 strong scaling tendency +0.5 slight scaling tendency, not corrosive 0.0 in balance, pitting possible –0.5 slightly corrosive, not scaling ≤–2.0 strongly corrosive
Layer corrosion	Corrosion of internal layers of wrought metal, occasionally resulting in exfoliation, i.e., detachment of unattacked layers.
LME	Embrittlement of a metal caused by penetration of other molten metals.
Magnetite	Fe_3O_4, black iron oxide, which is formed in water or steam in the case of deficiency of oxygen. It is magnetically attractable.
m-Alkalinity	The acid consumption in meq/L on titration of water up to pH 4.2.
Medium	See environment.
Metal dusting	Accelerated deterioration of metals in carbonaceous gases at elevated temperatures to form a dust-like corrosion product.
Methane (gas) embrittlement	An alternative term for decarburization or high-temperature hydrogen attack (which see).
Microbiologically induced corrosion (MIC).	Corrosion associated with the action of microorganisms present in the corrosion system. *Note*: This corrosion is also known as biological or microbial corrosion.
Nitriding	The absorption of nitrogen atoms by a metal; it may remain dissolved or form metal nitrides.
Oxygen scavenger	A chemical substance which liberates the boiler feed water from oxygen by means of a chemical reaction. An oxygen scavenger is used instead of or in addition to a deaerator.
p-Alkalinity	The acid consumption in meq/L on titration of alkaline (boiler) water up to pH 8.2.
Pitting corrosion	Corrosion resulting in pits, i.e., cavities extending from the surface into the metal.
Rebar corrosion	Corrosion of concrete reinforcement bars, also known as reinforcement corrosion.
Ryznar index	The Ryznar index (Ri) or stability index is an empirically derived quantity for the judgment of corrosive or scaling qualities of the water. This index can also be calculated from the pH and pH_s (see Langelier index): Ri = 2 pH_s – pH and is interpreted as follows: Ri tendency of the water <5.0 strong scaling 5.0–6.0 slight scaling tendency 6.0–6.5 in balance, pitting possible 6.5–7.5 slightly corrosive 7.5–9.0 strongly corrosive >9.0 very strongly corrosive
Salt corrosion	Corrosion underneath deposition of salts.
Sandelin phenomenon	This phenomenon was discovered by Mr. Sandelin and refers to the growth on of the zeta alloy layer during the galvanizing process of silicon-killed steel with Si levels above about 0.3%.
Season cracking	A term usually applied to SCC of brass, in ammoniacal environments.
Selective leaching	Corrosion of an alloy whereby the components react in proportions which differ from their proportions in the alloy (see also dealloying).
Sherardizing	The coating of iron and steel with zinc by heating in contact with zinc powder at a temperature below the melting point of zinc.
Sigma phase	A hard, brittle, nonmagnetic intermediate phase with a tetragonal crystal structure, containing 30 atoms per unit cell, space group $P4_2/mnm$, occurring in many binary and ternary alloys of the transition elements. The composition of this phase in the various systems is not the same, and the phase usually exhibits a wide range in homogeneity. Alloying with a third transition element usually enlarges the field of homogeneity and extends it deep into the ternary section.

Sigma-phase embrittlement	Embrittlement of iron–chromium alloys (most notably austenitic stainless steels) caused by precipitation at grain boundaries of the hard, brittle intermetallic sigma phase during long periods of exposure to temperatures between approximately 560°C and 980°C (1050 and 1800°F). Sigma-phase embrittlement results in severe loss in toughness and ductility and can make the embrittled material susceptible to intergranular corrosion.
Solder corrosion	Corrosion due to the use of excessive or inappropriate solder grease.
Stainless steel	All steels with a chromium content of at least 13%.
Steam blanketing	Reduction of wall thickness of the upper part of the inclined water tubes of a steam boiler due to magnetite (Fe_3O_4) flaking off, caused by insufficient cooling.
Stray current	Current flowing through paths other than the intended circuits.
Stray current corrosion	Corrosion due to stray current *Note*: The metal is attacked at the spot where the current leaves.
Stress corrosion	A process involving conjoint corrosion and straining of the metal due to residual or applied stresses. *Note*: Stress corrosion is specific to particular metals in particular solutions. Carbon steels in hot alkali solutions, austenitic steels in hot chloride solutions, and copper-based alloys in solutions containing ammonia can be susceptible.
SSC	Cracking due to stress corrosion.
Stress cracking in plastics	A process of deterioration of plastics involving conjoint chemical attack and straining of the plastic due to residual or applied stresses.
Sulfate-reducing bacteria	These bacteria, of which the genus Desulfovibrio is the most common, reduce sulfates to sulfides in anaerobic conditions (e.g., in nonaerated well water or under deposits in aerated water). The sulfide attacks steel and other metals. The presence of hydrogen or organic matter accelerates this corrosion.
Sulfidation	The reaction at high temperatures of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.
Sulfur corrosion	A form of sulfidation between 260°C and 540°C, occurring in carbon steels and low-alloyed steel in contact with sulfur-containing hydrocarbons (other terms: sulfidic corrosion and high-temperature sulfur corrosion).
Sweet corrosion	This term is used in oil and gas production for carbon dioxide corrosion, which often causes pitting and localized attack in oil or gas-producing systems.
Thermogalvanic corrosion	Corrosion resulting from an electrochemical cell caused by a thermal gradient.
Thermomechanical fatigue	Fatigue by which the repeated stress cycles are caused by variations in temperature.
Tin plague	Recrystallization of tin due to the allotropic transformation from β to α tin that occurs below the temperature of 18°C. The tin becomes brittle and disintegrates into powder.
Topatactical oxide	Oxide growing inward in the steel. The topatactical oxide is underneath the original metal surface.
Transgranular cracking	Cracking through the grains or crystals of a metal.
Tuberculation	The formation of localized corrosion products scattered over the surface in the form of knob-like mounds called tubercles. Tuberculation may occur by development of oxygen concentration cells after the formation of a rust layer by oxygen corrosion.
Under-deposit corrosion	Corrosion associated with, and taking place under, or immediately around, a deposit of corrosion products or other substance. *Note*: The corrosion is the result of the formation of a differential aeration cell.
Weld decay	A term applied to areas adjacent to welds of certain alloys which have been subjected to intergranular corrosion because of metallurgical changes in the alloy (commonly applied to certain grades of stainless steel).

INFORMATION ABOUT THE MICROPRINTS

Case History	*Magnification*	*Etching Agent*
01.01.04.04	×25	None
01.01.04.10	×100	Unknown
01.01.16.01	×100	35 s Natal 5%
01.01.18.02	×100	Color etching according to Beraha
01.01.20.04	×500	Unknown
01.01.22.02	×100	2% Nital
01.02.28.01	×25	None
01.04.18.01	×100	Nital
01.04.22.01	×100	Color etching according to Beraha
01.04.28.01	×500	2% Nital
01.06.14.02	×500	None
01.11.18.01	×50	None
01.11.18.03	×100	Nital
01.11.20.04	×50	None
01.11.20.06	×100	None
01.11.20.07	×50; ×100	Nital
01.11.30.01	×200	Nital
03.11.14.01	×100	None
04.01.19.01	×25	None
04.01.18.04	×25	None
04.01.28.02	×200	10% ammonium persulfate (electrolytic)
04.05.17.01	×50	Unknown
04.11.04.08	×200	Oxalic acid (electrolytic)
04.11.06.01	×50	Color etching according to Beraha
04.11.12.03	×25	None
04.11.12.04	×100	10 M NaOH (electrolytic)
04.11.12.06	×250	V_2A
04.11.18.05	×25	None
04.11.18.10	×100	2% Nital
04.11.18.13	×100	Oxalic acid
04.11.19.01	×50	None
04.11.19.06	×200	10% NaOH (electrolytic)
04.11.19.09	×100	Murakami
04.11.44.01	×200	V_2A
04.12.19.01 (up)	×575	20% NaOH (electrolytic)
04.12.19.01 (down)	×230	V_2A
04.18.22.01	×100	10 M NaOH (electrolytic)
05.03.06.02	×100	Nital
05.06.17.01	×50	Adler
05.11.06.02	×50	Oxalic acid (electrolytic)
05.11.18.01	×25	Unknown
06.02.28.01	×33	Unknown
06.05.16.01	×25	None
06.05.16.02	×50	Color etching according to Beraha
06.06.16.02	×25	None
06.06.18.01	×100	None
06.06.18.02	×250	H_2O + HCL + $FeCl_3$
06.11.16.02	×100	Ammonium persulfate
07.11.38.01	×50	50% Keller & Wilcox 50% Nital 0.1%
07.19.19.01	×200	1% NaOH
07.23.19.01	×25	None
08.25.24.01	×210	2 mL HCl + 5 mL HNO_3 + 93 mL methanol
09.11.20.01	×500	Kroll's reagent

INFORMATION ABOUT MAGNIFICATIONS OF SOME MACROPRINTS

Case History	*Magnification*	*Case History*	*Magnification*
01.01.04.6	×7.5	06.02.10.02	×10
01.01.28.01	×6.5	06.02.32.02	×7.5
01.05.01.01	×2.5	06.02.34.01	×2.5
01.06.04.01	×7.5	06.06.04.02	×15
04.01.32.07	×7.5	06.06.11.01	×2.5
04.06.34.01	×7.5	06.06.15.01	×2.5
04.11.04.01	×5.1	06.06.34.04	×8
04.19.18.01	×8.4		

QUALIFICATIONS AND COMPOSITIONS OF THE STAINLESS STEELS

A. AUSTENITIC STAINLESS STEELS

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
201	S20100	–	0.15	1.00	5.50–7.50	0.060	0.030	16.00–18.00	–	3.50–5.50	N 0.25
202	S20200	1.4371	0.15	1.00	7.50–10.00	0.060	0.030	17.00–19.00	–	4.00–6.00	N 0.25
203 EZ	S20300	–	0.08	1.00	5.00–6.50	0.04	0.18–0.35	16.00–18.00	0.50	5.00–6.50	Cu 1.75–2.25
205	S20500	–	0.12–0.25	1.00	14.00–15.00	0.060	0.030	16.50–18.00	–	1.00–1.75	N 0.32–0.40
216 (XM-17)	S21600	–	0.08	1.00	7.50–9.00	0.045	0.030	17.50–22.00	2.0–3.0	5.00–7.00	N 0.25–0.50
301	S30100	1.4310	0.15	1.00	2.00	0.045	0.030	16.00–18.00	–	6.00–8.00	–
302	S30200	1.4300	0.15	1.00	2.00	0.045	0.030	17.00–19.00	–	8.00–10.00	–
302 B	S30215	–	0.15	2.00–3.00	2.00	0.045	0.030	17.00–19.00	–	8.00–10.00	–
302 B MOD	–	–	0.08	2.00–3.00	2.00	0.030	0.030	17.00–19.00	–	11.00–14.00	–
302 HQ	–	–	0.08	1.00	2.00	0.030	0.030	17.00–19.00	–	9.00–10.50	Cu 3.0–4.0
303	S30300	1.4305	0.15	1.00	2.00	0.20	0.15 min.	17.00–19.00	(0.60)	8.00–10.00	Mo or Zr 0.60
303 L[2]	S30303	–	0.013	0.83	0.18	0.04	0.21	17.8	0.04	12.0	–
303 PLUS X	S30310	–	0.15	1.00	2.50–4.50	0.20	0.25 min.	17.00–19.00	0.60	7.00–10.00	–
303 Se	S30323	–	0.15	1.00	2.00	0.20	0.006	17.00–19.00	–	8.00–10.00	Se 0.15 min
303 Cu	S30330	–	0.15	1.00	2.00	0.15	0.10 min.	17.00–19.00	–	6.00–10.00	Cu 2.50–4.00; Se 0.10
303 S	S30308	–	0.15	1.00	2.00	0.02	0.15	17.00–19.00	–	8.00–11.00	–
303 Ma	S30345	–	0.15	1.00	2.00	0.05	0.11–0.16	17.00–19.00	0.40–0.60	8.00–10.00	Al 0.60–1.00
303 Pb	S30360	–	0.15	1.00	2.00	0.04	0.12–0.25	17.00–19.00	0.60	8.00–10.00	Pb 0.12–0.30
304	S30400	1.4301	0.08	1.00	2.00	0.045	0.030	18.00–20.00	–	8.00–10.50	–
304 H	S30409	1.4948	0.04–0.10	1.00	2.00	0.040	0.030	18.00–20.00	–	8.00–11.00	–
304 HN	S30452	–	0.04–0.10	1.00	2.00	0.045	0.030	18.00–20.00	–	8.00–10.50	N 0.10–0.16
304 L	S30403	1.4306	0.03	1.00	2.00	0.045	0.030	18.00–20.00	–	8.00–12.00	–
304 N	S30451	–	0.08	1.00	2.00	0.045	0.030	18.00–20.00	–	8.00–10.50	N 0.10–0.16
304 LN	S30453	1.4311	0.03	1.00	2.00	0.045	0.030	18.00–20.00	–	8.00–12.00	N 0.10–0.15
S30430	S30430	–	0.08	1.00	2.00	0.045	0.030	17.00–19.00	–	8.00–10.00	Cu 3.0–4.0
305	S30500	1.4303	0.12	1.00	2.00	0.045	0.030	17.00–19.00	–	10.50–13.00	–

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

( ) means optional.

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
307	S30700	–	0.15	1.00	3.75–4.75	0.045	0.030	19.00–22.00	–	9.00–10.50	–
308	S30800	1.4303	0.08	1.00	2.00	0.045	0.030	19.00–21.00	–	10.00–12.00	–
308 L	S30803	–	0.03	1.00	2.00	0.045	0.030	19.00–2100	–	10.00–12.00	–
309	S30900	1.4828	0.20	1.00	2.00	0.045	0.030	22.00–24.00	–	12.00–15.00	–
309 S	S30908	1.4833	0.08	1.00	2.00	0.045	0.030	22.00–24.00	–	12.00–15.00	–
309 S Cb	S30940	–	0.08	1.00	2.00	0.040	0.030	22.00–24.00	–	12.00–15.00	Cb 8 × C min. – 1.0
309 Cb	S30940	–	0.08	1.00	2.00	0.045	0.030	22.00–24.00	–	12.00–15.00	Cb 8 × C min.
309 Cb + Ta	–	–	0.08	1.00	2.00	0.045	0.030	22.00–24.00	–	12.00–15.00	Cb + Ta 8 × C min. – 1.0
310	S31000	1.4841	0.25	1.50	2.00	0.045	0.030	22.00–26.00	–	19.00–22.00	–
310 CB	S31040	–	0.08	1.50	2.00	0.045	0.030	24.00–26.00	–	19.00–22.00	Cb + Ta 10 × C min. – 1.10
310 S	S31008	1.4845	0.08	1.50	2.00	0.045	0.030	24.00–26.00	–	19.00–22.00	–
311	S31100	–	0.15	2.50	2.00	0.040	0.030	20[2]	–	25[2]	–
312	–	–	0.15	1.00	2.00	0.045	0.030	30[2]	–	9.00[2]	–
314	S31400	1.4841	0.25	1.50–3.00	2.00	0.045	0.030	23.00–26.00	–	19.00–22.00	–
316	S31600	1.4401; 1.4436	0.08	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	–
316 Cb	S31640	1.4580	0.08	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	Cb + Ta 10 × C min. – 1.10; N 0.10
316 F	S31620	–	0.08	1.00	2.00	0.200	0.100 min.	17.00–19.00	1.75–2.50	12.00–14.00	–
316 H	S31609	1.4919	0.04–0.10	1.00	2.00	0.040	0.030	16.00–18.00	2.00–3.00	10.00–14.00	–
316 L	S31603	1.4404; 1.4435	0.03	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	–
316 LN	S31653	1.4406; 1.4429	0.03	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	N 0.10–0.16
316 N	S31651	–	0.08	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	N 0.10–0.16
316 Ti	S31635	1.4571; 1.4573	0.08	1.00	2.00	0.045	0.030	16.00–18.00	2.00–3.00	10.00–14.00	Ti 5× C min.; N 0.10
316 LSi[2]	–	–	0.018	2.33	0.20	0.01	0.018	17.4	2.18	12.3	–
317	S31700	1.4449	0.08	1.00	2.00	0.045	0.030	18.00–20.00	3.00–4.00	11.00–15.00	–
317 L	S31703	1.4438	0.03	1.00	2.00	0.045	0.030	18.00–20.00	3.00–4.00	11.00–15.00	–
317 LM/LX/L PLUS	–	–	0.03	1.00	2.00	0.045	0.030	18.00–20.00	4.00–5.00	12.00–16.00	–
318	S31800	1.4583	0.08	1.00	2.00	0.045	0.030	17.00–19.00	1.75–2.75	13.00–15.00	Cb + Ta 10 × C min.
D 319	S31900	–	0.07	1.00	2.00	0.045	0.030	17.50–19.50	2.25–3.00	11.00–15.00	–

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
D 319 L	S31903	–	0.03	1.00	2.00	0.045	0.030	17.50–19.50	2.25–3.00	11.00–15.00	–
321	S32100	1.4541; 1.4878	0.08	1.00	2.00	0.045	0.030	17.00–19.00	–	9.00–1200	Ti 5 × C min.
321 H	S32109	–	0.04–0.10	1.00	2.00	0.040	0.030	17.00–20.00	–	9.00–12.00	Ti 4 × C min. – 0.60
322	S32200	–	0.08	1.00	1.00	0.040	0.030	17[2]	0.70	7[2]	–
326	S32600	–	0.05	0.6	1.00	–	–	25.00–27.00	–	6.00–7.00	Ti 0.25
329	S32900	1.4460	0.20	0.75	1.00	0.040	0.030	23.00–28.00	1.00–2.00	2.50–5.00	–
330	N08330	1.4864	0.15	1.50	2.00	0.045	0.040	14.00–17.00	–	33.00–37.00	–
330 HC[2]	–	–	0.40	1.25	1.50	–	–	19.0	–	35.0	–
332[2]	S33200	–	0.04	0.50	1.00	0.045	0.030	21.5	–	32.0	–
347	S34700	1.4550	0.08	1.00	2.00	0.045	0.030	17.00–19.00	–	9.00–13.00	Cb + Ta 10 × C min.; Co 0.20
347 H	S34709	–	0.04–0.10	1.00	2.00	0.040	0.030	17.00–20.00	–	9.00–13.00	Cb + Ta 8 × C min. – 1.00
347 F Se	S34723	–	0.08	1.00	2.00	0.045	0.15–0.30	17.00–19.00	–	9.00–13.00	Cb + Ta 10 × C min. – 1.00 + Se
347 Se[2]	S34723	–	0.04	0.5	1.00	0.14	–	18.00	–	11.00	Se 0.15 min.; Cb + Ta 10 × C min.
348	S34800	1.4546	0.08	1.00	2.00	0.045	0.030	17.00–19.00	–	9.00–13.00	Cb + Ta 10 × C min.; Ta 0.10; Co 0.20
348 H	S34809	–	0.04–0.10	1.00	2.00	0.045	0.030	17.00–20.00	–	9.00–13.00	Cb or Ta 10 × C min.; Cu 0.2; Ta 0.10
384	S38400	–	0.08	1.00	2.00	0.045	0.030	15.00–17.00	–	17.00–19.00	–
385	S38500	–	0.08	1.00	2.00	0.045	0.030	11.50–13.50	–	14.00–16.00	–
386	S38600	–	0.03	1.00	1.00	–	–	17.5[2]	–	15.5[2]	–
387	S38700	–	0.02	0.5	0.5	–	–	17.7[2]	–	9.5[2]	Cu 3.5[2]
18-8-2 (XM-15)	S38100	–	0.08	1.5–2.5	2.00	0.03	0.03	17.0–19.0	–	17.5–18.5	N 0.08–0.18
18-18 PLUS	–	–	0.15	1.00	17.0–19.0	0.045	0.03	17.5–19.5	0.5–1.5	–	Cu 0.5–1.5; N 0.4–0.6
20 Cb-3	N08020	–	0.07	1.00	2.00	0.045	0.035	19.0–21.0	2.0–3.0	32.0–38.0	Cu 3.0–4.0; (Cb 8 × C min.)
20 Mo-6	–	–	0.03	0.50	1.00	0.03	0.03	22.0–26.0	5.0–6.7	33.0–37.0	Cu 2.00–400
254 SMO	S31254	–	0.02	0.80	1.00	0.030	0.010	19.5–20.5	6.0–6.50	17.5–18.5	Cu 0.50–1.00; N 0.18–0.22
904 L; 2 RK 65	N08904	1.4539	0.02	1.00	2.00	0.045	0.035	19.0–23.0	4.0–5.0	23.0–28.0	Cu 1.0–2.0
AL-6x	N08366	–	0.03	0.75	2.00	0.030	0.003	20.0–22.0	6.0–7.0	23.5–26.5	–
Cronifer 2328	–	–	0.04	0.75	0.75	0.030	0.015	22.0–24.0	2.5–3.0	26.0–28.0	Cu 2.5–3.5; Ti 0.40–0.70
Cryogenic Tenelon (XM-14)	S21460	–	0.12	1.00	14.0–16.0	0.06	0.03	17.0–19.0	–	5.0–6.0	N 0.35–0.50

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
JS-777	–	–	0.04	1.00	2.00	0.045	0.035	19.0–23.0	4.0–5.0	24.0–26.0	Cu 1.9–2.5
Nitronic 32[2]	S24100	–	0.10	0.5	12.0	–	–	18.0	–	1.6	N 0.35
Nitronic 33	S24000	–	0.08	1.00	11.50–14.50	0.060	0.030	17.0–19.0	–	2.25–3.75	N 0.20–0.40
Nitronic 40	S21900	–	0.08	1.00	8.0–10.0	0.06	0.03	18.0–20.0	–	5.0–7.0	N 0.15–0.40
Nitronic 50	S21910	–	0.06	1.00	4.0–6.0	0.04	0.03	20.5–23.5	1.5–3.0	11.5–13.5	N 0.2–0.4; Cb 0.1–0.3; V 0.1–0.3
Nitronic 60	S21800	–	0.10	3.5–4.5	7.0–9.0	0.04	0.03	16.0–18.0	_	8.0–9.0	–
Sanicro 28	N08028	–	0.020	1.00	2.0	0.020	0.015	26.0–28.0	3.0–4.0	29.5–32.5	Cu 0.6–1.4
Tenelon	S21400	–	0.12	0.3–1.00	14.5–16.0	0.045	0.03	17.0–18.5	–	0.75	N 0.35

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

B. FERRITIC STAINLESS STEELS

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
405	S40500	1.4002; 1.4724	0.08	1.00	1.00	0.040	0.030	11.50–14.50	–	–	Al 0.10–0.30
409	S40900	1.4512	0.08	1.00	1.00	0.045	0.045	10.50–11.75	–	0.50	Ti 6 × C min. – 0.75
429	S42900	–	0.12	1.00	1.00	0.040	0.030	14.00–16.00	–	–	–
430	S43000	1.4016; 1.4742	0.12	1.00	1.00	0.040	0.030	16.00–18.00	–	–	–
430 F	S43020	1.4104	0.12	1.00	1.25	0.060	0.150 min.	16.00–18.00	(0.60)	–	–
430 FSe	S43023	–	0.12	1.00	1.25	0.060	0.060	16.00–18.00	–	–	Se 0.15 min.
430 M[2]	–	–	0.06	0.5	0.5	–	–	16	1.8	–	–
430 Ti	S43036	1.4510	0.10	1.00	1.00	0.040	0.030	16.00–1950	–	0.75	Ti 5 × C min. – 0.75
434	S43400	1.4113	0.12	1.00	1.00	0.040	0.030	16.00–18.00	0.75–1.25	–	–
434 F[2]	S43420	–	0.03	0.45	0.45	–	0.3	17.5	1.0	–	–
436	S43600	–	0.12	1.00	1.00	0.040	0.030	16.00–18.00	0.75–1.25	–	Cb or Ta 5 × C min. – 0.70
442	S44200	–	0.20	1.00	1.00	0.040	0.035	18.00–2300	–	–	–
443	S44300	–	0.20	1.00	1.00	0.040	0.030	18.00–23.00	–	0.50	Cu 0.90–1.25
444 (18–2)	S44400	1.4521	0.025	1.00	1.00	0.040	0.030	17.50–19.50	1.75–2.5	1.00	N 0.035; (Ti + Cb) min. 0.2 + 4 (C + N)
446	S44600	1.4762	0.20	1.00	1.50	0.040	0.030	23.00–27.00	–	–	N 0.25
18 SR[2]	–	–	0.04	1.00	0.030	–	–	18.0	–	–	Al 2.0; Ti 0.4
182 FM	S18200	–	0.08	1.00	2.50	0.040	0.15 min.	17.50–19.50	–	–	–
439 (XM-8)	S43035	–	0.07	1.00	1.00	0.040	0.030	17.00–19.00	–	0.50	Ti 0.20 + 4 (C + N) min. – 1.10 max.; A1 0.15; N 0.04
E-Brite 26-1	S44627	–	0.010	0.40	0.40	0.020	0.020	25.00–27.50	0.75–1.50	0.50	N 0.015; Cu 0.2; Ni + Cu 0.5; Cb 0.05–0.20
Monit	S44635	–	0.025	0.75	1.00	0.040	0.030	24.50–26.00	3.50–4.50	3.5–4.5	Ti + Cb 0.03–0.06
Sea-Cure/SC-1	S44660	–	0.025	0.75	1.00	0.040	0.030	25.00–27.00	2.50–3.50	1.5–3.5	(Ti + Cb) 0.2 + 4 (C + N) min.
A1 29-4 C	S44735	–	0.025	0.75	1.00	0.040	0.030	28.00–30.00	3.50–4.50	0.50	Ti 0.2 + 4 (C + N) min.
A1 29-4-2	S44800	–	0.010	0.20	0.30	0.025	0.020	28.00–30.00	3.50–4.20	2.0–2.5	–

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

C. DUPLEX STAINLESS STEELS

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
329[2]	S32900	–	0.08	–	–	–	–	26	1.5	4.5	–
CD-4 M CU[2]	J93370	–	0.04	–	–	–	–	25	2	5	Cu 3
SAF 2304[2]	S32304	–	0.030	–	–	–	–	23	–	4	N 0.05–0.20
3 RE 60[2]	S31500	1.4435	0.030	1.7	–	–	–	18.5	2.7	4.9	S 1.7; N 0.05–0.1
SAF 2205/AF 22[2]	S31803	1.4462	0.030	–	–	–	–	22	3	5	N 0.08–0.20
44 LN[2]	S31200	–	0.030	–	–	–	–	25	1.7	6	N 0.14–0.20
7 Mo PLUS[2]	S32950	–	0.03	–	–	–	–	26.5	1.5	4.8	N 0.1–0.35
Ferralium 255[2]	S32550	–	0.04	–	–	–	–	25	3	6	Cu 2; N 0.1–0.25
DP 3[2]	S31260	–	0.030	–	–	–	–	25	3	7	Cu 0.5; W 0.3; N 0.10–0.30
SAF 2507[2]	S32750	–	0.030	–	–	–	–	25	4	7	N 0.24–0.32

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

D. MARTENSITIC STAINLESS STEELS

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
403	S40300	1.4000; 1.4001	0.15	0.50	1.00	0.040	0.030	11.50–13.00	–	–	–
410	S41000	1.4006	0.15	1.00	1.00	0.040	0.030	11.50–13.50	–	–	–
410 L[2]	S41003	–	0.017	0.88	0.42	0.006	0.018	12.4	–	–	–
410 S	S41008	1.4001	0.08	1.00	1.00	0.040	0.030	11.50–13.50	–	0.60	–
410 Cb	S41040	–	0.15	1.00	1.00	0.040	0.030	11.50–13.50	–	–	Cb 10 × C min.
414	S41400	–	0.15	1.00	1.00	0.040	0.030	11.50–13.50	–	1.25–2.50	–
414 L[2]	S41403	–	0.06	0.15	0.5	–	–	12.50–13.00	0.50	2.50–3.00	A1 0.03
416	S41600	1.4005	0.15	1.00	1.25	0.060	0.150	12.00–14.00	(0.60)	–	Zr or Mo 0.60
416 PLUS × (XM-6)	S41610	–	0.15	1.00	1.50–2.50	0.060	0.150	12.00–14.00	0.60	–	–
416 Se	S41623	–	0.15	1.00	1.25	0.060	0.060	12.00–14.00	–	–	Se 0.15 min.
420	S42000	1.4021	0.15 min.	1.00	1.00	0.040	0.030	12.00–14.00	–	–	–
420 F	S42020	–	0.15 min.	1.00	1.25	0.060	0.150	12.00–14.00	0.60	–	–
420 FSe	S42023	–	0.30–0.40	1.00	1.25	0.060	0.060	12.00–14.00	–	–	Se 0.15 min.
422	S42200	1.4935	0.20–0.45	0.75	1.00	0.040	0.030	11.50–13.50	0.75–1.25	0.50–1.00	V 0.15–0.30; W 0.75–1.25
431	S43100	1.4057	0.20	1.00	1.00	0.040	0.030	15.00–17.00	–	1.25–2.50	–
431 MOD	–	–	0.15–0.25	1.00	1.00	–	–	10.00–13.00	0.5	1.00–2.00	–
431 MOD	–	–	0.08–0.15	1.00	1.00	–	–	15.00–17.00	–	1.50–2.50	N 0.03–0.13; C + N 0.22
440 a	S44002	–	0.60–0.75	1.00	1.00	0.040	0.030	16.00–18.00	0.75	–	–
440 B	S44003	1.4112	0.75–0.95	1.00	1.00	0.040	0.030	16.00–18.00	0.75	–	–
440 C	S44004	1.4125	0.95–1.20	1.00	1.00	0.040	0.030	16.00–18.00	0.75	–	–
440 F	S44020	–	0.95–1.20	1.00	1.25	0.060	0.15 min.	16.00–18.00	(0.75)	–	Mo or Zr 0.75
440 FSe	S44023	–	0.95–1.20	1.00	2.25	0.060	0.060	16.00–18.00	–	–	Se 0.15 min.
501	S50100	–	0.10 min.	–	–	–	–	4.0–6.0	0.40–0.65	–	–
502	S50200	–	0.10	–	–	–	–	4.0–6.0	0.40–0.65	–	–

[1] Single values are maximum values unless otherwise indicated.

[2] Nominal composition.

Parenthesis represents optional.

E. PRECIPITATION HARDENING STAINLESS STEELS

AISI CLASSIFICATION OR TRADE NAME	UNS No.	WERKSTOFF Nr. DIN	COMPOSITION (WT %)[1]								
			C	Si	Mn	P	S	Cr	Mo	Ni	Others
PH 13-8 Mo	S13800	–	0.05	0.10	0.10	0.01	0.008	12.25–13.25	2.0–2.5	7.5–2.5	Al 0.90–1.35; N 0.01
15-5 PH	S15500	–	0.07	1.00	1.00	0.04	0.03	14.0–15.5	–	3.5–5.5	Cu 2.4–4.5; Cb + Ta 0.15–0.45
17-4 PH	S17400	–	0.07	1.00	1.00	0.04	0.03	15.5–17.5	–	3.0–5.0	Cu 3.0–5.0; Cb + Ta 0.15–0.45
17-7 PH	S17700	–	0.09	1.00	1.00	0.04	0.03	16.0–18.0	–	6.5–7.75	A1 0.75–1.5
AM 350 (type 633)	S35000	–	0.07–0.11	0.50	0.5–1.25	0.04	0.03	16.0–17.0	2.5–3.25	4.0–5.0	N 0.07–0.13
AM 355 (type 634)	S35500	–	0.10–0.15	0.50	0.5–1.25	0.04	0.03	15.0–16.0	2.5–3.25	4.0–5.0	–
AM 363[2]	–	–	0.04	0.05	0.15	–	–	11.0	–	4.0	Ti 0.25
Custom 450 (XM-25)	S45000	–	0.05	1.00	1.00	0.03	0.03	14.0–16.0	0.5–1.0	5.0–7.0	Cu 1.25–1.75; Cb 8 × C min.
Custom 455 (XM-16)	S45500	–	0.05	0.50	0.50	0.04	0.03	11.0–12.5	0.5	7.9–9.5	Cu 1.5–2.5; Ti 0.8–1.4; Cb 0.1–0.5
PH 15-7 Mo (type 632)	S15700	–	0.09	1.00	1.00	0.04	0.03	14.0–16.0	2.0–3.0	6.5–7.75	A1 0.75–1.5
Stainless W (type 635)	S17600	–	0.08	1.00	1.00	0.04	0.03	16.0–17.5	–	6.0–7.5	A1 0.4; Ti 0.4–1.2
17-10 P[2]	–	–	0.07	0.5	0.75	0.28	–	17.0	–	10.5	–
630[2]	S17400	1.4542	0.04	0.6	0.28	–	–	16.00	–	4.25	Cu 3.30; Cb or Ta 0.27
631[2]	S17700	1.4568	0.07	0.30	0.50	–	–	17.00	–	7.10	Al 1.17
632	S15700	1.4532	0.07	0.30	0.50	–	–	15.10	2.25	7.10	Al 1.17
633[2]	S35000	–	0.10	0.30	0.75	–	–	16.50	2.75	4.25	N 0.09
634[2]	S35500	–	0.13	0.30	0.75	–	–	15.50	2.75	4.25	N 0.10
660[2]	K66286	1.4980	0.05	0.60	1.45	–	–	14.75	1.30	25.20	Ti 2.15; Al 0.22; V 0.28; B 0.004

CORROSION ATLAS

CASE HISTORY

01.01.01.01

MATERIAL	Carbon steel.
SYSTEM	Boiler feed system.
PART	Feed line from deaerator to boiler.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Many pits covered with knob-like mounds of iron oxide corrosion products (tubercles; see also Case Histories 01.05.01.01, 01.06.01.01, and 01.06.01.02).
TIME IN SERVICE	About 2 years.
ENVIRONMENT	Deaerated feedwater is a mixture of steam condensate and dealkalized and softened makeup water; pH 5; chloride (Cl^-) 10 p.p.m.; temperature 105°C.
CAUSE	Excessive oxygen in the feedwater owing to malfunctioning deaerator.
REMEDY	• Improve deaerator operation: identify the cause of the malfunctioning by internal inspection to examine atomizers and steam injection nozzles and by measurement of the residual oxygen content under various loads. • Improve the boiler feedwater composition, keeping it alkaline.

CORROSION ATLAS

CASE HISTORY

01.01.01.02

MATERIAL	Carbon steel (35.8).
SYSTEM	Cornertube boiler (1.7 MPa).
PART	Economizer pipe (before and after laboratory cleaning).
PHENOMENON	Oxygen corrosion.

APPEARANCE	The upper pipe, cleaned with acid, shows pitting. In the lowest (not cleaned) pipe, the pits are covered with caps of iron oxide.
TIME IN SERVICE	About 2 years.
ENVIRONMENT	Deaerated feedwater, 105°C (mixture of demineralized water and steam condensate with dosing of sodium sulfite in the boiler feed pipe).
CAUSE	Poor operation of the deaerator due to underloading of the atomizers, combined with an underdosage of sulfite caused by an incorrect analysis of the sulfite content of the boiler water.
REMEDY	• Replace the economizer. • Chemically clean boiler in order to halt the corrosion already present in the rest of the boiler. • Modify the atomizing phase of the deaerator to match the lower load. • Periodically check the operation of the deaerator.

CORROSION ATLAS

CASE HISTORY

01.01.01.03

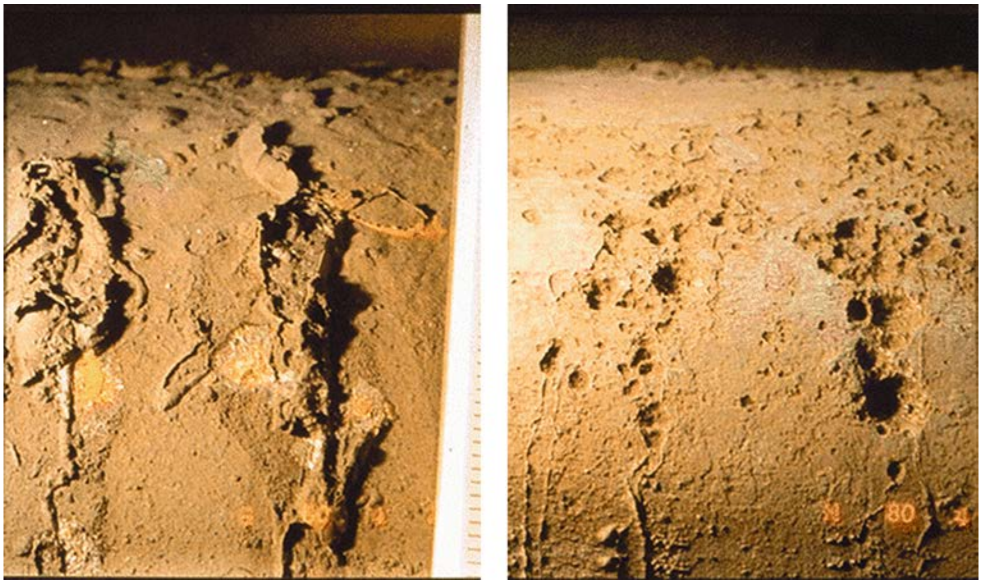
MATERIAL	Carbon steel.
SYSTEM	High-pressure water-tube boiler.
PART	Economizer pipe.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Longitudinal crack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Boiler feedwater in the pipe; flue gases around the pipe.
CAUSE	The application of periodical shot-peening, to clean the flue gas side of the economizer, led to regular disturbance of the magnetite layer inside. The damaged spot is sensitive to further attack by traces of oxygen in the boiler feedwater.
REMEDY	• Regular inspection of the setting of the distributor pivot in the shot-peening unit. • Alternative: change to ultrasonic cleaning.

CORROSION ATLAS

CASE HISTORY
01.01.01.04

MATERIAL	Carbon steel (35.8).
SYSTEM	Shell-type fire-tube boiler (1.2 MPa).
PART	Fire tube (before and after cleaning).
PHENOMENON	Oxygen corrosion.



APPEARANCE	Pitting covered with blisters; pits about 2 mm in depth. The right-hand photo shows the tube after the corrosion products were brushed away.
TIME IN SERVICE	13 years.
ENVIRONMENT	Poorly conditioned boiler water.
CAUSE	Failure to use oxygen scavengers during the first 8 years' operation (no deaerator present).
REMEDY	Dosing of an oxygen scavenger (tubes replaced).

CORROSION ATLAS

CASE HISTORY

01.01.01.05

MATERIAL	Carbon steel (35.8).
SYSTEM	Shell-type fire-tube boiler (1.9 MPa).
PART	Fire tubes.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Pitting attack underneath corrosion nodules at the bottom of the fire tubes.
TIME IN SERVICE	Approximately 10 years.
ENVIRONMENT	Boiler water; p alkalinity 12–20 meq/l (600–1000 p.p.m. $CaCO_3$); chloride (Cl^-) 130–220 p.p.m.; phosphate (PO_4^{3-}) 50–70 p.p.m.; iron (Fe^{2+}) 15–50 p.p.m.
CAUSE	Malfunctioning deaerator: as the deaerator was being charged, the pressure fell below 1.25 bar and the temperature below 105°C because of excessive over-capacity of the makeup water pump. As a result of the leak, blockage with boiler water salts had occurred elsewhere in the fire tubes.
REMEDY	The makeup water pump should be throttled in such a way that the volume of feedwater is in accordance with the capacity of the steam pressure regulator in the steam supply line.

CORROSION ATLAS

CASE HISTORY

01.01.01.06

MATERIAL	Carbon steel (35.8).
SYSTEM	Water-tube boiler (8.5 MPa).
PART	Downcomer tube from drum.
PHENOMENON	Oxygen corrosion.

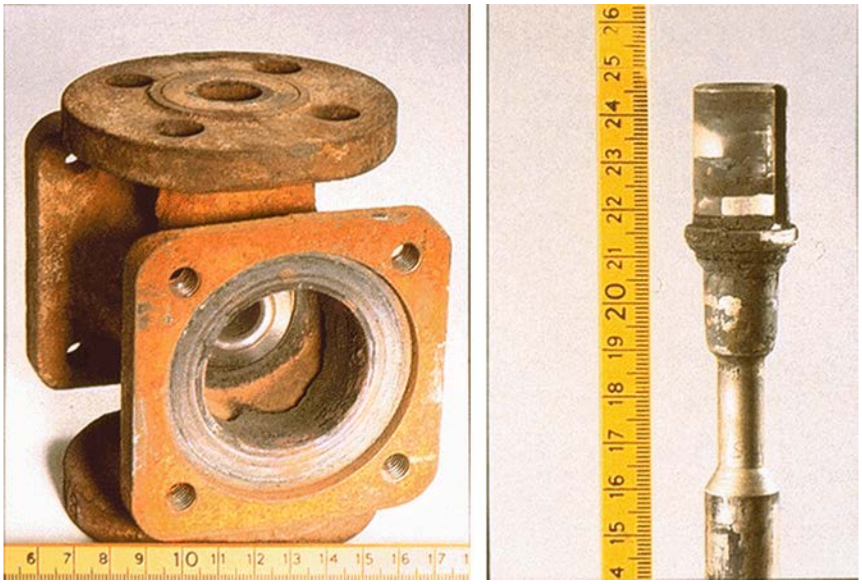
APPEARANCE	Small clean pits in the upper part of the downcomer tubes below the drum.
TIME IN SERVICE	11 years.
ENVIRONMENT	Conditioned boiler water.
CAUSE	Poor conditioning owing to insufficient excess of hydrazine during wet lay-up of the boiler in shutdown periods.
REMEDY	• Maintain a higher excess of hydrazine (at least 100 p.p.m.) in the boiler water during the wet lay-up, with periodical checks on the excess. • Alternative to hydrazine: a modem nontoxic organic oxygen scavenger, for example, erythorbic acid (D-isoascorbic acid) or hydroquinone.

CORROSION ATLAS

CASE HISTORY

01.01.01.07

MATERIAL	Cast steel (casing) and stainless steel (valve).
SYSTEM	Steam system (0.7 MPa).
PART	Steam control valve.
PHENOMENON	Oxygen corrosion.



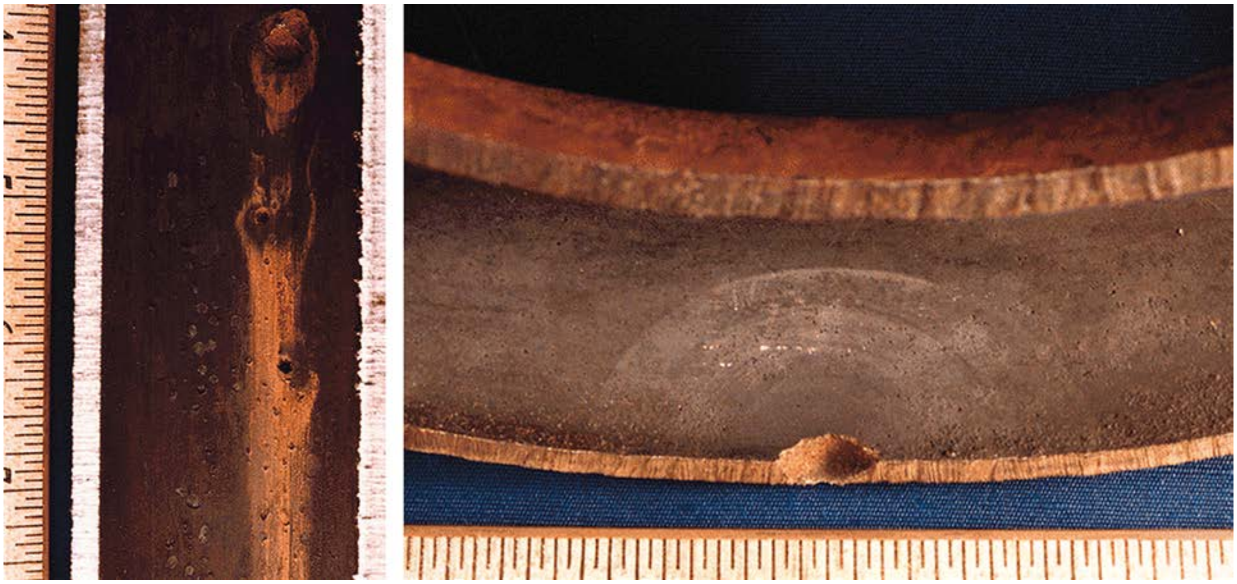
APPEARANCE	Magnetite deposits in the valve.
TIME IN SERVICE	The valve seized up after a few months.
ENVIRONMENT	Oxygen-containing steam.
CAUSE	Excessive pick-up of magnetite took place in the steam pipes owing to the presence of oxygen in the steam. Part of the magnetite was entrained by the steam and deposited in the valves (see also Case Histories 01.01.01.09 and 01.04.01.03).
REMEDY	Deoxygenation of the boiler feedwater by deaeration or dosing of an oxygen scavenger.

CORROSION ATLAS

CASE HISTORY

01.01.01.08

MATERIAL	Carbon steel (ASME SA-205-TI, containing 0.5% molybdenum).
SYSTEM	Water-tube recovery boiler.
PART	Vertical and horizontal superheater tube (outer diameter: 5.1 cm).
PHENOMENON	Oxygen corrosion.



APPEARANCE	Pitting with gravity-induced drainage of corrosion products on the vertical section (left). Elliptical water rings surrounding the pit on the horizontal U-bend section (right).
TIME IN SERVICE	10 years. Corrosion took place during lay-up over the summer.
ENVIRONMENT	Nitrogen and moisture.
CAUSE	The oxygen pits were discovered during a hydrotest of the boiler that had been in wet lay-up over the summer. The superheater section had been in dry lay-up under a nitrogen blanket. It is apparent that, despite the precautions of dry lay-up, the tube had been exposed to condensed moisture and atmospheric oxygen.
REMEDY	Employ the dry lay-up method not only for the superheater but also for the boiler as well.

CORROSION ATLAS

CASE HISTORY

01.01.01.09

MATERIAL	Carbon steel.
SYSTEM	Steam system.
PART	Siphon of a condensate drain (left) and a steam sieve (right).
PHENOMENON	Oxygen corrosion.

APPEARANCE	Blockage due to magnetite deposition.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Oxygen-containing steam.
CAUSE	The deaerator performed inefficiently due to the supply of high-pressure condensate which expanded in the deaerator. As a result, the deaerator did not receive any fresh steam, and therefore, the feed-water was insufficiently deaerated. The steam produced by the boiler consequently contained oxygen, which gave rise to excessive magnetite formation. Some of the magnetite was entrained with the steam, thereby causing blockages (see also Case History 01.01.01.07).
REMEDY	The high-pressure condensate should first be expanded or cooled before being fed to the deaerator. Any expansion steam should be routed to a low-pressure steam system.

CORROSION ATLAS

CASE HISTORY

01.01.03.01

MATERIAL	Carbon steel.
SYSTEM	Vertical waste-heat boiler of a catalytic cracker.
PART	Quench cooler pipe section.
PHENOMENON	Caustic corrosion.

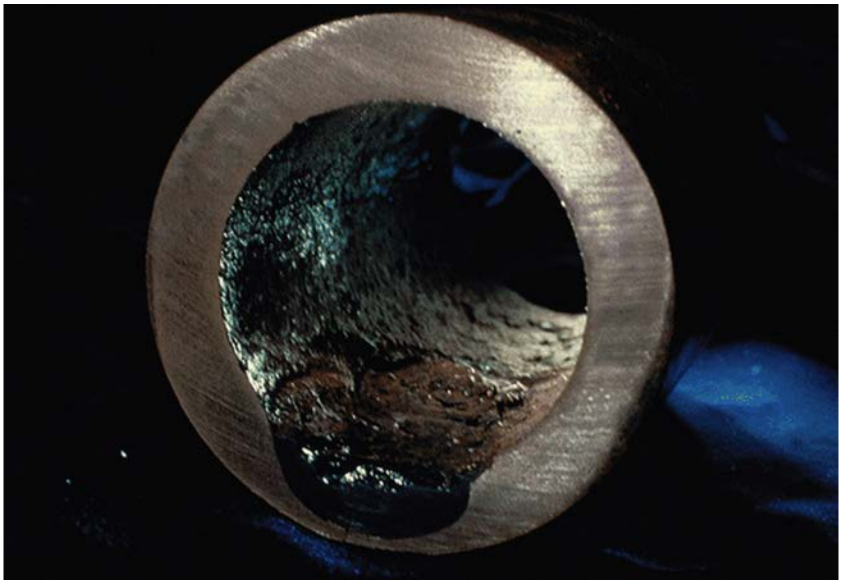
APPEARANCE	Uniform attack with cracking.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Alkaline boiler water around the pipes. Cracked gases, 400–900°C, through the pipes.
CAUSE	As a result of defects in the water treatment, deposits had formed on the pipe plate, under which the boiler water concentrated strongly, leading to high local caustic concentrations. Caustic attacks the protecting magnetite layer as well as the steel itself according to $4NaHO + Fe_3O_4 \rightarrow 2NaFeO_2 + Na_2FeO_2 + H_2O$ and $Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2$ (see also Case Histories 01.01.03.02 and 01.11.03.01).
REMEDY	Prevent deposits by improvement of the boiler water treatment and its testing.

CORROSION ATLAS

CASE HISTORY

01.01.03.02

MATERIAL	Carbon steel (ASME SA-210, similar to AISI 1020).
SYSTEM	Water-tube boiler (pressure 14.5 MPa).
PART	Wall tube.
PHENOMENON	Caustic corrosion (high pH gouging).



APPEARANCE	Deep gouging beneath insulating internal deposits.
TIME IN SERVICE	13 years.
ENVIRONMENT	Boiler water. Water treatment: congruent control and sodium polyphosphate.
CAUSE	Deposits shield the metal from the bulk water. Steam that forms under these thermally insulating deposits escapes and leaves behind a corrosive alkaline residue that can deeply gouge the metal surface. Sodium hydroxide will first dissolve magnetite: $4NaOH + Fe_3O_4 \rightarrow 2NaFeO_2 + Na_2FeO_2 + 2H_2O$. When magnetite is removed, the sodium hydroxide may react directly with the iron: $Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2$. The formed hydrogen can lead to further corrosion: hydrogen damage (see Case History 01.01.20.05).
REMEDY	• Reduce the amount of available free sodium hydroxide by a water-treatment program based on coordinated phosphate. • Prevent excessive waterside deposition by annual inspection and cleaning of the boiler if necessary.

CORROSION ATLAS

CASE HISTORY

01.01.04.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Shell-type fire-tube boiler (1.2 MPa).
PART	Fire tube.
PHENOMENON	Acid corrosion.

APPEARANCE	Grooved attack over the entire surface.
TIME IN SERVICE	Corrosion took place in 3 h.
ENVIRONMENT	Cleaning acid (inhibited hydrochloric acid 9.5%, 95°C). Chemical cleaning was necessary following deposition of iron oxide and hardness sediments.
CAUSE	The uncontrolled performance of a chemical cleaning treatment to the boiler, with failure to notice inhibitor breakdown. Combined with an excessive pipe wall temperature, this resulted in 400 kg of steel being dissolved on a heated surface of 100 m^2. The damage was the result of poor workmanship (see also Case History 01.01.04.04).
REMEDY	The fire tubes were replaced at the cleaning firm's expense.

CORROSION ATLAS

CASE HISTORY

01.01.04.02

MATERIAL	Carbon steel (35.8).
SYSTEM	High-pressure water-tube boiler, fired with heavy oil.
PART	Furnace evaporator tube.
PHENOMENON	Acid corrosion (dew-point corrosion).

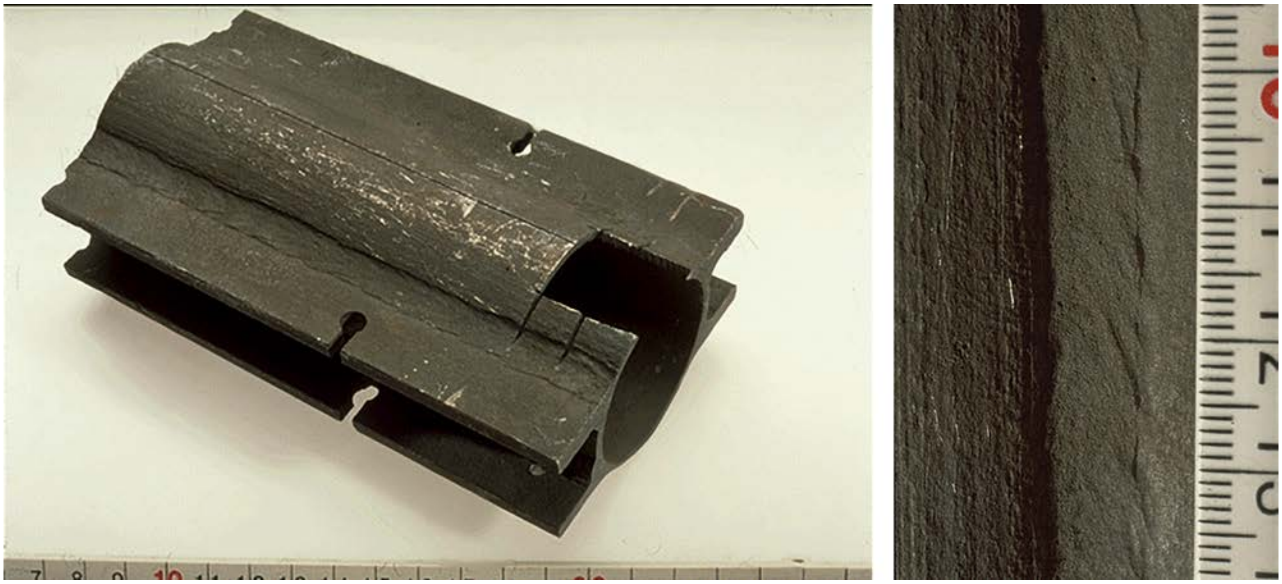
APPEARANCE	Uniform attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Deposits with acidic sulfur components at the flue gas side.
CAUSE	During shutdown, the sulfur compounds reacted with water to form sulfuric acid, which attacked the steel. This acid corrosion is also defined as dew-point corrosion during idle periods (see also Case History 01.01.04.09).
REMEDY	• After taking the boiler out of service, remove fire-side deposition from metal surfaces immediately using high-pressure water sprays. This should be followed by a lime wash to neutralize remaining acidic substances. • Alternative: change to firing with low-sulfur oil or natural gas.

CORROSION ATLAS

CASE HISTORY

01.01.04.03

MATERIAL	Carbon steel.
SYSTEM	Refuse incinerator.
PART	Electric resistance welded furnace tube.
PHENOMENON	Acid corrosion (dew-point corrosion).



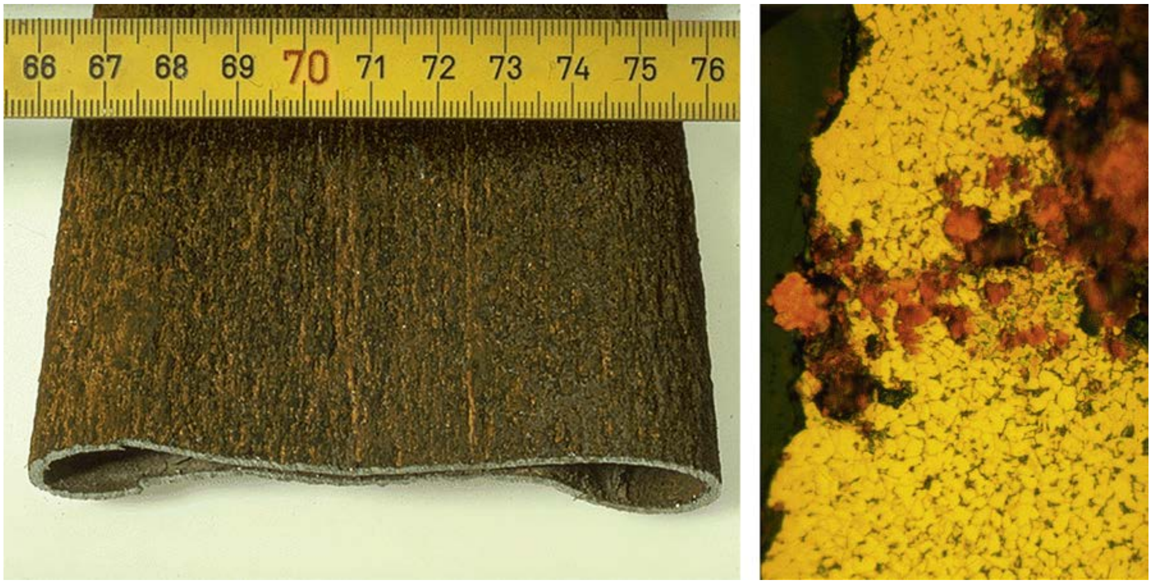
APPEARANCE	Severe attack to the longitudinal seam weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Flue gases contaminated with HCl originating from the combustion of plastics (polyvinyl chloride etc.).
CAUSE	As a result of a difference in structure between the weld and the base material, partly caused by welding at low frequency, the weld seam is selectively attacked by the HCl (at temperatures below the dew point). This dew-point corrosion during service is also called cold-end corrosion (for selective attack of the weld, see also Case History 01.11.04.01).
REMEDY	• Use a seamless tube; or • Higher frequency welding; or • Application of postweld heat treatment for normalizing the welds.

CORROSION ATLAS

CASE HISTORY

01.01.04.04

MATERIAL	Carbon steel.
SYSTEM	Shell-type fire-tube boiler (1.6 MPa).
PART	Fire tube.
PHENOMENON	Acid corrosion.



APPEARANCE	Grooved attack, tube imploded under pressure testing at 11 bar after cleaning.
TIME IN SERVICE	About 40 h (duration of the cleaning operation).
ENVIRONMENT	Cleaning acid (inhibited HCl 6%); average temperature (calculated subsequently) about 90°C. The boiler was chemically cleaned in view of the presence of organic contamination entrained with the condensate.
CAUSE	Errors made during the cleaning operation: • Firing the boiler filled with cleaning acid, allowing the wall temperature of the flame pipes to rise to excessive levels. • Using an inhibitor unsuitable for industrial cleaning purposes. • The lack of any monitoring during cleaning, as a result of which among other things the formation of $FeCl_3$ was not detected in time and additional attack took place. This case also is the result of poor workmanship (see also Case History 01.01.04.01).
REMEDY	The boiler had to be renewed; total damage $300,000. Note: chemical cleaning should be performed by specialized firms.

CORROSION ATLAS

CASE HISTORY
01.01.04.05

MATERIAL	Carbon steel (ASME SA-192, similar to AISI 1012).
SYSTEM	Water-tube boiler (pressure 1.1 MPa).
PART	Horizontal economizer tube (diameter: 6.0 cm).
PHENOMENON	Acid corrosion (low pH gouging).

APPEARANCE	A large elliptically shaped gouge covered with a thick, irregular layer of hard dark iron oxides with a laminated structure.
TIME IN SERVICE	7 years.
ENVIRONMENT	Boiler water conditioned with chelant. Makeup water treatment: water softener and reverse osmosis. Boiler water analysis: conductivity 10 mS/m, hardness 0 ppm.
CAUSE	Leakage of sodium chloride from the generation of a water softener coupled with non-nucleate boiling in the hot end of the economizer, caused by excessively high heat fluxes. The heat fluxes in this area were 40% higher than design values. This phenomenon may also be regarded as heat-flux corrosion. The concentration of acid-producing salts may induce hydrolysis to produce localized low pH conditions, while the bulk water remains alkaline: $M^+ Cl^- + H_2O \rightarrow MOH\downarrow + H^+ Cl^-$. The hydrogen formed in the reaction of HCl with steel can lead to further corrosion: hydrogen damage (see Case Histories 01.01.20.02, 01.01.20.04, and 01.01.20.07).
REMEDY	• Prevent inadvertent release of regeneration chemicals from makeup water equipment. • Prevent excessively high heat fluxes by shortening the economizer.

CORROSION ATLAS

CASE HISTORY

01.01.04.06

MATERIAL	Carbon steel (ASME 210, similar to AISI 1020).
SYSTEM	Water-tube boiler (pressure 13.5 MPa).
PART	Vertical wall tube (OD: 6.3 cm).
PHENOMENON	Acid corrosion.

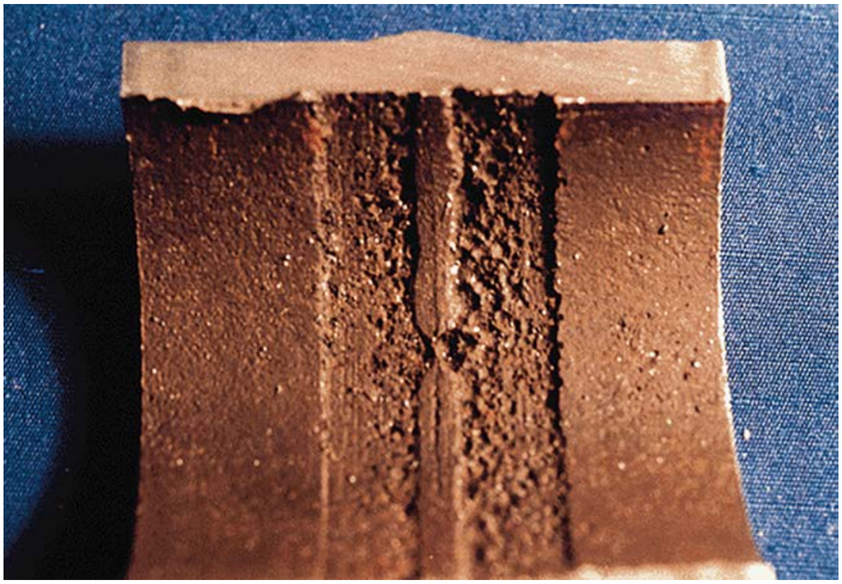
APPEARANCE	Etched, bright metallic. The photo, taken at 7.5 magnification, reveals irregular islands of uncorroded metal standing 0.12 mm above the surrounding corroded surface.
TIME IN SERVICE	15 years. Corrosion took place in 24 h.
ENVIRONMENT	Citric acid during cleaning.
CAUSE	It is suspected that a combination of thermal decomposition of the inhibitor and lack of proper monitoring was responsible for the corrosion, i.e., poor workmanship (see also Case Histories 01.01.04.01 and 01.01.04.04).
REMEDY	During acid cleaning, give careful attention to cleaning solution temperatures, exposure time, and frequent monitoring of solution chemistry.

CORROSION ATLAS

CASE HISTORY

01.01.04.07

MATERIAL	Carbon steel (ASME 210, similar to AISI 1020).
SYSTEM	Water-tube boiler (pressure 10.3 MPa).
PART	Vertical wall tube (outer diameter: 7.6 cm).
PHENOMENON	Acid corrosion.



APPEARANCE	Strong grooved attack of the internal surfaces of wall tubes opposite external circumferential welds.
TIME IN SERVICE	30 years. Corrosion took place over numerous, successive acid cleanings.
ENVIRONMENT	Mineral acid.
CAUSE	Residual stresses remaining from the weld make the heat-affected zones subject to preferential corrosion when exposed to strong acid (see also Case History 01.01.04.03).
REMEDY	Damage of this type may be minimized by careful attention to cleaning solution temperature, exposure time, and frequent monitoring of solution chemistry during acid cleaning.

CORROSION ATLAS

CASE HISTORY

01.01.04.08

MATERIAL	Carbon steel (ASME SA-106-B, similar to AISI 1030).
SYSTEM	Oil-fired water-tube boiler.
PART	Horizontal economizer tube (OD: 4.8 cm).
PHENOMENON	Acid corrosion (cold-end corrosion).

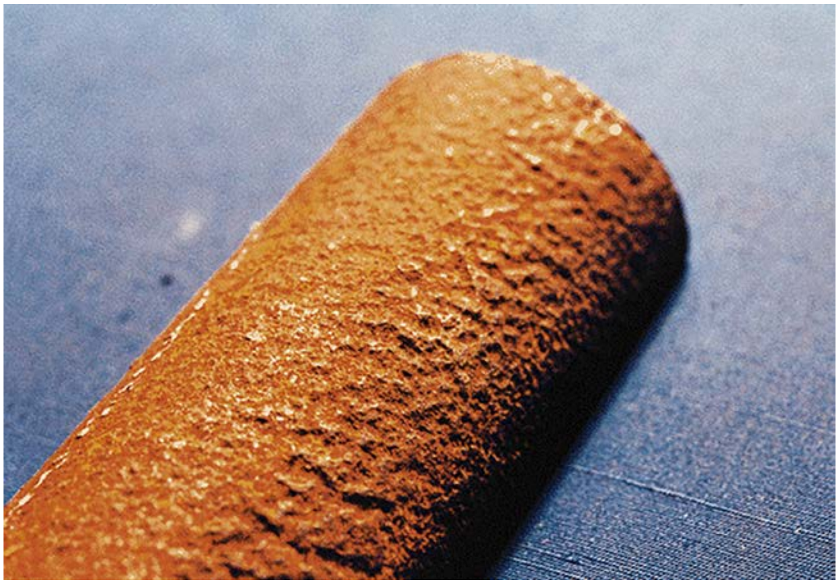
APPEARANCE	The external surface, including fin surfaces, exhibited smooth, general metal loss.
TIME IN SERVICE	Unknown.
ENVIRONMENT	SO_2 and SO_3-containing flue gases. Temperature: entry: 300°C; exit: 185°C.
CAUSE	Condensation of sulfuric acid at the cold end of the boiler, the economizer, where the temperature of the metal drops below the sulfuric acid dew point of the flue gas. The sulfuric acid attacks the steel (dew-point corrosion). The oil contained 1.9% S. The pH of a 1% slurry of the corrosion products was measured at 2.3 (see also Case History 01.01.04.03).
REMEDY	• Specify fuel with low sulfur and low moisture content. • Operating the boiler at or below 5% excess air will keep the SO_3 percentage as low as possible. • Substantial design changes are often required to eliminate metals with surface temperatures below the sulfuric acid dew point. • Feed fuel additives as a chemical solution of the problem.

CORROSION ATLAS

CASE HISTORY

01.01.04.09

MATERIAL	Carbon steel (ASME SA-192, similar to AISI 1012).
SYSTEM	Black liquor-fired recovery water-tube boiler (pressure 4.1 MPa).
PART	Vertical screen tube (OD: 5.1 cm).
PHENOMENON	Acid corrosion (dew-point corrosion).



APPEARANCE	General metal loss with an irregular surface contour.
TIME IN SERVICE	10 years.
ENVIRONMENT	Sulfur-containing deposits.
CAUSE	Combustion of black liquor gives sulfurous ash deposits covering the tubes. As the boiler cools during idle periods, the temperature of its external surface may drop below the dew point, allowing moisture to form on the tube surface. The acidic solution formed attacks the steel (see also Case History 01.01.04.02).
REMEDY	• Remove the fire-side deposition from metal surfaces immediately after boiler shutdown using high-pressure water sprays, followed by a lime wash to neutralize remaining acidic substances. • Keep the boiler fire side dry, by circulation of warm boiler water (by means of a heat exchanger and another boiler), or by circulation of dried air. • In general, specify fuels with lower sulfur content to prevent dew-point corrosion.

CORROSION ATLAS

CASE HISTORY

01.01.04.10

MATERIAL	Carbon steel (35.8).
SYSTEM	Waste-incineration boiler.
PART	Header of the vaporizer section of the rotating drum furnace.
PHENOMENON	Dew-point corrosion.

APPEARANCE	Pitting attack to the welds, which form the connection between the header and the vaporizer tubes. More specifically in the weld zone with a characteristic cast structure (stalk-shaped crystals).
TIME IN SERVICE	8 years (during which leakages occurred regularly).
ENVIRONMENT	Acid off-gases condensing in boiler feedwater (demineralized makeup water + recycled condensate). Acid deposits consisting of silicates, iron oxide, and chlorides.
CAUSE	Because of leaking economizer tubes, part of the vaporizer section was regularly hosed with water, resulting in local dew-point corrosion due to contact with the acid off-gases. This caused pitting attack to the welds as these are partly less corrosion resistant because as weld metal hardens a coarse cast structure is formed with segregation phenomena (see microphoto), which makes these parts less homogeneous and hence more sensitive to corrosion.
REMEDY	Partial replacement of the economizer.

CORROSION ATLAS

CASE HISTORY

01.01.04.11

MATERIAL	Carbon steel (35.8).
SYSTEM	Shell-type boiler; 0.15 MPa.
PART	Fire tubes.
PHENOMENON	Acid corrosion.

APPEARANCE	Severe localized uniform corrosion with a yellow and red corrosion scale.
TIME IN SERVICE	3 months (upper tube) to 2 years (lower tube).
ENVIRONMENT	Boiler water (P-alkalinity: 10–20 meq/L; chloride: 100–400 ppm Cl; phosphate; 25–50 ppm P_2O_5; sulfite: 50–100 ppm Na_2SO_3; sulfate: 5000–10,000 ppm Na_2SO_4.
CAUSE	This was suspected to be a form of acid corrosion by the sulfite (sulfurous acid). Investigation by Kema (see next page) led to the following conclusions: In view of the uniform attack, the presence of the sulfur-rich compound on the oxide-metal interface, and the local pits underneath the oxide layer where the sulfur-rich compound was found, the corrosion is believed very probably to be a consequence of an acid sulfur compound. It may be that the heat load coupled with high sulfite dosages enables an acid to form, such as sulfuric acid, sulfurous acid, or polythionic acid.
REMEDY	• Replace the sulfite by another oxygen scavenger. • Change to thermal deaeration of the feedwater. • Use a calmed steel (with higher Si-content) which is more resistant to acids.

Microscopic research by Kema Nederland B.V.

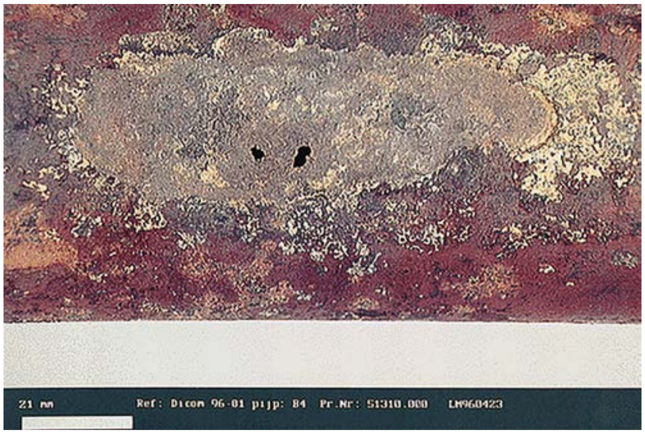


Fig. 1 Close-up of one of the pipes.

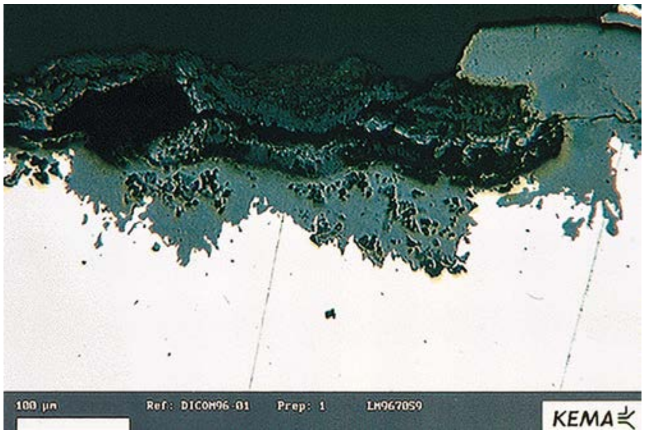


Fig. 2 Photograph taken with incident light.

Fig. 3 Photograph taken with polarized light.

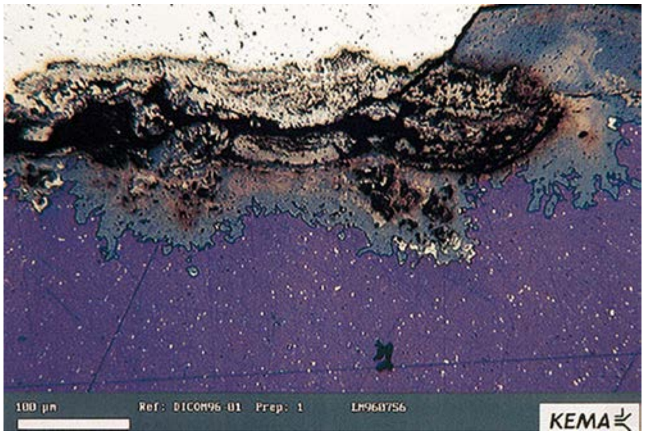


Fig. 4 DICOM image.

DISCUSSION

Various photomicrography techniques were applied: normal incident light, polarized light, and the DICOM imaging technique (Figs. 2, 3, and 4). In the polarized light photograph (Fig. 3), a yellowish-orange corrosion product is found. Electron microscopy and EDS analyses were used to analyze the phases at various locations. In all the specimens, a sulfur-rich compound is found on the oxide-metal interface. The phase which reflects orange in polarized light is also found to contain much sulfur. Note the skeleton structure in the oxide and the pits on the oxide-metal interface, where a clear sulfur enrichment is found. In the electron microscopy image (not reproduced here), even small intergranular sites of attack are visible.

CORROSION ATLAS

CASE HISTORY

01.01.06.01

MATERIAL	Steel (13 CrMo 9 10).
SYSTEM	Oil-fired water-tube boiler (6.1 MPa).
PART	Superheating tube.
PHENOMENON	High-temperature corrosion (oxidation).

APPEARANCE	External uniform attack leading to cracking by superheating.
TIME IN SERVICE	5 years.
ENVIRONMENT	Deposit containing over 70% sodium sulfate and 4% vanadium oxide.
CAUSE	The presence of oxides of heavy metals (V, W, Nb) catalyzes the oxidation at high temperature. Heavy oil contains sulfur, vanadium, and sodium. At wall temperatures above 600°C, vanadium oxide and sodium sulfate melts occur on the superheater tubes, leading to corrosion of the steel. This phenomenon is also known as hot corrosion or in oil-fired boilers oil-ash corrosion.
REMEDY	Initially, dosing of various oil additives proved ineffective; subsequently, for other reasons as well, switched to firing sulfur-free natural gas; the entire superheater was replaced.

CORROSION ATLAS

CASE HISTORY

01.01.07.01

MATERIAL	Carbon steel.
SYSTEM	Forced circulation water-tube boiler (pressure 10 MPa).
PART	Evaporator tube.
PHENOMENON	Heat-flux corrosion (chloride induced).

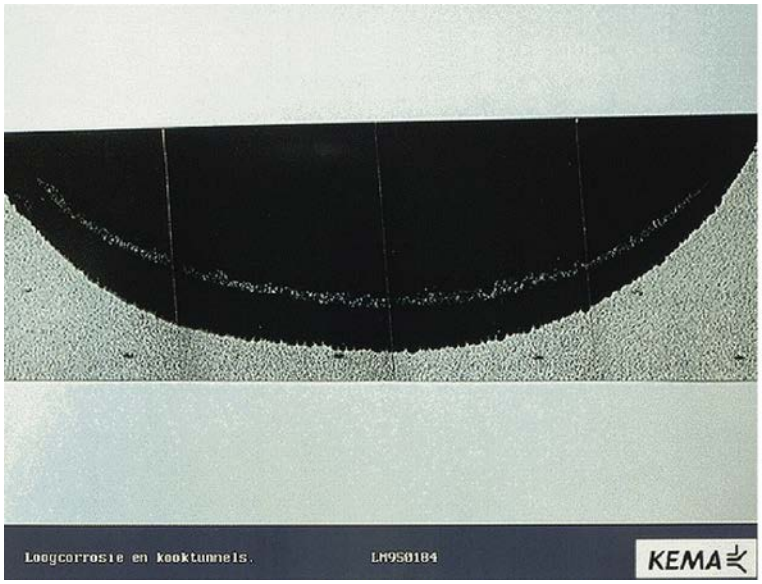
APPEARANCE	The weld and the surrounding pipe surface was corroded.
TIME IN SERVICE	5 years.
ENVIRONMENT	Inside: ammonia-conditioned boiler water.
CAUSE	Condenser inleakages resulted in chloride-containing boiler water. The present laminated oxide layers are typical of Cl-induced corrosion under heat-flux conditions. The corrosion started from the weld and expanded over the pipe surface. The weld material has too low corrosion resistance for application in evaporators. The critical $FeCl_2$ value was only 15, whereas the recommended selection criterion is 35. (Ref. Huijbregts, W.M.M.: “Corrosion in Power Stations,” paper presented at VGB conference: Chemistry at Power Stations, Essen, 1994.
REMEDY	• More attention was given to boiler water quality, and the condenser inleakages were prevented. • In this case, the tube was replaced without paying attention to the composition of the steel and welding material. • To prevent chloride-induced heat-flux corrosion: specify the acid-corrosion resistance of carbon steel (tube and welding material) for evaporators. A critical $FeCl_2$ value of at least more than 35 mmol is recommended.

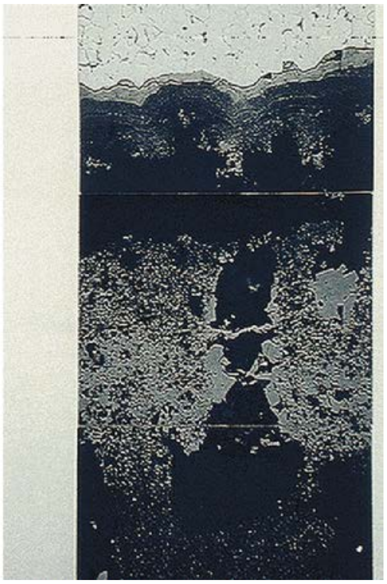
CORROSION ATLAS

CASE HISTORY

01.01.07.02

MATERIAL	Carbon steel.
SYSTEM	Experimental water-tube boiler.
PART	Evaporator tube.
PHENOMENON	Heat-flux corrosion (alkali-induced).



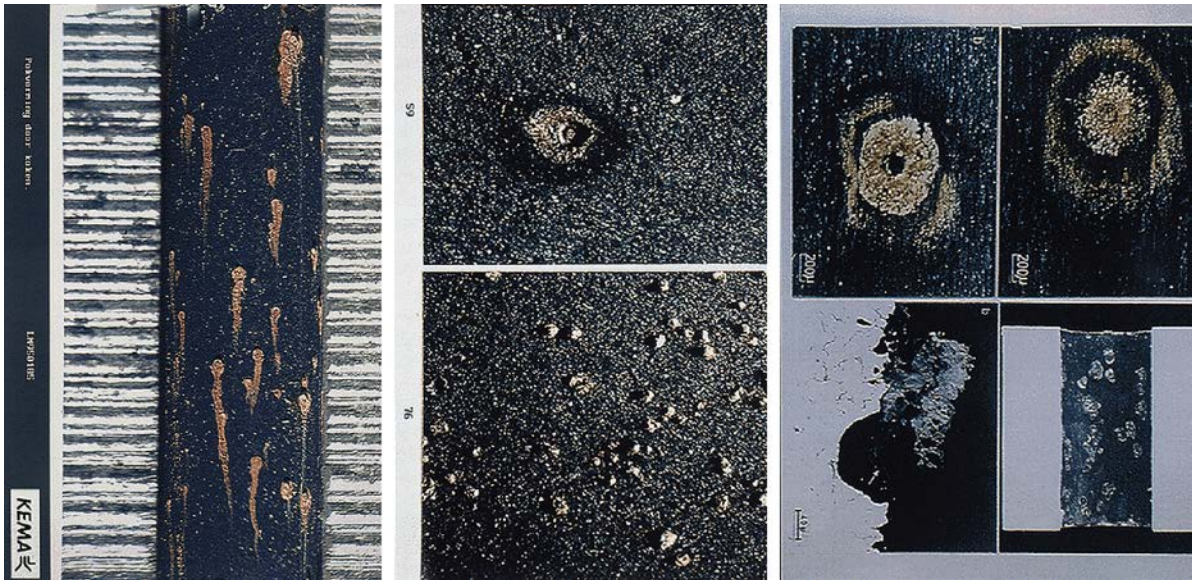


APPEARANCE	A thick porous oxide layer with pitting underneath the oxide scale. The topotactically grown oxide is very porous. The epitactical oxide layer on the outside consists of coarse crystalline magnetite octahedra.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	Boiler water with NaOH water treatment.
CAUSE	Water conditioning with non-volatile NaOH and presence of a fouling layer of iron oxides. Because of high heat flux under the deposit layer, the NaOH concentrates to high values, resulting in corrosion of the carbon steel.
REMEDY	• Chemical cleaning of the tubes to remove the fouling layer of iron oxides. • Changing the water chemistry method to a volatile method (with prevention of condenser cooling water inleakages).

CORROSION ATLAS

CASE HISTORY

01.01.07.03

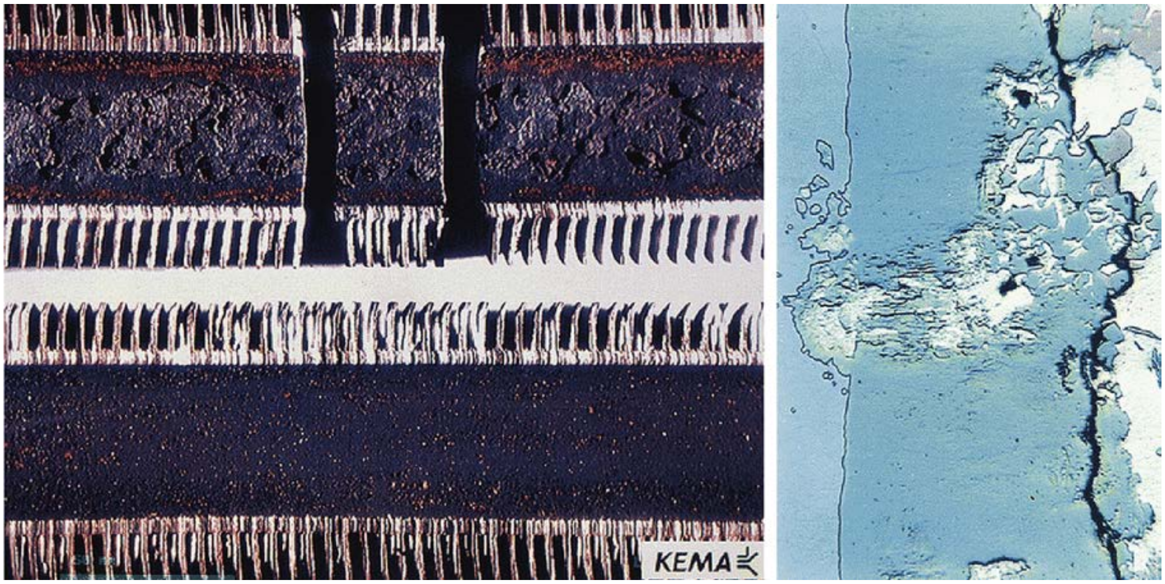
MATERIAL	Carbon steel.
SYSTEM	Experimental water-tube boiler.
PART	Evaporator tube.
PHENOMENON	Heat-flux corrosion (induced by nucleate boiling).
	
APPEARANCE	Pock-shaped pustules (like doughnuts), with pitting underneath.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	Boiler water with ammonia treatment.
CAUSE	Nucleate boiling causes deposit pustules to form, under which slight corrosion takes place in the case of nonsevere aggressive water. The original protective magnetite layer can often be found on the metal-deposit interface. In pure boiler water, this pitting is not a severe problem. In fouled boiler tubes, this nucleate boiling pitting can result in severe damage (see also Case History 05.01.07.01). The corrosion is frequently and erroneously ascribed to oxygen corrosion during shutdown periods.
REMEDY	• In the case of fouled boiler tubes, lower heat flux by mounting clay mass on the tubes with highest heat fluxes. • Avoid use of nonvolatile water conditioning chemicals and prevent cooling water inleakages.

CORROSION ATLAS

CASE HISTORY

01.01.07.04

MATERIAL	Carbon steel.
SYSTEM	Waste-heat boiler (pressure 4.0 MPa).
PART	Evaporator tube.
PHENOMENON	Heat-flux corrosion (induced by nucleate boiling).



APPEARANCE	Thick corrosion scale at the heat-flux side. Only slight deposits on the nonheated side. Pitting corrosion on the boundary of the thick corrosion scale.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Boiler water with volatile water treatment.
CAUSE	Contamination of the boiler water with a sulfur-containing chemical (S was demonstrated at the pits). In the pits, ferrous oxide was tangled, and occasional intergranular corrosion was found. At the inlet of the evaporator, there was very high heat flux, so that severe nucleate boiling (columnar boiling) took place. The resultant steam bubbles caused the formation of oxide-free tunnels, as can be seen on the microprint.
REMEDY	• Find the contamination source of the inleakage. • Lower the heat-flux by mounting clay mass on the tubes at the inlet of the evaporator.

CORROSION ATLAS

CASE HISTORY

01.01.14.01

MATERIAL	Carbon steel.
SYSTEM	Boiler feedwater system.
PART	Condensate tank bottom.
PHENOMENON	Galvanic corrosion with oxygen corrosion.

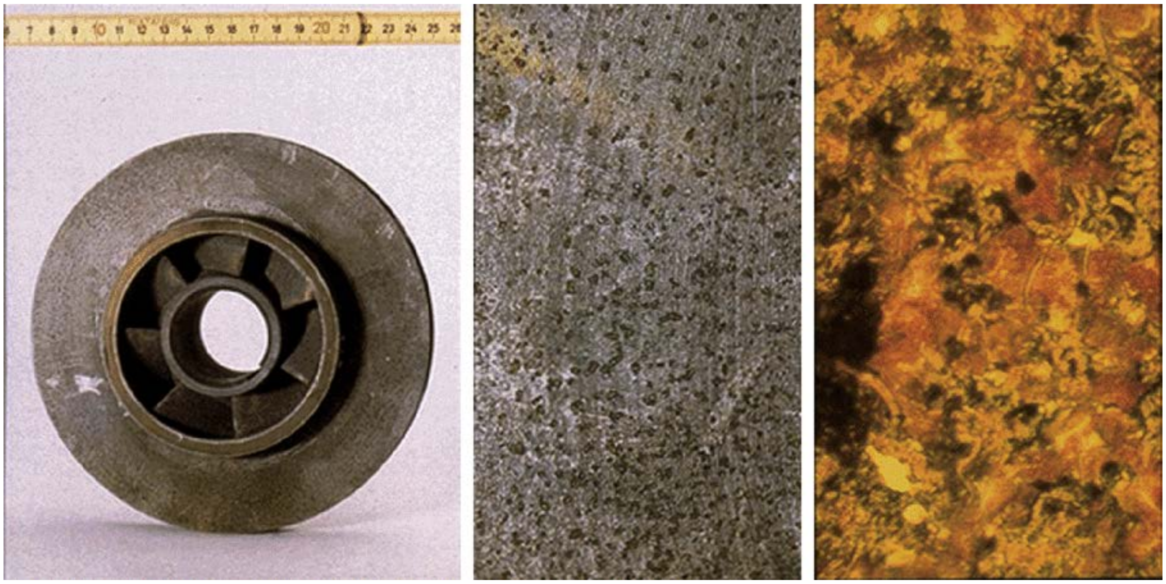
APPEARANCE	Ring-shaped overall attack under the stainless steel plate; pitting attack outside it.
TIME IN SERVICE	At least 6 years.
ENVIRONMENT	Mixture of return condensate and oxygen-containing demineralized makeup water; temperature 80–90°C.
CAUSE	A stainless steel plate was left behind, causing local galvanic corrosion of the carbon steel tank bottom. The presence of oxygen resulted in pitting attack.
REMEDY	• Apply effective inspection procedures before start-up to ensure no alien objects are left behind. • Prevent oxygen corrosion by coating the tank or constructing it of stainless steel AISI 316 L.

CORROSION ATLAS

CASE HISTORY

01.01.16.01

MATERIAL	CrNi cast iron.
SYSTEM	Boiler feedwater system.
PART	Boiler feed pump impeller.
PHENOMENON	Selective leaching (graphitic corrosion).



APPEARANCE	Soft granular surface which gives off black powder; material receded about 1 mm.
TIME IN SERVICE	1 ½ year (6000 operating hours).
ENVIRONMENT	Deaerated boiler feedwater consisting of demineralized water and condensate to which a mixture of di- and tri-sodium phosphate was added to alkalize the boiler water. pH 7.6–8.5; O_2 <0.01 p.p.m.; temperature 123°C.
CAUSE	The cast iron is attacked as a result of the low pH of the feedwater, the iron being dissolved and the carbon remaining (see also Case Histories 01.06.16.01 and 01.06.16.02).
REMEDY	• Increase the pH of the boiler feedwater by dosing ammonia to the pH value of 9–9.5 required by the pump manufacturer; or • Use bronze impellers.

CORROSION ATLAS

CASE HISTORY
01.01.18.01

MATERIAL	Carbon steel (DIN 17155).
SYSTEM	Boiler feedwater system.
PART	Deaerator (design pressure 0.25 MPa, design temperature 134°C).
PHENOMENON	Stress-corrosion cracking (environmentally induced cracking).

APPEARANCE	Cracking in an alongside weld seams (shown by magnetic particle fluorescent examination).
TIME IN SERVICE	15 years.
ENVIRONMENT	Feedwater (demineralized makeup and condensate); temperature 105°C; pressure 0.15 MPa.
CAUSE	The corrosion mechanism has not yet been definitely established. Presumably, it is a combination of residual stresses present at the welds and oxygen attack; in addition, fatigue due to vibrations may play a part.
REMEDY	• Grind away cracks, build up material if necessary, then anneal deaerator at 550°C, repeat magnetic particle fluorescent examination after repair. • In serious cases, re-weld or replace deaerator. • New deaerator to be annealed with postweld heat treatment.

CORROSION ATLAS

CASE HISTORY

01.01.18.02

MATERIAL	Carbon steel (35.8).
SYSTEM	Steam system (low pressure).
PART	Steam pipe section.
PHENOMENON	Intergranular stress-corrosion cracking (caustic stress-corrosion cracking).

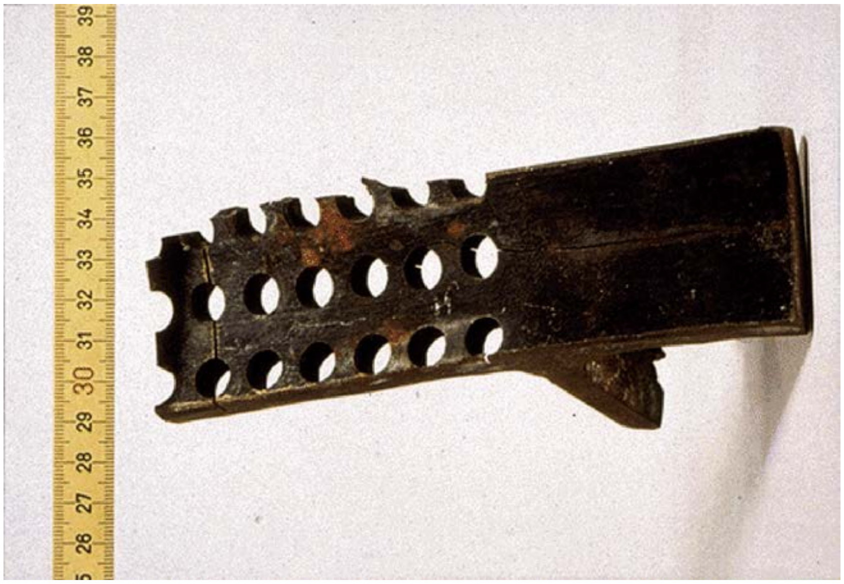
APPEARANCE	Crack at weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Low-pressure steam (0.35 MPa).
CAUSE	Because of a leak in the production process, 50% caustic soda entered the low-pressure steam system via the injection condensate for desuperheating. Under these circumstances, normally, harmless tensile stresses near welds led to caustic stress-corrosion cracking (see also Case Histories 01.01.18.05 and 01.11.18.01).
REMEDY	• Improve the quality control of the condensate by means of conductivity monitoring; or • Inject demineralized water.

CORROSION ATLAS

CASE HISTORY

01.01.18.03

MATERIAL	Carbon steel.
SYSTEM	Stripper steam system.
PART	Distributor pipe.
PHENOMENON	Intergranular stress-corrosion cracking (caustic stress-corrosion cracking).



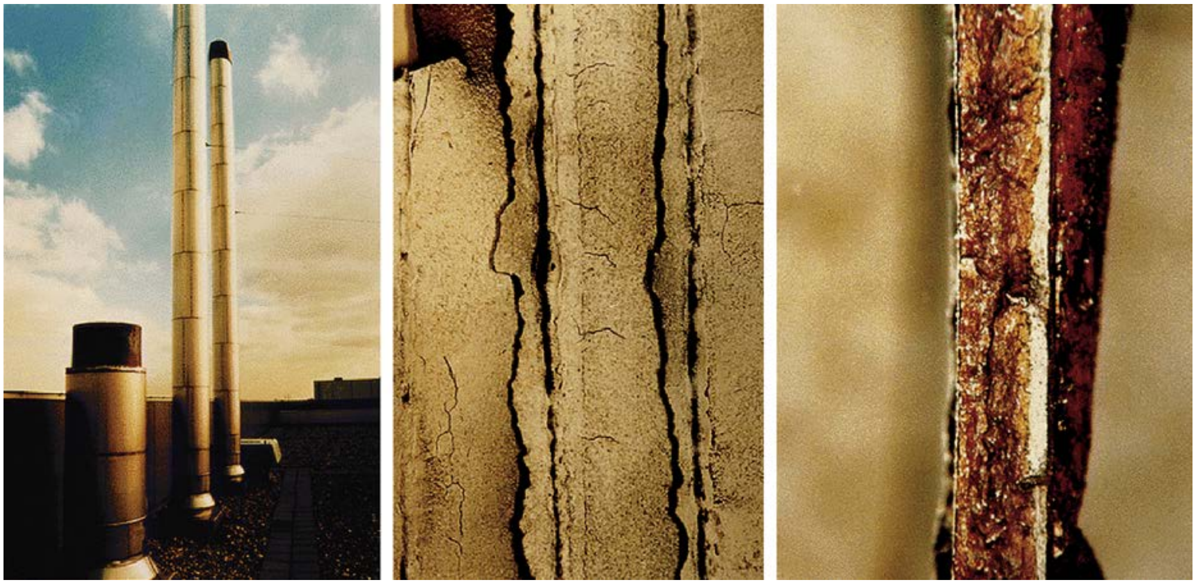
APPEARANCE	Cracks running from hole to hole.
TIME IN SERVICE	10 years.
ENVIRONMENT	Steam and aqueous environment with a high pH (11–12); temperature 140°C.
CAUSE	At the high temperature, the alkaline solution causes stress corrosion in carbon steel.
REMEDY	Normalize the steel.

CORROSION ATLAS

CASE HISTORY

01.01.18.04

MATERIAL	Carbon steel (Cor-Ten A).
SYSTEM	Gas-fired water-tube boiler.
PART	Chimney.
PHENOMENON	Nitrate stress-corrosion cracking (intergranular).



APPEARANCE	Multiple branched cracks near welds.
TIME IN SERVICE	2.5 years.
ENVIRONMENT	Exhaust gases containing nitrogen oxides.
CAUSE	Intermittent use of the boiler caused condensation of the exhaust gas in the chimney. The formed solution caused intergranular cracking of the weld area because of the presence of internal stresses (see also Case History 01.11.18.02).
REMEDY	Use Al-coated steel. That is fairly resistant to dilute concentrations of mineral acids to pH 4 (penetration ≤0.1 mm/year).

CORROSION ATLAS

CASE HISTORY

01.01.18.05

MATERIAL	Carbon steel (ASME SA-192, similar to AISI 1012).
SYSTEM	Water-tube boiler (pressure 5.5 MPa).
PART	Economizer tube bend (OD 5.1 cm).
PHENOMENON	Intergranular stress corrosion (caustic stress-corrosion cracking).

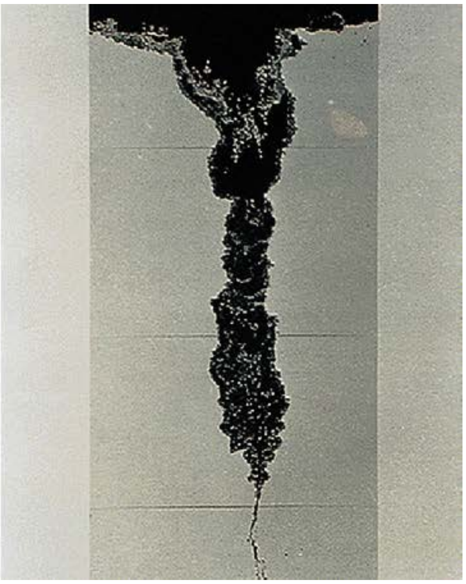
APPEARANCE	A pair of thick-walled cracks on opposite sides of the 90 degrees bend, located at opposite ends of the long axis of the oval cross-section of the bend.
TIME IN SERVICE	15 years.
ENVIRONMENT	Boiling water. Water treatment: phosphate.
CAUSE	The joint action of concentrated sodium hydroxide and tensile stresses: • The sodium hydroxide apparently concentrated beneath porous iron oxide deposits and led to shallow general metal loss and formation of crystalline magnetite. • The cracks originated at the bottom of shallow pits, which acted as stress concentrators, elevating the normal stress level. The longitudinal orientation of the cracks reveals that internal pressure provided the stresses necessary for stress-corrosion cracking.
REMEDY	• Keep internal surfaces sufficiently free of deposits. • Prevent pitting of internal surfaces through proper control of dissolved oxygen. • Avoid use of out-of-round tubes to prevent elevated stresses inherent in oval-shaped tubes.

CORROSION ATLAS

CASE HISTORY

01.01.18.06

MATERIAL	Carbon steel.
SYSTEM	Turbine.
PART	Wet steam pipe.
PHENOMENON	Stress-corrosion cracking.



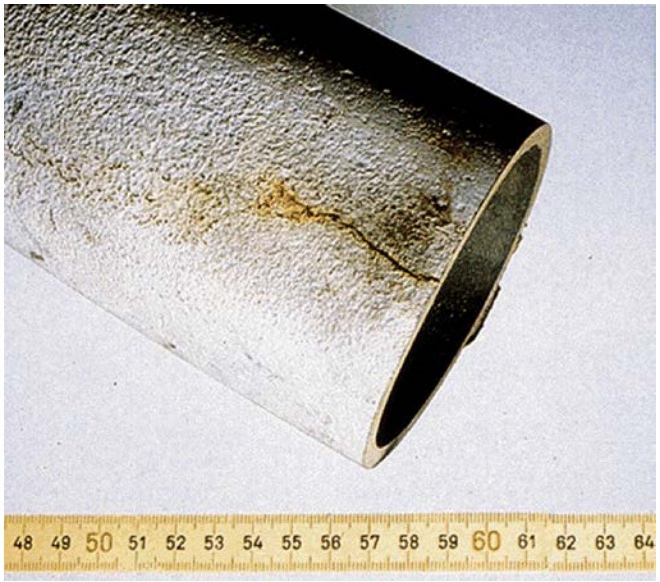
APPEARANCE	Pitting and stress-corrosion cracks. The cracks started at the pits transgranularly changing to intergranularly near the crack tips.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Wet steam.
CAUSE	Stagnant water was present in the bypass pipe. Pitting corrosion occurred, and cracks originated from the pits. The tube was cold-bent and not stress-relieved.
REMEDY	Replace with a tube, stress-relieved by annealing.

CORROSION ATLAS

CASE HISTORY

01.01.20.01

MATERIAL	Carbon steel.
SYSTEM	High-pressure boiler.
PART	Evaporator tube.
PHENOMENON	Hydrogen damage (intergranular hydrogen stress cracking).



APPEARANCE	Longitudinal cracks in cold-bent bend.
TIME IN SERVICE	Over 10 years.
ENVIRONMENT	Flue gas deposits with sulfuric acid compounds.
CAUSE	During the first stage of the neutralization process at the flue gas side (applied at shutdown), an acidic environment is created on the pipes as a result of the sulfur deposits present. Reaction between the resultant sulfuric acid and the steel forms hydrogen, thereby attacking the cold-bent steel and allowing fractures to occur (see also Case Histories 01.01.20.07, 01.11.20.06, and 01.11.20.07).
REMEDY	Use low-alloyed (hydrogen-resistant) steel.

CORROSION ATLAS

CASE HISTORY

01.01.20.02

MATERIAL	Carbon steel.
SYSTEM	Utility boiler (85 MW, 9 MPa).
PART	Water wall roof tube.
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack).

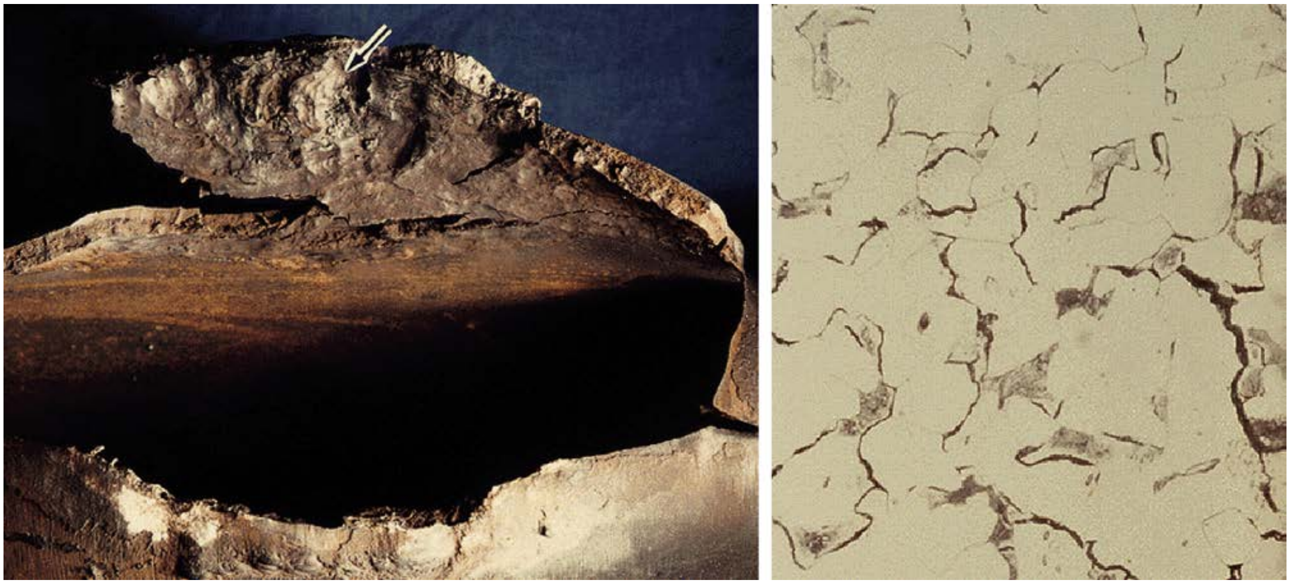
APPEARANCE	Brittle “window” rupture. Internal corrosion gouging.
TIME IN SERVICE	Not known.
ENVIRONMENT	Boiler water.
CAUSE	Internal underdeposit corrosion gouging on bottom side of nearly horizontal tube. Condenser leaks depressed boiler-water pH and led to acidic corrosion cells in areas of deposit. Hydrogen generation in gouge allowed diffusion of hydrogen into steel, reaction with iron carbide to form methane (CH_4), and intergranular cracking (see also the following cases).
REMEDY	Chemically clean boiler; avoid operating boiler with condenser leaks. Minimize boiler deposits.

CORROSION ATLAS

CASE HISTORY

01.01.20.03

MATERIAL	Carbon steel.
SYSTEM	Utility boiler (13.8 MPa).
PART	Water wall tube above the burners.
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack).



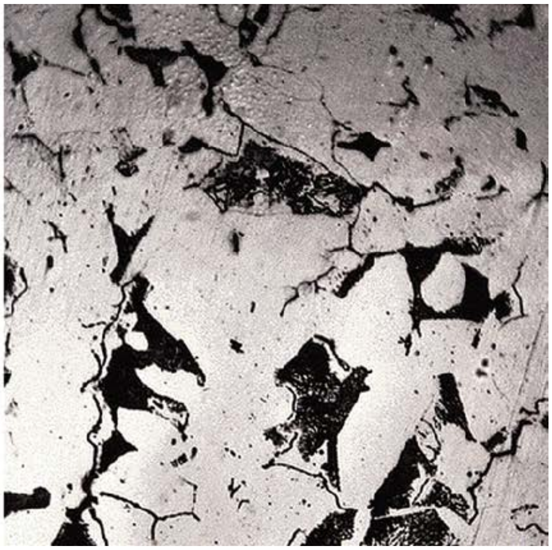
APPEARANCE	Brittle rupture. Internal corrosion gouging in areas of thick deposit.
TIME IN SERVICE	In service for 32 years.
ENVIRONMENT	Boiler water, coordinated phosphate program.
CAUSE	Localized build-up of internal deposit and underdeposit corrosion. Hydrogen generated at the base of corrosion gouge diffused into steel and reacted with iron carbide (Fe_3C) to form methane gas (CH_4). Intergranular cracking led to brittle fracture of tube.
REMEDY	Chemically clean boiler. Ultrasonic testing to identify and replace other damaged areas.

CORROSION ATLAS

CASE HISTORY

01.01.20.04

MATERIAL	Carbon steel (ASME SA-210, similar to AISI 1020).
SYSTEM	Water-tube boiler (pressure: 14.5 MPa).
PART	Vertical water wall tube (OD 6.3 cm).
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack [decarburization]).



APPEARANCE	A thick-walled burst with blunt fracture edge. Shallow gouging along the internal surface, free of deposits. Microstructure: intergranular microcracks with dark islands of pearlite.
TIME IN SERVICE	17 years.
ENVIRONMENT	Boiler water. Water treatment: congruent control.
CAUSE	Records indicated that condenser inleakage of low-level chloride salts had taken place. Coupled with departure from nucleate boiling (DNB), this caused low-pH gouging (see Case History 01.01.04.05). The formed atomic hydrogen diffuses into the steel causing decarburization. The steel cracks owing to pressure build-up of methane gas (see Case History 01.11.20.01). The microcracks shown on the microprint are typical of this form of hydrogen damage.
REMEDY	• Prevent condenser inleakage by continuously monitoring the quality of the condensate. • Prevent DNB by elimination of hot spots. • Prevent excessive waterside depositions by annual inspection and cleaning of the boiler if necessary.

CORROSION ATLAS

CASE HISTORY

01.01.20.05

MATERIAL	Carbon steel (ASME SA-210, similar to AISI 1020).
SYSTEM	Water-tube boiler (pressure 13.8 MPa).
PART	Nose slope water-wall tube (OD: 7.6 cm).
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack [decarburization]).

APPEARANCE	A thick-walled rapture. The smooth wavelike contours of the internally corroded surface are covered with black iron oxide. Intergranular microcracks were present below the corroded region.
TIME IN SERVICE	25 years.
ENVIRONMENT	Boiler water. Water treatment: co-ordinated phosphate.
CAUSE	Localized departure from nucleate boiling (DNB) in high heat flux areas resulted in concentration of sodium hydroxide, which caused deep caustic gouging. This phenomenon may also be regarded as heat-flux corrosion. The atomic hydrogen formed at the corrosion diffuses into the steel, causing decarburization. The hydrogen damage and resulting fracture were a direct consequence of the caustic gouging. The boiler is in peaking service.
REMEDY	Prevent DNB by elimination of hot spots.

CORROSION ATLAS

CASE HISTORY

01.01.20.06

MATERIAL	Carbon steel.
SYSTEM	Utility boiler (10.4 MPa).
PART	Water wall tube between upper and lower burners.
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack).

APPEARANCE	Brittle “window” rupture at butt weld. Internal corrosion gouging in areas of heavy deposit.
TIME IN SERVICE	Boiler had been in service 19 years.
ENVIRONMENT	Boiler water, co-ordinated phosphate program.
CAUSE	Accumulation of deposits at butt welds caused underdeposit corrosion gouging. Hydrogen generated by corrosion reaction diffused into steel and reacted with iron carbide to form methane (CH_4) at grain boundaries. Intergranular cracking resulted in brittle failure of tube at weld (see also Case Histories 01.01.20.03/04/05).
REMEDY	Replace tubes on affected wall of boiler. Minimize deposits inside boiler, shutdown boiler during pH upsets.

CORROSION ATLAS

CASE HISTORY

01.01.20.07

MATERIAL	Carbon steel (HSB 55 C; W.-Nr. 1.9877).
SYSTEM	Reactor with evaporating coils for producing steam (4 MPa, 250°C) and steam drum for separating the steam from the circulating boiler water.
PART	Wall piece with weld, thickness 27 mm.
PHENOMENON	Hydrogen damage (hydrogen-induced stress-corrosion cracking [HISCC]).

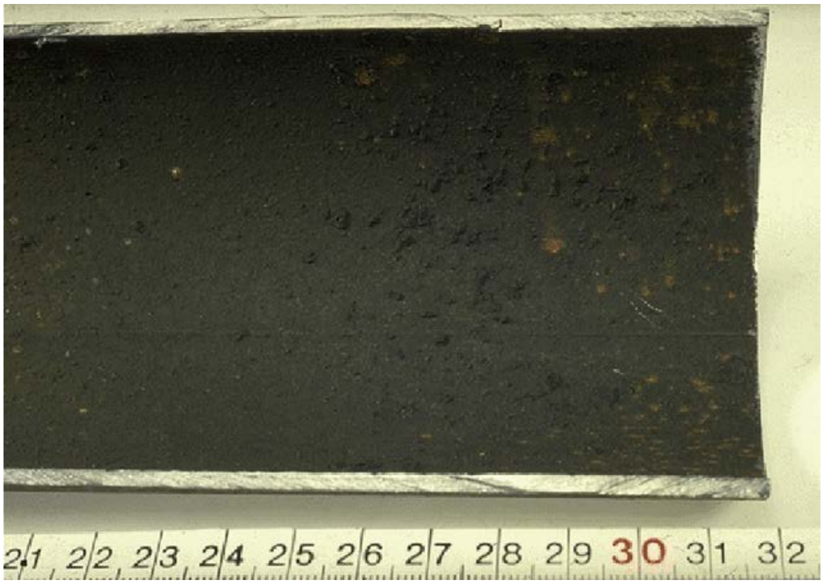
APPEARANCE	Intergranular fracture along the weld with transverse crack in the weld, brittle end fracture.
TIME IN SERVICE	15 years.
ENVIRONMENT	Boiler water and steam; water treatment: phosphate trisodium dosing for pH adjustment 9.0–9.5.
CAUSE	Acidic components in the boiler feedwater and too low level or absence of phosphate in the boiler water causes too low pH values (about 4). The formed atomic hydrogen diffuses into the steel to places with elevated stress conditioning. This results in HISCC caused by acid corrosion.
REMEDY	• Effective conditioning of the boiler water by means of trisodium phosphate dosing with careful monitoring. • Using lesser steel with adjusted processing techniques to reduce the hardness of the welds. • Annealing with postweld heat treatment to reduce the hardness and the stress level.

CORROSION ATLAS

CASE HISTORY

01.01.21.01

MATERIAL	Carbon steel.
SYSTEM	Boiler feedwater system.
PART	70 mm diameter boiler feedwater line with deaerator to boiler.
PHENOMENON	Chelant corrosion.



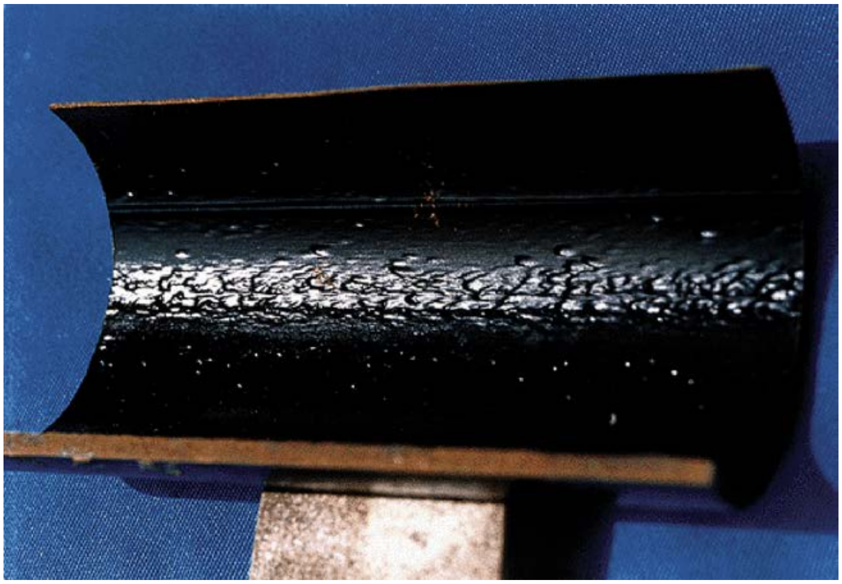
APPEARANCE	Uniform decrease of 60% of the original wall thickness of the line.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	A mixture of 50% decarbonated makeup water and 50% steam condensate, pH 8.0, temperature 105°C. In the feedwater line, a chelate product (40% EDTA) and catalyzed sulfite were dosed adjacently (guideline: 4 p.p.m. free Na-EDTA in the feedwater).
CAUSE	The feedwater regularly had an excessive oxygen content (2–3 p.p.m. O_2) in addition to an excessive content of EDTA (> 10 p.p.m.) as a result of poor operation of the deaerator and poor setting of the chemicals dosing. Chelate in oxygen-containing feedwater leads to corrosion by complex binding of the iron of the pipe wall (see also the following Case Histories).
REMEDY	• Improve the operation of the deaerator by also spraying the condensate and opening the deaerator line sufficiently. • Relocate the sulfite dosing point to the deaerator. • Replace the chelate product by a polymer chelate product in substoichiometric dosage. • Improve monitoring of the chemicals dosing.

CORROSION ATLAS

CASE HISTORY

01.01.21.02

MATERIAL	Carbon steel (ASME SA-178, similar to AISI 1012).
SYSTEM	Water-tube boiler (pressure 6.2 MPa).
PART	Wall tube (OD 6.3 cm).
PHENOMENON	Chelant corrosion.



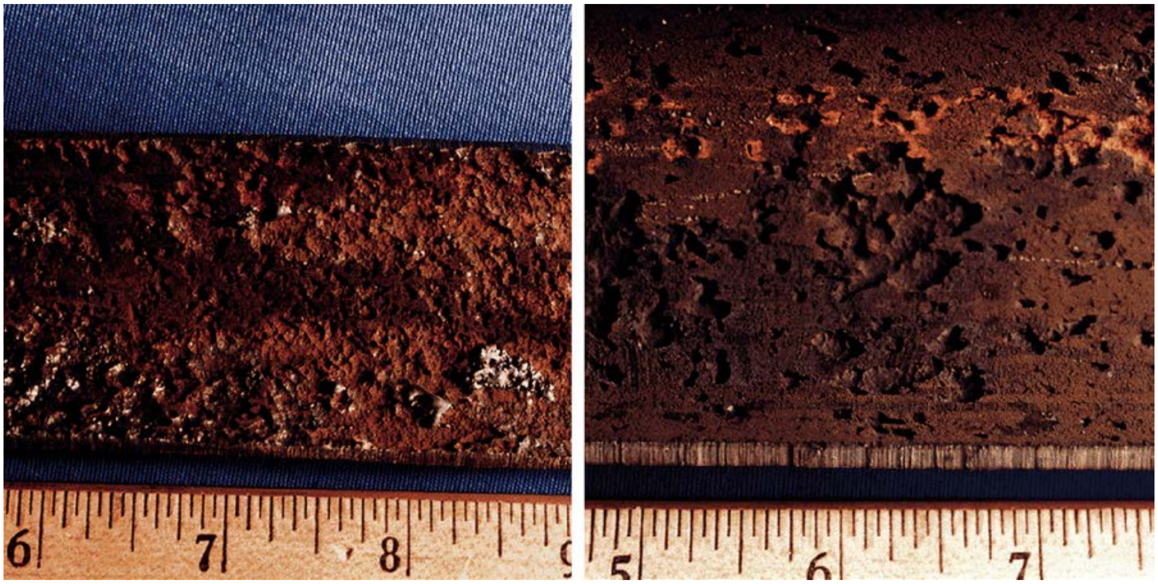
APPEARANCE	Comet-tail and horseshoe-shaped depressions.
TIME IN SERVICE	2 years.
ENVIRONMENT	Boiler water. Water treatment: scale control agents, oxygen scavengers, chelant.
CAUSE	High concentrations of chelants by overfeeding or by evaporation will attack magnetite according to the following reaction: $Fe_3O_4 + Fe + 8H^+ + 4\ \text{chelants} \rightarrow 4Fe\ (II)\ \text{chelant} + 4H_2O$. Excessive levels of dissolved oxygen synergize with excessive levels of chelant to produce jagged metal-surface contours.
REMEDY	• Close control of chelant and dissolved oxygen levels in the feedwater is imperative. • Take special care in case of inconsistent feedwater quality and when chelants are used in a dirty boiler. • Elimination of hot spots will prevent chelant corrosion. • Reducing fluid velocity and eliminating turbulent flow will also help to reduce chelant corrosion.

CORROSION ATLAS

CASE HISTORY

01.01.21.03

MATERIAL	Carbon steel (ASME SA-192, similar to AISI 1012).
SYSTEM	Water-tube boiler (pressure 3.3 MPa).
PART	Steam drum end of downcomer tubes (OD: 6.3 cm).
PHENOMENON	Chelant corrosion



APPEARANCE	Smooth, rolling, wavelike surface contours and islands of intact metal in affected areas. The entire internal surface was lightly covered with deposits and iron oxides.
TIME IN SERVICE	35 years; the corrosion occurred within a period of 7 months.
ENVIRONMENT	Boiler water. Water treatment: chelant.
CAUSE	Oxygen pitting was present along the waterline throughout the steam drum and on the steam-separation canisters. This is evidence that excessive levels of dissolved oxygen were present in the feedwater. The excessive oxygen levels, coupled with the presence of chelant, resulted in the corrosion observed. It is surmised that feedwater was short-circuiting through the affected area (see also the preceding Case Histories).
REMEDY	• This type of failure can be prevented by gaining control of dissolved oxygen. • Preventing short-circuiting of the feedwater is also a solution to this type of corrosion.

CORROSION ATLAS

CASE HISTORY

01.01.22.01

MATERIAL	Carbon steel (St 35.8).
SYSTEM	Water-tube boiler.
PART	Riser tube.
PHENOMENON	Liquid metal embrittlement.

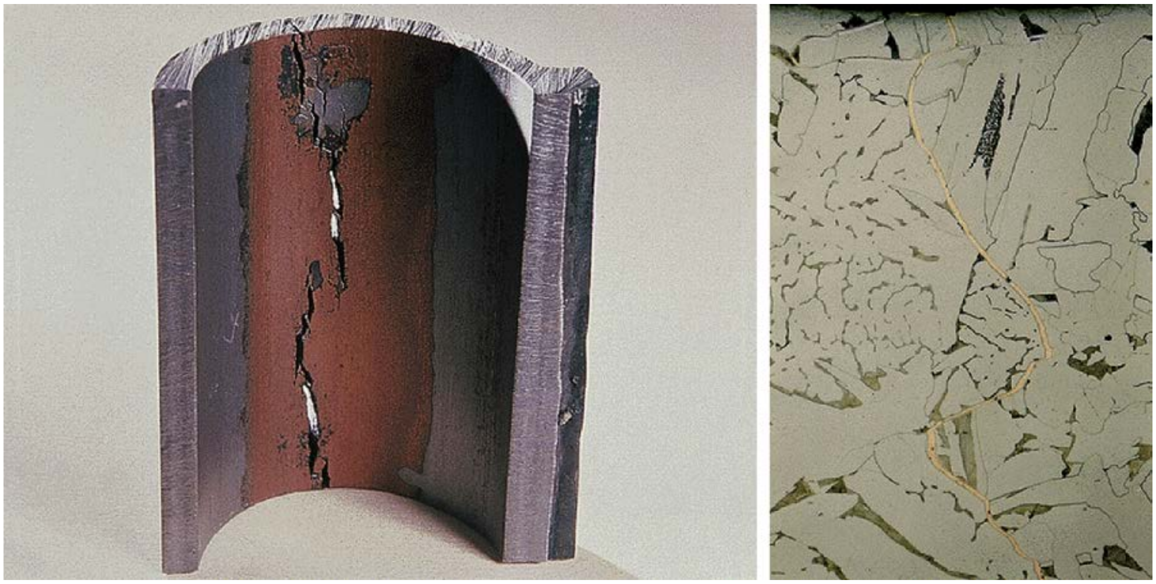
APPEARANCE	Intergranular cracking in HAZ and weld (root section) after overhaul. The cracks are covered with metallic copper.
TIME IN SERVICE	The boiler had been in service for several decades. The cracks appeared during pressure-testing after overhaul.
ENVIRONMENT	Boiler water.
CAUSE	At some locations inside the risers, a scale has formed that partly consists of metallic copper. During overhaul of the boiler, new convection pipes were welded to the risers. The welding heat caused the metallic copper to melt and penetrate via the austenite grain boundaries into the weld and HAZ (see also Case History 01.04.22.01).
REMEDY	The boiler should be chemically cleaned before overhaul to remove scale and metallic copper.

CORROSION ATLAS

CASE HISTORY

01.01.22.02

MATERIAL	Carbon steel.
SYSTEM	Utility boiler (14 MPa).
PART	Water wall tube, third burner level.
PHENOMENON	Liquid metal embrittlement.



APPEARANCE	Longitudinal through-wall cracks initiating on internal surface in region of metallic copper plating on hot side of tube. There was only minor wall thinning at the fracture lip, and some necking was apparent.
TIME IN SERVICE	Boiler had been in service for 20 years. Cracking occurred in less than 20 min during the overheating event.
ENVIRONMENT	Boiler water, coordinated phosphate program.
CAUSE	Prior chemical cleanings of boiler were done without specific copper removal step. Copper plating occurred on internal surface during cleaning operation. During normal operation, the boiler experienced a low drum level for 11 min prior to tube failures. Loss of normal circulation caused metal temperatures to significantly exceed 870°C. An adjacent wall tube exhibited a "thin-lipped burst" due to rapid overheating. With extremely high metal temperatures, molten copper penetrated along austenite grain boundaries, causing intergranular cracking and failure of this tube.
REMEDY	Boiler was chemically cleaned using a copper removal step to minimize metallic copper plating in the tubing.

CORROSION ATLAS

CASE HISTORY

01.01.25.01

MATERIAL	Carbon steel (37.2).
SYSTEM	Boiler feedwater system.
PART	Section from the bottom of the outdoor boiler feedwater tank.
PHENOMENON	Corrosion under insulation.

APPEARANCE	Severe pitting corrosion over a large area at the underside of the tank.
TIME IN SERVICE	23 years.
ENVIRONMENT	Internal: deaerated boiler feedwater. External: wet insulation.
CAUSE	Insulation was not watertight. Accumulation of oxygen-containing rainwater underneath the tank bottom insulation caused oxygen corrosion (see also Case History 01.02.25.01).
REMEDY	The attacked section was replaced, and the tank received an external coating. The insulation was made impervious to water ingress, and drain holes were provided at the underside.

CORROSION ATLAS

CASE HISTORY

01.01.28.01

MATERIAL	Low-alloyed steel (ASME SA-213 T22 = carbon steel + 2.25Cr + 1Mo).
SYSTEM	Power station water-tube boiler (pressure: 8.6 MPa).
PART	Vertical superheater tube near outlet header (OD: 4.4 cm).
PHENOMENON	Corrosion fatigue.

APPEARANCE	A thick-walled circumferential fracture with secondary unbranched transgranular cracks adjacent to the brittle fracture.
TIME IN SERVICE	5 years.
ENVIRONMENT	Superheated steam; temperature: 485°C.
CAUSE	The circumferential orientation of the cracks reveals that the stresses responsible were cyclic bending stresses, possibly caused by thermal expansion and contraction of the tube (see also Case Histories 01.21.28.01 and 04.11.28.02/03).
REMEDY	• Elimination or reduction of corrosion-fatigue cracking is realized by controlling cyclic tensile stresses, controlling environmental factors, and boiler redesign. • Reducing or eliminating cyclic operation of the boiler as well as extending startup and shutdown times may help eliminate or reduce corrosion-fatigue cracking.

CORROSION ATLAS

CASE HISTORY

01.01.30.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Vertical water-tube boiler (7.1 MPa).
PART	Water tube.
PHENOMENON	Creep rupture caused by overheating.

APPEARANCE	Fractured water tube.
TIME IN SERVICE	2 years.
ENVIRONMENT	Boiler water formed from steam condensate (98%) and demineralized water (2%), no chemical dosing.
CAUSE	Oxygen corrosion of the fire tube passing through this water tube (pipe-in-pipe system) caused water loss; the capacity of the makeup pump installed was insufficient; the low-water level safety device had been "bypassed" because it did not function owing to the low conductivity of the boiler water (constant alarm). As the water level fell, the burner was therefore not shut down; overheating caused a water tube to fracture after bulging and the boiler exploded.
REMEDY	• Dose hydrazine to prevent corrosion. • Dose trisodium phosphate in order to maintain sufficient alkalinity and conductivity, and • Regular checks of the low-water level safety device and the boiler water composition.

CORROSION ATLAS

CASE HISTORY

01.01.30.02

MATERIAL	Carbon steel (35.8).
SYSTEM	Water-tube boiler (9.1 MPa).
PART	Furnace tube.
PHENOMENON	Creep caused by overheating.

APPEARANCE	Local bulging of tube.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Conditioned boiler water.
CAUSE	Poor water circulation owing to blockage in headers caused by deposition of impurities (zinc and iron oxide) from the condensate.
REMEDY	Chemical cleaning of the boiler and improvement of condensate quality.

CORROSION ATLAS

CASE HISTORY

01.01.30.03

MATERIAL	Carbon steel (35.8).
SYSTEM	Gas-fired shell-type fire-tube boiler (0.7–0.8 MPa).
PART	Fire tube extremity of second pass.
PHENOMENON	Cracking caused by overheating.

APPEARANCE	Incipient cracks at protruding tube extremities.
TIME IN SERVICE	10 years.
ENVIRONMENT	Flue gases; 191°C.
CAUSE	Pipe extremities (second pass entry) extending from the tube plate into the combustion chamber were insufficiently cooled, allowing overheating to occur so that the tubes fracture and begin to leak.
REMEDY	Removal of protruding parts and securing of the tubes in the tube plate by means of a U-weld.

CORROSION ATLAS

CASE HISTORY

01.01.32.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Fluidized bed-fired water-tube boiler (5.1 MPa).
PART	Furnace wall tube.
PHENOMENON	Erosion.

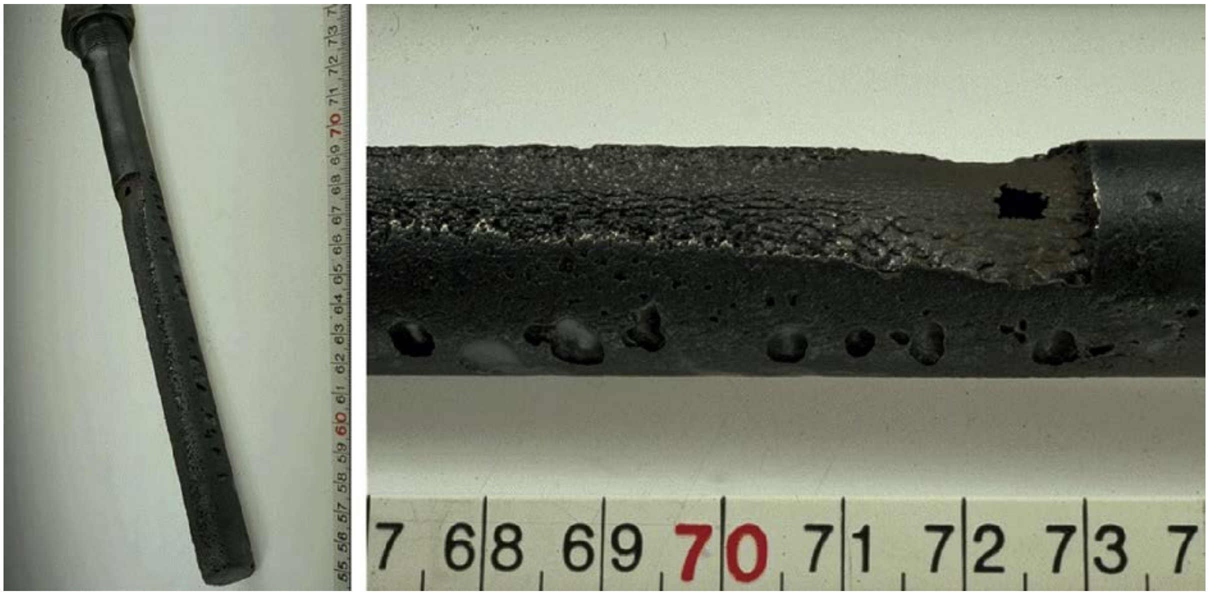
APPEARANCE	Evenly worn surface (upper left-hand area).
TIME IN SERVICE	6000 h.
ENVIRONMENT	Fluidized bed of sand, on which sludge, tree bark, and domestic refuse pellets are combusted at 850°C.
CAUSE	Erosion by sand turbulence.
REMEDY	The furnace refractory brickwork was raised by 80 cm.

CORROSION ATLAS

CASE HISTORY

01.01.32.02

MATERIAL	Low-alloyed steel (13 CrMo 44).
SYSTEM	Steam system.
PART	Thermometer bulb from turbine steam supply line.
PHENOMENON	Erosion (water-droplet impingement).



APPEARANCE	Material is uniformly eroded to the point of leakage perpendicular to the direction of flow, while the material is locally eroded at the sides.
TIME IN SERVICE	15 years.
ENVIRONMENT	Superheated steam. Temperature: 495°C; pressure: 10 MPa; velocity: 37 m/s.
CAUSE	The thermometer was positioned immediately downstream from the injection cooler. Water droplets still present in the steam caused the erosion (see also Case History 01.01.32.04).
REMEDY	Thermometer bulb replaced and relocated, further away from the injection cooler.

CORROSION ATLAS

CASE HISTORY

01.01.32.03

MATERIAL	Low-alloyed steel.
SYSTEM	Steam system.
PART	Flange from steam line to turbine.
PHENOMENON	Erosion (steam cutting).

APPEARANCE	Locally worn.
TIME IN SERVICE	2–3 days.
ENVIRONMENT	Steam at 8 MPa superheated to 350°C.
CAUSE	Leakage along seal surface, resulting in the superheated steam cutting into the flange. The result of poor workmanship.
REMEDY	Assure proper discipline (protocol) when packaging the flanges.

CORROSION ATLAS

CASE HISTORY

01.01.32.04

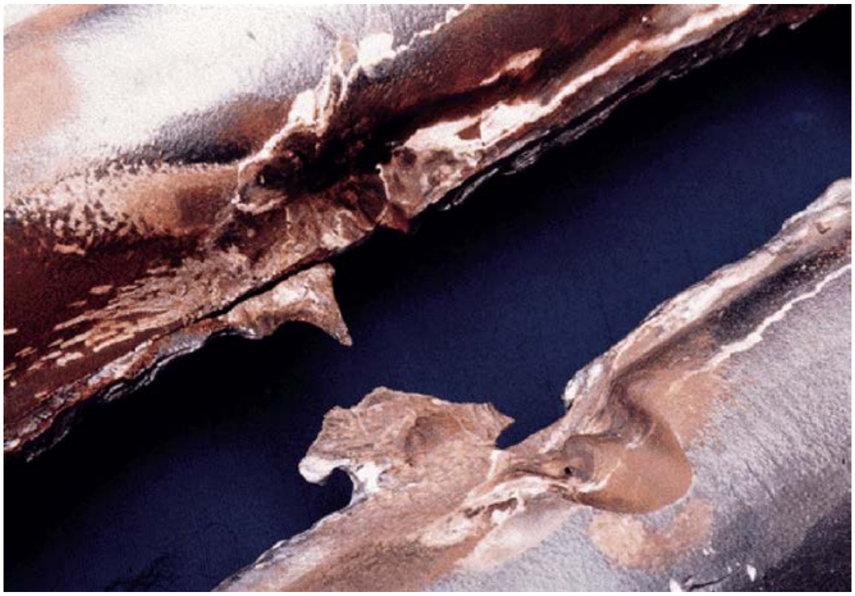
MATERIAL	Carbon steel.
SYSTEM PART	Steam system. Spectacle flange in 2 MPa steam line.
PHENOMENON	Erosion (water-droplet impingement).
	
APPEARANCE	Star-shaped erosion picture.
TIME IN SERVICE	Unknown, many years.
ENVIRONMENT	Saturated steam with condensate droplets; 2 MPa.
CAUSE	Impingement by water droplets against closed spectacle flange (see also Case History 01.01.32.02).
REMEDY	Assure proper dewatering of the steam and perform regular inspections on the blind flange.

CORROSION ATLAS

CASE HISTORY

01.01.32.05

MATERIAL	Carbon steel (SA 201 A1).
SYSTEM	Water-tube boiler (pressure: 17.2 MPa).
PART	Vertical front convection wall tube (OD: 7.0 cm).
PHENOMENON	Erosion (steam cutting).



APPEARANCE	Severe perforation (cutting) of tube.
TIME IN SERVICE	8 years.
ENVIRONMENT	Normal: flue gases.
CAUSE	The original failure occurred at a welded support bracket of another tube and was due to corrosion fatigue. Small corrosion-fatigue cracks were found at poorly fused support welds (poor workmanship!). The adjacent tube was breached by steam escaping from the original failure (see also Case History 01.01.32.03).
REMEDY	• Assure quality of support weld fusing. • Reduce temperature gradients during startup and shutdown.

CORROSION ATLAS

CASE HISTORY

01.01.32.06

MATERIAL	Carbon steel.
SYSTEM	Boiler (2.6 MPa).
PART	Superheater pipe.
PHENOMENON	Erosion.

APPEARANCE	Local external wear to the superheater pipe (see upper part).
TIME IN SERVICE	20,000 operating hours.
ENVIRONMENT	Sand-contaminated flue gases.
CAUSE	The boiler was fired with rice-chaff which was contaminated with sand. The sand particles caused external erosion of the superheater pipes (see also Case History 01.01.32.07).
REMEDY	• Position wearing plates before the superheater; or • Apply metal spray coating to the superheater pipes; or • Remove the sand particles from the rice-chaff before firing.

CORROSION ATLAS

CASE HISTORY

01.01.32.07

MATERIAL	Carbon steel.
SYSTEM	Shell-type fire-tube boiler (2.6 MPa).
PART	Steel insert fire-tube, entrance to third pass.
PHENOMENON	Erosion.

APPEARANCE	Insert smoothly worn down from inside to the point of leakage.
TIME IN SERVICE	2 months.
ENVIRONMENT	Sand-contaminated flue gases.
CAUSE	The boiler was fired with rice-chaff contaminated with sand. The sand particles caused severe erosion in the entrance to the smoke tubes (see also Case History 01.01.32.06).
REMEDY	The steel inserts were replaced with ceramic inserts.

CORROSION ATLAS

CASE HISTORY

01.01.33.01

MATERIAL	Impeller: nickel- and chromium-alloy cast iron. Diffuser ring (guide vane): cast iron.
SYSTEM	Boiler feedwater system.
PART	First impeller and diffuser ring of boiler feedwater pump (65 m^3/h, 5.1 MPa back pressure).
PHENOMENON	Cavitation erosion.

APPEARANCE	Material worn away locally.
TIME IN SERVICE	5 years.
ENVIRONMENT	Deaerated demineralized feedwater; temperature 105°C.
CAUSE	As a result of underloading (less than 25% of full load) by throttling on the suction side of the pump, the available suction head was insufficient to prevent the formation of steam and thereby cavitation at the inlet side. Pump cavitation is often caused by too high pressure differential between suction and discharge sides.
REMEDY	• Prevent underloading by operating with a single feed pump, rather than several pumps, for as long as possible; or • Set capacity at a minimum of 30% of full load by installing an overflow valve in a bypass line from the delivery side to the suction side of the pump.

CORROSION ATLAS

CASE HISTORY

01.01.33.02

MATERIAL	Carbon steel.
SYSTEM	Boiler feedwater system.
PART	Section of steam dome of two-stage deaerator.
PHENOMENON	Cavitation erosion.

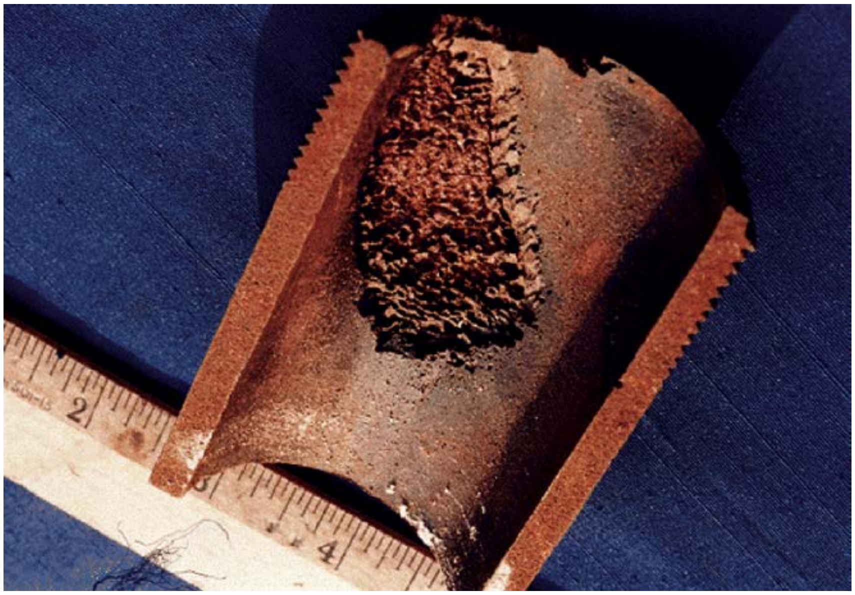
APPEARANCE	Material with sharp edges worn away to the point of leakage.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Reduced steam at 0.15 MPa.
CAUSE	The steam dome was damaged by cavitation as a result of the steam entering below the surface near the dome.
REMEDY	Modify the construction to prevent further cavitation.

CORROSION ATLAS

CASE HISTORY

01.01.33.03

MATERIAL	Mild steel.
SYSTEM	Water-tube boiler (pressure: 8.3 MPa).
PART	Horizontal blowdown line threaded into a tee (OD: 6.4 cm).
PHENOMENON	Cavitation damage.



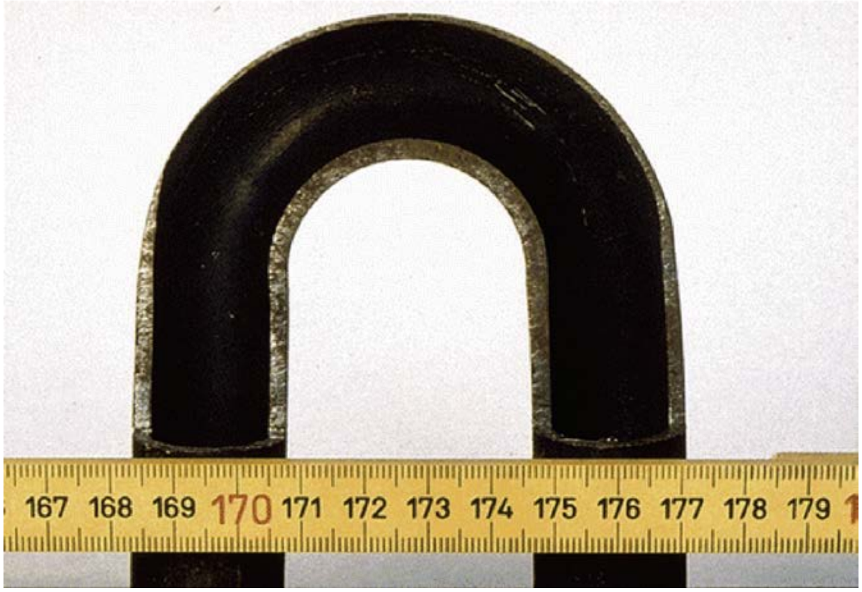
APPEARANCE	Severe localized wastage on internal surface, with perforation near the attachment of the pipe to tee.
TIME IN SERVICE	6 years (only during intermittent manual blowdown).
ENVIRONMENT	Boiler water. Water treatment: coordinated phosphate, oxygen scavenger.
CAUSE	The flow direction is severely changed in the pipe tee, causing strong turbulation and pressure changes leading to vapor bubble formation. The collapsing steam bubbles cause cavitation damage. In this case, the manual blowdown had been increased due to feedwater contamination from the preboiler system.
REMEDY	• Construct the blowdown line of a wider straight pipe and minimize manual blowdown by continuous blowdown. • Prevent contamination of the feedwater.

CORROSION ATLAS

CASE HISTORY

01.01.34.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Boiler.
PART	Economizer tube.
PHENOMENON	Erosion corrosion.



APPEARANCE	Material locally worn in the bend pieces.
TIME IN SERVICE	About 2 years.
ENVIRONMENT	Demineralized and deaerated boiler feedwater; steam velocity 1.74 m/s.
CAUSE	Steam formation in the economizer due to irregular distribution of the flue gases and flue gas temperature. Heat absorption by the economizer was found in practice to exceed the design data (see also Case History 01.01.34.06).
REMEDY	• Shortening of the economizer; or • Homogenization of the flue gas speed and temperature; or • Homogenization of the water temperature by placing a water box in the economizer; or • Construction of the economizer in a more erosion-resistant steel (more than 0.1% Cr, Cu, and Mo).

CORROSION ATLAS

CASE HISTORY

01.01.34.02

MATERIAL	Carbon steel (35.8).
SYSTEM	Steam system.
PART	Bend in steam pipe.
PHENOMENON	Erosion corrosion.

APPEARANCE	Here and there the line exhibits a clear flow pattern.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Steam 1.2 MPa, occasionally contaminated with boiler water owing to priming of the boiler caused by the high organic matter content (COD 1400 p.p.m.) in the boiler water by feeding with milk-contaminated flash steam condensate (steam velocity: 50 m/s).
CAUSE	Turbulence in the bend in addition to the presence of water droplets caused by priming of the boiler, leading to local damage of the magnetite layer.
REMEDY	• Enlargement of the bends in the steam pipe such that the steam velocity is limited to a maximum of 30 m/s. • Milk-contaminated flash steam condensate should not be used for boiler feed (improved quality control). • Boilers should be blown at a maximum COD of 250 p.p.m.

CORROSION ATLAS

CASE HISTORY

01.01.34.03

MATERIAL	Low-alloyed steel (SA-209 with 0.5% Mo).
SYSTEM	Coal-fired utility water-tube boiler (pressure 17.8 MPa).
PART	Superheater tube (OD: 5.1 cm).
PHENOMENON	Erosion corrosion (soot-blower attack).

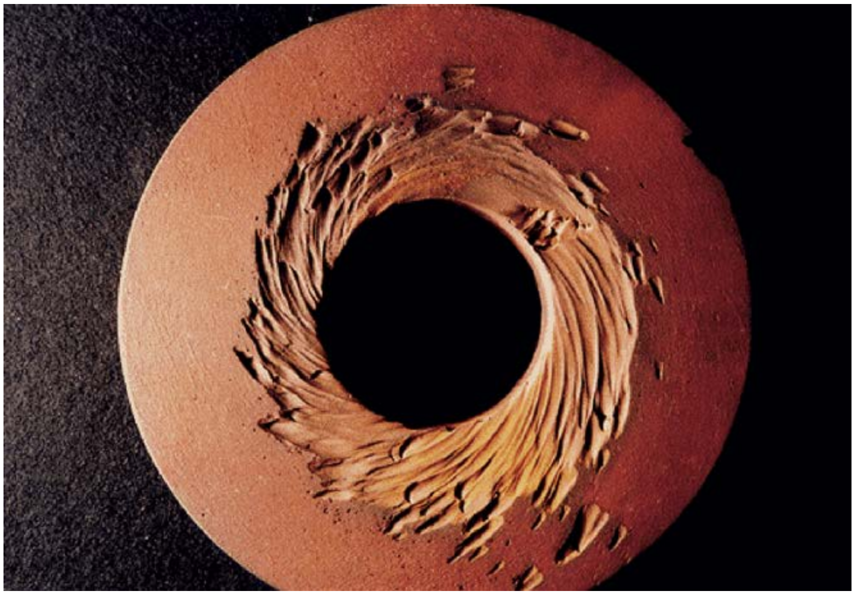
APPEARANCE	The outer surface is partly flattened. The tube bulged and ruptured on the thinned side (see also Case Histories 01.01.06.01 and 01.01.32.06).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Flue gases at the outer surface and periodically blower gas (steam or air).
CAUSE	Improperly aligned soot blowers caused near 90° impingement of condensed water droplets on the tube surface.
REMEDY	Repair and realignment of soot blower.

CORROSION ATLAS

CASE HISTORY

01.01.34.04

MATERIAL	Carbon steel (ASTM A 284).
SYSTEM	Boiler feedwater system.
PART	Feedwater pump spacer (diameter: 13.3 cm).
PHENOMENON	Erosion corrosion.



APPEARANCE	Smooth spiral grooves in an obvious flow pattern.
TIME IN SERVICE	4.5 months.
ENVIRONMENT	Feedwater: • Demineralized water with > 50 ppb dissolved oxygen; temperature 252°C.
CAUSE	Turbulent water flow in pump with relatively high concentration of dissolved oxygen in feedwater. The alloy was incorrect for this use.
REMEDY	• Changed to stainless steel American Iron and Steel Institute (AISI) 405. • Corrected deaerator function in order to reduce dissolved oxygen concentration.

CORROSION ATLAS

CASE HISTORY

01.01.34.05

MATERIAL	Carbon steel.
SYSTEM	Pressurized water reactor (PWR).
PART	Water separator.
PHENOMENON	Erosion corrosion.

APPEARANCE	One of two welded-together plates showed horseshoe-type erosion corrosion. Iron oxides were deposited on the uncorroded plate. Preferential attack of the weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Wet steam.
CAUSE	• High turbulence in the water separator. • Too low resistance of one of the steel plates because of the small amounts of Cu, Cr, and Mo in the steel. The Gkema value of the corroded plate was 87, the value of the uncorroded plate was 53.
REMEDY	• In this case, the steel plates were replaced without giving attention to the steel composition. • Specify the corrosion resistance of carbon steel (tube and welding material) for erosion–corrosion–sensitive components in the water steam system. A Gkema value of lower than 80 is recommended.

CORROSION ATLAS

CASE HISTORY

01.01.34.06

MATERIAL	Carbon steel.
SYSTEM	Water-tube boiler.
PART	Steaming economizer tube.
PHENOMENON	Erosion corrosion.

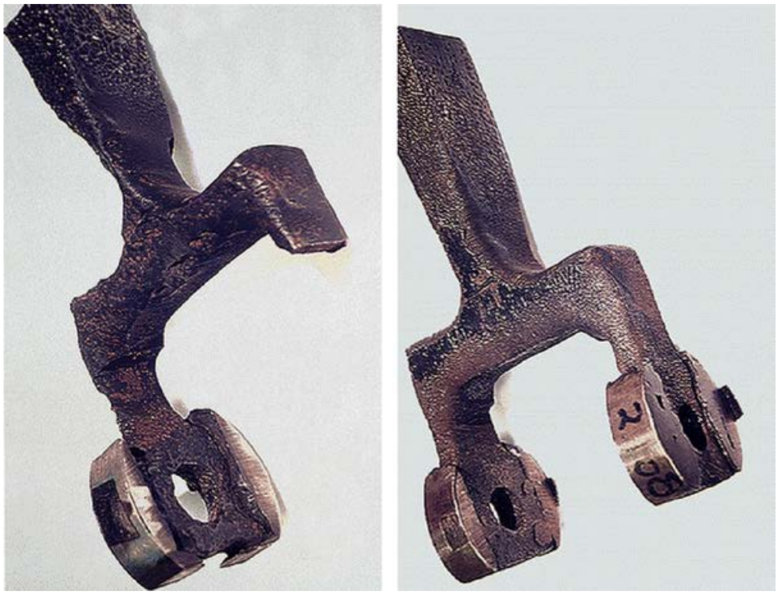
APPEARANCE	At the outer curve side: erosion corrosion (horseshoe-type attack); At the inner curve side: iron oxide deposit as coarse magnetite crystals.
TIME IN SERVICE	2 years.
ENVIRONMENT	Wet steam.
CAUSE	In the economizer, steam was formed, and two-phase flow occurred. The water ran at the outside of the bend; steam at the inside. The erosion–corrosion resistance of the steel was too low because of the small amounts of Cu, Cr, and Mo in the steel. Gkema value of the steel was 92 (see also Case History 01.01.34.01).
REMEDY	• In this case, the bends were replaced with a 1% Cr steel. • Specify the erosion–corrosion resistance of carbon steel (tube and welding material) for erosion–corrosion sensitive components in the water steam system. A Gkema value of lower than 80 is recommended.

CORROSION ATLAS

CASE HISTORY

01.01.34.07

MATERIAL	Carbon steel.
SYSTEM	Power station feedwater system.
PART	Switch levers of two water supply pumps in a power station.
PHENOMENON	Erosion corrosion.



APPEARANCE	Horseshoe-type attack on both levers. The lever with the lesser operating time was attacked more. The cladded stainless steel at the lever ends was uncorroded.
TIME IN SERVICE	Lever, left: 10,000 h (1 year). Lever, right: 40,000 h (4 years).
ENVIRONMENT	Demineralized makeup water.
CAUSE	High water turbulence and a carbon steel with too low resistance to erosion corrosion. The lever with an operating time of 10,000 h had a Gkema value equal to 95 because of the very small amounts of Cu, Cr, and Mo in the steel. The lever with the operating time of 40,000 h had a lower Gkema value of 85. This lever was corroded much less.
REMEDY	• In this case, the switch levers were replaced without special attention to the steel composition. • Specify the erosion corrosion resistance of carbon steel (tube and welding material) for erosion–corrosion–sensitive components in the water-steam system. A Gkema value of lower than 80 is recommended.

CORROSION ATLAS

CASE HISTORY

01.01.34.08

MATERIAL	Carbon steel (W.-Nr. 1.4922, X22CrMoV12.1).
SYSTEM	Steam turbine.
PART	Blade of the last row of the running blades.
PHENOMENON	Erosion corrosion (impingement).

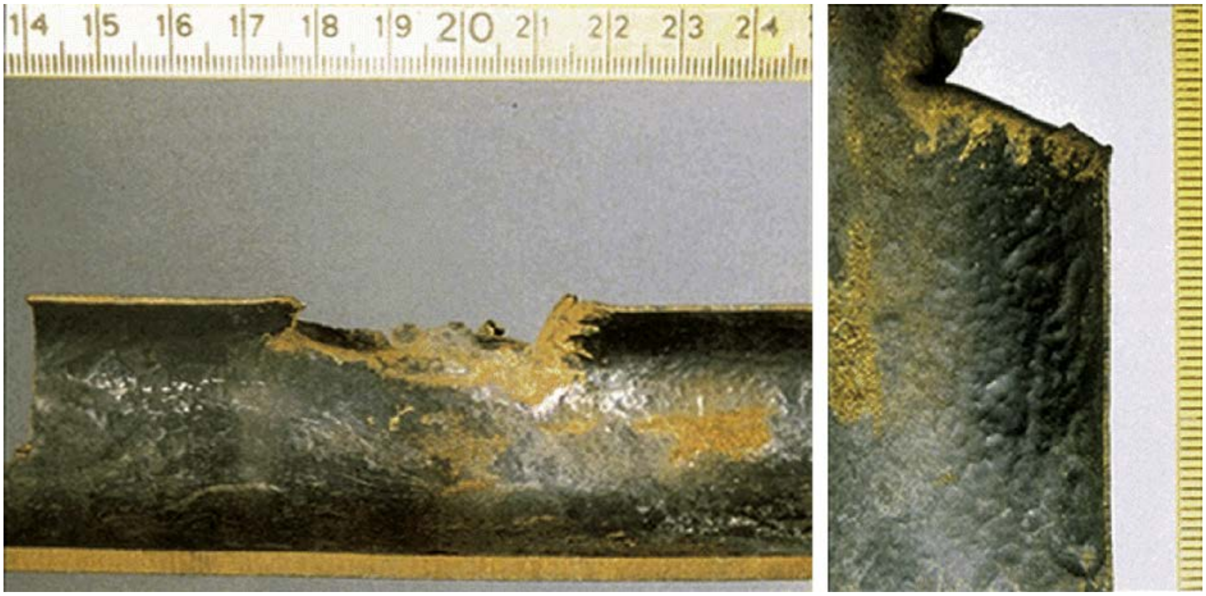
APPEARANCE	The material of the upper part exhibits sponge-type erosion (see also Case History 01.01.32.02).
TIME IN SERVICE	3 years.
ENVIRONMENT	Wet steam.
CAUSE	• The cooling water temperature control system was slow so that large temperature fluctuations occurred in the condenser steam conditions. • The blades were surface-hardened over a too small length.
REMEDY	The replaced blades were surface-hardened over the total length.

CORROSION ATLAS

CASE HISTORY

01.01.43.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Corner water-tube boiler (4.1 MPa).
PART	Inclined water tube from convection section.
PHENOMENON	Steam blanketing.



APPEARANCE	Internal irregular attack of the material in the upper part of the tube.
TIME IN SERVICE	6 years.
ENVIRONMENT	Steam at 4.1 MPa.
CAUSE	Excessive steam formation takes place owing to insufficient cooling of the water tubes. Steam bubbles cling to the upper part of the tubes. This causes a strong local decrease in cooling and locally increased magnetite growth takes place. If the bubbles are removed as the result of fluctuating load, the cooling will be temporarily restored, and the oxide formed flakes off. This phenomenon can lead to substantial reduction of wall thickness within a relatively short time.
REMEDY	Increase the through-flow of the water tubes by improvement of the boiler construction.

CORROSION ATLAS

CASE HISTORY

01.02.01.01

MATERIAL	Carbon steel (wall thickness 4 mm).
SYSTEM	Steam condensate system (1.5 MPa).
PART	Condensate pipe.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Sharp pitting without corrosion products.
TIME IN SERVICE	Leak after 8 months
ENVIRONMENT	Boiler water contaminated, oxygen-containing condensate; temperature 90–95°C.
CAUSE	The oxygen corrosion occurred because of malfunctioning of the deaerator (steam pressure regulator set too low) and was reinforced by the contamination of the condensate with boiler water (due to malfunctioning of the steam/moisture separator in the boiler).
REMEDY	Modification to the deaerator and modification to the steam/moisture separator.

CORROSION ATLAS

CASE HISTORY

01.02.01.02

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Float ball from heat exchanger steam trap.
PHENOMENON	Oxygen corrosion.

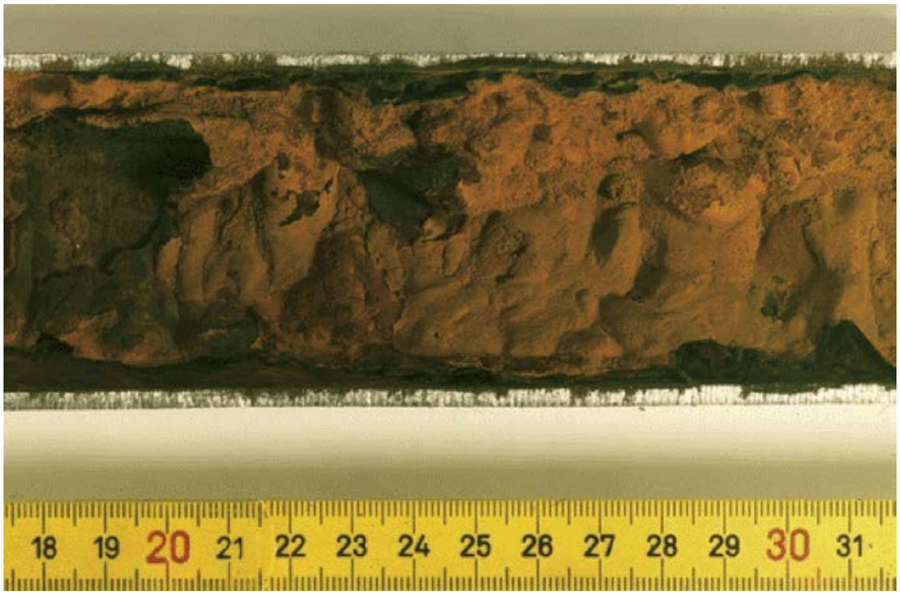
APPEARANCE	Pitting to the point of large holes.
TIME IN SERVICE	7 months.
ENVIRONMENT	Condensate contaminated by aerated dealkalized water due to leakage of the heat exchanger (see Case History 06.01.32.01); temperature approximately 100°C
CAUSE	The contamination with oxygen-containing water caused oxygen attack; because of alkalinity reduction of the makeup water and deaeration of the feedwater, the noncontaminated condensate was of good quality.
REMEDY	After repair of the leakage, for additional certainty, the trap was fitted with an AISI 316 stainless steel float ball.

CORROSION ATLAS

CASE HISTORY

01.02.01.03

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Condensate line.
PHENOMENON	Oxygen corrosion.



APPEARANCE	Pipe covered with corrosion products, under which the steel shows pitting attack.
TIME IN SERVICE	About 15 years.
ENVIRONMENT	Oxygen-containing steam condensate (temperature approximately 90°C).
CAUSE	Oxygen attack due to the absence of a deaerator; oxygen-binding chemicals were not dosed. The corrosion products remained in the pipe due to the low acidity of the condensate and the low flow rate.
REMEDY	In view of the small length of the condensate line, it is constructed of stainless steel. In the case of a large condensate system, it is preferable to apply deaeration of the feedwater or dosing of oxygen-binding chemicals.

CORROSION ATLAS

CASE HISTORY

01.02.02.01

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system (of 1.3 MPa steam supply).
PART	Horizontal condensate pipe.
PHENOMENON	Carbonic acid corrosion.

APPEARANCE	One-sided uniform corrosion at two levels, resulting from two different loads (day time and night time).
TIME IN SERVICE	1 year.
ENVIRONMENT	Corrosive condensate (boiler was fed with a mixture of softened makeup water with an alkalinity of 4 meq/L (200 p.p.m. $CaCO_3$) and 50% condensate; this mixture was deaerated).
CAUSE	Steel attacked by corrosive condensate; the condensate is corrosive because of the presence of carbon dioxide (CO_2), which is formed in the boiler and entrained with the steam.
REMEDY	Alkalinity reduction of the makeup water (in this case, by anion exchanger in chloride cycle). In view of the use of direct steam, it was not possible to dose chemicals into the steam; construction of the condensate system of stainless steel was out of the question for reasons of cost.

CORROSION ATLAS

CASE HISTORY

01.02.02.02

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Horizontal condensate pipe and deposits in a condensate pipe.
PHENOMENON	Carbonic acid corrosion.

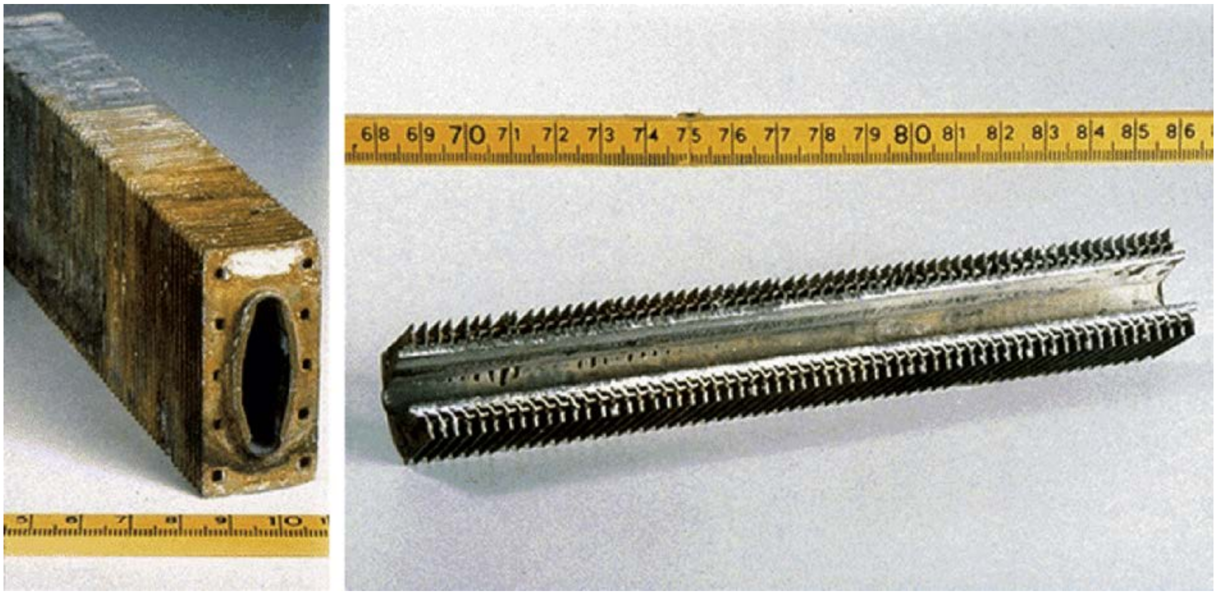
APPEARANCE	Uniform attack at the lower side. Remaining corrosion products in another line.
TIME IN SERVICE	12 years.
ENVIRONMENT	Corrosive condensate; temperature 90–100°C.
CAUSE	Attack by carbonic acid–containing condensate; corrosion products are not only fed to the boiler but can also cause local blockage of the condensate line.
REMEDY	Alkalinity reduction of the makeup water, thereby minimizing the carbonic acid content of the condensate.

CORROSION ATLAS

CASE HISTORY

01.02.02.03

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Vertical element from air heater (before and after sawing through).
PHENOMENON	Carbonic acid corrosion.



APPEARANCE	Uniformly grooved at one side.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Corrosive condensate due to the presence of a large quantity of carbonic acid originating from the decomposition of bicarbonate in the boiler; temperature 100°C.
CAUSE	Steel corroded by carbonic acid–containing condensate, grooved attack of the side exposed to the fan (where most condensation occurs).
REMEDY	• Alkalinity reduction of the makeup water; in view of the nature of the plant, it was not possible to dose chemicals into the steam. • Alternative option: construction of the air heater from AISI 304 stainless steel.

CORROSION ATLAS

CASE HISTORY

01.02.14.01

MATERIAL	Carbon steel (header), copper (tubes).
SYSTEM	Steam condensate system (0.4 MPa).
PART	Header from air heater.
PHENOMENON	Galvanic corrosion.

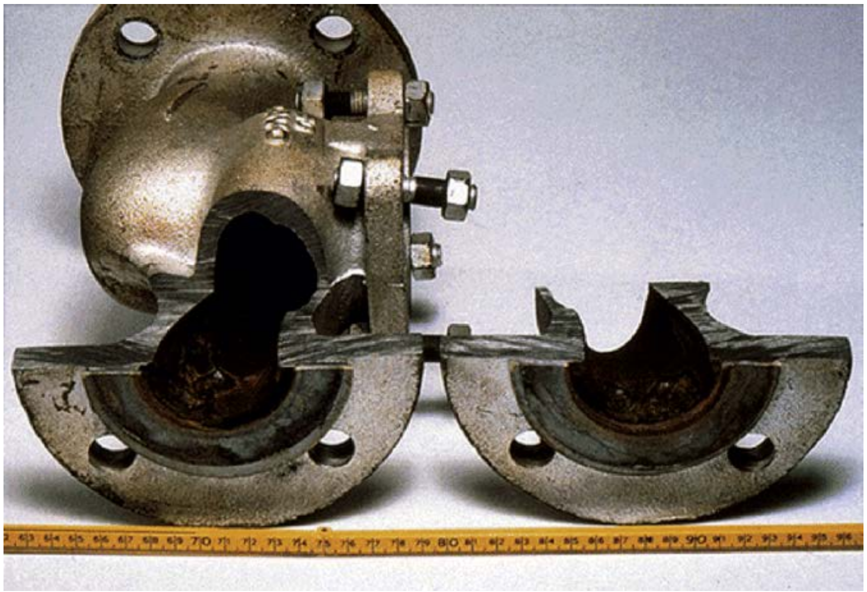
APPEARANCE	Grooved attack of the header where the tubes are attached and deformation of the tubes.
TIME IN SERVICE	1–2 years.
ENVIRONMENT	Corrosive, oxygen-containing condensate, occasionally contaminated with boiler water; temperature approximately 100°C.
CAUSE	Attack of the steel header due to galvanic corrosion by the copper/steel combination in conductive oxygen-containing condensate. Deformation of the protruding ends of the copper pipes caused by water hammer.
REMEDY	• Construction of the header from copper. • Improvement of the condensate quality by improved alkalinity reduction and deaeration and by preventing boiler foaming. • Improved dewatering of the air heaters. • Shortening the copper tubes in the header.

CORROSION ATLAS

CASE HISTORY

01.02.14.02

MATERIAL	Cast iron.
SYSTEM	Steam condensate system.
PART	Valve from condensate pipe.
PHENOMENON	Galvanic corrosion.



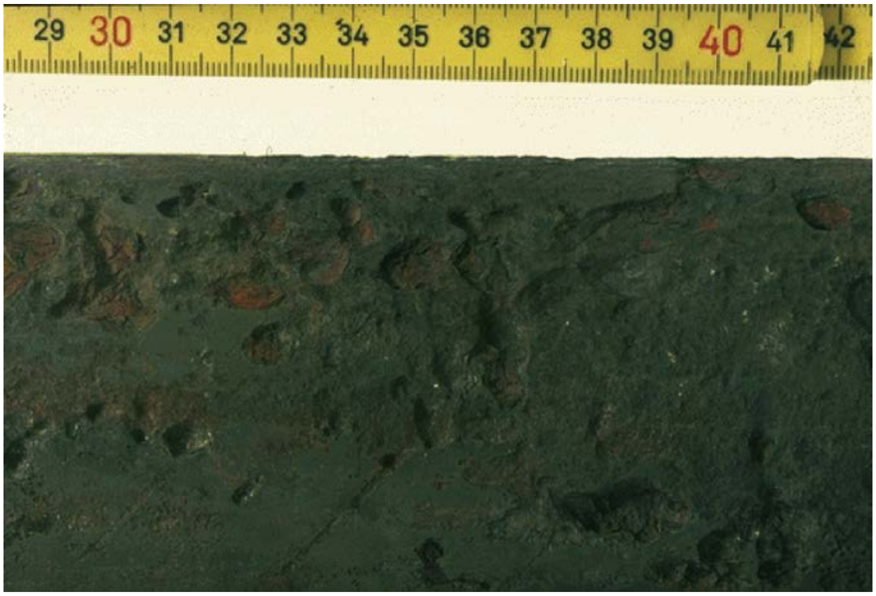
APPEARANCE	Locally severe attack at flange connection.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Moderate corrosive condensate; pH 6.6; temperature approximately 100°C.
CAUSE	The cast iron valve was incorporated in an AISI 304 stainless steel condensate pipe of a copper heat exchanger. The potential difference between copper/stainless steel and the cast iron caused galvanic corrosion to the valve.
REMEDY	• Construction of the valve from stainless steel as well; or • Use of Teflon isolating flanges.

CORROSION ATLAS

CASE HISTORY

01.02.25.01

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Pipe.
PHENOMENON	Corrosion under insulation.



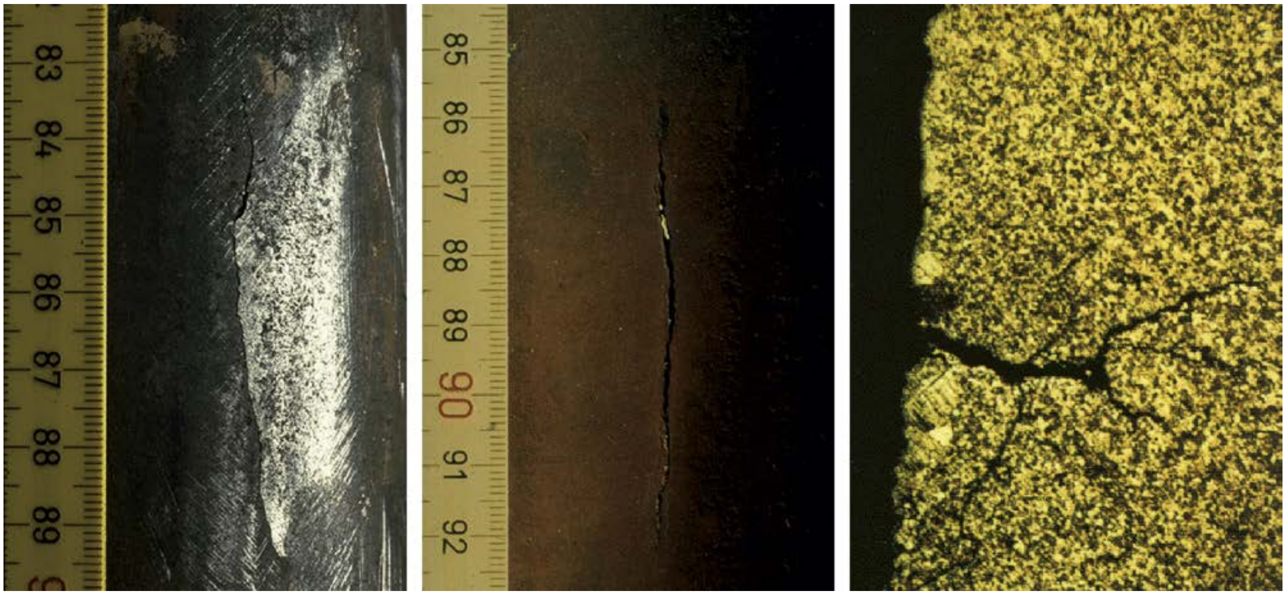
APPEARANCE	Pitting attack to lower part of pipeline. (The photograph has been placed upside down deliberately to reflect the real situation.)
TIME IN SERVICE	1 year.
ENVIRONMENT	Rainwater. Condensate temperature 95°C.
CAUSE	Very rapid corrosion by the ingress of (acid and salt containing) rainwater (see also Case Histories 01.01.25.01, 01.11.25.01, and 03.11.25.01).
REMEDY	• Fit an aluminum foil or apply a good paint system on the steel surface; or • Alternative solutions: fix a water-tight insulation or drain the plating by means of holes at the base.

CORROSION ATLAS

CASE HISTORY

1.02.28.01

MATERIAL	Carbon steel (ST 35).
SYSTEM	Condensate system.
PART	External condensate pipe.
PHENOMENON	Thermomechanical fatigue.



APPEARANCE	6 cm long fracture 4 cm away from the weld, with branches at the fracture tip. On the left external, internal at the center.
TIME IN SERVICE	About 1 year after replacement of the compensators by insert pieces.
ENVIRONMENT	Internal: good quality condensate (conductivity < 0.5 mS/m). Temperature: 60–100°C. External: glass wool insulation.
CAUSE	Poor steel quality; the microscopic examination revealed that the steel used is a pancake/rimmer (a fine-grained core, ASTM grain 10, and two sides with grain 6). During the steel production process, granular coarsening took place during the rolling cycle. As a result of removal of the expansion pieces, large tangential forces occur during load fluctuations and/or temperature changes so that cracking takes place in the shear direction along the grain boundaries (see also Case Histories 01.04.28.01, 01.11.28.03, and 04.11.28.01).
REMEDY	Introduce loops in the condensate line in order to absorb the expansion.

CORROSION ATLAS

CASE HISTORY

01.02.33.01

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Upper part of horizontal condensate pipe.
PHENOMENON	Cavitation erosion.

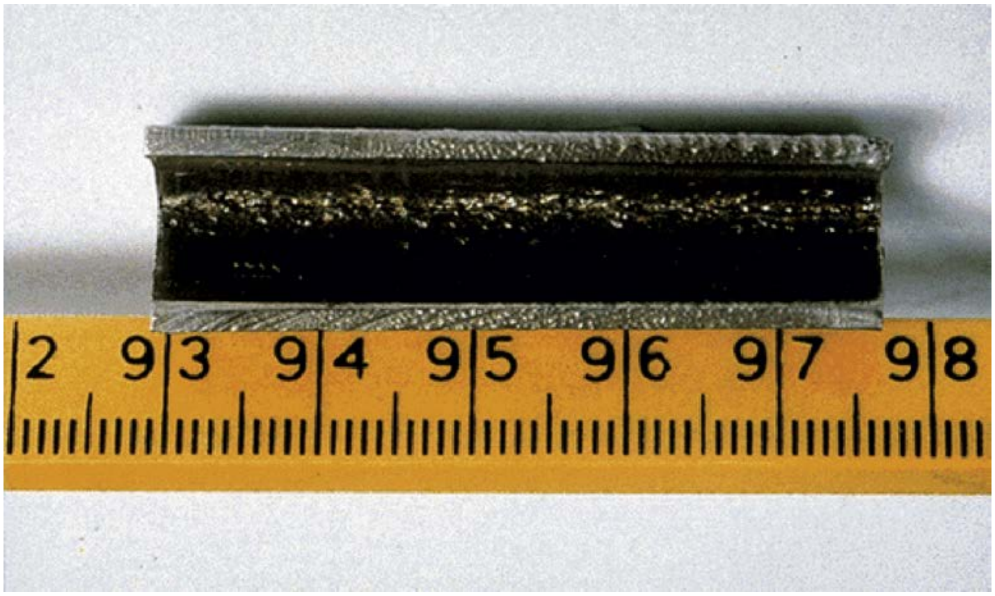
APPEARANCE	Attack with sharp edges, concentrated at the upper side of the pipe.
TIME IN SERVICE	A few years.
ENVIRONMENT	Oxygen-free and low carbonic acid condensate.
CAUSE	A condensate/steam mixture from a leaking steam trap was fed in upstream at the upper side of the line. The entrained steam imploded in the relatively colder condensate present in the line, thereby causing cavitation with preferential attack to the weld (see also Case Histories 01.02.33.04 and 01.02.33.05).
REMEDY	Improved maintenance of steam traps.

CORROSION ATLAS

CASE HISTORY

01.02.33.02

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Pipe of air heater used as steam cooler.
PHENOMENON	Cavitation erosion.



APPEARANCE	Local attack with sharp edges on the bottom of the oval pipe.
TIME IN SERVICE	2–3 years.
ENVIRONMENT	Condensate (free of oxygen and carbonic acid owing to properly functioning deaerator and demineralization of the makeup water); temperature 100–120°C.
CAUSE	Condensate accumulation took place due to poor drainage of the horizontally positioned steam cooler so that the feed steam imploded in the cooled condensate, accompanied by loud crackling noises. The sharp bend of the oval pipe was preferentially attacked probably due to the different structure caused by the residual stresses.
REMEDY	In the present case, the rotational speed of the fan positioned underneath the steam cooler was reduced, which yielded improved drainage at the expense of capacity. Replacement of the thermal steam trap by a lower-placed float-type trap can improve drainage without loss of capacity.

CORROSION ATLAS

CASE HISTORY

01.02.33.03

MATERIAL	Cast iron.
SYSTEM	Steam condensate system.
PART	Condensate pump impeller.
PHENOMENON	Cavitation erosion.

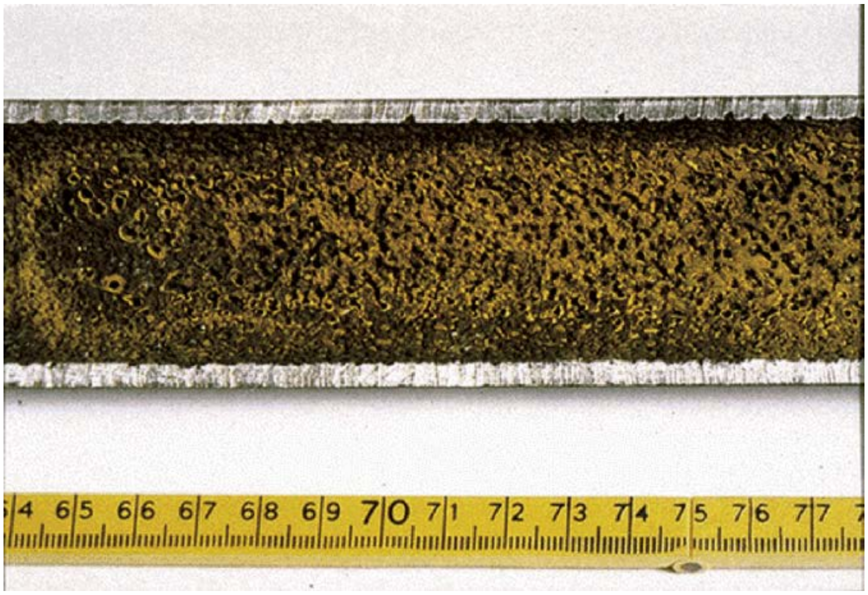
APPEARANCE	Local wear.
TIME IN SERVICE	6 months.
ENVIRONMENT	Condensate, varying in temperature from 60°C to 90°C.
CAUSE	The condensate pump was positioned beside the open condensate tank so that there was insufficient delivery pressure to prevent steam formation in the pump at 90°C. Implosion of the steam bubbles at the discharge side caused the cavitation (see also Case History 04.11.33.01).
REMEDY	Lower position of pump or higher position of condensate tank.

CORROSION ATLAS

CASE HISTORY

01.02.33.04

MATERIAL	Carbon steel.
SYSTEM	Condensate preheater of a boiler (gas turbine waste-heat boiler. 4.1 MPa). Installed in stack to recover heat from the flue gases.
PART	Pipe from preheater.
PHENOMENON	Cavitation erosion.



APPEARANCE	Pitting.
TIME IN SERVICE	About 3 years.
ENVIRONMENT	Steam condensate low in oxygen and carbonic acid (boiler feed with completely desalted and deaerated water); temperature from 60°C rising to 141°C.
CAUSE	Incorrect positioning of the control valve, namely in the condensate feed line, allowed vacuum to form in the preheater, because of the “hanging” water column, when the valve was closed. The formed steam imploded in the cold condensate when the valve was opened (see also Case History 01.06.33.01).
REMEDY	Relocation of the control valve in the discharge line prevented the formation of vacuum.

CORROSION ATLAS

CASE HISTORY

01.02.33.05

MATERIAL	Carbon steel.
SYSTEM	Condensate system.
PART	Condensate pipe.
PHENOMENON	Cavitation erosion.

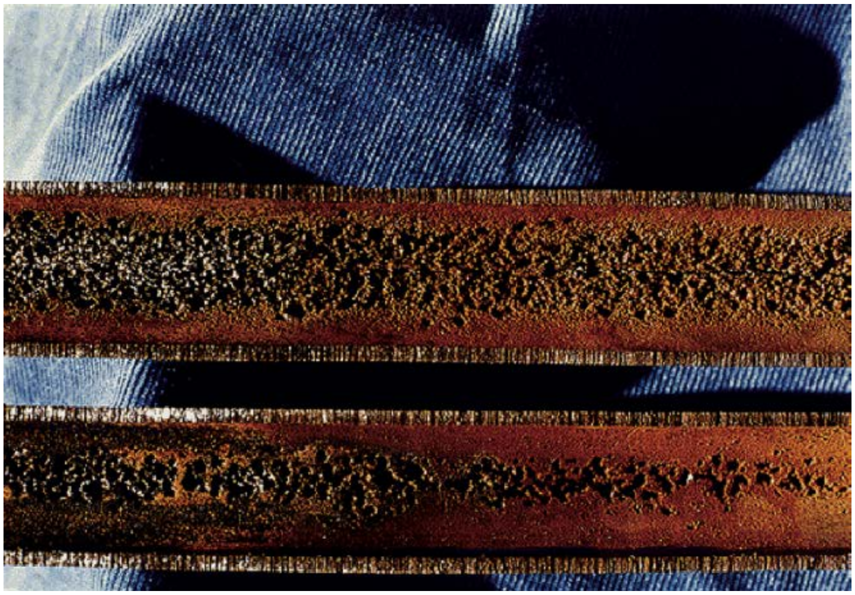
APPEARANCE	Sharp-edged pits in a sponge-like pattern.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Condensate.
CAUSE	When high-pressure condensate was supplied in a low-pressure condensate line, expansion of the high-pressure condensate caused steam bubbles to form, which imploded in the low-pressure condensate.
REMEDY	• High-pressure and low-pressure condensate should be returned separately to the boiler house; or • Expand the high-pressure condensate before feeding it to the low-pressure condensate, and the expansion steam can be routed into a low-pressure steam line.

CORROSION ATLAS

CASE HISTORY

01.02.33.06

MATERIAL	Mild steel.
SYSTEM	Turbine exhaust steam-cooling system.
PART	Horizontal fin-fan condenser tube (OD: 2.5 cm).
PHENOMENON	Cavitation erosion.



APPEARANCE	A rough, jagged contour of deep, overlapping pits, free of corrosion products, in opposite areas (top and bottom of the internal surface). Note longitudinal crack.
TIME IN SERVICE	2.5 years.
ENVIRONMENT	Internal: steam and condensate (pressure: 276 kPa); pH 8.5–8.8 with excursions to 6.9.
CAUSE	The cavitation damage was caused by cyclic vibration of the tube in the vertical plane, which led to rapid pressure changes of the condensing flow in the tube. Microstructural examination revealed deformation twins (Neumann bands) in metal grains at wasted surfaces. Coupled with the opposite sides attack, this confirms the diagnosis of cavitation damage (see also Case History 01.06.33.05).
REMEDY	Prevent vibration of the tubes by reducing flow velocity.

CORROSION ATLAS

CASE HISTORY

01.02.34.01

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Condensate pipe.
PHENOMENON	Erosion corrosion.

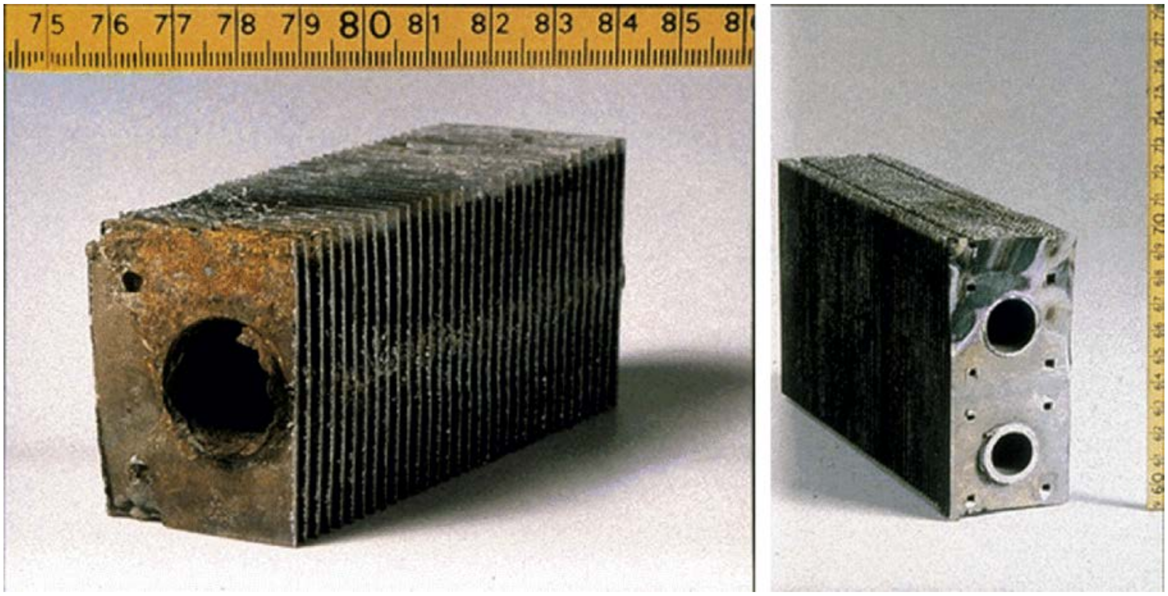
APPEARANCE	Severe attack, in bend.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Slightly corrosive condensate; temperature approximately 100°C.
CAUSE	Underdimensioned bends in combination with high condensate velocity causes strong turbulence, as a result of which the corrosion products are continuously removed, and the attack is reinforced by erosion.
REMEDY	• Complete elimination of the corrosive nature of the condensate by alkalizing the latter to pH 8.5 by dosing morpholine (toxic!). • Alternative: replace the bends by larger-dimensioned specimens.

CORROSION ATLAS

CASE HISTORY

01.02.34.02

MATERIAL	Carbon steel.
SYSTEM	Steam condensate system.
PART	Air heater tubes.
PHENOMENON	Erosion corrosion.



APPEARANCE	Preferential attack to one of the pipes; uniform attack to the material over the entire surface of the first 20 cm.
TIME IN SERVICE	8 years.
ENVIRONMENT	Steam/condensate, noncorrosive owing to demoralization of the makeup water and deaeration of the feedwater; temperature 130°C.
CAUSE	Poor steam distribution in steam feed header of the air heater; this causes local strong flow and condensation, leading to highly localized erosion corrosion.
REMEDY	Steam distribution was improved by introducing it at several points in the header; for additional certainty, the dewatering of the steam was also improved and a screen was positioned in the steam pipe to entrap particles.

CORROSION ATLAS

CASE HISTORY

01.04.01.01

MATERIAL	Carbon steel (35.8).
SYSTEM	Central heating system.
PART	Boiler fire tube.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	Untreated city water; 70–90°C.
CAUSE	Frequent makeup during construction of the large-scale central heating system because of the construction of the new hospital in phases.
REMEDY	• Unnecessarily excessive makeup during new construction can be avoided by making use of section valves so that water loss is limited. • In the present case, water consumption after startup was found to be zero, so it was decided not to apply water treatment. • The corroded fire tubes were of course replaced.

CORROSION ATLAS

CASE HISTORY

01.04.01.02

MATERIAL	Carbon steel.
SYSTEM	Central heating system.
PART	Circulating pump rotor.
PHENOMENON	Oxygen corrosion.

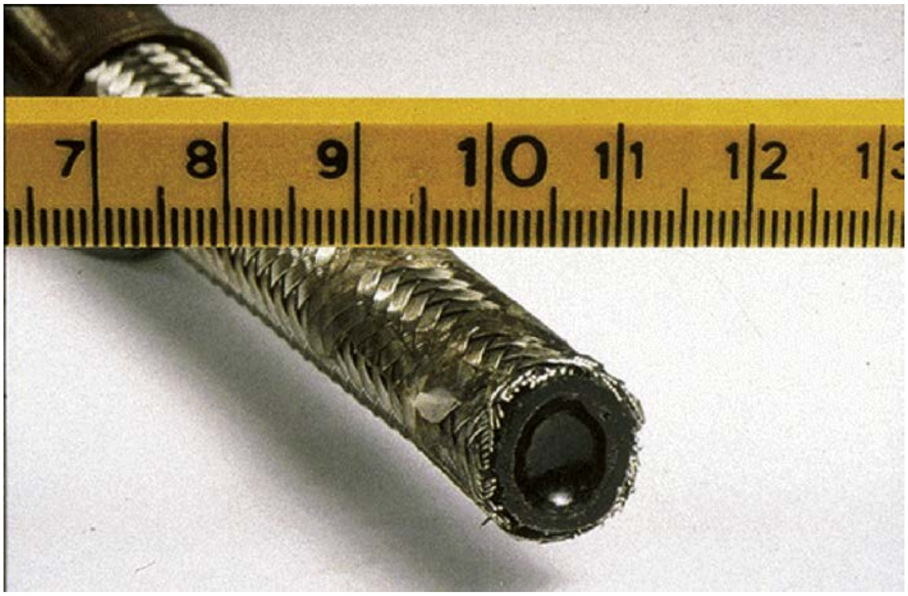
APPEARANCE	Deposition of black iron oxide (magnetite) on the rotor.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Heating water at 70–90°C, without dosing of chemicals.
CAUSE	Entry of air (e.g., via seals) into the heating water as a result of which corrosion of the central heating system occurred. The resultant magnetite was deposited in the magnetic field of the rotor, causing it to seize (see also Case Histories 01.01.01.07 and 01.04.01.03).
REMEDY	• Removal of magnetite from the system. • Optional dosing of a corrosion inhibitor. • Prevention of air entry by using metallic seals and not using air-permeable plastic pipes (see also Case History 01.04.01.03).

CORROSION ATLAS

CASE HISTORY

01.04.01.03

MATERIAL	Carbon steel and cast iron.
SYSTEM	Central heating system.
PART	Radiator connection hose of polytetrafluoroethylene (Teflon).
PHENOMENON	Oxygen corrosion.



APPEARANCE	Deposition of black iron oxide (magnetite) leading to complete blockage.
TIME IN SERVICE	Several years.
ENVIRONMENT	Central heating water, nonconditioned; temperature 70–90°C.
CAUSE	Formation of magnetite owing to corrosion of the heating system by the penetration of oxygen via seals and the Teflon hoses themselves. The magnetite deposits in the Teflon hoses (see also Case Histories 01.01.01.07 and 01.04.01.02).
REMEDY	• Chemical cleaning of the system. • Replacement of the Teflon hoses by rigid or flexible metal connection pipes. • Optionally dosing an oxygen scavenger.

CORROSION ATLAS

CASE HISTORY

01.04.01.04

MATERIAL	Carbon steel.
SYSTEM	Central heating system.
PART	Boiler fire tube.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Fire tube covered with thick layer of knob-like mounds of brown corrosion products (tubercles).
TIME IN SERVICE	16 years.
ENVIRONMENT	System water (untreated mains water). Temperature: 70–90°C.
CAUSE	• The use of underdimensioned expansion tanks allowed reduced pressure (vacuum) to occur in the system when it was not operational. Air was drawn in as a result. • Besides the fire tubes the underground circulation pipes were also attacked, allowing water loss and requiring frequent water replenishment.
REMEDY	• Use large expansion tanks and monitor water consumption (maximum 10% of system capacity/year). • Change to dosing an oxygen scavenger and supplying deaerated water.

CORROSION ATLAS

CASE HISTORY

01.04.04.01

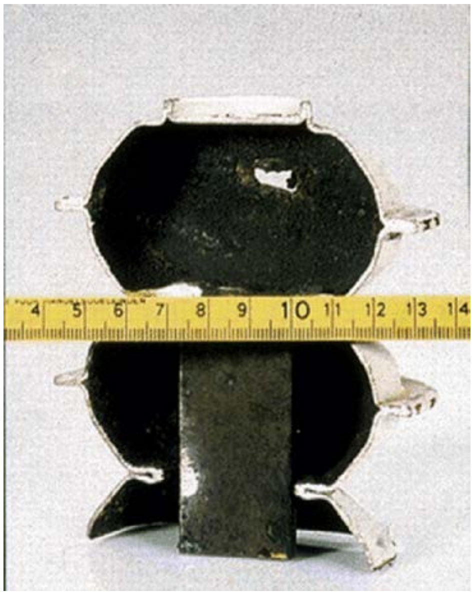
MATERIAL	Carbon steel (33-1, “black steel”).
SYSTEM	Workshop heating system.
PART	Flue-gas heated radiant tubes.
PHENOMENON	Acid corrosion.

APPEARANCE	Severe general corrosion on the inside (left photo).
TIME IN SERVICE	Less than 2 years (normally more than 6–8 years).
ENVIRONMENT	Flue gas (550–50°C, mainly CO_2-containing).
CAUSE	The air used to combust natural gas contains traces of a volatile solvent. This product, mainly trimethylchloride, lowered the condensate’s pH significantly by the formation of hydrochloric acid and led to a major repair of the installation (see also Case Histories 02.01.04.01 and 07.04.04.01).
REMEDY	Avoid ingress of such harmful solvents or use a more corrosion-resistant material for the condensing parts.

CORROSION ATLAS

CASE HISTORY

01.04.15.01

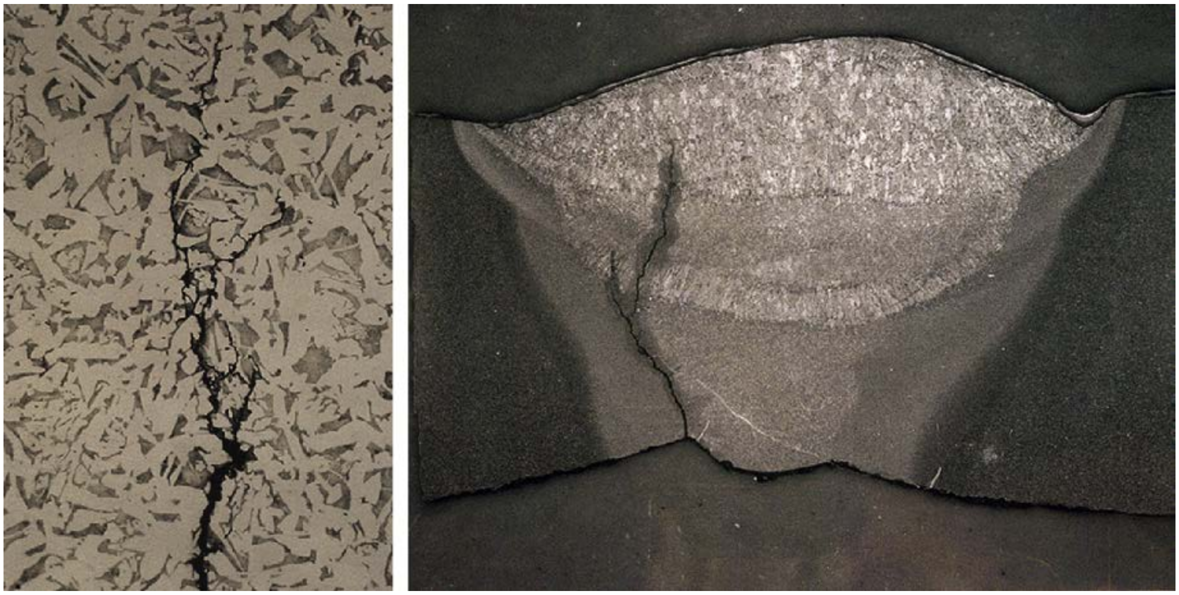
MATERIAL	Carbon steel.
SYSTEM	District heating system.
PART	Lower part of radiator.
PHENOMENON	Under-deposit corrosion.
	
APPEARANCE	Local attack under deposit.
TIME IN SERVICE	3 years.
ENVIRONMENT	Oxygen-containing warm hard water, 70–90°C, to which a film-forming amine was added.
CAUSE	Because of frequent leakage of the subterranean pipelines due to external corrosion, a large amount of makeup water had to be supplied to the system. The resultant hardness and rust sludge settled at the bottom of the radiators, leading to the formation of differential aeration cells. This caused attack to the material under the sludge (see also Case Histories 01.05.15.01 and 01.06.15.01). The water loss caused flooding of the residents' gardens.
REMEDY	• Short-term: chemical cleaning of the system by means of dispersants and switching to making up with softened water and improving the film-amine dosing (continuous instead of discontinuous). • Long-term: prevention of leakages in the subterranean pipelines by the installation of jacket pipes.

CORROSION ATLAS

CASE HISTORY

01.04.18.01

MATERIAL	Carbon steel.
SYSTEM	Closed hot and cold water system (T = 8–85°C).
PART	Piping, mainly HAZ of welds.
PHENOMENON	Nitrate stress-corrosion cracking.



APPEARANCE	Intergranular cracks starting in a pit. Left photo: in base metal; right photo: between weld and HAZ.
TIME IN SERVICE	6 months.
ENVIRONMENT	NO_3^- > 2000 ppm; temperature: 86–89°C (hot water system); pH 7 or lower.
CAUSE	Unexpected bacterial conversion of the inhibitor nitrite (NO_2^-) into the corrosive nitrate (NO_3^-) during a period out of service with water inside the pipes. Deposits were formed on the carbon steel surface, causing an increase in NO_3^- and pitting. In service at temperatures >50°C, more NO_3^- and intergranular cracking initiating from the pit.
REMEDY	• Adding biocide to inhibitor; or • Change inhibition to a molybdate inhibitor.

CORROSION ATLAS

CASE HISTORY

01.04.22.01

MATERIAL	Cadmium-coated low-alloyed steel (B7).
SYSTEM	Heating system (with heating oil).
PART	Valve bolts.
PHENOMENON	Liquid metal embrittlement.

APPEARANCE	Brittle fracture of the bolts.
TIME IN SERVICE	30 min.
ENVIRONMENT	Heating oil; 340°C.
CAUSE	Attack by molten cadmium (intergranular penetration; see also Case History 01.01.22.01).
REMEDY	Use of uncoated bolts.

CORROSION ATLAS

CASE HISTORY

01.04.25.01

MATERIAL	Carbon steel.
SYSTEM	Central heating system.
PART	Insulated pipe section.
PHENOMENON	Corrosion under insulation.

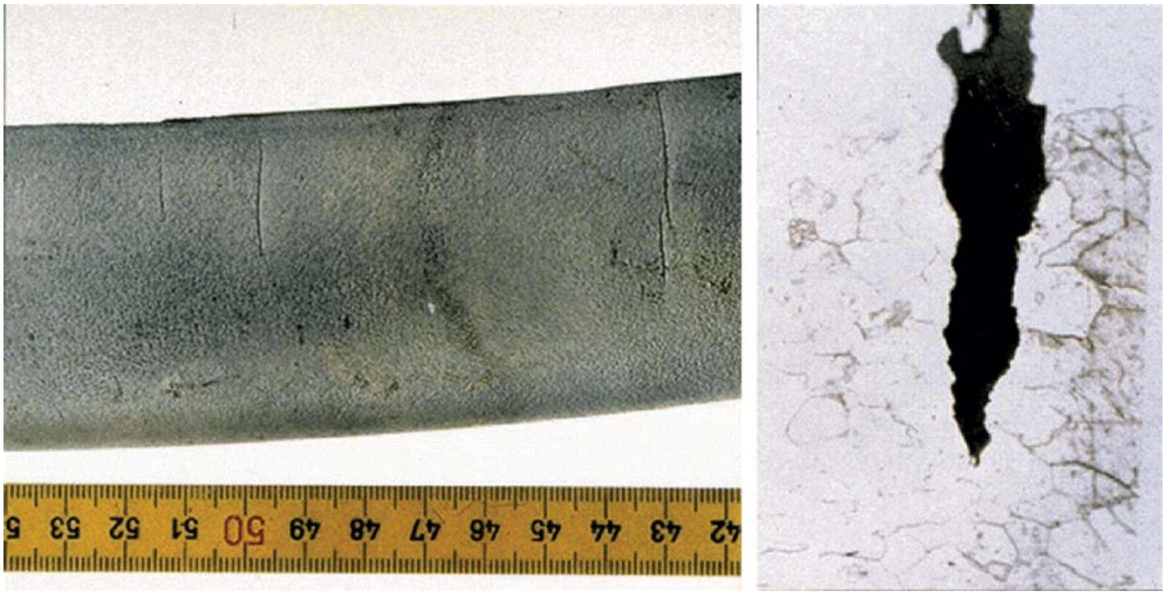
APPEARANCE	Externally, the pipe exhibits uniform corrosion to the point of leakage near the connection.
TIME IN SERVICE	3 years.
ENVIRONMENT	Wetted insulation (polyisocyanurate).
CAUSE	Because of the short thread, the fitting of the connection was not suitable for the use of a sealing washer, so that hot water escaped (poor workmanship). As a result of evaporation, the salt content beneath the insulation became high (26% NaCl in the moisture of the deposit). The steel was attacked by the combination of salt-containing moisture and oxygen ingress (see also Case History 04.01.25.01).
REMEDY	• Use fittings with sufficient thread if it is desired to use sealing washers, or • Use a different thread seal, e.g., hemp.

CORROSION ATLAS

CASE HISTORY

01.04.28.01

MATERIAL	Carbon steel.
SYSTEM	Autoclave heating system (with heating oil).
PART	External part of heating coil.
PHENOMENON	Thermomechanical corrosion fatigue.



APPEARANCE	Fine, parallel cracks ("magnafluxed" pipe). (The photograph has been placed upside down deliberately in order to reflect the real situation.)
TIME IN SERVICE	15 years.
ENVIRONMENT	At the outside: industrial atmosphere; at the inside: heating oil, 270–340°C.
CAUSE	High stresses caused by fluctuating temperatures, combined with atmospheric oxidation (corrosion products found in the cracks; see also Case Histories 01.02.28.01, 01.11.28.03, and 04.11.28.01).
REMEDY	• Improvement of the design. • Regular preventive magnetic fracture examination of the existing plant to prevent leakages.

CORROSION ATLAS

CASE HISTORY

01.05.01.01

MATERIAL	Carbon steel.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Oxygen corrosion with tuberculation.

APPEARANCE	Pitting with corrosion tubercles.
TIME IN SERVICE	$1\frac{1}{2}$ years.
ENVIRONMENT	Oxygen-containing deferrized well water; bicarbonate (HCO_3^-) 0.4 mEq/l (20 ppm $CaCO_3$); temperature 45 C.
CAUSE	Use of untreated steel for oxygen-containing water; also, because of the low bicarbonate hardness (temporary hardness) of the water, no protective lime-rust layer was formed. As rust accumulates, oxygen migration is reduced through the corrosion product layer. Regions below the rust layer become oxygen depleted. An oxygen concentration cell then develops. Corrosion naturally becomes concentrated into small regions beneath the rust, and tubercles are born (see also Case Histories 01.05.01.02, 01.06.01.01, and 01.06.01.02).
REMEDY	Construct water pipes from 316 stainless steel or plastic.

CORROSION ATLAS

CASE HISTORY

01.05.01.02

MATERIAL	Carbon steel.
SYSTEM	Raw water transmission pipeline system.
PART	Pipe section.
PHENOMENON	Oxygen corrosion and tuberculation.

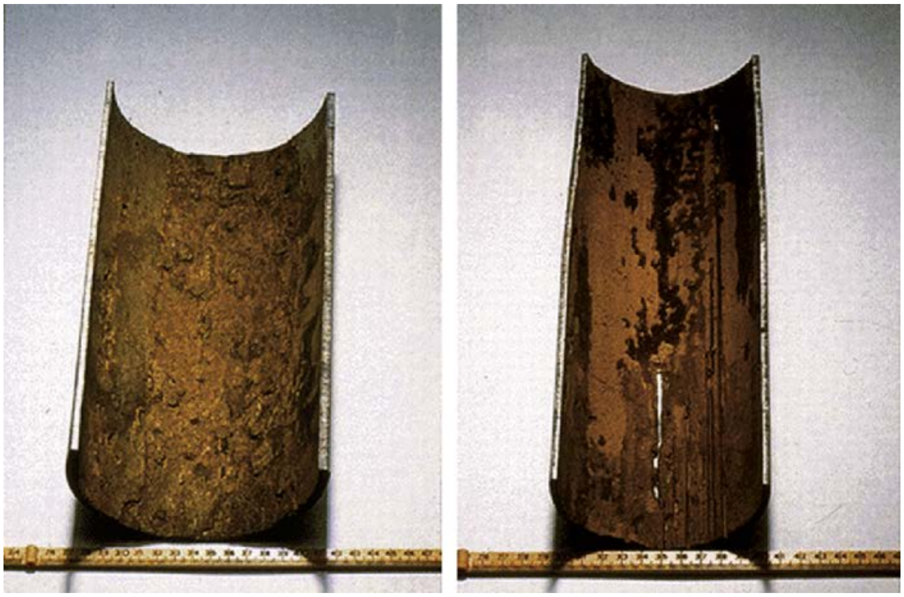
APPEARANCE	Severe tuberculation of corrosion products.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Surface water from a lake.
CAUSE	Attack by oxygen followed by aeration cell formation and tuberculation. The anaerobic conditions underneath the tubercles led to sulfide corrosion caused by the development of sulfate-reducing bacteria.
REMEDY	Construct the supply pipe of coated steel or plastic.

CORROSION ATLAS

CASE HISTORY

01.05.02.01

MATERIAL	Carbon steel.
SYSTEM	Cold tap water system.
PART	Pipe section.
PHENOMENON	Carbonic acid corrosion.



APPEARANCE	Severe attack over a large area, with localized corrosion and narrow, deep grooves in longitudinal direction.
TIME IN SERVICE	Approximately 5 years.
ENVIRONMENT	Corrosive, untreated, anaerobic well water; temperature approximately 15°C.
CAUSE	Carbon dioxide in the well water combined with high velocity (in the right-hand pipe).
REMEDY	Construct the water pipe system from plastic or coated steel (baked coating).

CORROSION ATLAS

CASE HISTORY

01.05.15.01

MATERIAL	Carbon steel.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Local attack leading to leak.
TIME IN SERVICE	$2\frac{1}{2}$ years.
ENVIRONMENT	Tap water heated to 85°C by a boiler. Boiler with copper heating tubes (steam passing through tubes) and steel jacket. In order to prevent corrosion of the steel jacket, the boiler was provided with cathodic protection by means of aluminum sacrificial anodes.
CAUSE	Deposition of aluminum hydroxide (originating from the anodes) in the pipes, which led to corrosion as a result of formation of differential aeration cells (see also Case History 01.06.15.01).
REMEDY	Cleaning of the system and fitting of the boiler with platinum-coated titanium anodes. Use of aluminum sacrificial anodes can also cause dezincification of brass fittings (see Case History 06.05.16.03) and also fouling of the boiler, blockage of the pipes and an excessively high aluminum content of the water, making it unsuitable for drinking purposes.

CORROSION ATLAS

CASE HISTORY

01.05.17.01

MATERIAL	Carbon steel.
SYSTEM	Cold tap water system.
PART	Pipe section.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Pitting underneath corrosion pocks.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Standing tap water (dead section of pipe). Pocks consist of Fe_3O_4 with 0.4% SO_4^{2-}; negative reaction to sulfide, presumably due to conversion to sulfate by extended exposure to air.
CAUSE	In an anaerobic environment, sulfide can be formed from sulfate by means of sulfate-reducing bacteria. Steel is attacked by sulfide.
REMEDY	Dead sections in water systems should be avoided. Use coated steel, galvanized steel, stainless steel or plastic pipes for cold tap water systems.

CORROSION ATLAS

CASE HISTORY

01.05.18.01

MATERIAL	Carbon steel.
SYSTEM	Water transport system (not yet in use).
PART	Pipe section (OD: 10 cm).
PHENOMENON	Carbonate stress-corrosion cracking.

APPEARANCE	Left photograph: Inner view of the round weld after magnetic testing. Right photograph: Branched intergranular cracks initiated at the fusion line of the root weld leading to leakage.
TIME IN SERVICE	The leak was discovered during hydrostatic pressure testing.
ENVIRONMENT	The pipeline was degreased by purging with a solution of sodium carbonate (3%) in water (60 ppm Cl) at a temperature of about 80°C. Hydrostatic pressure testing was performed at 6–7 bar and 120°C, about 0.5 years after purging of the pipeline.
CAUSE	Carbon steel is known to be subject to carbonate stress corrosion at temperatures above about 100°C. Weld thermal stresses and stress concentration at the root fusion line caused initiation (see also Case History 04.11.18.10).
REMEDY	Use carbonate-free detergent or keep the temperature (even during purging or pressure testing) well below 100°C.

CORROSION ATLAS

CASE HISTORY

01.05.26.01

MATERIAL	Carbon steel.
SYSTEM	Hot tap water system.
PART	Underground pipe section.
PHENOMENON	Stray current corrosion.

APPEARANCE	Severe attack at a single site.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Groundwater.
CAUSE	Stray currents originating from a neighboring oil storage tank provided with cathodic protection; the material is attacked where the current leaves the pipe back to the storage tank (see also Case Histories 03.14.26.01 and 03.14.26.02).
REMEDY	• Potential connection: Discharge stray current via copper wire to the storage tank, incorporating a resistance to prevent excessive current from being withdrawn from the cathodically protected tank; or • Drainage: Discharge the current via drainage anodes; or • Provide this pipe with cathodic protection as well.

CORROSION ATLAS

CASE HISTORY

01.06.01.01

MATERIAL	Carbon steel.
SYSTEM	Cooling water system (open, circulating, with cooling tower).
PART	Pipe section.
PHENOMENON	Oxygen corrosion with tuberculation.

APPEARANCE	Pitting attack underneath large tubercles.
TIME IN SERVICE	2 years.
ENVIRONMENT	Cooling water existing of concentrated well water; pH: 7; temperature 30°C.
CAUSE	The oxygen in the cooling water causes the formation of hydrous ferric oxide ($Fe(OH)_3$) on the steel surface. As rust accumulates, oxygen migration through the corrosion product layer is reduced. Regions below the rust layer become oxygen depleted. An oxygen concentration cell then develops. Corrosion naturally becomes concentrated into small regions beneath the rust, and tubercles are born (see also Case Histories 01.05.01.01/02).
REMEDY	• Dosing of corrosion inhibitors. • Additionally, replacement of the well water by demineralized water for make-up purposes (demineralized water available for other purposes, with sufficient surplus capacity).

CORROSION ATLAS

CASE HISTORY

01.06.01.02

MATERIAL	Mild steel.
SYSTEM	Once-through cooling-water system.
PART	Horizontal water supply line for a steel mill (OD: 137 cm).
PHENOMENON	Oxygen corrosion and tuberculation.

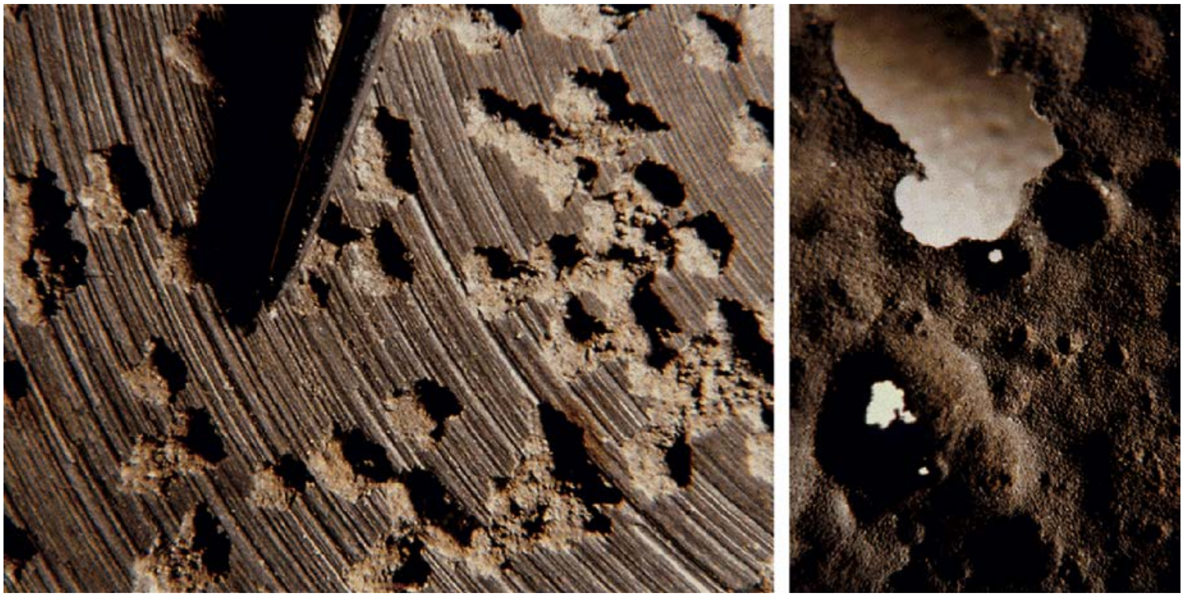
APPEARANCE	Large tubercles (up to 15 cm diameter) with dark interior and preferential weld attack. The tubercle floor shows a shallow dish-shaped depression.
TIME IN SERVICE	23 years.
ENVIRONMENT	Lake Michigan water treated with dispersant; heavily fouled with grease and oil.
CAUSE	Development of oxygen concentration cells beneath a corrosion product layer formed in oxygenated water. The tubercle contents were fairly acidic due to hydrolysis of $FeCl_2$ into HCl, which accelerated the attack. Tuberculation is in fact a next step after general oxygen attack. The contamination with oil and grease had thickened the layer and enhanced the attack.
REMEDY	• Effective cleaning of the mains. • Implement system operations changes to reduce grease and oil fouling. • Complete the water treatment with corrosion inhibitors and biocides; or • Replace the steel pipe by a coated or plastic pipe.

CORROSION ATLAS

CASE HISTORY

01.06.04.01

MATERIAL	Carbon steel.
SYSTEM	Primary metal-rolling oil-coolant system.
PART	Part of valve (left) and bracket (right) from a spray system.
PHENOMENON	Acid corrosion.



APPEARANCE	Valve: Heavy pitting. Bracket: General wastage with superimposed pitting.
TIME IN SERVICE	8 years in service; corrosion took place in several weeks.
ENVIRONMENT	Mill coolant (≈ 5% oil, 95% demineralized water), temperature 60°C.
CAUSE	An upset that permitted hydrochloric acid to mix with the mill coolant, which caused a pH drop from 5 to 2. Because demineralized water was used, even small amounts of acid contamination caused severe pH upset.
REMEDY	Continuous control of the pH of the mill coolant so that timely measures can be taken (alkalizing or freshening the coolant).

CORROSION ATLAS

CASE HISTORY

01.06.04.02

MATERIAL	Carbon steel.
SYSTEM	Cooling system in a fossil utility.
PART	Horizontal cooling pipe (OD: 7.6 cm).
PHENOMENON	Acid corrosion.

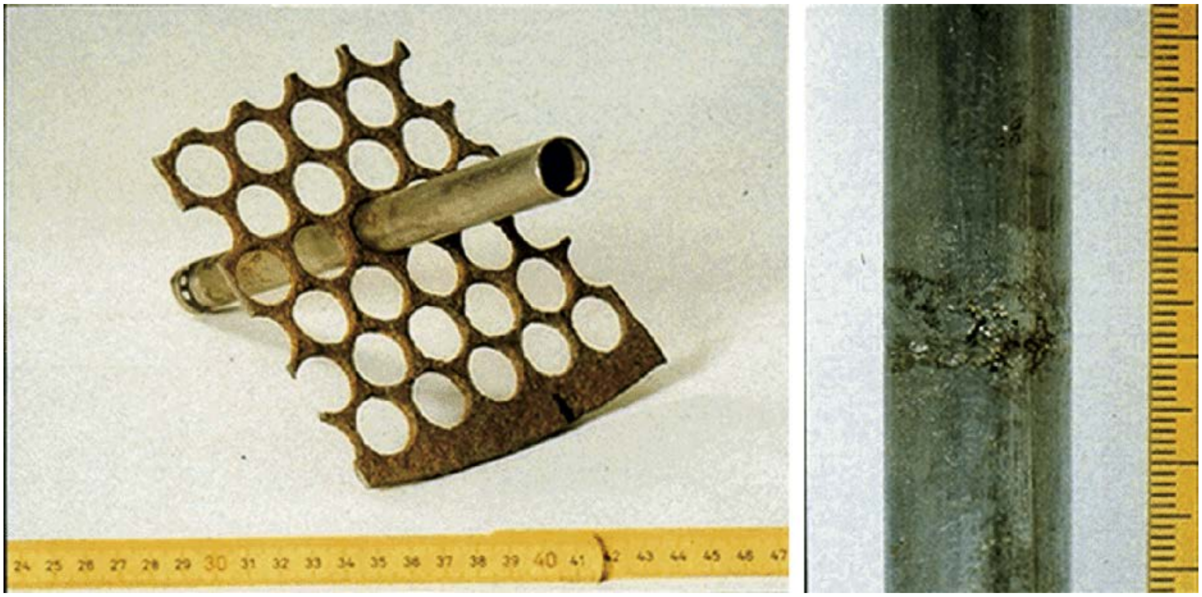
APPEARANCE	Heavy pitting with pronounced undercutting. Almost no internal corrosion products in pits.
TIME IN SERVICE	Less than 30 days.
ENVIRONMENT	Cooling water. Sulfuric acid depressed pH to less than 2 for at least 1 week.
CAUSE	Carbon steel is not resistant to diluted sulfuric acid solutions. Attack is especially rapid when pH falls below 4. A 10-m^3 tank of sulfuric acid was accidentally drained into a cooling tower basin during a holiday (poor workmanship!). After about 1 week the cooling water pH was still below about 2.
REMEDY	Emergency blow-down procedures (and other procedural modifications) were begun after piping began to leak throughout the plant and the upset was discovered. Massive additions of caustic were begun until pH in tower basin reached 6. All acid feed was suspended, and lockout procedures were initiated to prevent accidental acid upsets in the future.

CORROSION ATLAS

CASE HISTORY

01.06.14.01

MATERIAL	Baffle: carbon steel; pipes: stainless steel (AISI 304).
SYSTEM	Once-through cooling water system.
PART	Heat exchanger.
PHENOMENON	Galvanic corrosion (with general corrosion and crevice corrosion).



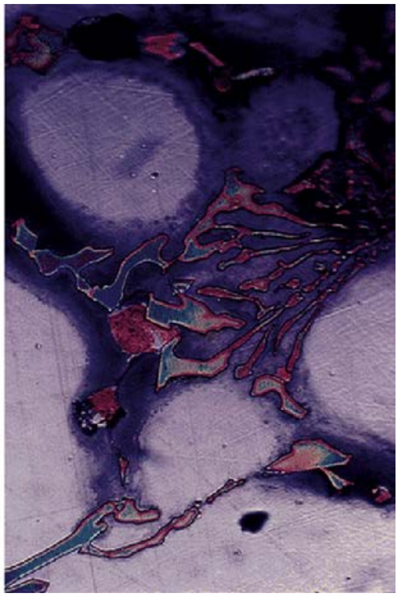
APPEARANCE	Uniform attack to baffle, pitting to tubes in crevices.
TIME IN SERVICE	10 years.
ENVIRONMENT	Around the pipes: Cooling water at 45–47°C, 85 ppm Cl^-; through the pipes: Product.
CAUSE	Untreated carbon steel is attacked by this cooling water, and the corrosion is reinforced by the galvanic couple with stainless steel (see also Case Histories 01.01.14.01 and 01.11.14.01); in the crevices with the baffle, the stainless steel tubes are attacked by crevice corrosion (see also Case History 04.06.13.02).
REMEDY	Use baffles and tubes constructed from a single material, e.g., AISI 316 or SMO 254 stainless steel; the latter is more resistant to crevice corrosion.

CORROSION ATLAS

CASE HISTORY

01.06.14.02

MATERIAL	Austenitic cast iron (Ni-resist type D2).
SYSTEM	Once-through cooling water system.
PART	Bearing of a circulating pump.
PHENOMENON	Galvanic corrosion.



APPEARANCE	Uniform attack.
TIME IN SERVICE	One year.
ENVIRONMENT	Aerated water with 75 ppm Cl^- is used as lubricant cooling water.
CAUSE	The result of a material analysis of the bearing shows a copper content of 6.4% instead of the material specification of 0%. At the microstructure level, copper is present as heterogeneous precipitations (see microprint). Attack of the Ni-resist is due to the copper/iron combination in conductive oxygen-containing water.
REMEDY	Use Ni-resist type D2 with a chemical composition according to specification.

CORROSION ATLAS

CASE HISTORY

01.06.15.01

MATERIAL	Cast iron.
SYSTEM	Open circulating cooling water system.
PART	Blind flange.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Pitting and uniform attack.
TIME IN SERVICE	3 years.
ENVIRONMENT	Cooling water: pH 7.5–8.0; conductivity 120 mS/m; chloride 300 ppm; calcium hardness 500 ppm $CaCO_3$. Deposition of sand and bacterial slime.
CAUSE	As a result of the formed deposition, differential aerations cells occurred which cause the cast iron to become anodic underneath the deposition and subject to attack (see Case History 01.05.15.01).
REMEDY	• Dosing of a dispersant and a biocide. • Partial flow filtration.

CORROSION ATLAS

CASE HISTORY

01.06.16.01

MATERIAL	Grey cast iron.
SYSTEM	Cooling water system.
PART	Cooling water pump check valve.
PHENOMENON	Selective leaching (graphitic corrosion).

APPEARANCE	Outer edge black due to graphitic corrosion.
TIME IN SERVICE	6 years.
ENVIRONMENT	River water; chloride (Cl^-) 300–500 ppm
CAUSE	Attack of the cast iron by the river water, the iron being dissolved and the carbon remaining (see also Case Histories 01.01.16.01 and 01.14.16.01).
REMEDY	Replace the check valve by a coated grey cast iron valve or by one made of steel or bronze.

CORROSION ATLAS

CASE HISTORY

01.06.16.02

MATERIAL	Grey cast iron.
SYSTEM	Once-through cooling-water system.
PART	Horizontal subterranean supply line (OD: 25 cm).
PHENOMENON	Selective leaching (graphitic corrosion).

APPEARANCE	Brittle fracture in the pipe bottom; External: Graphitically corroded cast iron (black); Internal: a thin layer of reddish iron oxides.
TIME IN SERVICE	25 years.
ENVIRONMENT	External: Moist soil. Internal: Cooling water.
CAUSE	Aggressive soil. Microstructural examination of the external surface revealed an interconnecting network of graphite flakes embedded in an iron-oxide matrix. Heavy equipment initiated a fracture in the severely corroded pipe bottom. The fracture propagated in response to stresses imposed by internal pressure.
REMEDY	Graphitic corrosion can be prevented by: • Specifying another material such as: silicon cast iron, white cast iron, cast steel or plastic. • Applying an appropriate protective coating on the grey cast iron pipes, possibly in conjunction with cathodic protection. Take care to avoid coating damage when laying the line.

CORROSION ATLAS

CASE HISTORY

01.06.17.01

MATERIAL	Carbon steel.
SYSTEM	Once-through cooling system.
PART	Flange from conveyor line.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Locally severe attack.
TIME IN SERVICE	3 years.
ENVIRONMENT	Unaerated well water with high concentrations of sulfate, phosphate, organic matter and ammonium.
CAUSE	Attack by sulfide formed by the development, under anaerobic conditions, of sulfate-reducing bacteria which convert sulfate into sulfide. (Sulfide was identified in the corrosion products originating from the line.) (See also Case History 01.06.17.03.)
REMEDY	In view of the fact that chemical cleaning of the system (in a food factory) was out of the question because of the high levels of H_2S that would be formed and water treatment (aeration and deferrization) was too expensive in view of the large quantity of water, the solution chosen was plastic lines.

CORROSION ATLAS

CASE HISTORY

01.06.17.02

MATERIAL	Carbon steel.
SYSTEM	Open circulating cooling water system.
PART	Corrosion coupon.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Shallow pitting corrosion which has spread in the form of “flakes.”
TIME IN SERVICE	Two months.
ENVIRONMENT	Cooling water: pH 8.5–9.0; conductivity 200 mS/m; chloride 200 ppm; sulfate 250 ppm; calcium hardness 400–480 ppm $CaCO_3$; organic inhibitor.
CAUSE	Development of sulfate-reducing bacteria (SRB) under anaerobic conditions (under scale), as a result of which the steel is attacked by sulfide. SRB demonstrated with the API broth test: positive, formation of black iron sulfide.
REMEDY	Dosing of a dispersant to prevent scaling.

CORROSION ATLAS

CASE HISTORY

01.06.17.03

MATERIAL	Carbon steel.
SYSTEM	Emergency service once-through cooling water system.
PART	Horizontal conveyor pipe (OD: 8.9 cm; wall thickness: 0.572 cm).
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Heavy tuberculation on pipe interior. The circumferential weld-backing ring was heavily corroded. The weld was riddled with mildly undercut, gaping pits, confined to fused and heat-affected zones.
TIME IN SERVICE	5 years.
ENVIRONMENT	Cooling water near ambient temperature, intermittent low flow. Daily chlorination for 1 h. Total anaerobic bacteria in wet material removed from corrosion site 35,000, of which 30,000 sulfate reducers.
CAUSE	Corrosion by sulfate-reducing bacteria in view of: • large amount of iron sulfide in the pits; • high bacterial counts (25,000 sulfate reducers in the corrosion products in the pits); • pit morphology: The major depression is cavernous and shows lateral propagation.
REMEDY	• Keep the flow high enough to prevent deposition of particles (or side-stream filtration). • Dose corrosion inhibitors and dispersant in addition to chlorination. • Prevent formation of crevices in the tubes (acting as shielded locations for deposit concentrations). • Apply plastic lines.

CORROSION ATLAS

CASE HISTORY

01.06.21.01

MATERIAL	Carbon steel.
SYSTEM	Pressurized closed cooling water circuit.
PART	EDTA dosing nozzle in flash tank.
PHENOMENON	Chelant corrosion.

APPEARANCE	Severe uniform attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	Steam from flashed cooling water and chelant: EDTA (the heated cooling water was flashed from 1 to 0.6 MPa, temperature 160°C).
CAUSE	The dosing nozzle was situated above the water level in the steam phase. Consequently, chelant tended to concentrate at the nozzle. The nozzle was corroded by the high EDTA concentration and the simultaneous presence of oxygen (see also Case Histories 01.01.21.01/02/03).
REMEDY	Move the nozzle to a location below water level in the flashed oxygen-free cooling water.

CORROSION ATLAS

CASE HISTORY

01.06.33.01

MATERIAL	Carbon steel.
SYSTEM	Through-flow cooling water system.
PART	Flange downstream of control valve.
PHENOMENON	Cavitation erosion.

APPEARANCE	Local pitting corrosion of the material.
TIME IN SERVICE	Two years.
ENVIRONMENT	Surface water, flowing, maximum 40°C.
CAUSE	The closing speed of the open/close control valve was too high, so that as it closed rapidly vacuum was drawn downstream of the valve, by the water column in the long length of pipe behind it. The subsequent implosion of this vacuum caused water hammer downstream of the control valve.
REMEDY	Retard the closing speed of the control valve, e.g., by means of a throttling plate in the compressed air line to the valve or by switching over to a motor-operated valve (see also Case Histories 01.02.33.04 and the following cases).

CORROSION ATLAS

CASE HISTORY

01.06.33.02

MATERIAL	Carbon steel.
SYSTEM	Cooling water system.
PART	4”–6″ reducing pipe.
PHENOMENON	Cavitation corrosion.

APPEARANCE	Material worn away locally.
TIME IN SERVICE	2.5 years.
ENVIRONMENT	Water with CO_2 and traces of styrene and benzene; pH 6; temperature 60°C; flow rate 130 m^3/h.
CAUSE	Water vapor bubbles form in the 60°C water as a result of the pressure drop of 0.15–0.2 MPa along the upstream control valve. These vapor bubbles implode in the pipe behind the control valve. The released energy damaged the pipe wall (see Case History 01.04.33.01).
REMEDY	Replace the 4″ control valve by a 6″ control valve. This larger valve will not (according to calculations) cause cavitation under the prevailing process conditions.

CORROSION ATLAS

CASE HISTORY

01.06.33.03

MATERIAL	Cast iron.
SYSTEM	Circulating cooling water system of diesel engine.
PART	Cylinder block and cylinder sleeve.
PHENOMENON	Cavitation/erosion corrosion.

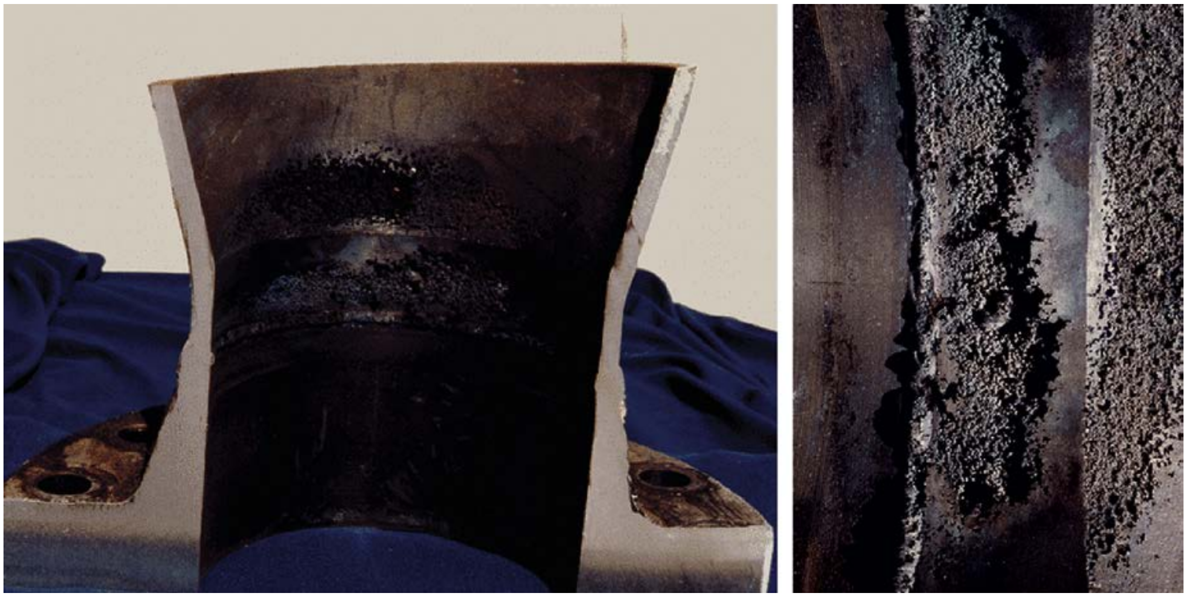
APPEARANCE	Severe local attack.
TIME IN SERVICE	One year.
ENVIRONMENT	Brackish water with a high chloride level (approximately 9000 ppm Cl^-), at temperatures up to 80°C.
CAUSE	Cast iron was subjected to cavitation erosion and to erosion corrosion owing to the formation and collapse of vapor bubbles as well as to the presence of oxygen and the high chloride level.
REMEDY	• Use potable water (or even better distilled or deionized water). • Use special additives or antifreeze for inhibiting corrosion. • Use of closed pressurized systems to eliminate oxygen.

CORROSION ATLAS

CASE HISTORY

01.06.33.04

MATERIAL	Cast steel.
SYSTEM	Spray-cooling system.
PART	Expansion valve flange in horizontal supply line.
PHENOMENON	Cavitation erosion.



APPEARANCE	Jagged, spongelike metal loss downstream of protruding weld bead and again in the region of diameter increase.
TIME IN SERVICE	6 years.
ENVIRONMENT	Internal: Untreated lake water intermittently chlorinated. External: air.
CAUSE	The damage was apparently due to severely turbulent flow past a partially closed valve, coupled with flow disruption across the weld bead and pressure reduction in the region of diameter increase (see Case History 01.01.33.03).
REMEDY	• Operate the valve in the fully open position. • Specify a cavitation-resistant material such as hardened carbon steel, hardened stainless steel, or carbon steel overlaid with a cavitation-resistant material.

CORROSION ATLAS

CASE HISTORY

01.06.33.05

MATERIAL	Grey cast iron.
SYSTEM	Diesel-engine cooling system.
PART	Vertical cylinder liner.
PHENOMENON	Cavitation corrosion.

APPEARANCE	Vertical alignment of jagged, cavernous pits.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Internal: hot combustion gases, moving piston. External: Cooling water containing ethylene glycol.
CAUSE	Cavitation occurred on the cooling water side due to vibrations generated as the engine was running. Cavitation destroys the protective iron oxide covering of the metal. The iron oxide spontaneously reforms over the bare metal but is subsequently removed by impacting microjets from cavitation. Hence, the cavitation damage with respect to the metal is indirect, affecting the iron-oxide covering rather than the metal itself.
REMEDY	• Reduction or elimination of the vibration (sources of such vibration include piston slap, loose bearings and an out-of-balance crank shaft or piston). • Corrosion inhibitors added to the coolant have also been successful.

CORROSION ATLAS

CASE HISTORY

01.06.34.01

MATERIAL	Carbon steel.
SYSTEM	Cooling water system.
PART	Pipe section with branch.
PHENOMENON	Erosion corrosion.

APPEARANCE	Local excavation of the material
TIME IN SERVICE	2 to $2\frac{1}{2}$ years.
ENVIRONMENT	Cooling water which is periodically displaced by air, via the branch positioned perpendicular to the line, to make way for a cold calcium chloride brine.
CAUSE	Violent turbulence caused by injection of the air into the water-filled pipe.
REMEDY	• Introduction of air via an injection pipe bent in the direction of flow. • Alternative: a hardened steel shield placed opposite the air inlet.

CORROSION ATLAS

CASE HISTORY

01.06.34.02

MATERIAL	Cast iron.
SYSTEM	Cooling water system.
PART	Cooling water pump impeller.
PHENOMENON	Erosion corrosion.

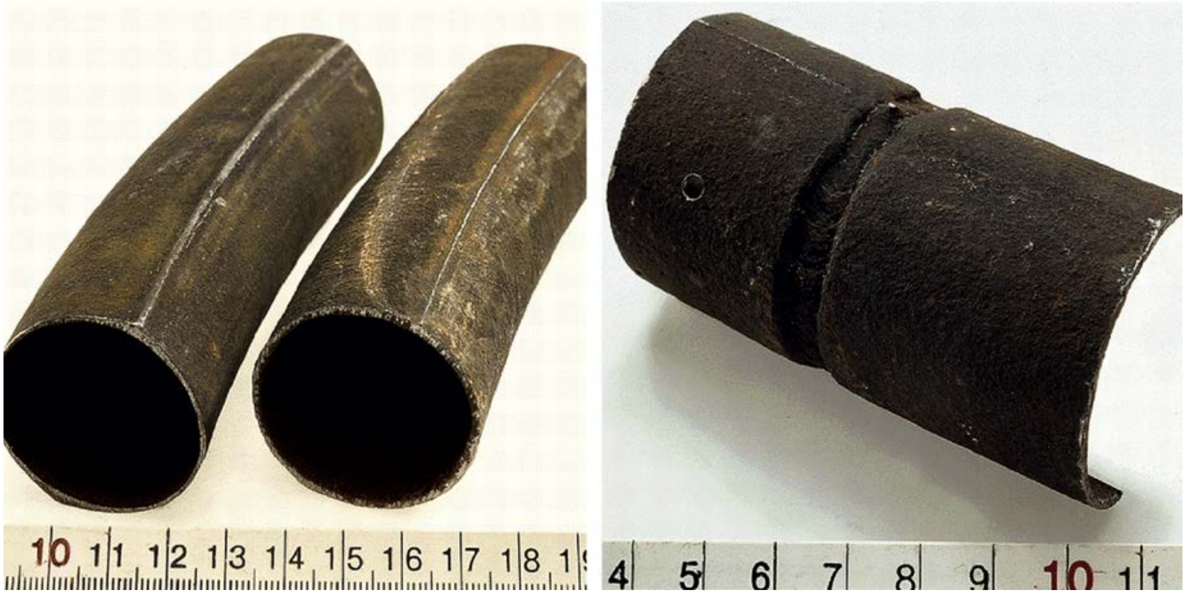
APPEARANCE	Material locally worn away entirely.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Cooling water; temperature 15–20°C.
CAUSE	Intake opening just under water level, so that an eddy arose and the air–water mixture drawn in caused the erosion corrosion.
REMEDY	Inlet opening should point downwards and/or be positioned deeper.

CORROSION ATLAS

CASE HISTORY

01.07.04.01

MATERIAL	Carbon steel.
SYSTEM	A ship flue-gas cooler (vertical, countercurrent).
PART	Tubes placed in coils.
PHENOMENON	Acid corrosion (dew-point corrosion).



APPEARANCE	The tubes show a pickled surface, caused by uniform corrosion from outside. The wall thickness has been reduced from 2.6 to 1.1 mm. The weld even shows a preferential attack to 0.5 mm thickness.
TIME IN SERVICE	5 years.
ENVIRONMENT	Inside: Mineral oil which is heated from 150 to 200°C. Outside: Flue-gases which are cooled from 300 to 210°C. The flue-gases are produced by the ship's main engine, which is fed with residual marine fuel containing maximum Sulfur monoxide (S.O). wt% sulfur.
CAUSE	The high sulfur content of the residual marine fuel causes sulfurous deposits on the tubes. The minimum wall temperature of 150°C is high enough to prevent dew-point corrosion by sulfuric acid during service. However, in the cold state the cooler is cleaned with drinking water, causing dilute sulfuric acid which is corrosive to mild steel. Only at the edge, where the coil tubes rest on one another, is there no space for pollution and therefore no corrosion occurs at the specific site, as the photographs shown.
REMEDY	This corrosion can be prevented by cleaning immediately after shut-down, with water alkalined by ammonia (see also Case History 01.01.04.09). Perhaps the effectiveness of the 20 Hz ultrasonic cleaner present at the bottom of the cooler can be increased additionally.

CORROSION ATLAS

CASE HISTORY

01.07.14.01

MATERIAL	Carbon steel soldered to copper.
SYSTEM	Freon cooling system.
PART	Compressor suction pipe.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Grooved attack to the steel surface.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Condensation on the uninsulated cold pipe.
CAUSE	Copper-containing condensation water running from the copper pipe over the steel pipe.
REMEDY	Appropriate insulation of the pipe.

CORROSION ATLAS

CASE HISTORY

01.07.25.01

MATERIAL	Carbon steel.
SYSTEM	Cooling system (ammonia).
PART	Insulated steel pipe.
PHENOMENON	Corrosion under insulation.

APPEARANCE	External pitting.
TIME IN SERVICE	10 years.
ENVIRONMENT	Internal: Ammonia gas, −10°C; external: pipe coated with a bitumen product and provided with polyurethane insulation.
CAUSE	The insulation was not vapor-tight, so that condensation water and ice were regularly formed when the cooling system was switched off and started up again. The bitumen product had hardened and was tending to flake off, so it provided inadequate protection. The steel was subjected to pitting corrosion owing to the presence of oxygen.
REMEDY	Before fitting the insulation, provide the pipes with a coating and then make the insulation vapor tight by means of a vapor barrier. The insulation shells' seams should be sealed by tape and/or compound.

CORROSION ATLAS

CASE HISTORY

01.08.04.01

MATERIAL	Carbon steel (ductile iron).
SYSTEM	Wastewater transport system.
PART	Pump impeller.
PHENOMENON	Acid attack.
	
APPEARANCE	A rough eroded surface. At the exits, material is partly worn away.
TIME IN SERVICE	3 years.
ENVIRONMENT	Water with some ppm phenol; temperature 50°C, maximum 100°C.
CAUSE	pH drop caused by contamination with sulfuric acid as a result of a failure. Because of the high temperature, cavitation may also have taken place.
REMEDY	Since future contamination with sulfuric acid cannot be excluded: • Construct the pump completely of AISI 316 and • Dilute the wastewater with cold water to reduce the acid concentration to maximum 1% and the temperature to maximum 50°C. At this temperature, cavitation will be prevented too. • Continuous monitoring of pH and temperature.

CORROSION ATLAS

CASE HISTORY

01.10.01.01

MATERIAL	Carbon steel.
SYSTEM	Fire extinguishing system.
PART	Underground pipe.
PHENOMENON	Oxygen corrosion.

APPEARANCE	Uniform corrosion of pipe wall and preferential attack of weld under deposits.
TIME IN SERVICE	20 years.
ENVIRONMENT	Aerated water with low flow (the system is also used for cleaning operations and illegal cooling).
CAUSE	The unprotected steel pipe is attacked by oxygen. Galvanic effects take place as a result of difference in the microstructure of weld and Heat Affected Zone (HAZ), leading to preferential attack of the weld.
REMEDY	Replaced by glass fiber-reinforced epoxy pipe.

CORROSION ATLAS

CASE HISTORY

01.10.17.01

MATERIAL	Carbon steel.
SYSTEM	Sprinkler extinguishing system (wet).
PART	Pipe section.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Local attack under the corrosion products, to the point of leakage.
TIME IN SERVICE	10 years.
ENVIRONMENT	Cold mains water, containing sulfate.
CAUSE	Attack by sulfide formed by sulfate-reducing bacteria in the anaerobic environment (sulfide was identified in the corrosion products and the water from the sprinkler system).
REMEDY	• Chemical cleaning of system. • Charging system with condensate or demineralized water or with mains water, but in the latter case draining and replenishing regularly (once a month).

CORROSION ATLAS

CASE HISTORY

01.11.02.01

MATERIAL	Carbon steel (ASTM A 106).
SYSTEM	Transport line from gas well to treatment plant.
PART	Straight pipe section and bend (13 cm wall thickness) (both sections coated afterward for preserving in good condition).
PHENOMENON	Flow-enhanced carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Left: pits and selective attack to the weld. Right: pitted, irregular attack at the outside of the bend.
TIME IN SERVICE	15 months.
ENVIRONMENT	Wet CO_2-containing natural gas at high pressure (180 bar).
CAUSE	High production velocities cause turbulence around the root of the weld and collision contact of the wet gas with the outside of the bend, resulting in local decrease in inhibitor efficiency.
REMEDY	Reduction of the flow velocities and sometimes controlled root reinforcement by specific welding procedures.

CORROSION ATLAS

CASE HISTORY

01.11.02.02

MATERIAL	Carbon steel.
SYSTEM	Natural gas well.
PART	Connecting piece (wall thickness 8 mm) on well tubing.
PHENOMENON	Turbulence-enhanced carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Pipe section severely attacked downstream side, at the screwed connection.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Wet carbon dioxide–containing natural gas.
CAUSE	The slight irregularity at the connection caused high turbulence, preventing formation of a protective iron carbonate scale.
REMEDY	Controlled flow velocity and enhanced corrosion protection by means of downhole inhibitor injection.

CORROSION ATLAS

CASE HISTORY

01.11.02.03

MATERIAL	Carbon steel.
SYSTEM	Gas production station piping.
PART	Pipe section (8 mm wall thickness).
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Local attack to the point of penetration near welded pipe supports.
TIME IN SERVICE	Several years.
ENVIRONMENT	Wet carbon dioxide–containing gas.
CAUSE	The welding treatment affected the structure of the steel, resulting in galvanically enhanced localized corrosion at a location where water was able to collect. The supports may have cooled the pipe locally (forming a cold bridge), leading to additional condensation.
REMEDY	• Improved treatment with corrosion inhibitors, and • Improved pipe support design where possible (use of dishes clamped to T-beam).

CORROSION ATLAS

CASE HISTORY

01.11.02.04

MATERIAL	Carbon steel.
SYSTEM	Natural gas well.
PART	Well tubing connection piece.
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Severe pitting and grooves in the longitudinal direction.
TIME IN SERVICE	Several years.
ENVIRONMENT	Wet carbon dioxide–containing natural gas.
CAUSE	Both turbulence and wireline work inside the pipe have reduced the formation of protective iron carbonate scales, thereby enhancing CO_2 corrosion.
REMEDY	Control flow velocities and inhibitor injection downhole.

CORROSION ATLAS

CASE HISTORY

01.11.02.05

MATERIAL	Carbon steel.
SYSTEM	Crude oil storage tank.
PART	Bottom plate weld.
PHENOMENON	Attack by aggressive water.

APPEARANCE	Sharp groove adjacent to the weld, like knife-line attack of stabilized stainless steel (see Case History 04.11.19.04).
TIME IN SERVICE	5 years.
ENVIRONMENT	Crude oil and aqueous bottom layer.
CAUSE	The heat-affected zone dissolved electrolytically, because this zone was less noble in relation to the rest of the plate.
REMEDY	Attack by aggressive water can be prevented by application of a coating to the bottom. In this case, no measures have been taken because the lowest bottom plate was still intact, so there was no danger of leakage.

CORROSION ATLAS

CASE HISTORY

01.11.02.06

MATERIAL	Carbon steel (API grade J-55).
SYSTEM	Oil well.
PART	Casing (OD: 219 mm), located at a depth of 122 m.
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Localized external casing corrosion of the mesa type.
TIME IN SERVICE	37 years.
ENVIRONMENT	Formation water containing carbon dioxide.
CAUSE	Direct contact of the casing with a formation containing corrosive water. (Ref. Gordon, B.A., Grimes, W.D. and Treseder, R.S.: "Casing corrosion in the South Belridge Field", Materials Performance (1984) 23, No. 3, 9) (see also Case Histories 01.11.02.01/02/03/04).
REMEDY	Provide positive cement cover of the casing in locations where corrosive formation waters exist. Apply cathodic protection where feasible.

CORROSION ATLAS

CASE HISTORY

01.11.02.07

MATERIAL	Carbon steel.
SYSTEM	Blast furnace gas pipe.
PART	Bottom pipe wall.
PHENOMENON	Carbonic acid corrosion.

APPEARANCE	Severe terraced attack.
TIME IN SERVICE	5 years.
ENVIRONMENT	Condensation water from blast furnace gas containing 16–29% CO_2.
CAUSE	The carbonic acid in the water attacks the steel. Underdeposit corrosion under precipitated sediment occurs at the same time.
REMEDY	On reconstruction, protection was provided in the form of a coal tar epoxy coating.

CORROSION ATLAS

CASE HISTORY

01.11.03.01

MATERIAL	Carbon steel.
SYSTEM	Caustic soda transport system.
PART	Pipe.
PHENOMENON	Caustic corrosion.

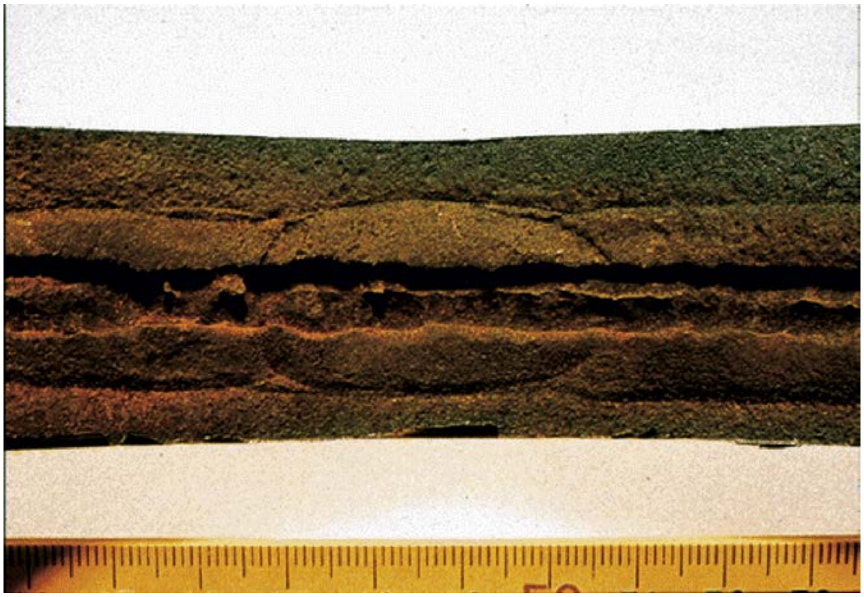
APPEARANCE	Local reduction in wall thickness by uniform attack.
TIME IN SERVICE	4 years.
ENVIRONMENT	50% NaOH; wall temperature maximum 140°C.
CAUSE	NaOH attack at the steam tracing, due to locally excessive wall temperature during product standstill steel is attacked by caustic according to: $Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2 \uparrow$. (See also Case History 01.01.03.01.)
REMEDY	Use of a self-regulating electric tracing, allowing the temperature to be kept lower.

CORROSION ATLAS

CASE HISTORY

01.11.04.01

MATERIAL	Carbon steel.
SYSTEM	Sulfuric acid transport system.
PART	Pipe section.
PHENOMENON	Acid corrosion.



APPEARANCE	Selective leaching of the weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	71% H_2SO_4; temperature 40°C.
CAUSE	The difference in structure between the weld and the pipe material leads to selective attack to the weld (the oval ring at the center betrays the presence of a local repair in the weld) (For selective attack to the weld, see also Case Histories 01.01.04.03 and 01.10.01.01 and refer also to section stainless steel.)
REMEDY	Normalizing of the weld.

CORROSION ATLAS

CASE HISTORY

01.11.04.02

MATERIAL	Carbon steel.
SYSTEM	Outdoor transport system for vegetable oil.
PART	Pipe section on support, pipe insulated with glass wool and equipped with steam tracing.
PHENOMENON	Acid corrosion.

APPEARANCE	Internal uniform corrosion with a pickled metallic blank appearance exactly where the line rests on the support, while the 2-mm-thick wall eroded through locally.
TIME IN SERVICE	Several years.
ENVIRONMENT	For 1 to $1\frac{1}{2}$ hours a day, palm oil stearin, temperature 100–110°C and containing 0.5–1% fatty acid, is pumped through the line after it has been preheated with hot air for half an hour. Afterward the line is purged with cold air.
CAUSE	Condensation of moisture from the hot air, and condensation of volatile fatty acids from the product, selective to the uninsulated contact points with the support, forming a “cold bridge.” As a result of accumulation of the fatty acids, the pH can fall to around 5. It may be that polymerization is also involved in the formation of acids.
REMEDY	• Eliminate the cold bridge by applying insulation between the line and support. • Prevent condensation by first conditioning the hot air by drying it or by keeping the line in continuous operation by recirculation of the oil (the latter solution is more expensive of energy than drying the air).

CORROSION ATLAS

CASE HISTORY

01.11.04.03

MATERIAL	Carbon steel (ASTM A 106, grade B).
SYSTEM	Sulfuric acid transport system.
PART	Pipe bend curving from the vertical to the horizontal, with electrical tracing at the outside of the bend.
PHENOMENON	Acid corrosion (hydrogen grooving).

APPEARANCE	A long sharp groove 1.5 mm wide, becoming increasingly deep until it penetrates the 5mm-thick pipe wall, then fanning out in several dozen small grooves.
TIME IN SERVICE	Several years.
ENVIRONMENT	95–96% sulfuric acid, temperature 25°C, maximum wall temperature 40°C. Pressure 3.5 bar, flow rate 1 m/s. Regular stagnant conditions.
CAUSE	Carbon steel possesses good resistance to concentrated sulfuric acid at ambient temperature and low flow rate (<0.9 m/s), due to the precipitation of a ferrous sulfate layer which acts as a corrosion barrier ($Fe + H_2SO_4 \rightarrow FeSO_4 + H_2$). Under special conditions (when strong acid is not moving), the steady passage of the hydrogen bubbles on a preferred path can disturb the ferrous sulfate layer. The normal steady state of low corrosion will be disrupted and grooving will result with high local corrosion rates of 3–7 mm/yr. The local high wall temperature has accelerated the corrosion.
REMEDY	• Maintain a minimum velocity of 0.3 m/s, or • Apply anodic protection, or • Use Hypalon® or glass linings at places sensitive to hydrogen grooving, or • Construct these parts from AISI 316 for sulfuric acid concentrations of 90–100.3%, or • Use baked phenolic linings or claddings (in tanks) made from Carpenter Alloy 20-Cb-3 or Hastelloy C276 for protection in 70–105% sulfuric acid.

CORROSION ATLAS

CASE HISTORY

01.11.04.04

MATERIAL	Carbon steel (pipe) and cast iron (flange).
SYSTEM	Sulfuric acid supply system.
PART	3/4″ pipe section with flange.
PHENOMENON	Acid corrosion.

APPEARANCE	Grooved attack in the rolling direction of the pipe and pitting attack to the flange pipe.
TIME IN SERVICE	<1 h.
ENVIRONMENT	Sulfuric acid 98% and steam.
CAUSE	The sulfuric acid line was blown through with steam because it was blocked. The resultant dilution and high temperature caused the rapid attack. Unlike concentrated sulfuric acid, dilute sulfuric acid is aggressive to carbon steel.
REMEDY	In the event of blockage, the pipe should be drained as fully as possible and neutralized with dilute sodium hydroxide before being steamed or otherwise cleaned. Flush with demineralized water afterward.

CORROSION ATLAS

CASE HISTORY

01.11.04.05

MATERIAL	Carbon steel.
SYSTEM	Chemical transport system.
PART	Vertical overfall line from pump to storage tank.
PHENOMENON	Acid corrosion.

APPEARANCE	Pitting, each pit consists of narrowing rings.
TIME IN SERVICE	4 months.
ENVIRONMENT	Sulfuric acid 96%; flow rate: 0.5 m/sec; temperature 15–20°C.
CAUSE	Probably local breakdown of the passive iron sulfate layer by contaminations in the sulfuric acid (moist, air) or local variations in concentration with continually alternately passivation and activation, resulting in the corrosion picture illustrated. Present mill scale can cause serious pitting too.
REMEDY	The overfall line was replaced.

CORROSION ATLAS

CASE HISTORY

01.11.04.06

MATERIAL	Carbon steel.
SYSTEM	Crude distiller.
PART	Dead-end nozzle on mild vacuum column.
PHENOMENON	Acid corrosion (dew-point corrosion).

APPEARANCE	Local attack with grooves.
TIME IN SERVICE	4 years.
ENVIRONMENT	Hydrocarbons, water and hydrochloric acid.
CAUSE	Condensation of hydrochloric acid occurred in a cold nozzle due to wet insulation.
REMEDY	• Operate at higher temperatures. • Appropriate insulation.

CORROSION ATLAS

CASE HISTORY

01.11.06.01

MATERIAL	Low-alloyed steel (5 CrMo 0.5).
SYSTEM	Feedstock plant for rubber manufacture.
PART	10″ transfer pipe between furnace and reactor.
PHENOMENON	High-temperature corrosion (metal dusting).

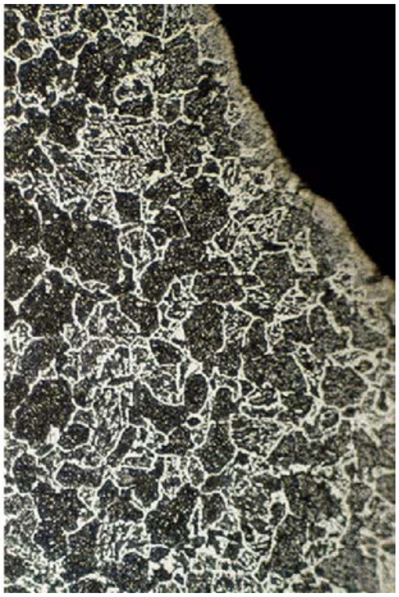
APPEARANCE	Severe pitting corrosion in the form of wide, basin-shaped pits.
TIME IN SERVICE	15 months.
ENVIRONMENT	Butylene. Temperature 535°C. Pressure 1 bar.
CAUSE	The reaction with carbon components from the gas phase leads to excessive formation of chromium carbides by internal carburization. This leads to disintegration of the metal into a pulverized mixture of carbon, metal parts, metal oxides, and metal carbides. These corrosion products are easily removed in a gas flow, leaving pits behind. Metal dusting is a special form of carburization.
REMEDY	Replacement by 20 Cr and 15 Ni pipes.

CORROSION ATLAS

CASE HISTORY

01.11.06.02

MATERIAL	Low-alloyed steel (2.25 Cr 1 Mo steel).
SYSTEM	Oil refinery–catalytic reformer.
PART	Vertical heater, U-tube.
PHENOMENON	High-temperature corrosion (metal dusting).



APPEARANCE	Pitted surface with various types of pits. Absence of scale or deposits.
TIME IN SERVICE	Tubes have been in operation for 12 years. Pits probably formed in short period of time.
ENVIRONMENT	Desulfurized naphtha feed with hydrogen. Total pressure 1 MPa. Temperature around 600°C.
CAUSE	Operation at temperature slightly over the design temperature, most likely in combination with low sulfur level.
REMEDY	Closer temperature control in operation. Consider material upgrade.

CORROSION ATLAS

CASE HISTORY

01.11.06.04

MATERIAL	Carbon steel.
SYSTEM	Sulfur recovery unit.
PART	Tube sheet of waste heat boiler.
PHENOMENON	High-temperature corrosion (sulfidation).

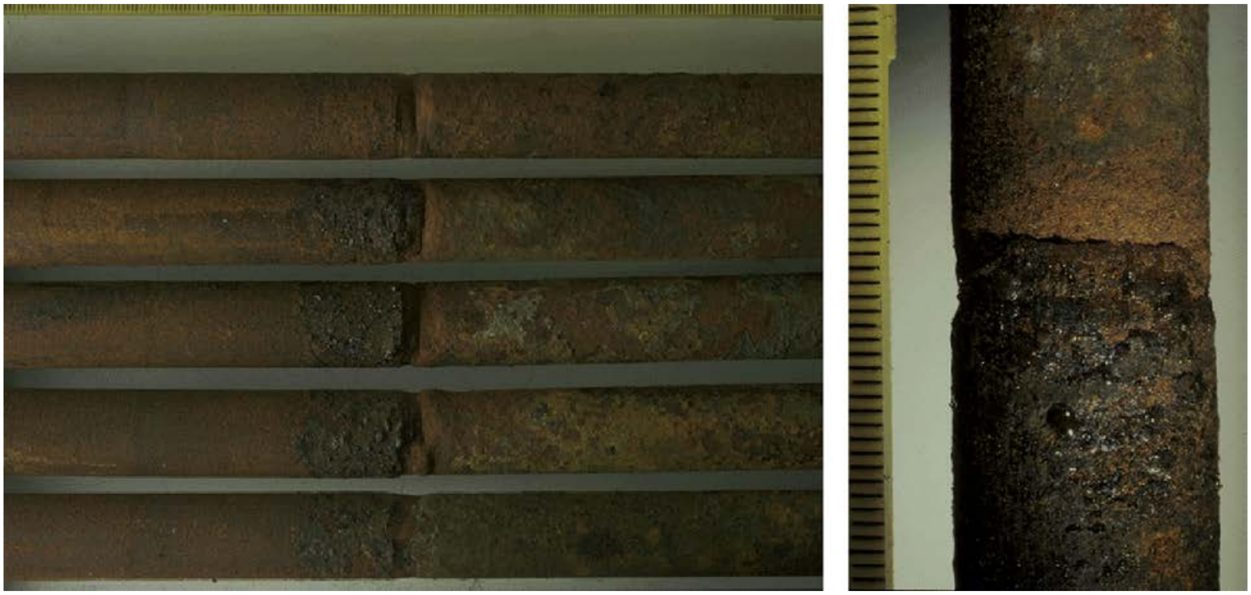
APPEARANCE	General corrosion.
TIME IN SERVICE	4 years.
ENVIRONMENT	Hot gases in reducing environment at 1000–1200°C.
CAUSE	Refractory and tube inserts were damaged, causing ingress of hot gases between the tube sheet and refractory. This in turn caused high-temperature sulfidation (see also Case Histories 05.01.06.01 and 05.19.06.01).
REMEDY	Apply an effective technique to bond the refractory to the tube sheet and use appropriate tube inserts.

CORROSION ATLAS

CASE HISTORY

01.11.06.05

MATERIAL	Carbon steel 35.8.
SYSTEM	Desulfurization plant.
PART	Pipes from the heavy gas oil heat exchanger.
PHENOMENON	High-temperature corrosion (sulfur corrosion).



APPEARANCE	Just behind the pipe plate, the wall thickness of the pipes in the upper part of the horizontal bundle has decreased from 2.25 to 1.2–1.5 mm. The left-hand part is fitted in the pipe plate (200 mm).
TIME IN SERVICE	2.5 years.
ENVIRONMENT	Around the pipes: sulfur-containing oil (0.24% S, >0.1% H_2) which is heated from 35 to 155°C. Through the pipes: desulfurized oil fed at a temperature of 235°C (according to specification!).
CAUSE	As a result of overloading of the plant in response to the large demand for low-sulfur oil and also because of the deposition of sludge, the local wall temperature considerably exceeded the design temperature of 235°C. Attack took place at a temperature >250°C at the hottest place (immediately after the pipe plate) by hydrogen sulfide present in the oil, originating from decomposition of the organic sulfur compounds during distillation. The presence of H_2 promoted this attack because hydrogen converts organic sulfur compounds to hydrogen sulfide. The corrosion rate depends on the partial pressure of H_2S.
REMEDY	• Prevent overloading and sludge formation (the latter by means of modified design); or • Construct the heat exchanger of stainless steel AISI 316 L with extra low carbon content and Nb stabilized (e.g., W.-Nr. 1.4575 or 1.4581).

CORROSION ATLAS

CASE HISTORY

01.11.06.06

MATERIAL	Carbon steel.
SYSTEM	Distillation column.
PART	Bottom effluent line.
PHENOMENON	High-temperature corrosion (sulfur corrosion).

APPEARANCE	Pipe exhibits local reduction of wall thickness and has fractured (outside left, inside right).
TIME IN SERVICE	$\frac{1}{2}$ year.
ENVIRONMENT	Hydrocarbons and sulfur compounds originating from sulfur-containing crude oil. Temperature 390°C. Pressure 25 bar.
CAUSE	Rapid and local wall thickness reduction due among other things to turbulence and accelerated sulfur corrosion. By altering the operating conditions, namely applying a higher temperature, the sulfur corrosion was accelerated, thereby substantially reducing the operating time. The pipe fracture caused a fire which led to total destruction of the plant.
REMEDY	• Alterations in the process conditions should be submitted to the corrosion department in advance. • Alternative: construct the pipe of 12 CrMo 19 5 (see also Case History 01.11.06.08).

CORROSION ATLAS

CASE HISTORY

01.11.06.07

MATERIAL	Carbon steel.
SYSTEM	Slurry system.
PART	Attachment weld of two pipe sections from a transport pipeline.
PHENOMENON	High-temperature corrosion (sulfur corrosion).

APPEARANCE	Uniform attack to the left side of the weld.
TIME IN SERVICE	About 10 years.
ENVIRONMENT	Slurry consisting of hydrocarbons with sulfur and catalyst particles. Temperature 360°C. Pressure 10 bar.
CAUSE	Both API and ASTM pipes were used in the slurry system. Following the occurrence of corrosion, a metal analysis was performed which showed that the ASTM pipe had a higher silicium content than the API pipe, namely 0.23% against 0.1%, which made it more corrosion-resistant. The API pipe section is shown on the left.
REMEDY	ASTM pipe is now used.

CORROSION ATLAS

CASE HISTORY

01.11.06.08

MATERIAL	Straight piece: carbon steel; bend piece: steel (12 CrMo 19 5; W.-Nr. 1.7362).
SYSTEM	High-vacuum distillation unit.
PART	Process pipe.
PHENOMENON	High-temperature corrosion (sulfur corrosion).

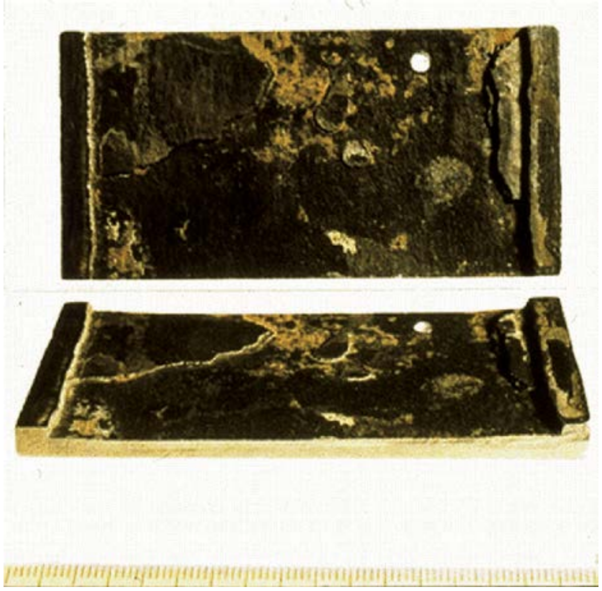
APPEARANCE	Uniform attack to a pipe section.
TIME IN SERVICE	2 years.
ENVIRONMENT	Hydrocarbons and sulfur compounds (organic and inorganic); temperature approximately 380°C.
CAUSE	By error, a carbon steel pipe section was incorporated which is not resistant to sulfur corrosion.
REMEDY	Construction of the entire pipe from 12 CrMo 19 5 steel, and in future improvement of the quality control.

CORROSION ATLAS

CASE HISTORY

01.11.06.09

MATERIAL	Base material: steel (10 CrMo 9 10; W.-Nr. 1.7380), welded-up at the sides with AISI 347 stainless steel.
SYSTEM	Desulfurization unit.
PART	Reactor test block.
PHENOMENON	High-temperature corrosion (sulfur corrosion).



APPEARANCE	Uniform attack of the base material.
TIME IN SERVICE	4 years.
ENVIRONMENT	Hydrocarbons with H_2S and H_2; temperature 350–385°C; partial hydrogen pressure approximately 30 bar. Sulfur corrosion is also known as sulfidic corrosion.
CAUSE	In the presence of hydrogen, the base material is attacked by sulfur at this high temperature.
REMEDY	Use AISI 347 stainless steel cladding.

CORROSION ATLAS

CASE HISTORY

01.11.06.10

MATERIAL	Low-alloyed steel (5 CrMo 0.5).
SYSTEM	High-vacuum distillation unit.
PART	Roof furnace tube.
PHENOMENON	High-temperature corrosion (oxidation).

APPEARANCE	Internally, coke deposition with external scaling and wall thickness reduction.
TIME IN SERVICE	About 8 years.
ENVIRONMENT	External: flue gases at 410°C. Internal: Hydrocarbons originating inter alia from the bottom fraction of primary distillation.
CAUSE	The wall temperature rose to excessive levels due to coke deposition at the top of the pipe (i.e., not the flame side). As a result, severe external scaling occurred due to combustion and the wall thickness decreased. The pipe fractured as a result of these factors.
REMEDY	• Prevention by regular decoking, e.g., with steam and oxygen. • Monitoring of the wall thickness by regular inspection, also at the rear of the pipes.

CORROSION ATLAS

CASE HISTORY

01.11.14.01

MATERIAL	Bolt: carbon steel; plate: 12% Cr steel (AISI 410).
SYSTEM	Distillation column.
PART	Tray clamp.
PHENOMENON	Galvanic corrosion.
	
APPEARANCE	Severe attack to bolt and nut over their entire surface.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hydrocarbons contaminated with traces of salts.
CAUSE	Two different steel grades in a conductive environment leads to galvanic corrosion to the less noble steel (couple action) (see also Case History 01.06.14.01).
REMEDY	Use bolts made of 12% Cr steel.

CORROSION ATLAS

CASE HISTORY

01.11.14.02

MATERIAL	Carbon steel attached to stainless steel.
SYSTEM	Sulfuric acid transport system.
PART	Pipe section.
PHENOMENON	Galvanic corrosion and erosion corrosion.

APPEARANCE	Uniform attack of the carbon steel pipe.
TIME IN SERVICE	3 years.
ENVIRONMENT	96–98% sulfuric acid; ambient temperature; velocity: 1 m/s.
CAUSE	Carbon steel is normally resistant to concentrated sulfuric acid, as a passivating iron sulfate skin is formed. In this case, the potential difference between the stainless steel and the carbon steel, as well as erosion caused by the meanwhile eroded welded joint, prevented build-up of this skin (see also Case History 01.11.34.03).
REMEDY	Construct the pipe completely of carbon steel or stainless steel. Lower the velocity of H_2SO_4 in carbon steel pipeline to <0.6 m/s.

CORROSION ATLAS

CASE HISTORY

01.11.17.01

MATERIAL	Carbon steel.
SYSTEM	Product storage tank.
PART	Bottom plate.
PHENOMENON	Microbiologically induced corrosion.

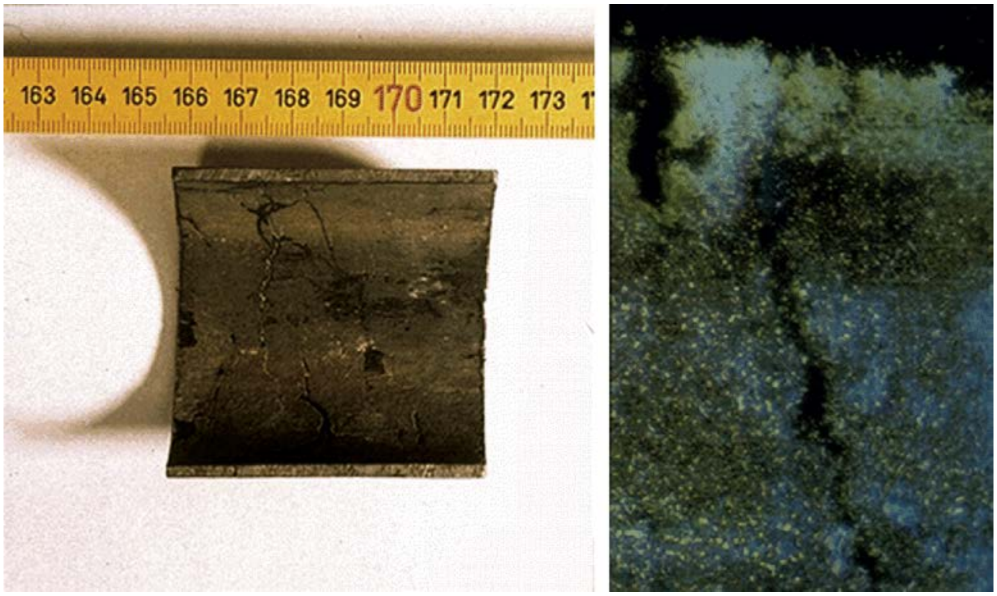
APPEARANCE	Severe local attack (external).
TIME IN SERVICE	6 years.
ENVIRONMENT	Groundwater.
CAUSE	The insulation in the tank pad below the tank was found to be contaminated with sulfate. In combination with the high groundwater level, this led to the growth of sulfate-reducing bacteria. The resultant sulfide attacked the steel.
REMEDY	Raise the pad so that the tank no longer stands in the groundwater, and use sulfate-free insulation (e.g., cellular glass).

CORROSION ATLAS

CASE HISTORY

01.11.18.01

MATERIAL	Carbon steel.
SYSTEM	Caustic soda transport system.
PART	Pipe section.
PHENOMENON	Intergranular stress corrosion (caustic stress-corrosion cracking).



APPEARANCE	Cracking at suspension point.
TIME IN SERVICE	3–4 years.
ENVIRONMENT	31% NaOH; temperature 50°C.
CAUSE	Combination of stresses at the suspension point coupled with the high alkalinity (see also Case Histories 01.01.18.02, 01.01.18.05, and 01.11.18.04).
REMEDY	Replace the pipe by a new pipe with multiple supports in order to reduce the stresses.

CORROSION ATLAS

CASE HISTORY

01.11.18.02

MATERIAL	Carbon steel.
SYSTEM	Urea autoclave.
PART	Carbon steel jacket with a stainless steel lining.
PHENOMENON	Intergranular stress corrosion (nitrate stress-corrosion cracking).

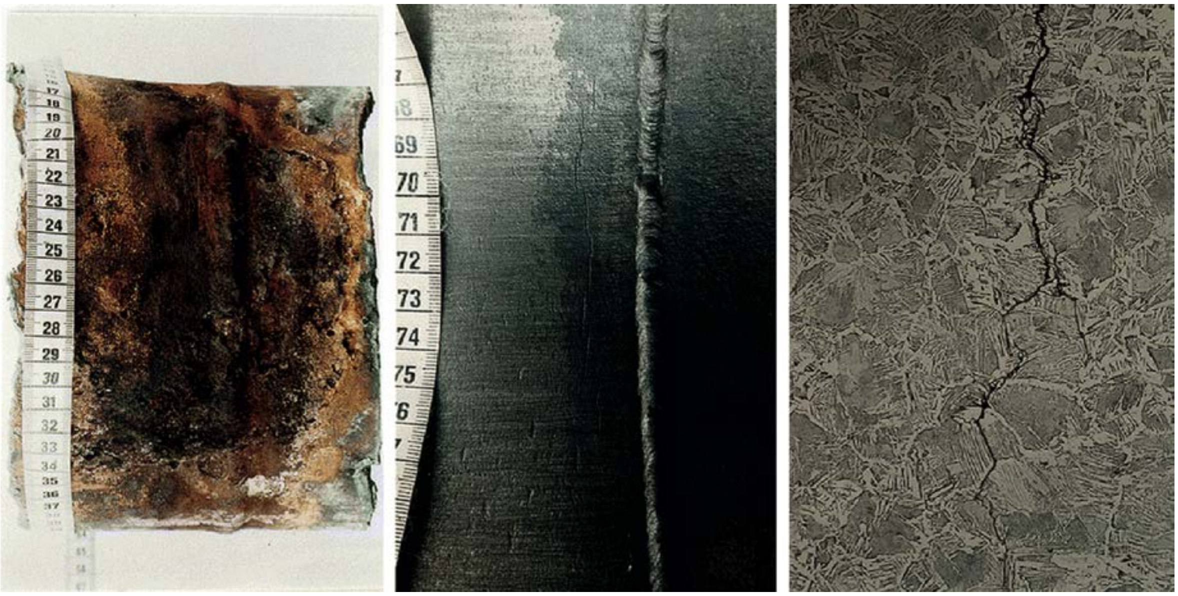
APPEARANCE	Cracking transverse to the weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Nitrate-containing rainwater, entering through faults in the aluminum insulation plating. Wall temperature about 150°C (see also Case Histories 01.01.18.04 and 04.11.18.10).
CAUSE	Intergranular stress corrosion caused by nitrate.
REMEDY	The reactor was positioned under a roof in order to keep it dry.

CORROSION ATLAS

CASE HISTORY

01.11.18.03

MATERIAL	Carbon steel.
SYSTEM	Sour water stripper.
PART	Insulated overhead line to sulfur recovery unit.
PHENOMENON	Carbonate/bicarbonate stress-corrosion cracking.



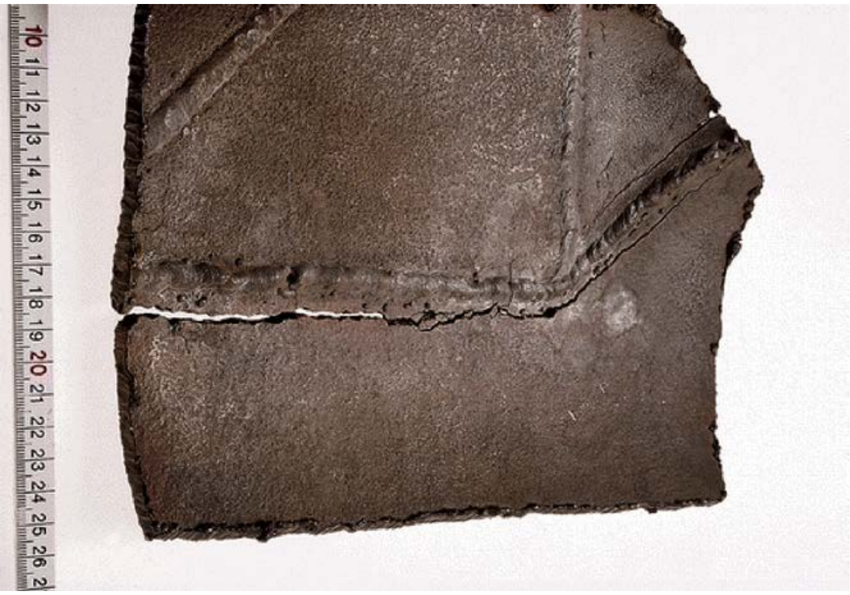
APPEARANCE	Intergranular cracking near the weld.
TIME IN SERVICE	14 years.
ENVIRONMENT	Wet sour gas containing CO_2, H_2O, H_2S, and NH_3.
CAUSE	The potential problem in the line is condensation of the wet sour gas resulting in general corrosion and/or stress corrosion cracking. The line has been protected against these phenomena by steam tracing. However, water ingress under the insulation reduced the metal temperature, resulting in condensation. At the outside surface, underlagging corrosion was present. In this instance, the corrosives have provoked stress-corrosion cracking, resulting in leakage (see also Case History 01.05.18.01).
REMEDY	Maintaining the metal temperature above dew point by prevention of water ingress by both repair of the insulation and sealing-off the protective sheathing in an effective way.

CORROSION ATLAS

CASE HISTORY

01.11.18.04

MATERIAL	Carbon steel.
SYSTEM	Caustic soda scrubber for scrubbing benzene.
PART	Off-gas line.
PHENOMENON	Stress-corrosion cracking (caustic stress-corrosion cracking).



APPEARANCE	Selective cracking in the heat-affected zones beside the weld.
TIME IN SERVICE	$\frac{1}{2}$ year.
ENVIRONMENT	Benzene with caustic soda droplets. Temperature 80°C.
CAUSE	With the combination of stresses and caustic soda at the present temperature, carbon steel is subject to stress corrosion (see also Case Histories 01.01.18.02 and 01.11.18.01).
REMEDY	Stress-relief post-weld treatment.

CORROSION ATLAS

CASE HISTORY

01.11.20.01

MATERIAL	Carbon steel.
SYSTEM	Cooling tower with heat exchanger.
PART	Cooler pipe from heat exchanger (with aluminum brass jacket pipe, see Case History 06.06.18.01).
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack, decarburization).

APPEARANCE	Laminar Assuring.
TIME IN SERVICE	Several years.
ENVIRONMENT	Through the steel pipe: a high-pressure (150 bar) gas mixture of hydrogen, nitrogen, and ammonia at approximately 240°C.
CAUSE	Under these conditions, molecular hydrogen (H_2) dissociates at the steel surface to atomic hydrogen (H), which readily diffuses into the steel, where it reacts with the cementite (Fe_3C) of the steel to form methane gas ($Fe_3C + 2H_2 \rightarrow 3Fe + CH_4$). The steel cracks owing to pressure build-up (see also Case Histories 01.01.20.02/03/04/05/06 and 01.11.20.03).
REMEDY	Application of 0.5 Mo steel or one of the Cr-Mo steels, depending on the metal temperature and hydrogen partial pressure (according to the Nelson curves, see API 941).

CORROSION ATLAS

CASE HISTORY

01.11.20.02

MATERIAL	Carbon steel.
SYSTEM	Desulfurization plant.
PART	6″ pipe to the furnace.
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack).

APPEARANCE	Crack beside the weld.
TIME IN SERVICE	6 years.
ENVIRONMENT	Hydrocarbons with hydrogen; temperature 300°C; partial hydrogen pressure 25–30 bar.
CAUSE	Injudicious moving of the hydrogen injection point. This exposed the existing carbon steel pipe system to “hot hydrogen.” The heat-affected zone beside the weld was selectively attacked as a result.
REMEDY	Application of a hydrogen-resistant material (low-alloyed Cr–Mo steel).

CORROSION ATLAS

CASE HISTORY

01.11.20.03

MATERIAL	Carbon steel.
SYSTEM	Platformer.
PART	Ballast plate.
PHENOMENON	Hydrogen damage (high-temperature hydrogen attack, decarburization).

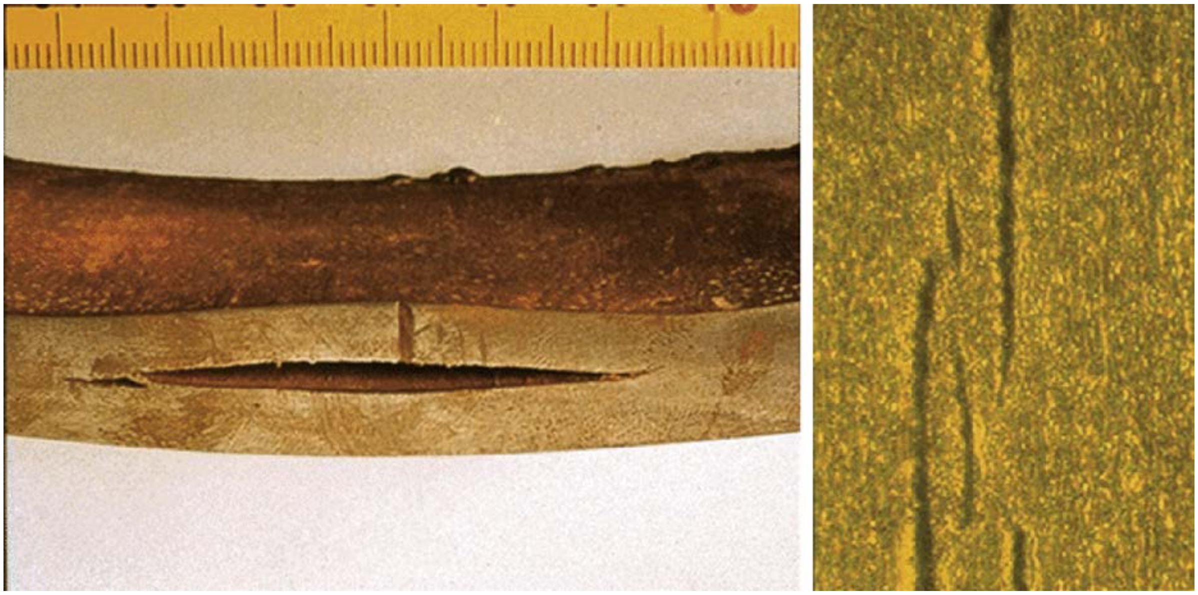
APPEARANCE	Blistering.
TIME IN SERVICE	2 years.
ENVIRONMENT	Naphtha (gasoline) and hydrogen gas; temperature approximately 500°C.
CAUSE	Atomic hydrogen diffuses into the metal where it forms methane by reacting with the carbon of the metastable carbides. Pressure build-up causes the metal to crack (see also Case History 01.11.20.01).
REMEDY	Use of low-alloyed (hydrogen-resistant) steel.

CORROSION ATLAS

CASE HISTORY

01.11.20.04

MATERIAL	Carbon steel.
SYSTEM	Hydrofluoric alkylation plant.
PART	Wall.
PHENOMENON	Hydrogen damage (hydrogen blistering, cold hydrogen attack).



APPEARANCE	Blistering.
TIME IN SERVICE	10 years.
ENVIRONMENT	Hydrocarbons; HF vapors; temperature 60°C.
CAUSE	The atomic hydrogen released by electrochemical corrosion diffuses into the steel until it is obstructed by contaminations in the steel. At this point, molecular hydrogen is formed. The resultant pressure build-up then causes blisters in the material (see also Case History 01.23.20.01).
REMEDY	Use of “purer” steel.

CORROSION ATLAS

CASE HISTORY

01.11.20.05

MATERIAL	Steel (34 CrNiMo 6; W.-Nr. 1.6582).
SYSTEM	Reactor.
PART	Nut with bolt.
PHENOMENON	Hydrogen damage (hydrogen embrittlement).

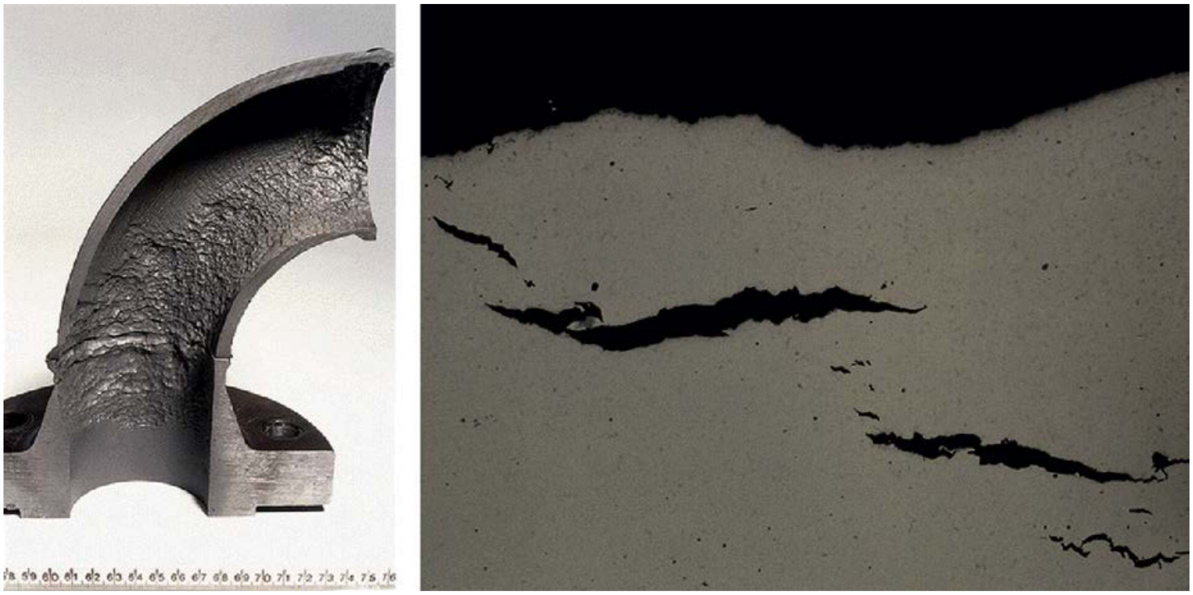
APPEARANCE	Bolt completely broken off.
TIME IN SERVICE	A few years.
ENVIRONMENT	Industrial atmosphere.
CAUSE	The large screw thread can easily retain rainwater, which is acidified by the industrial atmosphere. The atomic hydrogen formed during corrosion diffuses in the steel, thereby causing its strength to diminish.
REMEDY	The space between bolt and nut should be sealed.

CORROSION ATLAS

CASE HISTORY

01.11.20.06

MATERIAL	Carbon steel (flange: ASTM A 105, bend: ASTM A 234 WPB), with sulfur contents of, respectively, 0.009% and 0.004% (low-sulfur types)).
SYSTEM	Hydrodesulfurization unit.
PART	Flange and bend upstream of depressuring valve, from an interconnecting line between high-pressure and low-pressure separators.
PHENOMENON	Hydrogen damage (hydrogen-induced cracking) and general corrosion.



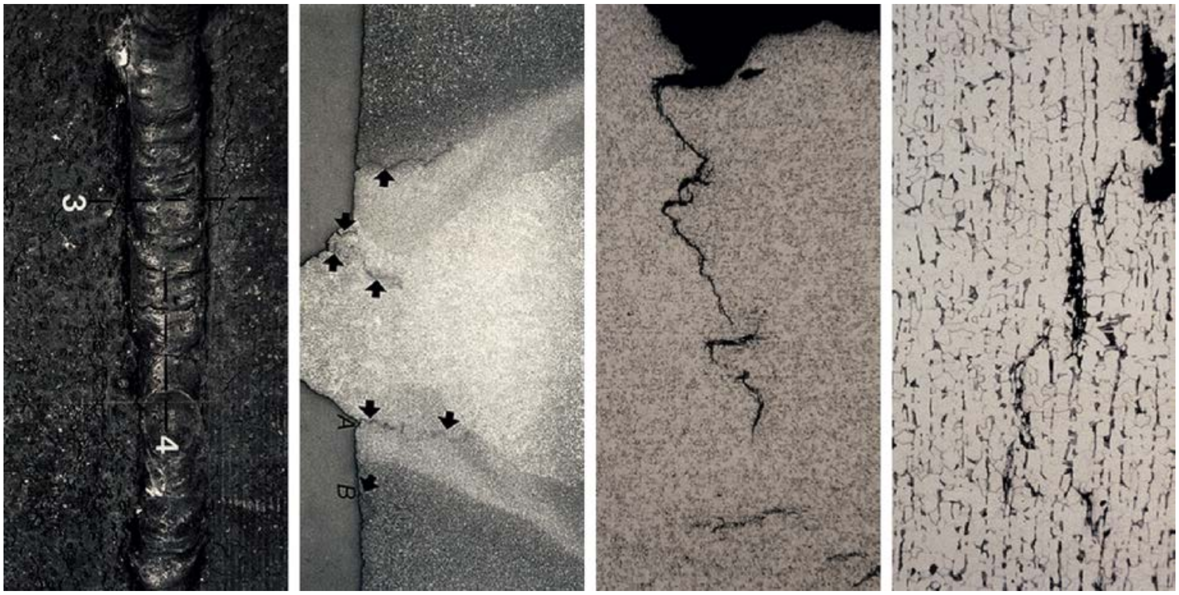
APPEARANCE	Thinning and internal cracking.
TIME IN SERVICE	7 years
ENVIRONMENT	Hydrocarbons containing small amounts of H_2O, H_2S, and NH_3.
CAUSE	The sublimation temperature of NH_4HS is a function of the partial pressure of both H_2S and NH_3. The conditions at the location of the bend/flange are such that salts of NH_4HS will precipitate (desublimation). Under wet conditions, general corrosion will occur. Apparently, the charging of the carbon steel with hydrogen, liberated by the corrosion process was such that hydrogen-induced cracking was produced as well. This occurred notwithstanding the low sulfur content, which in general is an adequate measure to prevent this phenomenon.
REMEDY	Either the application of heat tracing to maintain the operating temperature in excess of the sublimation temperature or the application of a water wash treatment.

CORROSION ATLAS

CASE HISTORY

01.11.20.07

MATERIAL	Carbon steel (ASTM A 105 N).
SYSTEM	Amine unit.
PART	Outlet header of overhead condenser (air-fin bank).
PHENOMENON	Hydrogen damage [stress-oriented hydrogen-induced cracking (SOHIC)].



APPEARANCE	Stepwise transgranular cracking in the zone between the round weld and the base material (ferrite and perlite).
TIME IN SERVICE	May occur within a short period: weeks.
ENVIRONMENT	The overhead product: condensate containing residual hydrocarbons, NH_3, H_2S, pH >9. Temperature 40–45°C.
CAUSE	Under the prevailing conditions, carbon steel may be sensitive to SOHIC. Contributing factors are regions with either relatively high or relatively low hardness values in combination with stress raisers due to, e.g., poor weld penetration. In the former case, SOHIC will be initiated as sulfide stress-corrosion cracking, whereas in the second case, cracking is caused by a combination of hydrogen charging and local high strains.
REMEDY	Risks of SOHIC will be reduced by the following measures: • selection of HIC-resistant steel, • normalized condition, • welding of root run by the Gas tungsten arc welding (GTAW) process, • application of a Post Weld Heat Treatment (PWHT). The most effective way to prevent Stress orientated Hydrogen Induced cracking (SOHIC) is to select a superaustenitic stainless steel containing 6% Mo.

CORROSION ATLAS

CASE HISTORY

01.11.22.01

MATERIAL	Carbon steel.
SYSTEM	Zinc recuperation furnace for processing zinc-containing slag (Simson furnace).
PART	Link of an iron chain.
PHENOMENON	"Gaseous metal embrittlement."

APPEARANCE	Flaking-off scale formation and brittle fracture.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Zinc vapors at 450–600°C in the upper part of furnace; operating temperature of furnace underneath 1800 degrees.
CAUSE	Zinc vapors diffuse along the grain boundaries into the steel of the chain, as a result of which intermetallic iron–zinc compounds are formed which have an embrittling effect. In the core of the link, 0.04% (400 ppm) of zinc was found. On the outside, this was 1% (10,000 ppm). By analogy with the term "Liquid metal embrittlement" (see Case History 01.04.22.01), this case could be referred to as "Gaseous metal embrittlement."
REMEDY	Manufacture the chain using brass, or replace it regularly.

CORROSION ATLAS

CASE HISTORY

01.11.25.01

MATERIAL	Carbon steel insulated with glass wool.
SYSTEM	Mercaptan transport system.
PART	Pipe section.
PHENOMENON	Corrosion under insulation.

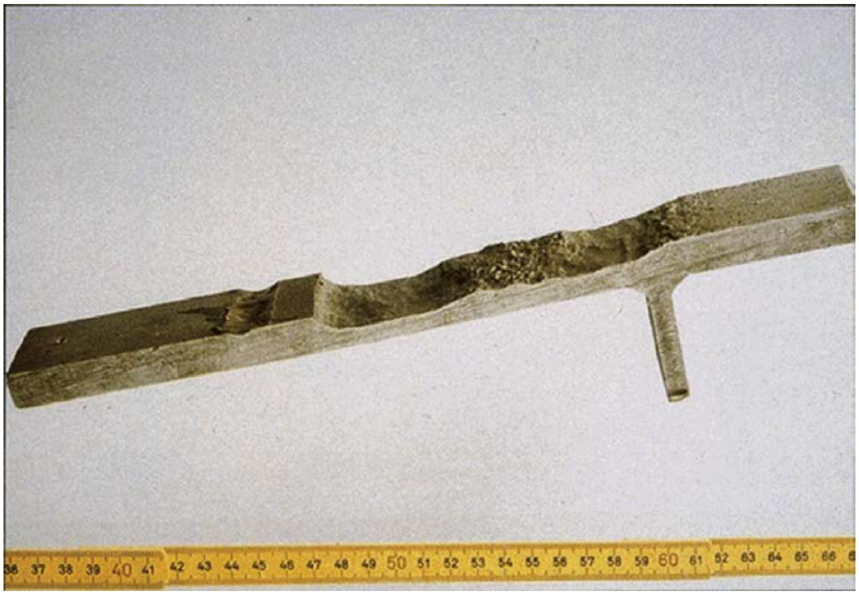
APPEARANCE	Irregular general attack.
TIME IN SERVICE	6 years.
ENVIRONMENT	Internal: mercaptan, 50°C; external: moisture originating from rain, penetrating through defects in the insulation.
CAUSE	Regular wetting of the pipe surface with contaminated rainwater (acid rain), which evaporates on the warm pipe. The pipe cracked owing to decrease of wall thickness (see also Case Histories 01.02.25.01 and 03.11.25.01).
REMEDY	Provide the pipe with a polyethylene coating or with an aluminum foil and then insulate it.

CORROSION ATLAS

CASE HISTORY

01.11.25.02

MATERIAL	Carbon steel.
SYSTEM	Oil distillation plant.
PART	Column wall.
PHENOMENON	Corrosion under insulation.



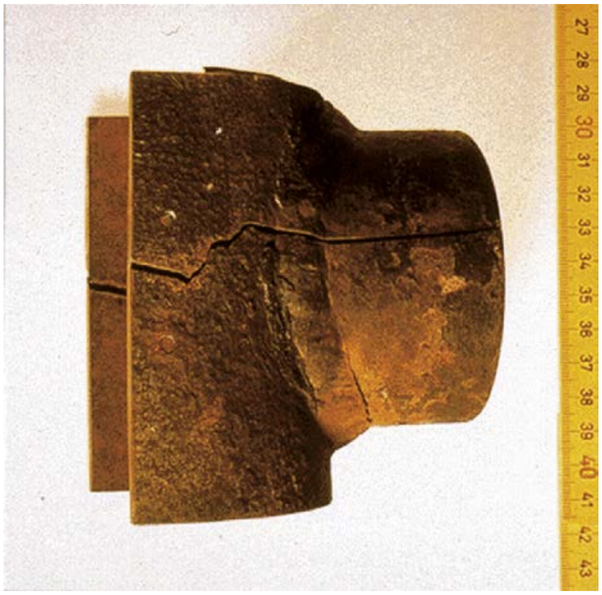
APPEARANCE	Locally severe attack.
TIME IN SERVICE	15 years.
ENVIRONMENT	Insulation saturated with contaminated rainwater; temperature approximately 80°C.
CAUSE	The wall was attacked by ingress of water into the insulation. The contaminated rainwater evaporates on the wall surface, leading to severe corrosion.
REMEDY	• Seal insulation properly (prevent water ingress by constructional means, seal crevices with compound). • Provide wall with a paint system.

CORROSION ATLAS

CASE HISTORY

01.11.28.01

MATERIAL	Carbon steel.
SYSTEM	Platformer.
PART	T-piece (3″/4″).
PHENOMENON	Fatigue.



APPEARANCE	Distortionless crack in the horizontal plane.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Naphtha (gasoline).
CAUSE	The 3″ branch piece was not properly supported and was therefore subjected to strongly fluctuating loads (poor workmanship!) (see also Case Histories 01.11.28.02 and 04.01.28.01/03).
REMEDY	Installation of proper support.

CORROSION ATLAS

CASE HISTORY

01.11.28.02

MATERIAL	Carbon steel.
SYSTEM	Conveyor belt in a cheese store.
PART	Chains.
PHENOMENON	Low cycle fatigue or strain fatigue.

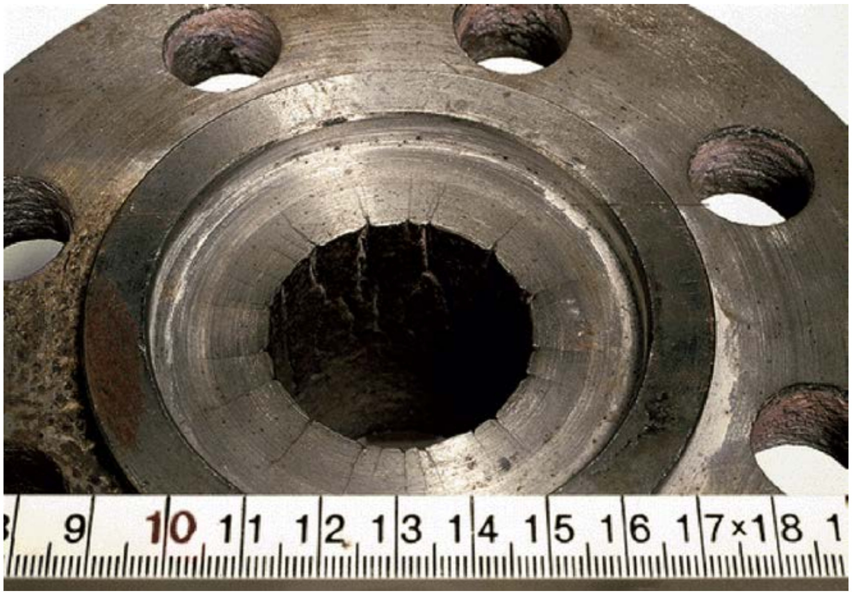
APPEARANCE	Cracks and rupture.
TIME IN SERVICE	Several years.
ENVIRONMENT	Warm humid air, chemical cleaning solution (phosphoric acid).
CAUSE	Failure was noticed during reinstallation of chemically cleaned chains. Polluted chains were supplied in such a way that they had to be stressed during handling (hoisting etc.). Cracking could have been caused either by the way in which the chemical cleaning was performed (stressed components) or merely by selection of an incorrect treatment for these (already strain-aged) components.
REMEDY	Avoid additional stresses in material during and immediately after performing a chemical cleaning operation. (Note: Polluted chains were previously supplied in stainless steel boxes. Chemical treatment of chains was carried out inside these perforated boxes.)

CORROSION ATLAS

CASE HISTORY

01.11.28.03

MATERIAL	Carbon steel ASTM A 105 (W.-Nr. 1.0305).
SYSTEM	Reactor.
PART	Flange in steam and cooling water delivery line.
PHENOMENON	Thermomechanical corrosion fatigue.



APPEARANCE	After removal of the corrosion products, the pipe section of the flange shows numerous perpendicular low-branched radial cracks, also running axially.
TIME IN SERVICE	10 years.
ENVIRONMENT	Alternately, steam at 3.0 MPa and 223°C and cooling water at 25°C.
CAUSE	In the reactor concerned, first an exothermic reaction has to be initiated with steam and then cooled with water as the reaction proceeds. The alternate expansion and contraction of the material has led to thermal fatigue cracking. Corrosion has occurred in the cracks (see also Case Histories 01.02.28.01, 01.04.28.01, and 04.01.28.02).
REMEDY	• Replace with new flange of same material; or • Switch to tougher material with more deformability.

CORROSION ATLAS

CASE HISTORY

01.11.29.01

MATERIAL	Steel: API 5 L grade B (Bessemer steel).
SYSTEM	Crude oil distillation unit.
PART	Process pipe.
PHENOMENON	Ageing.

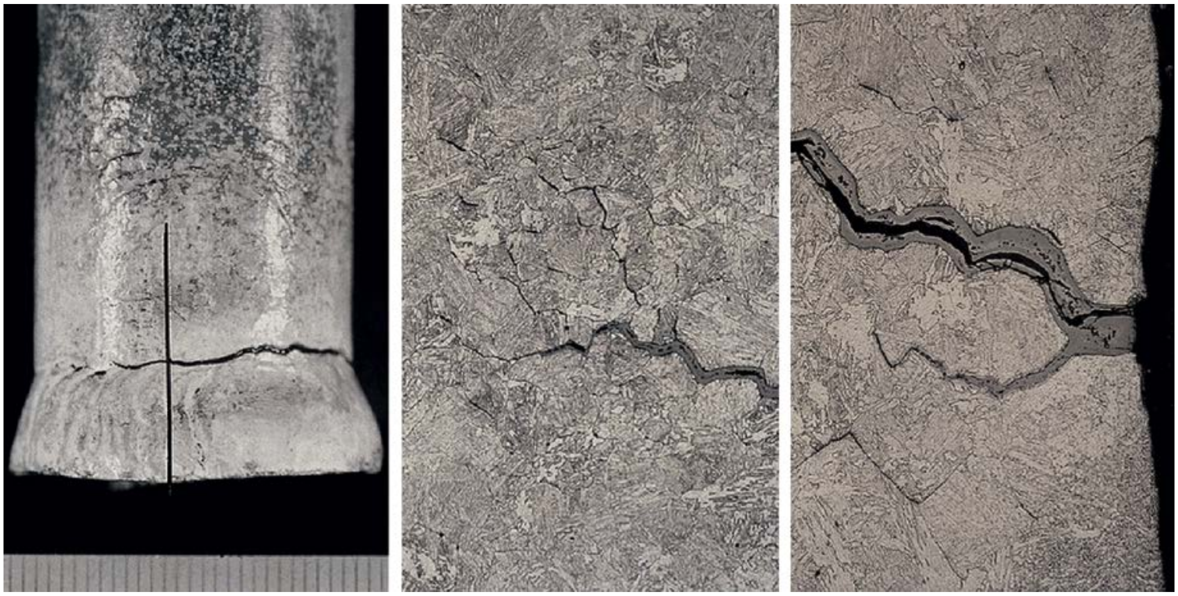
APPEARANCE	Brittle fracture.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Crude oil distillates.
CAUSE	Ageing of the steel, as a result of which embrittlement occurs at high temperature.
REMEDY	Use steel which is not susceptible to ageing.

CORROSION ATLAS

CASE HISTORY

01.11.30.01

MATERIAL	Low-alloyed carbon steel (ASTM A 335 grade P11: 1.25 Cr 0.5 Mo-steel).
SYSTEM	Hydrogen manufacturing reformer furnace.
PART	Inlet header pigtails (OD: 26.7 mm, wall thickness: 2.87 mm).
PHENOMENON	Creep embrittlement.



APPEARANCE	Left photo : pigtail with intergranular cracking in the HAZ revealed by magnetic particle inspection; Right photos : micro of the crack mouth and the crack tip.
TIME IN SERVICE	2 years.
ENVIRONMENT	Hydrogen; operating temperature of 510°C.
CAUSE	CrMo steels may suffer from creep embrittlement as a function of both chemical composition, especially the level of impurities, and operating temperature. In the creep-embrittled condition, cracking will occur when plastic deformations are imposed. The inlet header pigtails satisfied all conditions for cracking.
REMEDY	Replacement by either 1.25 Cr 0.5 Mo or 2.25 Cr 1 Mo steel with low impurity levels.

CORROSION ATLAS

CASE HISTORY

01.11.30.02

MATERIAL	Carbon steel.
SYSTEM	Regenerator for cyclones.
PART	Lug of a bracket.
PHENOMENON	Creep.

APPEARANCE	Cracking with fracture.
TIME IN SERVICE	Several weeks.
ENVIRONMENT	CO/CO_2 atmosphere. Operating temperature 620°C, excursions to 800°C. Pressure about 0.5 bar.
CAUSE	Owing to the absence of molybdenum, the creep strength is too low, which allowed fracture to occur.
REMEDY	Use Mo-containing material (check for the presence of Mo).

CORROSION ATLAS

CASE HISTORY

01.11.32.01

MATERIAL	Carbon steel (37).
SYSTEM	Brewery.
PART	Spent grain transport pipe.
PHENOMENON	Erosion.

APPEARANCE	Pipe worn over entire surface.
TIME IN SERVICE	4 years (after transporting 25,000 tons of spent grain).
ENVIRONMENT	Spent grain (dried bran); transportation air; temperature 75°C.
CAUSE	The spent grain particles transported at high velocity wore the line out.
REMEDY	Accept the attack. To extend the life span, replace the pipe by one with greater wall thickness.

CORROSION ATLAS

CASE HISTORY

01.11.32.02

MATERIAL	Carbon steel.
SYSTEM	Gas transport system.
PART	Screwed nipple near choke (wall thickness 14 mm).
PHENOMENON	Erosion.

APPEARANCE	Material worn away smoothly.
TIME IN SERVICE	Several years.
ENVIRONMENT	Solids-containing natural gas.
CAUSE	High flow velocities downstream from choke connected to the nipple combined with the presence of solids originating from the formation caused this corrosion.
REMEDY	Reduce flow velocities.

CORROSION ATLAS

CASE HISTORY

01.11.34.01

MATERIAL	Carbon steel.
SYSTEM	Soda solution transport system.
PART	Pipe bend.
PHENOMENON	Erosion corrosion.

APPEARANCE	Local attack.
TIME IN SERVICE	2–3 months.
ENVIRONMENT	24°Bé (approximately 20%) soda solution; temperature: 60°C.
CAUSE	Erosion corrosion due to excessive velocity (4–4.5 m/s).
REMEDY	Velocity of the soda solution in the pipe was reduced to 1 m/s.

CORROSION ATLAS

CASE HISTORY

01.11.34.02

MATERIAL	Steel (12 CrMo 19 5; W.-Nr. 1.7362).
SYSTEM	High-vacuum distillation unit.
PART	Furnace tube.
PHENOMENON	Erosion corrosion.

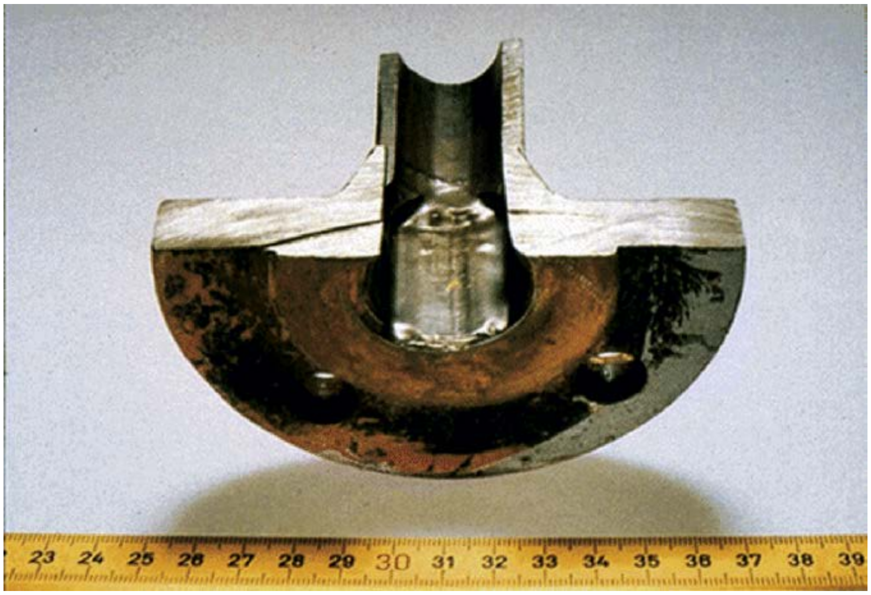
APPEARANCE	Both uniform and pining.
TIME IN SERVICE	1 year.
ENVIRONMENT	Hydrocarbons with naphthenic acid (organic aids in crude oil); temperature approximately 300°C; high velocities.
CAUSE	Naphthenic acid can lead to extremely high rates of corrosion (see also Case History 01.11.34.05).
REMEDY	• Neutralize acids and reduce velocity, or • Select another steel grade, e.g., stainless steel (AISI 316), which is more resistant to naphthenic acid.

CORROSION ATLAS

CASE HISTORY

01.11.34.03

MATERIAL	Carbon steel.
SYSTEM	Sulfuric acid transport system.
PART	Flange in pipe.
PHENOMENON	Erosion corrosion.



APPEARANCE	Severe local attack.
TIME IN SERVICE	3 years.
ENVIRONMENT	96% H_2SO_4; velocity 0.8–0.9 m/s; temperature 15–20°C.
CAUSE	Locally severe turbulence resulting from an excentrically positioned seal, preventing the build-up of a passivating iron sulfate skin.
REMEDY	Assembly procedure should prevent such errors.

CORROSION ATLAS

CASE HISTORY

01.11.34.04

MATERIAL	Carbon steel.
SYSTEM	Crude oil distillation column.
PART	Tops rundown pipeline.
PHENOMENON	Erosion corrosion.

APPEARANCE	Surface exhibits grooved etching.
TIME IN SERVICE	About 2 years.
ENVIRONMENT	Hydrocarbons with traces of HCl. Temperature 80°C.
CAUSE	Attack by HCl traces in combination with high velocity.
REMEDY	Reduction of the HCl content in the product by means of neutralization.

CORROSION ATLAS

CASE HISTORY

01.11.34.05

MATERIAL	Carbon steel.
SYSTEM	High-vacuum distillation unit.
PART	Vapor line.
PHENOMENON	Erosion corrosion.

APPEARANCE	Pitting corrosion picture on a section of the pipe.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hydrocarbon with traces of naphthenic acid. Temperature 300°C.
CAUSE	As in Case History 01.11.07.04, this was also a case of the mixed usage of ASTM and API piping, only the API material being subject to attack (see also Case History 01.11.34.02).
REMEDY	- Use ASTM pipe. - Neutralize the naphthenic acid.

CORROSION ATLAS

CASE HISTORY

01.11.34.06

MATERIAL	Carbon steel.
SYSTEM	Chemicals transport system.
PART	Pump bolt.
PHENOMENON	Erosion corrosion.

APPEARANCE	Material irregularly eroded all over the surface.
TIME IN SERVICE	10 years.
ENVIRONMENT	Glycol, glycolic acid, carbon dioxide, and water. Temperature 160°C.
CAUSE	Glycolic acid and carbon dioxide at a certain minimum velocity cause erosion corrosion of the carbon steel.
REMEDY	Use bolts made from the more corrosion-resistant stainless steel AISI 316.

CORROSION ATLAS

CASE HISTORY

01.11.34.07

MATERIAL	Carbon steel.
SYSTEM	Sulfuric acid transport system.
PART	Main distribution pipe.
PHENOMENON	Erosion corrosion.

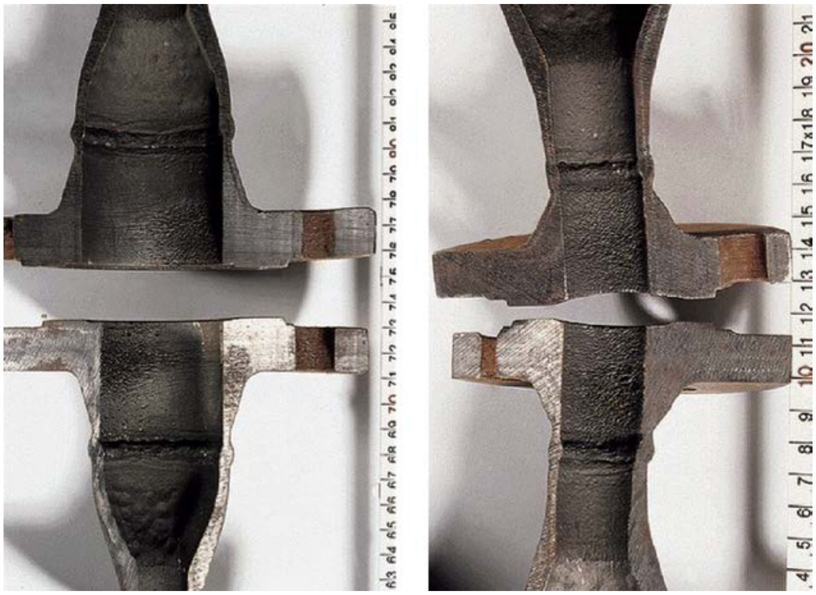
APPEARANCE	Locally, uniform attack to upper part of pipe.
TIME IN SERVICE	3 years.
ENVIRONMENT	96% sulfuric acid; 0.5 m/s; temperature 15–20°C.
CAUSE	In view of the site of the attack, namely the upper part of the pipe, the corrosion is most likely attributable to turbulent flow because of the presence of a retained air bubble leading to erosion corrosion.
REMEDY	Highest points in the transport system should be regularly vented.

CORROSION ATLAS

CASE HISTORY

01.11.34.08

MATERIAL	Carbon steel.
SYSTEM	Oil refinery, crude oil distillation.
PART	Side stream of high-vacuum unit.
PHENOMENON	Erosion corrosion.



APPEARANCE	General attack upstream and especially downstream a weld.
TIME IN SERVICE	17 years.
ENVIRONMENT	Gasoil, temperature 300–330°C, varying conditions with regard to sulfur content and acidity (Total Acid Number).
CAUSE	High flow conditions causing turbulence near the weld, which in turn removed protective layers giving the corroding acid/sulfur species access to the bare metal (see also Case History 01.11.34.02).
REMEDY	Carbon steel has been replaced by low-alloyed steel.

CORROSION ATLAS

CASE HISTORY

01.12.04.01

MATERIAL	Carbon steel.
SYSTEM	Air scrubber system.
PART	Prescrubber caustic pump.
PHENOMENON	Acid corrosion.

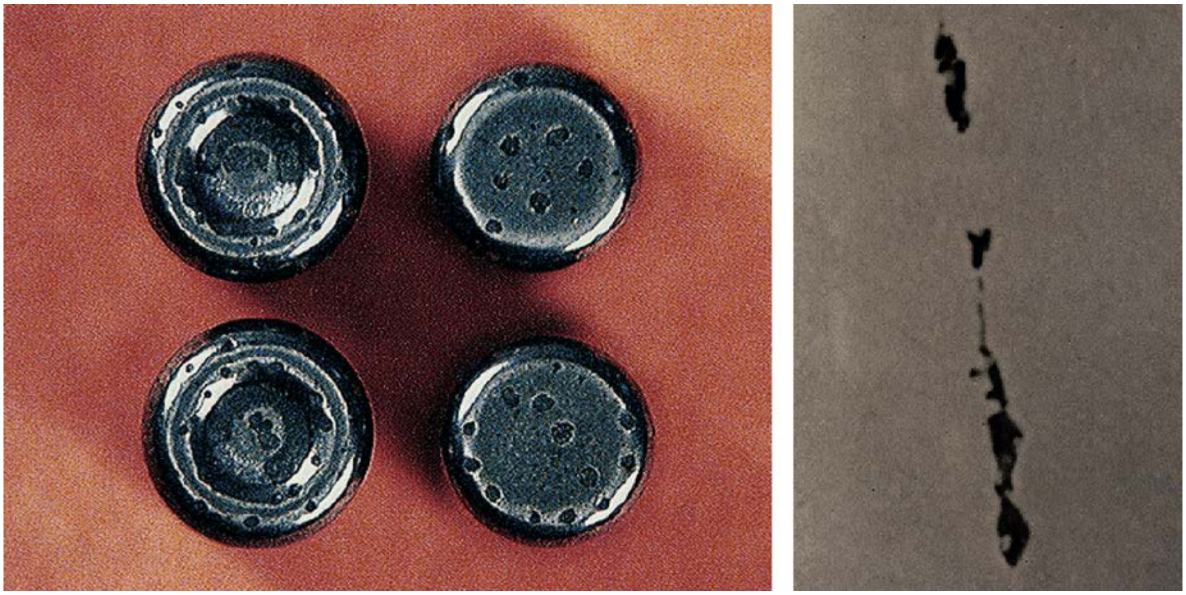
APPEARANCE	Overall shallow pitting.
TIME IN SERVICE	3 months.
ENVIRONMENT	10% NaOH with aniline and traces of mercaptobenzaldehyde (MCB). Temperature: 15–55°C, pressure: 1.0 MPa, streaming.
CAUSE	Breakthrough of HCl gas that was neutralized insufficiently by NaOH.
REMEDY	• Adjustments in process technique, and • Construction of the pump of Si cast iron (Si > 14.2% + Mo + Cr + Cu) or duplex stainless steel (SAF 2205).

CORROSION ATLAS

CASE HISTORY

01.12.42.01

MATERIAL	Carbon steel 100 Cr 6 (W.-Nr. 1.3505).
SYSTEM	Rotary drum for production of ball bearings.
PART	Ball bearings for tapered roller bearings (dimensions: length 7.5 mm, OD 6 mm).
PHENOMENON	End grain attack.



APPEARANCE	Pitting at the extremities of the ball bearings, depth 0.15–0.20 mm, diameter 0.4–0.5 mm, circular shaped with cone shaped to the inside.
TIME IN SERVICE	Maximum 16 h during tumbling.
ENVIRONMENT	Well water with abrasive (Al_2O_3). At the end of the tumbling process, sodium silicate is added as corrosion inhibitor. pH: 12; temperature 50–60°C.
CAUSE	Sodium silicate is not only effective as a corrosion inhibitor but can also be an aggressive agent under defined circumstances (temperature, pH, concentration, see also Case History 02.04.27.01). Attack of the steel surface cut perpendicular to the rolling direction took place at the end of the non-metallic inclusions (stringers). MnS inclusions are shown by EDX analysis and X-ray (performed by HMC Technology, Leiden, Netherlands) (see also Case Histories 04.11.42.01 and 05.11.42.01).
REMEDY	• Reduce sodium silicate dosing to a pH of 10–10.5. • Alternative: select and test an organic-based corrosion inhibitor.

CORROSION ATLAS

CASE HISTORY

01.14.14.01

MATERIAL	Malleable cast iron.
SYSTEM	Gas supply system.
PART	Underground coupling.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Highly localized attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Soil.
CAUSE	Galvanic coupling with copper indoor piping.
REMEDY	• Install, of an isolating plastic insert. • Use wrapping tape (polyethylene with butylene rubber) with at least 50% overlap.

CORROSION ATLAS

CASE HISTORY

01.14.16.01

MATERIAL	Grey cast iron.
SYSTEM	Gas supply system.
PART	Underground pipe.
PHENOMENON	Selective leaching (graphitic corrosion).

APPEARANCE	Left-hand photograph: Graphitization visible on cut section. Right-hand photograph: Depth of attack visible after blasting (different pipe section).
TIME IN SERVICE	29 years.
ENVIRONMENT	Anaerobic soil.
CAUSE	Sulfate-reducing bacteria converted sulfate into sulfide, as a result of which the cast iron is attacked and graphitic corrosion takes place (see also Case History 01.06.16.01).
REMEDY	Replaced by polyethylene pipe.

CORROSION ATLAS

CASE HISTORY

01.16.24.01

MATERIAL	Cor-Ten steel (slow-rusting carbon steel with several tens of percents manganese, copper, silicon, and chromium).
SYSTEM	Civil engineering structures.
PART	Left: balcony railing of apartment; Right: jet screen at airport.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	The Cor-Ten steel is uniformly corroded, and corrosion products have travelled to the concrete structure.
TIME IN SERVICE	3 and 5 years, respectively.
ENVIRONMENT	Marine atmosphere.
CAUSE	Cor-Ten steel is covered with a compact, less moisture absorbing rust layer, due to the alloy metals, but does not possess long-term resistance to corrosion in marine and industrial atmospheres.
REMEDY	Although Cor-Ten steel is often chosen deliberately because of aesthetic considerations, the staining of the concrete structure is not acceptable. Under these circumstances, the use of coated steel or hot-dip galvanized steel is preferable.

CORROSION ATLAS

CASE HISTORY

01.16.24.02

MATERIAL	Carbon steel.
SYSTEM	Lattice bridge.
PART	Part of girder.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Layered corrosion.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Atmosphere.
CAUSE	The humid atmosphere attacks the insufficiently protected steel, forming stratified oxide layers. Stratification of corrosion products is common in intermittent wet–dry conditions. This form of corrosion is also called “packing corrosion” or “exfoliation” (see also Case History 07.11.19.01).
REMEDY	Provide girders with an effective coating.

CORROSION ATLAS

CASE HISTORY

01.21.12.01

MATERIAL	Carbon steel.
SYSTEM	Dredger.
PART	Ship's shell.
PHENOMENON	Chloride attack and under-deposit corrosion.

APPEARANCE	Pitting corrosion, also underneath mussels.
TIME IN SERVICE	Several months.
ENVIRONMENT	Seawater (tropics).
CAUSE	The high chloride content of the seawater causes pitting of the steel; in addition, as a result of mussels growing on the ship's shell differential aeration cells will form, and the oxygen-lean areas – i.e., under the mussels – will become anodic and subject to attack.
REMEDY	• Treat the ship's shell with a marine growth inhibitor, in combination with • Application of zinc anodes (cathodic protection).

CORROSION ATLAS

CASE HISTORY

01.21.17.01

MATERIAL	Carbon steel.
SYSTEM	Ship.
PART	Bilge water pipe section through heated fuel tank (70°C).
PHENOMENON	Microbiologically induced corrosion (MIC).

APPEARANCE	Extensive pitting and wall thinning; tunneling in rolling direction with preferential attack of the weld.
TIME IN SERVICE	Approximately 3 years.
ENVIRONMENT	Ship's bilge: seawater (polluted harbor water).
CAUSE	Development of acetic acid–producing bacteria (Clostridia aceticum), promoted by high temperature of environment (see also the following Case History).
REMEDY	Cleaning, removal of deposits and sludge (will be difficult in practice). After ballasting, replace harbor water by fresh seawater.

CORROSION ATLAS

CASE HISTORY

01.21.17.02

MATERIAL	Carbon steel.
SYSTEM	Ship.
PART	Bottom plate of bilge compartment.
PHENOMENON	Microbiologically induced corrosion (MIC).

APPEARANCE	Extensive pitting and wall thinning, tunneling in rolling direction of plate.
TIME IN SERVICE	Approximately 3 years.
ENVIRONMENT	Oil and waste water from engine room, drinking water maker etc., that collected in bilge compartment and remained there for extended periods.
CAUSE	Development of acetic acid–producing bacteria (Clostridia aceticum), leading to corrosion of bottom plate by acetic acid.
REMEDY	Regular cleaning of compartment.

CORROSION ATLAS

CASE HISTORY

01.21.28.01

MATERIAL	Carbon steel.
SYSTEM	Dredge.
PART	Chain link.
PHENOMENON	Corrosion fatigue.

APPEARANCE	Partly ductile fracture with distinct fatigue rings and corrosion pitting, partly brittle fracture with pits (see fracture surface on the right-hand photograph).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Regular immersion in brackish harbor water.
CAUSE	Fatigue occurred during operation; the link concerned had been jammed, as a result of which torsional forces had occurred and the link had suffered external damage (see also Case History 01.01.28.01).
REMEDY	Use a different design without chains.

CORROSION ATLAS

CASE HISTORY

01.23.20.01

MATERIAL	Carbon steel.
SYSTEM	Carbon dioxide scrubbing tower.
PART	Wall.
PHENOMENON	Hydrogen damage (hydrogen blistering, cold hydrogen attack).

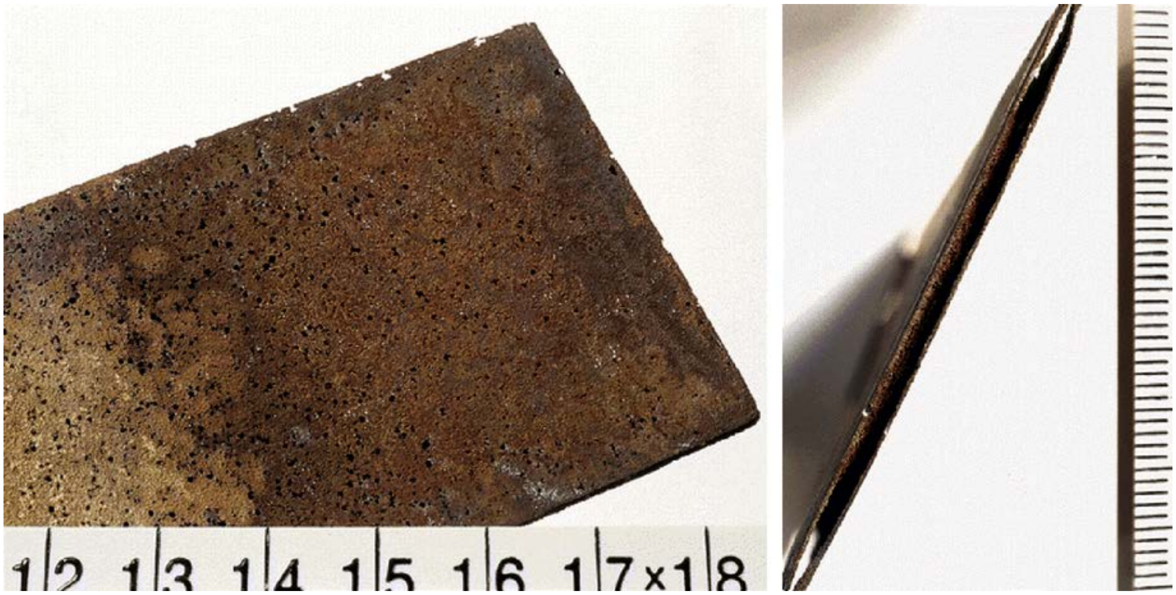
APPEARANCE	Formation of cavities in the steel.
TIME IN SERVICE	Many years.
ENVIRONMENT	Water with absorbed CO_2.
CAUSE	Diffusion into the steel of atomic hydrogen formed by slight corrosion. The diffusion stops at contaminations in the steel. Here, atomic hydrogen (H) is converted into molecular hydrogen (H_2). Pressure build-up then causes the steel to fracture (see also Case History 01.11.20.04).
REMEDY	• Change-over to another (non-corrosive) scrubbing liquid, or • Use of better quality purer steel, or • Acceptance of the corrosion, monitoring its progress.

CORROSION ATLAS

CASE HISTORY

01.24.04.01

MATERIAL	Low-alloyed steel.
SYSTEM	Test rig.
PART	Carbon steel test plate (thickness 2.5 mm).
PHENOMENON	Acid corrosion.



APPEARANCE	Severe corrosion on surface and on cutting edges.
TIME IN SERVICE	About 20 days.
ENVIRONMENT	Sulfuric acid pickling bath; inhibited; concentration: 12% w/w, sulfuric acid in water; temperature: 70°C.
CAUSE	Carbon steel is not resistant in sulfuric acid at this concentration and temperature. As a result of the deformation and activation by cutting of the edges, they corroded more than the sheet surface (see also Case History 04.24.04.01).
REMEDY	Use a more resistant material. Passiviation of edges after cutting.

CORROSION ATLAS

CASE HISTORY

01.25.14.01

MATERIAL	Carbon steel.
SYSTEM	Cut wire of flare.
PART	End of wire with nipple.
PHENOMENON	Galvanic corrosion.

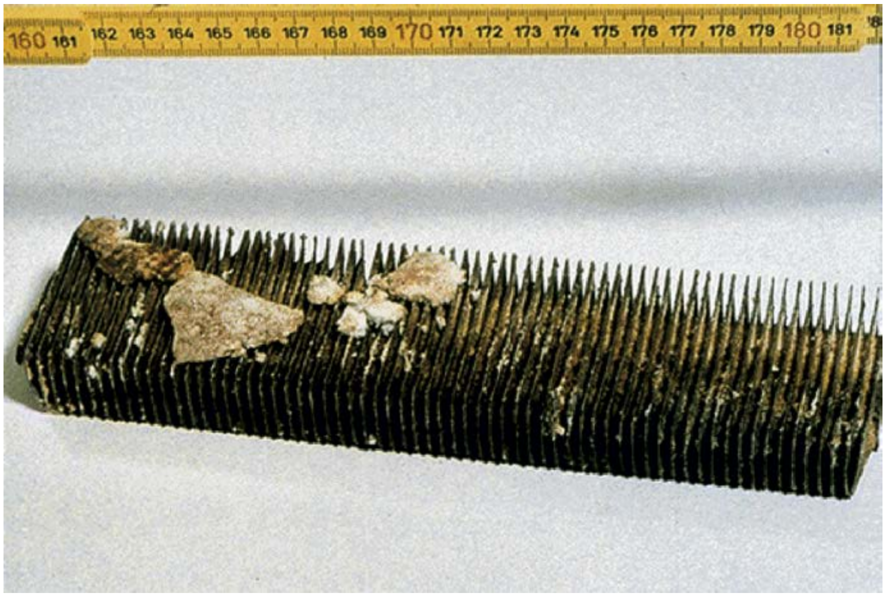
APPEARANCE	Corrosive attack and fracture of guy wire in nipple. The picture shows a longitudinal section of the nipple.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Open air. Because of badly performed copper brazing of the carbon steel wire inside the stainless steel nipple, the part of the wire inside the nipple was exposed to stagnant moisture and water.
CAUSE	The different alloys used (carbon steel, stainless steel, and copper alloy) caused an electrochemical cell inside the nipple. As the carbon steel protected the more noble alloys, it went into solution.
REMEDY	Prevent the existing electrochemical cell inside the nipple by appropriate soldering so that water cannot enter the nipple.

CORROSION ATLAS

CASE HISTORY

02.01.04.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Boiler heat recovery system (water-tube boiler, 4.5 MPa).
PART	Flue gas heat exchanger.
PHENOMENON	Acid corrosion (cold end corrosion).



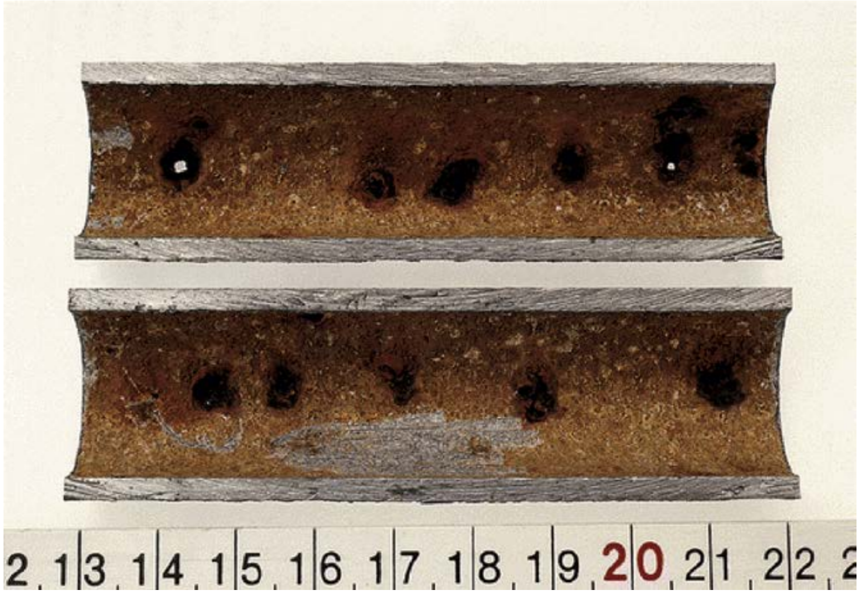
APPEARANCE	Uniform attack.
TIME IN SERVICE	3 months.
ENVIRONMENT	Around the heat exchanger: Flue gases which were cooled from 124–129 °C to 92–105 °C and flue gas condensate at 80 °C, pH 3.8; through the heat exchanger: Water which was heated, in a closed system, from 50 to 120 °C. On the horizontal elements deposits of basic zinc chloride.
CAUSE	Condensation on the heat exchanger as the plant started up regularly, coupled with the presence of 3 mg of HCl/m^3 in the flue gases owing to contamination of the combustion air with trichloroethylene. Blockage of the heat exchanger with corrosion products, at the flue gas side, reduced the boiler capacity by 40% (see Case History 01.04.04.01).
REMEDY	Because construction of the heat exchanger of corrosion-resistant material (high-alloyed stainless steel, Teflon, Monel or titanium) or purification of the combustion air would have been uneconomic, heat recovery was discontinued.

CORROSION ATLAS

CASE HISTORY

02.02.01.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Condensate system.
PART	Line.
PHENOMENON	Oxygen and galvanic corrosion.



APPEARANCE	Pitting to leakage.
TIME IN SERVICE	2 years.
ENVIRONMENT	Condensate contaminated with 50% salt-containing boiler water. Temperature 90 °C.
CAUSE	Pitting due to the presence of oxygen in the condensate reinforced by reversal of potential of the zinc/iron cell above 60 °C and chloride ions originating from the contamination with boiler water. The latter had also caused deposition of hardness salts from the boiler water.
REMEDY	• Improve steam/water separation. • Construct lines of stainless steel (AISI 316). • Use softened water for boiler make-up. • Dose an oxygen scavenger.

CORROSION ATLAS

CASE HISTORY

02.02.02.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Steam condensate system.
PART	Element from air heater and steam trap.
PHENOMENON	Carbonic acid corrosion.

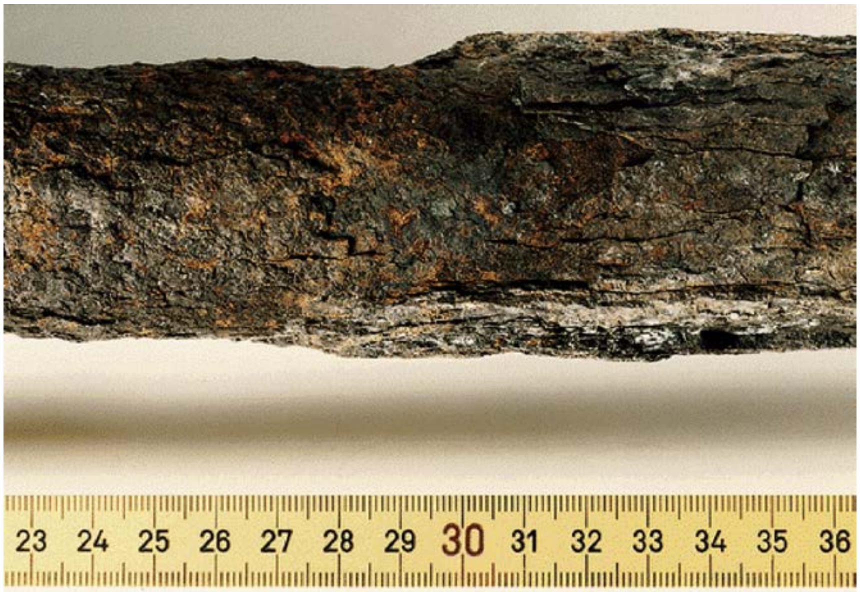
APPEARANCE	Uniform corrosion.
TIME IN SERVICE	7 months.
ENVIRONMENT	Corrosive condensate, 90–100 °C.
CAUSE	Corrosive condensate attacks zinc and steel. Zinc from the galvanized air heater was deposited in the steam trap as zinc oxide.
REMEDY	• In this case, it was possible to switch to water with a much lower bicarbonate content for make-up purposes. This reduces the aggressivity of the condensate. • Alternatives: Alkalinity reduction of the make-up water and/or dosing of film-forming amine or construct the air heaters of stainless steel.

CORROSION ATLAS

CASE HISTORY

02.04.13.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Central heating system, 90–70 °C.
PART	Pipe transit though brickwork wall immediately above floor.
PHENOMENON	Crevice corrosion.



APPEARANCE	Pipe covered with layered corrosion products.
TIME IN SERVICE	40 years.
ENVIRONMENT	Humid atmosphere.
CAUSE	Oxygen-containing flushing water remaining in the gap between the pipe and wall first attacks the zinc coating and then the steel, resulting in the layered build-up of corrosion products.
REMEDY	The pipe should be provided with a moisture barrier, e.g., a plastic pipe (a ‘pipe-in-pipe’ system), with thermal insulation applied between the steel pipe and the plastic pipe.

CORROSION ATLAS

CASE HISTORY

02.04.14.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot water system, 160 °C.
PART	Heating tube from make-up water vessel.
PHENOMENON	Galvanic corrosion (reversal of potential).

APPEARANCE	Pitting attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	Softened water, 60 °C, to which hydrazine was added before make-up to the system. Hot water at 160 °C passing through the tubes.
CAUSE	Reversal of potential in the zinc/iron couple as a result of the high temperature of the water in combination with the water composition (high contents of bicarbonate and nitrate). The galvanized steel will be attacked as the pores have becomes less noble (see also Case Histories 02.05.14.01/02).
REMEDY	Construct the tubes from stainless steel AISI 316 L, or inject water from the hot water system into the make-up tank directly.

CORROSION ATLAS

CASE HISTORY

02.04.24.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Central heating system.
PART	Expansion vessel.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Local rust patches.
TIME IN SERVICE	2 years.
ENVIRONMENT	Moist atmosphere.
CAUSE	Insufficient cleaning (degrease and/or cleanse by pickling) of the steel prior to galvanizing, as a result of which there was locally no zinc present on the steel due to poor adhesion. As a result, local corrosion took place caused by condensation of water on the surface.
REMEDY	Repair: Vessel to be blasted, degreased, pickled and then regalvanized. Prevention: Clean the steel thoroughly before galvanizing.

CORROSION ATLAS

CASE HISTORY

02.04.27.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Central heating system.
PART	Circulation pipe, internally and externally galvanized.
PHENOMENON	Silicate corrosion.

APPEARANCE	Brown corrosion nodules on the galvanized surface, with pitting underneath leading to leak in threaded end.
TIME IN SERVICE	2–3 years.
ENVIRONMENT	Mains water with soluble silicates added to prevent corrosion. Temperature: Maximum 60 °C.
CAUSE	An acid environment is formed underneath (amorphous, gel-like) silicate-containing deposition as a result of the exchange of cations such as calcium and iron, releasing an equivalent quantity of hydrogen ions. The metal surface is attacked due to the increase in acidity. This process occurs both on a bare steel surface and on a galvanized steel surface, and both at ambient temperature and elevated temperature. The corrosion is strongly accelerated by the addition of extra silicate (Ref. Helsen. J.A., Huybrechts, P., Braber, M.J.: "Corrosion initiation of steel in potable water by silicates", International Congress on Metallic Corrosion, Vol. 2, Toronto, Canada, 1984).
REMEDY	Stop the dosing of silicate; circulation system chemically cleaned and if necessary replaced, in which case bare steel would be preferable.

CORROSION ATLAS

CASE HISTORY

02.05.02.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Underground cold water piping system.
PART	Pipe.
PHENOMENON	Aggressive water.

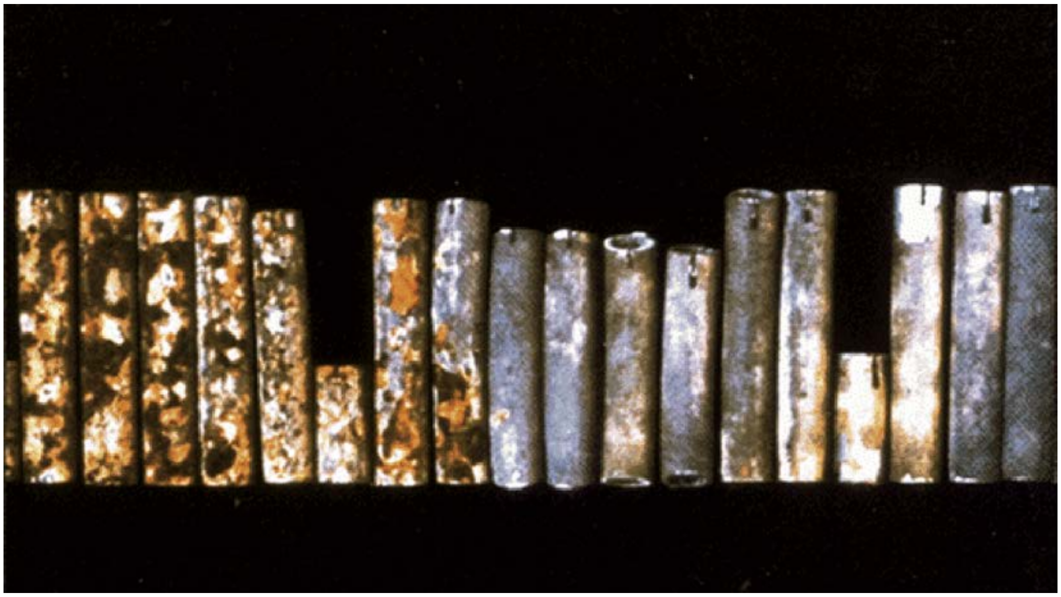
APPEARANCE	Grooved attack at regular interspacing (about 5.5 cm).
TIME IN SERVICE	About 2 years.
ENVIRONMENT	Groundwater (continuous).
CAUSE	Poor overlap of the wrapping tape. The aggressive groundwater was thereby able to attack the pipe surface.
REMEDY	Make sure of at least 50% overlap, or apply a duplex system (coating the galvanized steel).

CORROSION ATLAS

CASE HISTORY

02.05.14.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot tap water system.
PART	Heating tube (sawn into pieces) of the hot water storage boiler.
PHENOMENON	Galvanic corrosion (reversal of potential).



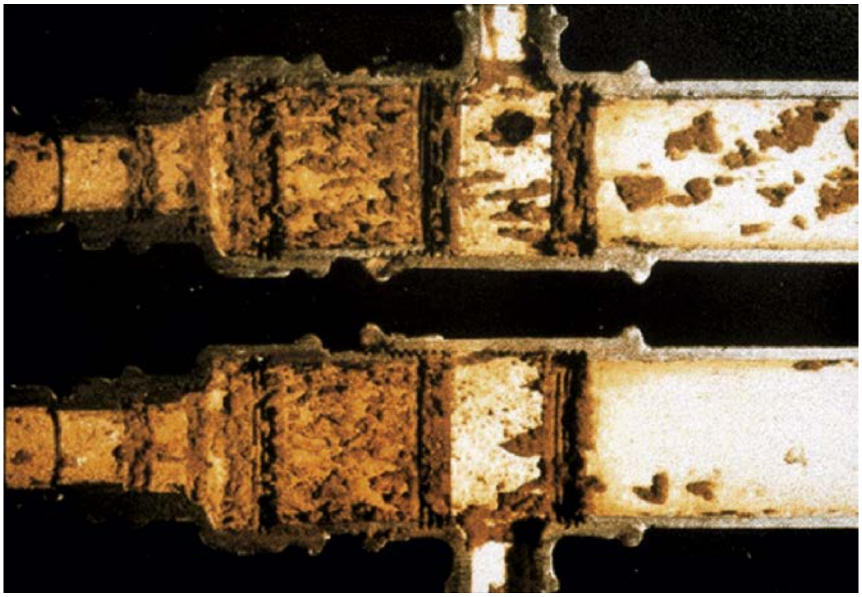
APPEARANCE	Local pitting attack to the hottest part of the tube.
TIME IN SERVICE	1 year.
ENVIRONMENT	Mains water around the tubes; hot water at 130 °C through the tubes.
CAUSE	Reversal of potential in the zinc/iron couple, in this case above a wall temperature of 70 °C; the cold part exhibits no attack. Above that temperature, blisters first formed and then burst, after which the bare steel surface is attacked by the ennoblement of the zinc potential (see also Case History 02.04.14.01).
REMEDY	Galvanized steel should not be used at temperatures above 60 °C, especially not in contact with waters with a high content of bicarbonate or nitrate. The presence of ≥25 ppm SO_4^{2-} prevents this reversal of potential.

CORROSION ATLAS

CASE HISTORY

02.05.14.02

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot tap water system.
PART	Pipe.
PHENOMENON	Galvanic corrosion (reversal of potential).



APPEARANCE	Pitting attack.
TIME IN SERVICE	2 years.
ENVIRONMENT	A mixture of hard and softened mains water; total hardness 3.5–4.0 mEq/l (175–200 ppm $CaCO_3$); bicarbonate (HCO_3^-) 6.4 mEq/l (320 ppm $CaCO_3$); for corrosion control, a mixture of (poly)phosphates was added; temperature 60–90 °C.
CAUSE	Reversal of potential in the zinc/iron couple due to the high temperature of the tap water in combination with the high content of bicarbonate; this corrosion can be prevented by dosing phosphates, but an underdosage was applied (see also Case history 02.04.14.01).
REMEDY	Construction of the hot tap water system from corrosion-resistant material, e.g., copper, stainless steel or glass fiber–reinforced vinyl ester. In hot tap water systems, the dosing of chemicals is generally prohibited. N.B.: For hygienic reasons, reducing the water temperature cannot be recommended (in view of the development of legionnella bacteria which causes legionnaires' disease).

CORROSION ATLAS

CASE HISTORY

02.05.14.03

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot tap water system.
PART	Wall of hot water storage tank.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Severe local attack.
TIME IN SERVICE	3 months.
ENVIRONMENT	Hot mains water (45–75 °C).
CAUSE	Galvanic corrosion caused by the potential difference between the hot-dip galvanized steel wall and the copper rivets.
REMEDY	Construction of the hot water storage boiler entirely from copper or AISI 316 L stainless steel.

CORROSION ATLAS

CASE HISTORY

02.05.14.04

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Galvanic corrosion (deposition corrosion).

APPEARANCE	Pitting throughout pipe.
TIME IN SERVICE	About one year.
ENVIRONMENT	Deferrized well water; temperature 45–60 °C.
CAUSE	Formation of cells by deposition of copper (originating from the copper boiler) on the galvanized steel and galvanic corrosion because of the couple action between the copper welds and the galvanized pipe (see also Case history 02.06.14.02).
REMEDY	• Construct the boilers and the pipes from 316 L stainless steel, and apply partial softening of the water to prevent deposits (differential aeration cells). • Optionally, construct the pipes of heat-resistant plastic or coated steel.

CORROSION ATLAS

CASE HISTORY

02.05.14.05

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Cold tap-water system.
PART	Pipe.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Pipe section at connection to brass check valve; severely corroded on the left and fractured on the right.
TIME IN SERVICE	15 years.
ENVIRONMENT	Internal: cold mains water, flowing. External: wet due to condensation.
CAUSE	Cell formation resulting from the combination of galvanized steel/brass/galvanized steel. The brass is slightly affected by dezincification, presumably due to the formation of differential aeration cells underneath condensation droplets.
REMEDY	Make pipe of copper or plastic, or apply a good insulation with vapor barrier.

CORROSION ATLAS

CASE HISTORY

02.05.14.06

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Hot tap water system.
PART	Galvanized steel casing of electric heating element.
PHENOMENON	Galvanic corrosion (reversal of potential).

APPEARANCE	Severe attack to the galvanized steel. In addition, calcium deposition on casing and element (above and underneath new casings).
TIME IN SERVICE	One year.
ENVIRONMENT	Hot tap water. Temperature >60 °C.
CAUSE	Reversal of potential of the iron–zinc couple at temperatures >60 °C (see also Case history 02.05.14.01).
REMEDY	Removal of galvanized steel casing.

CORROSION ATLAS

CASE HISTORY

02.05.24.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Water supply in a cattle shed.
PART	Drinking troughs.
PHENOMENON	Atmospheric corrosion (white rust).

APPEARANCE	Uniform corrosion with locally abundant zinc corrosion products.
TIME IN SERVICE	3 weeks outdoor storage.
ENVIRONMENT	Rainwater.
CAUSE	Vertical stacking too close together, as a result of which the air circulation was insufficient for the rainwater to evaporate. The zinc coating is attacked, with formation of zinc oxide hydrate, known as "white rust."
REMEDY	Inspection revealed that there was no question of reduced coating thickness, so that regalvanizing was not necessary; all that was required was removal of the white rust areas by brushing. If the troughs are again stacked, a space of at least 1 cm should be maintained between the flat parts of the stack should be laid at a slope.

CORROSION ATLAS

CASE HISTORY

02.06.14.01

MATERIAL	Sherardized carbon steel.
SYSTEM	Cooling water system.
PART	Left-hand: cooling water pump filter bolt; right-hand: new bolt.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Severe uniform attack over entire surface.
TIME IN SERVICE	A few months.
ENVIRONMENT	River water.
CAUSE	The bolts are subjected to galvanic attack as a result of couple action between the sherardized carbon steel bolts and the stainless steel filter gauze.
REMEDY	Use stainless steel bolts.

CORROSION ATLAS

CASE HISTORY

02.06.14.02

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Cooling water system.
PART	Piping.
PHENOMENON	Galvanic corrosion (deposition of noble ions).

APPEARANCE	Overall attack.
TIME IN SERVICE	One year.
ENVIRONMENT	Seawater at ambient temperatures. Anti-fouling impressed current system with copper anodes.
CAUSE	(Galvanized) carbon steel is subjected to galvanic attack as a result of couple action between steel and copper after deposition of the copper ions on the steel surface (copper content of the deposit: 1%).
REMEDY	• Use of an alternative antifouling technique, or • Optimize the impressed current system by minimizing the copper ion production for antifouling.

CASE HISTORY

02.06.14.03

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Ammonia evaporator of chilled water system.
PART	Tube bends.
PHENOMENON	Galvanic corrosion (deposition corrosion).

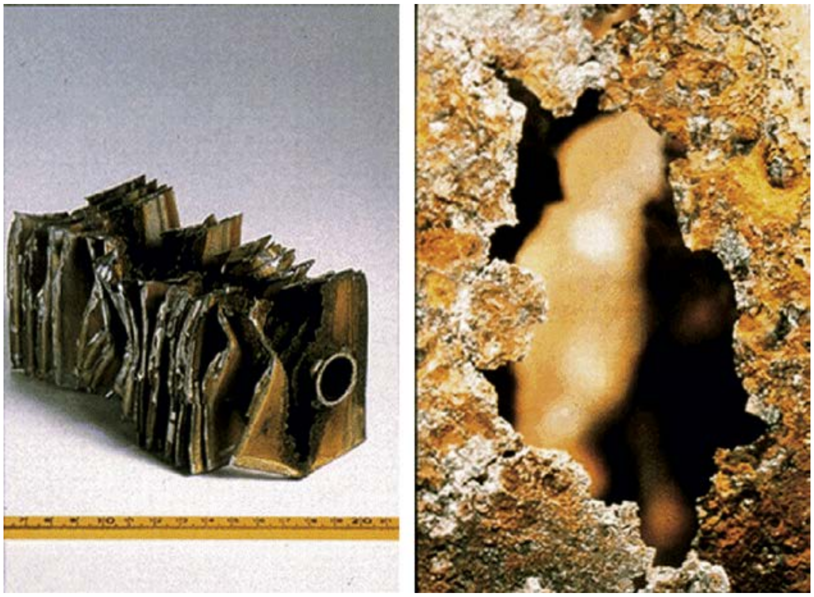
APPEARANCE	Pitting.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Circulating chilled water; temperature 6–8 °C. NH_4^+: 200 ppm; copper 50 ppm (corroded from the copper air coolers in the system); zinc: 2 ppm.
CAUSE	Porosity of the evaporator welds caused leakage of ammonia into the cooled water. The first result was corrosion and leakage of the copper air coolers. They were renewed. The second result was depletion of the copper in the cooled water, which originated from the corrosion of the air coolers onto the galvanized surface of the evaporator. This caused pitting by galvanic corrosion (deposition corrosion, see also Case history 02.05.14.01).
REMEDY	The material choice was fundamentally wrong. Combination of galvanized steel and copper in a circulating water system causes corrosion problems. Construction of the evaporator and coolers of the same material, galvanized steel, or better stainless steel would have been a better choice.

CORROSION ATLAS

CASE HISTORY

02.07.02.01

MATERIAL	Continuous hot-dip zinc-coated steel (Sendzimir process).
SYSTEM	Ammonia cooling installation for air cooling.
PART	Evaporator.
PHENOMENON	Attack by corrosive water.



APPEARANCE	Uniform attack to zinc and steel.
TIME IN SERVICE	5 years.
ENVIRONMENT	Ice (frozen condensed moisture from the cooled air); corrosive deferrized well water (sprayed above evaporator for periodical thawing of the ice) (Langelier index –2.6, Ryznar index 11.3).
CAUSE	Because of the highly corrosive well water, no protective patina coating (of basic zinc salt) is formed. Corrosion of zinc is accelerated by the presence of many pores and fractures in the zinc coating. The corrosion products force the zinc coating away.
REMEDY	Provide new evaporator with better galvanization and reduce the corrosiveness of the well water by removing the carbon dioxide.

CORROSION ATLAS

CASE HISTORY

02.08.15.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Sewage treatment plant.
PART	Aeration tank distributor pieces.
PHENOMENON	Underdeposit corrosion.

APPEARANCE	Pitting underneath crusts of sludge deposit.
TIME IN SERVICE	$4\frac{1}{2}$ years.
ENVIRONMENT	Aerated waste water with chloride (Cl^-) 300 ppm; nitrate (NO_3^-) 25 ppm; pH 7.9; activated sludge 2–4 ppm.
CAUSE	Sludge deposit on the hot-dip galvanized ducts obstructs the aeration of the zinc, allowing the local formation of differential aeration cells. Underneath the deposit, the material is exposed to pitting corrosion. The resultant zinc oxide hydroxide, together with the sludge deposit, forms a thick crust.
REMEDY	Replacement by new distributor pieces treated with a duplex system (hot-dip galvanized followed by coating).

CORROSION ATLAS

CASE HISTORY

02.10.15.01

MATERIAL	Hot-dip galvanized steel 37.1.
SYSTEM	Fire-extinguishing system.
PART	Dry sprinkler line.
PHENOMENON	Under-deposit corrosion.

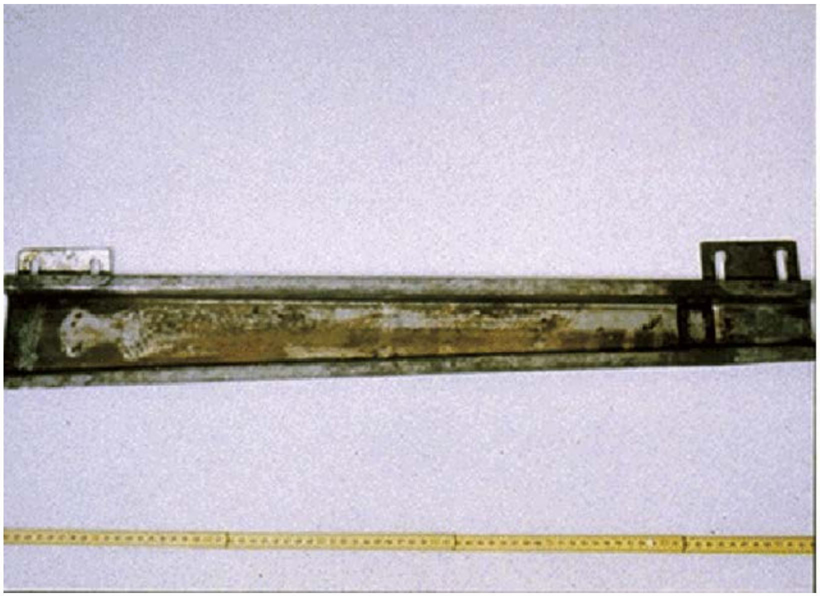
APPEARANCE	After removal of the 4- to 5-mm-thick light- to grey-brown deposit, consisting of iron oxide and zinc oxide, it was found that the zinc layer had disappeared at many sites, with pitting attack and selective attack to the weld.
TIME IN SERVICE	2 years.
ENVIRONMENT	After pressure-testing, remaining mains water was replenished with condensate from the undried air from the air compressor.
CAUSE	The lengthy presence of a considerable quantity of mains water in the lower part of the pipe had prevented the formation of a protective layer of basic zinc carbonate (zinc patina). “White rust” was formed, and aeration cells originated. The resultant corrosion products were wetted with condensate from the compressed air, allowing the corrosion to continue (see also Case Histories 02.05.24.01 and 02.08.15.01).
REMEDY	• Manufacture lines from uncoated carbon steel and install them with the weld seam upward, or use seamless pipe. • Dry the compressed air.

CORROSION ATLAS

CASE HISTORY

02.11.03.01

MATERIAL	Continuous hot-dip zinc-coated steel (Sendzimir process).
SYSTEM	Milk products storage and distribution system.
PART	Conveyor plate.
PHENOMENON	Alkalinity corrosion.



APPEARANCE	Uniform attack, with rust formation.
TIME IN SERVICE	6 months.
ENVIRONMENT	Daily cleaning with high-pressure softened water, to which alkaline cleaning chemicals were added; pH 10.1–11.3.
CAUSE	Galvanized steel is not resistant to water with a pH > 8.5, since no patina layer is formed. Moreover, the galvanization method applied yielded a zinc coating of only 20–25 µm, without formation of iron–zinc alloy. This coating is therefore extremely sensitive to attack. Softened water in itself is also aggressive to zinc.
REMEDY	• Construct the system in stainless steel or hot-dip galvanized steel (zinc coating approximately 100 µm). • In the latter case, use less aggressive cleaning chemicals and of nonsoftened cleaning water. • Or derust and repaint the system periodically.

CORROSION ATLAS

CASE HISTORY

02.11.22.01

MATERIAL	Zinc-coated steel.
SYSTEM	Extrusion die.
PART	Bolt.
PHENOMENON	Solid metal–induced embrittlement.

APPEARANCE	Left: a new bolt. Right: Used bolt with brittle fracture.
TIME IN SERVICE	3 months.
ENVIRONMENT	Inside atmosphere; high temperature (270 °C).
CAUSE	Embrittlement of bolt material by zinc penetration. This occurs at a temperature above 240 °C but below the melting point of zinc (see also Case history 01.04.22.01).
REMEDY	Use uncoated bolts.

CORROSION ATLAS

CASE HISTORY

02.16.10.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Cattle shed.
PART	Rear support of partition wall between the cows.
PHENOMENON	Ammonia corrosion.

APPEARANCE	Irregular pitting.
TIME IN SERVICE	$1\frac{1}{2}$ years.
ENVIRONMENT	Cow manure.
CAUSE	The defective construction (plastic sleeve was applied too low) and failure to remove the manure regularly allowed the zinc coating to be dissolved by ammonia and corrosive substances from the manure, after which the steel was attacked and rusted through.
REMEDY	Install new partitions, making sure that the protective plastic sleeve reaches the proper height (approximately 10 cm above the beam).

CORROSION ATLAS

CASE HISTORY

02.16.12.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Gate on rollers.
PART	Tubular railings.
PHENOMENON	Chloride attack.

APPEARANCE	Pitting (typical of chloride corrosion).
TIME IN SERVICE	$2\frac{1}{2}$ years.
ENVIRONMENT	Atmosphere.
CAUSE	During the galvanizing process, flux (zinc ammonium chloride) and zinc oxide-substances which when wet are corrosive to steel remained on certain railings.
REMEDY	Replace the corroded railings and re-galvanize the entire gate.

CORROSION ATLAS

CASE HISTORY

02.16.12.02

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Roof structure of a horticultural glasshouse.
PART	Upper tube of the roof truss.
PHENOMENON	Chloride attack.

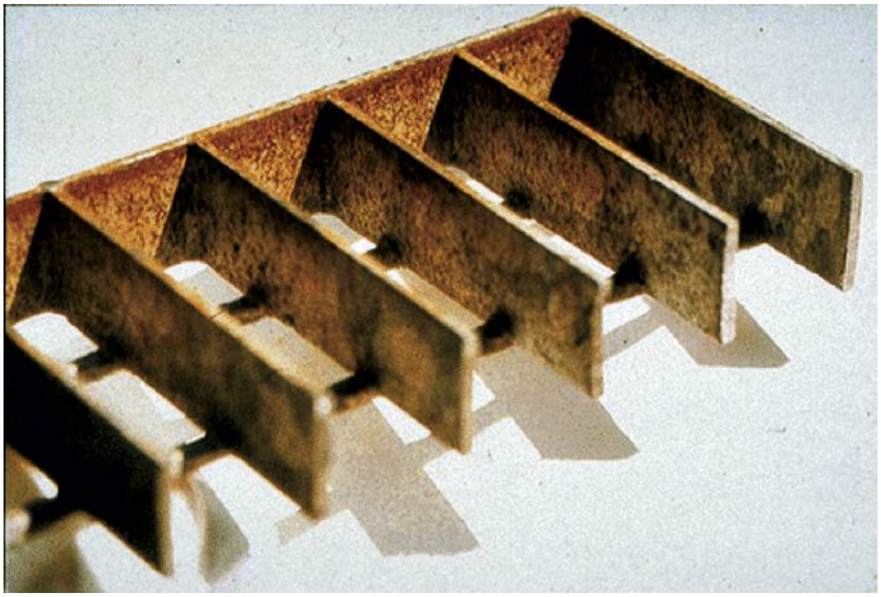
APPEARANCE	Left: pipe section partially filled with deposit. Right: pipe section corroded through, with pitting.
TIME IN SERVICE	14 years.
ENVIRONMENT	Humid atmosphere.
CAUSE	Because the outflow orifice provided for galvanizing purposes had been made at an incorrect site and was much too small, zinc and flux ash residues (zinc ammonium chloride) were unable to escape sufficiently. Particularly the flux ash residues, when wet, are corrosive in relation to steel (see also Case History 02.16.12.01).
REMEDY	Replace trusses by new trusses having a larger outflow orifice at the appropriate site.

CORROSION ATLAS

CASE HISTORY

02.16.24.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Grating floors of an outdoor chemical plant.
PART	Part of a floor section.
PHENOMENON	Atmospheric corrosion.



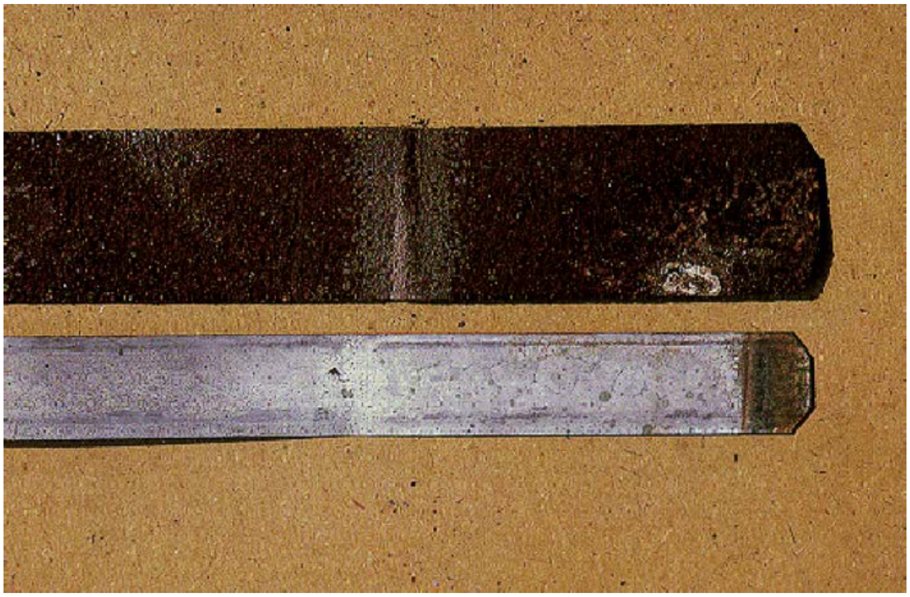
APPEARANCE	Brown rust spots.
TIME IN SERVICE	3 months.
ENVIRONMENT	Industrial atmosphere.
CAUSE	Abrasive dust originating from grinding and welding operations to the pipelines remained on the hot-dip galvanized gratings. The iron particles began to corrode and caused the brown color of the zinc surface. Accordingly, this attack was caused by poor workmanship.
REMEDY	The gratings cannot be cleaned, the only solution is disassembly and regalvanization. To prevent such attack, cover galvanized constructions before starting the activities.

CORROSION ATLAS

CASE HISTORY

02.16.24.02

MATERIAL	Hot-dip galvanized and zinc-electroplated steel.
SYSTEM	Horticultural glasshouse.
PART	Attachment strips.
PHENOMENON	Atmospheric corrosion.



APPEARANCE	The upper strip is uniformly corroded, but the lower strip exhibits no corrosion apart from the extremities.
TIME IN SERVICE	4–5 years.
ENVIRONMENT	Marine atmosphere.
CAUSE	The upper zinc-electroplated strip (zinc layer 10 µm) proved to be insufficiently corrosion-resistant in the marine atmosphere. By contrast, the hot-dip galvanized strip (zinc layer 40–50 µm) proved to be sufficiently corrosion resistant.
REMEDY	The electroplated snips should be replaced by hot-dip galvanized strips.

CORROSION ATLAS

CASE HISTORY

02.16.24.03

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Structure.
PART	Weld.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Only the weld is uniformly corroded.
TIME IN SERVICE	4 years.
ENVIRONMENT	Rural atmosphere.
CAUSE	Damage to the zinc layer during welding. The weld was not protected and therefore corroded. The abutting zinc layer prevented the rust formation from spreading.
REMEDY	After welding galvanized steel, the welds should be protected by means of an appropriate zinc compound paint.

CORROSION ATLAS

CASE HISTORY

02.16.24.04

MATERIAL	Continuous hot-dip zinc-coated steel (Sendzimir process).
SYSTEM	Glasshouse.
PART	Beam.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Uniform attack with rust formation.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Atmosphere.
CAUSE	The combination of an excessively thin permeable zinc coating with SO_2 vapors originating from a boiler plant installed nearby. The manufacturer had provided a 2-year warranty on the galvanized steel.
REMEDY	Continuous hot-dip zinc-coated steel is not suitable for outdoor use. In this case, the galvanized steel structure was replaced by an aluminum structure. Alternative: After pickling, the corroded structure could be hot-dip galvanized and provided with a coating (duplex system).

CORROSION ATLAS

CASE HISTORY

02.16.24.05

MATERIAL	Sherardized steel.
SYSTEM	Platform of outdoor installation.
PART	Bolt with nut.
PHENOMENON	Atmospheric corrosion.

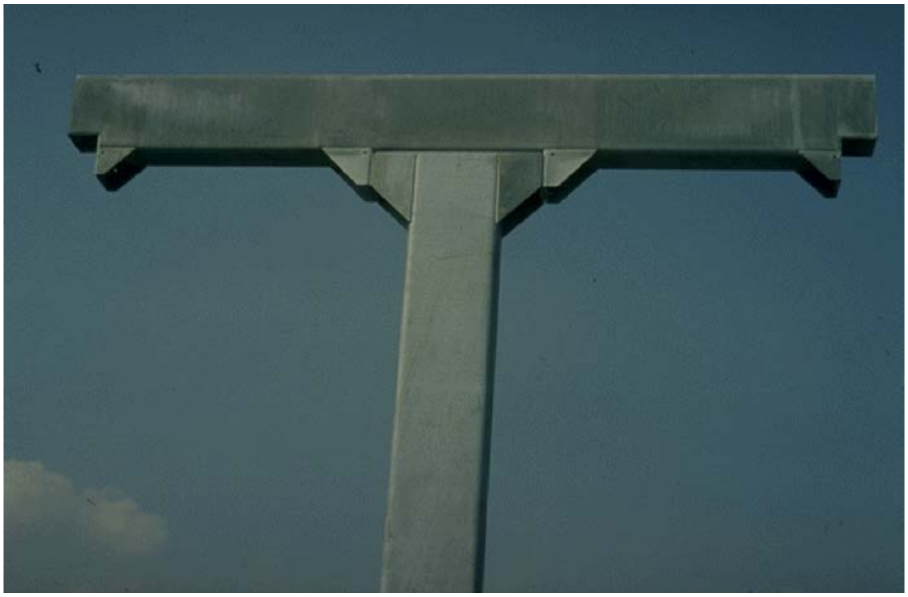
APPEARANCE	Bolt head and nut rusted at one side.
TIME IN SERVICE	2 days.
ENVIRONMENT	Industrial atmosphere, contaminated with sulfur dioxide and ammonium nitrate (acid deposition).
CAUSE	Sherardized steel is not resistant to this aggressive atmosphere, the still fresh, unoxidized zinc layer being rapidly attacked, after which corrosion of the steel occurs.
REMEDY	After brushing off the corrosion products in mildly alkaline demineralized water, the bolts and nuts were painted with a coal tar epoxy paint.

CORROSION ATLAS

CASE HISTORY

02.16.31.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Auction building.
PART	Structural beams.
PHENOMENON	Sandelin phenomenon.



APPEARANCE	Cross-beam exhibits an abnormal, grey-veined appearance.
TIME IN SERVICE	Not applicable.
ENVIRONMENT	Not applicable.
CAUSE	The cross-beam is manufactured from silicon-killed steel, which renders the steel more reactive in the presence of molten zinc, with the zeta layer growing profusely during galvanizing and while the coating is cooling down. The effect can be severe, usually at silicon levels above about 0.3%, with the alloy layer growing through to the surface of the coating. This is in contrast to the coating on the vertical beam which is made from unkilled steel where the normal relatively pure eta surface zinc layer is present. The same effect also occurs in semi-killed steel (Si content above 0.03%) but it is normally only significant at silicon levels above about 0.05%, with a substantial reduction in the rate of zeta alloy formation at about 0.11%.
REMEDY	The resultant overall thicker coating provides a proportionately higher degree of corrosion protection but excessively thick coatings should be handled with care as they can be brittle and therefore liable to damage. If the galvanizer is provided in advance with an analysis of the steel offered for galvanizing, he can make appropriate adjustments to the process to avoid excessively thick and brittle coatings. This Sandelin phenomenon does not occur with aluminum-killed steel when reactive levels of silicon are not present.

CORROSION ATLAS

CASE HISTORY

02.17.24.01

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Street equipment.
PART	Left: Letter-box support profile; right: Traffic bollard.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Brown corrosion visible only on the south-west and west sides.
TIME IN SERVICE	20 and 17 years, respectively.
ENVIRONMENT	Marine-industrial atmosphere, contaminated with SO_2, NO_2, chlorides, and fluorides carried on south-westerly/westerly winds from an industrial district located at a distance of 15 km.
CAUSE	Attack to the zinc coating and the steel surface by the contaminants carried on the wind. Strong one-sided attack by the prevailing local wind direction and wetting by acid rain (differential atmospheric corrosion).
REMEDY	Replacement of these elements by new hot-dip galvanized components, possibly with one or two coats of paint (duplex system). Reconditioning is no longer possible because excessive rust formation has already taken place.

CORROSION ATLAS

CASE HISTORY

02.17.24.02

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Street equipment.
PART	Lamp-post.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Brown corrosion products in and beside the crevice around the hatch in the post.
TIME IN SERVICE	About 12 years.
ENVIRONMENT	Rural, mild industrial atmosphere.
CAUSE	Difference in aeration between the crevice and the rest of the post surface creates a differential cell, allowing rust formation to take place due to the rainwater remaining in the crevice. Rust water has caused brown discoloration to the lower part of the post.
REMEDY	See Case History 02.17.24.01.

CORROSION ATLAS

CASE HISTORY

02.17.24.03

MATERIAL	Zinc electroplated steel.
SYSTEM	Separating structures.
PART	Left: Wire netting of fence Right: Barbed wire fence.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Rust formation on the wire netting and the barbed wire, with corrosion patches on the tubes.
TIME IN SERVICE	About 10 and 14 years, respectively.
ENVIRONMENT	Urban and marine atmosphere, respectively.
CAUSE	The zinc-electroplated wire netting and the barbed wire corroded because of the thin coating layer of 5–8 μm. Corrosion products from the netting and the barbed wire deposited on the hot-dip galvanized pipes (coating thickness 50–80 μm). The stainless-steel clamps of the fence moreover caused galvanic corrosion of the zinc layer on the contact areas with the galvanized tubes.
REMEDY	Use zinc-electroplated and then PVC-coated netting/barbed wire, with hot-dip galvanized steel clamps.

CORROSION ATLAS

CASE HISTORY

02.17.24.04

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Separating structure.
PART	Fence posts.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	The posts are uniformly corroded or exhibit areas of rust. The attachment fittings are not corroded.
TIME IN SERVICE	14 years.
ENVIRONMENT	Marine-industrial atmosphere.
CAUSE	Difference in zinc layer thickness between the two hot-dip galvanized steel components causes difference in corrosion. The posts are covered with a 60- to 75-μm zinc layer. The cast-iron fittings, however, are covered with a 90- to 130-μm layer.
REMEDY	Because reconditioning with paint coating systems was not feasible, the rusted fence parts were replaced by others which were more effectively galvanized.

CORROSION ATLAS

CASE HISTORY

02.17.24.05

MATERIAL	Hot-dip galvanized and zinc-electroplated steel.
SYSTEM	Street equipment.
PART	Fastening strips on a waste-bin.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	The fastening strips are uniformly corroded. The lamp-post itself is not.
TIME IN SERVICE	14 years.
ENVIRONMENT	Urban atmosphere.
CAUSE	The zinc-electroplated strips are insufficiently corrosion-resistant by contrast to the hot-dip galvanized lamp-post. The waste-bin had been treated with a duplex system: Hot-dip galvanized plus polyurethane paint.
REMEDY	The strips should also be made of hot-dip galvanized steel (see also Case History 02.16.24.02).

CORROSION ATLAS

CASE HISTORY

02.17.24.06

MATERIAL	Hot-dip galvanized steel.
SYSTEM	Separating structure.
PART	Barrier alongside a mountain road.
PHENOMENON	Atmospheric corrosion.
	
APPEARANCE	Part of the barrier exhibits uniform corrosion.
TIME IN SERVICE	Probably less than 5 years.
ENVIRONMENT	Rural atmosphere.
CAUSE	Part of the hot-dip galvanized barrier had been repaired after a car had collided into it. It had subsequently been derusted and painted by hand. Evidently, this repair job had been substandard, and the corrosion resistance was poor by comparison with the rest of the barrier.
REMEDY	Remove the damaged part, cleanse by pickling and hot-dip galvanize once again.

CORROSION ATLAS

CASE HISTORY

02.20.13.01

MATERIAL	Zinc (6–9 μm) electroplated steel.
SYSTEM	Automotive system.
PART	Hydraulic lift cylinder, mounted in steel tube by means of an adhesive.
PHENOMENON	Crevice corrosion.

APPEARANCE	Overall attack of the zinc coating.
TIME IN SERVICE	1 year.
ENVIRONMENT	Normal road conditions.
CAUSE	Wetting by capillary activity caused corrosion of the zinc coating. Zinc is sensitive to crevice corrosion. This resulted in leakage of water to the hydraulic system.
REMEDY	Redesign of the hydraulic lift and application of a better gluing process.

CORROSION ATLAS

CASE HISTORY

02.24.01.01

MATERIAL	Hot-dip galvanized, zinc-electroplated, and continuous zinc-electroplated steel.
SYSTEM	Laboratory rig.
PART	Three plates.
PHENOMENON	Oxygen corrosion.

APPEARANCE	The left-hand plate (hot-dip galvanized) exhibits no corrosion, the center plate (electroplated) is slightly corroded and the right-hand plate (continuous electroplated) is severely corroded.
TIME IN SERVICE	18 months (at sequences of 8 h *in* – 16 h *out* of mains water, etc.).
ENVIRONMENT	Mains water, room temperature.
CAUSE	The difference in corrosion is due to difference in quality of the zinc layer. Besides the thickness of zinc layer, this is also affected by the presence of iron–zinc alloys, as in the case of hot-dip galvanized steel. Thickness of zinc layer, left plate: 50–60 μm. Thickness of zinc layer, center plate: 10 μm. Thickness of zinc layer, right plate: 1–2 μm.
REMEDY	For applications in mains water at room temperature, of all zinc application methods *hot-dip* galvanizing is the only eligible type.

CORROSION ATLAS

CASE HISTORY

02.24.12.01

MATERIAL	Zinc electroplated steel.
SYSTEM	Weathering test.
PART	Panel.
PHENOMENON	Chloride attack.

APPEARANCE	Zinc layer locally disappeared and steel surface uniformly corroded
TIME IN SERVICE	8 months.
ENVIRONMENT	Standing unaerated seawater.
CAUSE	Zinc-electroplated steel with a zinc layer thickness of only 2–3 µm is not resistant to seawater, not even for a short period of exposure.
REMEDY	• Provide panels with a duplex ssystem (hot-dip galvanizing, layer thickness >100 µm, with, e.g., two layers of coal tar/epoxy coating, layer thickness 300–500 µm). • Alternative: spray the blasted steel surface with a 100- to 150-µm-thick aluminum coating.

CORROSION ATLAS

CASE HISTORY

02.24.24.01

MATERIAL	Hot-dip galvanized and duplex coated steel.
SYSTEM	Test rig.
PART	Test plates.t
PHENOMENON	Atmospheric corrosion.

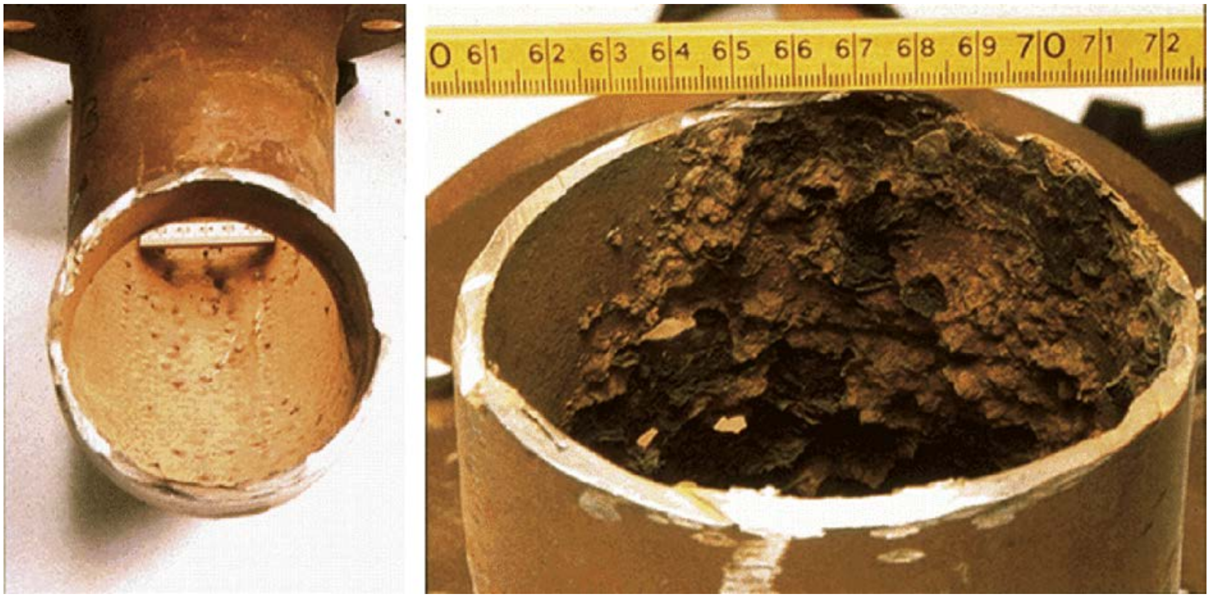
APPEARANCE	Two microphotos: On the left a steel surface provided with a duplex system, on the right a hot-dip galvanized steel surface.
TIME IN SERVICE	About 12 years.
ENVIRONMENT	Marine-industrial atmosphere.
CAUSE	The zinc layer of the hot-dip galvanized steel plate had been attacked by the aggressive atmosphere. Part of the zeta alloy layer (upper layer) and the delta-1 layer are still present. The pure zinc layer (eta layer) has corroded away entire. After galvanizing, the left-hand plate had been directly coated with a polyvinyl butyral wash primer, a cresylic formaldehyde resin (10 µm), and a top coating of vinyl acrylate copolymer (20 µm). The duplex system prevented any attack to the zinc layer whatsoever.
REMEDY	Application of duplex systems is preferred where hot-dip galvanized steel is exposed to the effects of aggressive climates.

CORROSION ATLAS

CASE HISTORY

03.01.40.01

MATERIAL	Baked coating of phenol formaldehyde resin on carbon steel.
SYSTEM	Boiler feedwater system.
PART	Suction branch pipes of a feedwater tank.
PHENOMENON	Coating failure.



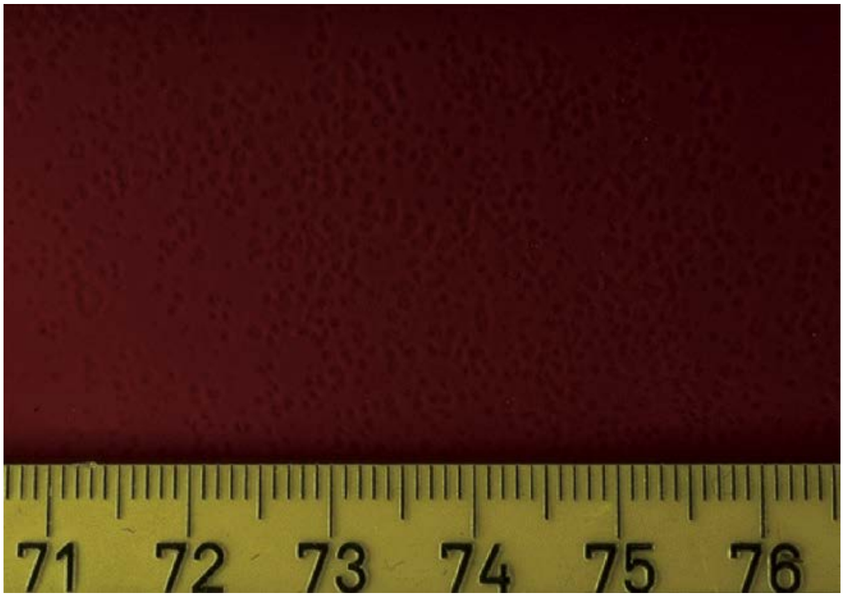
APPEARANCE	Blisters in coating and pitting underneath corrosion nodules.
TIME IN SERVICE	3 years.
ENVIRONMENT	Mixture of condensate and softened make-up water (aggressive and oxygen-containing); temperature 60–65 °C.
CAUSE	The coating contained pores due to poor application. These led to entry of water, blistering, under-rusting, and finally to flaking-off of the coating and severe corrosion to the tank by the aggressive feedwater (see also Case Histories 03.05.40.01 and 03.21.40.03).
REMEDY	• Replacement of the branch pipes and repair of the coated tank locally with cold-hardening epoxy coating. • A better option would be to grit-blast the tank and recoat it, checking the coating for pores by means of spark-testing. • Alternative: Construction of the tank from stainless steel.

CORROSION ATLAS

CASE HISTORY

03.04.40.01

MATERIAL	Carbon steel with a baked epoxy coating.
SYSTEM	Central heating system expansion vessel.
PART	External surface.
PHENOMENON	Coating failure.



APPEARANCE	About 30% of the surface of the coating is covered with closely juxtaposed pits.
TIME IN SERVICE	During production.
ENVIRONMENT	Not applicable.
CAUSE	The presence of polycyclic aromatic hydrocarbons (PAHs) in the drawing oil used, which made the vessels difficult to degrease. As a result, residues of drawing oil remained on the surface, leading to local poor adhesion of the powder coating and consequent formation of small craters.
REMEDY	Use PAH-free drawing oil, which is moreover less damaging to the environment.

CORROSION ATLAS

CASE HISTORY

03.05.40.01

MATERIAL	Baked coating of phenol formaldehyde resin on carbon steel.
SYSTEM	Hot water storage boiler with copper bundle and coated steel case.
PART	Boiler case section.
PHENOMENON	Coating failure.

APPEARANCE	Pitting with corrosion blisters.
TIME IN SERVICE	5 years.
ENVIRONMENT	Untreated mains water at 80 °C (steam through the copper tubes of the boiler).
CAUSE	Pores in the coating due to poor application. Corrosion was galvanically reinforced by the copper bundle.
REMEDY	• Removal of the coating by grit-blasting of the boiler after which it has to be recoated, keeping a good check for the presence of pores (by spark-testing); or • Replacement of the boiler by a copper-lined boiler, or by a steel boiler provided with cathodic protection (retaining the copper bundle).

CORROSION ATLAS

CASE HISTORY

03.05.40.02

MATERIAL	Coal tar epoxy coating (two coats) over steel.
SYSTEM	Water supply system.
PART	Internally coated water transmission line (coating thickness 450–500 μm).
PHENOMENON	Coating failure (intercoat delamination).

APPEARANCE	Severe delamination of the second coat from the first. Note the complete lack of bond between coats.
TIME IN SERVICE	A few months.
ENVIRONMENT	Fresh water.
CAUSE	Poor adhesion between the two coats caused by overcuring of the original coat and condensation of moisture on the surface even though it was dry when the second coat was applied. This is a common failure of coal tar epoxy. Rain, dew, and condensation create a condition on the surface that does not allow the second coat to adhere.
REMEDY	• Select a coating that is soluble in its own solvents (such as lacquer-type coatings). Apply second coat before the first is thoroughly cured, or • Make sure the coal tar epoxy is applied under dry conditions • If condensation occurs, lightly blast the coal tar epoxy surface before applying the second coat

CORROSION ATLAS

CASE HISTORY

03.05.40.03

MATERIAL	Alkyd coating (two coats) on steel.
SYSTEM	Conveyor pipe system for water.
PART	Externally coated pipe.
PHENOMENON	Coating failure (underfilm corrosion).

APPEARANCE	Broken tubercles, with rust increasing in volume under unbroken film lifting off surface (similar to undercutting).
TIME IN SERVICE	Several months.
ENVIRONMENT	Severe marine atmosphere.
CAUSE	Poor adhesion because alkyd coatings tend to cure and become more porous over time. Water, oxygen, and salt penetrate and cause severe rusting and pitting. Underfilm corrosion of this type is most prevalent with surface-oxidizing coatings, such as oil base paints and alkyd coatings.
REMEDY	Apply alkyd over a robust anticorrosive primer (such as inorganic zinc) or change to a high-performance coating system.

CORROSION ATLAS

CASE HISTORY

03.06.14.01

MATERIAL	Coated carbon steel.
SYSTEM	Through-flow cooling water system.
PART	Channel head of heat exchanger.
PHENOMENON	Galvanic corrosion.

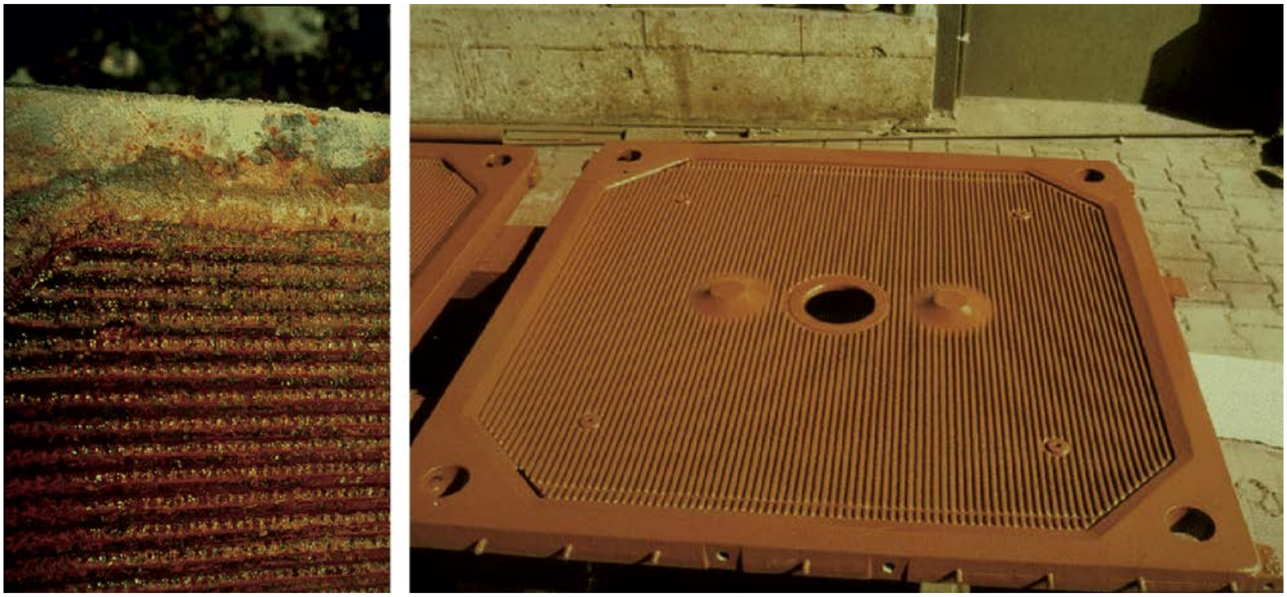
APPEARANCE	Severe attack in particular immediately beside the pipe plate, which was also attacked itself. On the left, the channel head with temporary coating; on the right, after blasting.
TIME IN SERVICE	Within 3 months.
ENVIRONMENT	Brackish cooling water through the pipes. Ethylene around the pipes.
CAUSE	The pipe bundle was made of cupronickel, the channel head was coated. This combination leads to severe galvanic corrosion at flaws in the coating (pores and areas damaged when the bundle was inserted).
REMEDY	To prevent galvanic corrosion, the bundle must be internally coated like the channel head, preferably with a baked coating. The bundle can also be made of coated carbon steel. This is a less expensive and more reliable design than the original one.

CORROSION ATLAS

CASE HISTORY

03.08.04.01

MATERIAL	Cast iron (with a coating unsuited for this purpose).
SYSTEM	Sewage treatment plant.
PART	Filter pressure plates (1200 × 1200 × 50 mm) of a sludge dewatering unit.
PHENOMENON	Acid corrosion and erosion.



APPEARANCE	Left: original coating disappeared, severe fouling and attack underground. Right: the same plate after application of synthetic coating.
TIME IN SERVICE	5 years.
ENVIRONMENT	Sludge conditioned by the addition of ferric chloride and chalk. Pressure 15–16 bar. The filter pressure plates were cleaned with 5% hydrochloric acid for a period of 24 hours several times a year.
CAUSE	The dosages of $FeCl_3$ and $Ca(OH)_2$ are often imprecise and incorrectly adjusted, as a result of which an aggressive environment frequently occurs. The $CaSO_4$ gypsum formed is not homogeneous, and it also has an abrasive action. Corrosion can even take place during the periodical cleaning treatments. So, both chemical and mechanical attack takes place.
REMEDY	By applying good-quality thermally cured special synthetic coating (baked), the plates were recommissioned and have already been successfully used for several years. Careful blasting, passivating, etc., should be carried out as a surface pretreatment is of essential importance in this reconditioning job.

CORROSION ATLAS

CASE HISTORY

03.08.14.01

MATERIAL	Carbon steel, coated with coal tar epoxy.
SYSTEM	Sewage treatment plant.
PART	Skimmer in settling tank.
PHENOMENON	Galvanic corrosion.

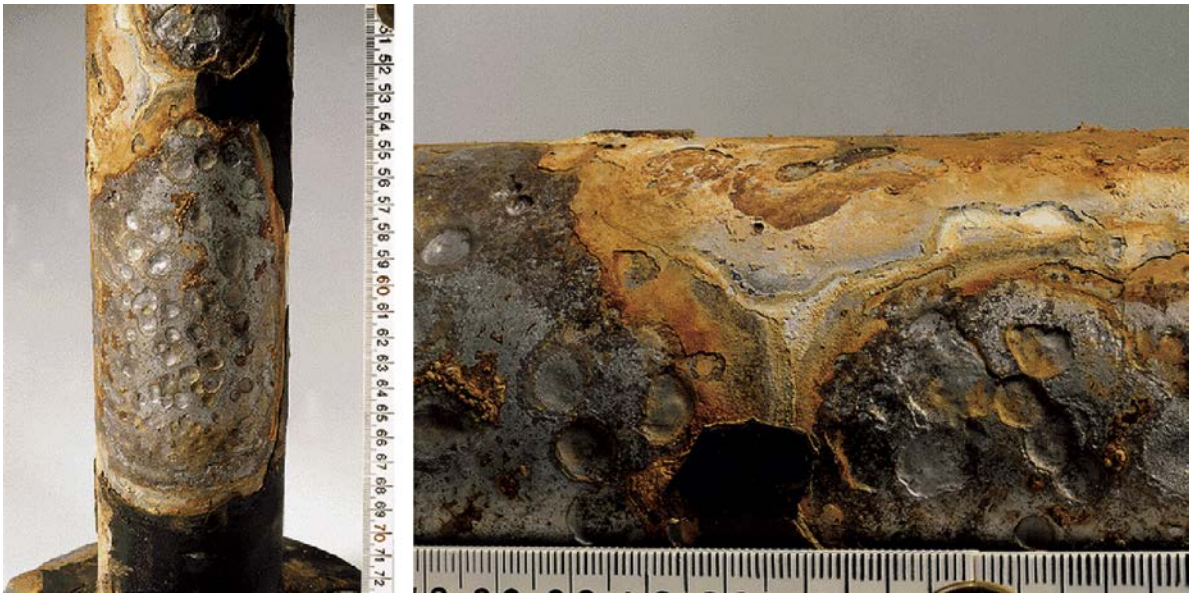
APPEARANCE	Local flaking-off of the coating, with pitting attack of the steel.
TIME IN SERVICE	$\frac{1}{2}$ year after fitting stainless-steel cap.
ENVIRONMENT	Sewage, highly conductive.
CAUSE	After the stainless steel cap was fitted, a bimetallic contact was created between the pores in the coating and the stainless steel, leading to galvanic corrosion (see also Case Histories 03.05.40.01 and 03.06.14.01).
REMEDY	Repair the coating and then: • provide the cap with electric isolation at the suspension points, or • provide cathodic protection and perform regular inspections, or • construct the cap of plastic.

CORROSION ATLAS

CASE HISTORY

03.08.17.01

MATERIAL	Bitumen-coated steel.
SYSTEM	Waste water treatment plant.
PART	Aerator tube of aeration basin.
PHENOMENON	Microbiologically induced corrosion (MIC).



APPEARANCE	Flaked-off bitumen coating, shiny metallic steel surface with extensive pitting.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Waste water from potato flour mill.
CAUSE	Short shut-down period caused degradation of the active slime in the basin. This yielded conditions in which coating attack and attack of the steel by sulfate-reducing bacteria could occur.
REMEDY	Maintain aeration of basin. No attack occurs under normal operating conditions.

CORROSION ATLAS

CASE HISTORY

03.10.17.01

MATERIAL	Bitumen-coated steel.
SYSTEM	Fire-extinguishing system.
PART	Underground transport pipeline.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Locally severe bowl-shaped attack.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Sand bed with gravel, in marshy soil.
CAUSE	When the soil was compacted, the bitumen coating suffered local damage due to the presence of gravel. At these places, corrosion took place as a result of sulfate reduction by sulfate-reducing bacteria, in which the sulfide formed attacks the steel. This case is obviously the result of poor workmanship (see also Case History 03.14.17.02).
REMEDY	• In view of the position of the underground pipeline below roads and buildings, in this case it was decided not to replace the underground pipeline and a new above-ground pipeline was constructed. • When embedding underground pipelines, the soil should not be overcompacted or pure sand without gravel, etc., should be used.

CORROSION ATLAS

CASE HISTORY

03.11.01.01

MATERIAL	Carbon steel with coating applied in situ.
SYSTEM	Gas production station piping.
PART	Straight pipe section with weld (wall thickness 7 mm).
PHENOMENON	Oxygen corrosion.

APPEARANCE	Attack near field weld at coating failure.
TIME IN SERVICE	5 years or more.
ENVIRONMENT	Aerated disposal water of high salinity (15–20%); pH approximately 5; temperature about 35 °C.
CAUSE	When a field weld is coated, it is difficult to provide root penetration with a successful coat. As a result, local coating insufficiency leads to corrosion damage. This damage is the result of poor workmanship.
REMEDY	• Improved weld quality to prevent excessive root penetration; • Reduce the corrosivity of disposal water by preventing oxygenation during storage or by chemically binding the oxygen, and • Dosing a corrosion inhibitor.

CORROSION ATLAS

CASE HISTORY

03.11.02.01

MATERIAL	Carbon steel (factory coated).
SYSTEM	Disposal well for injection of co-produced formation water.
PART	Pipe section (wall thickness 11 mm) near upset of the well tubing.
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

APPEARANCE	Large hole at the coating damage.
TIME IN SERVICE	2 years.
ENVIRONMENT	Formation water with carbon dioxide and possibly oxygen present; temperature ≤40 °C.
CAUSE	Corrosion due to the aggressive formation of water occurred at sites where the coating had been damaged during manufacture, transport, or installation.
REMEDY	• Check the coating quality and improve handling of coated pipes, local conditions permitting; • Corrosion protection by dosing inhibitor.

CORROSION ATLAS

CASE HISTORY

03.11.02.02

MATERIAL	Epoxy-coated carbon steel.
SYSTEM	Oil well.
PART	Section of the well tubing and upset screwed connection (wall thickness 11–6 mm and 6 mm).
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

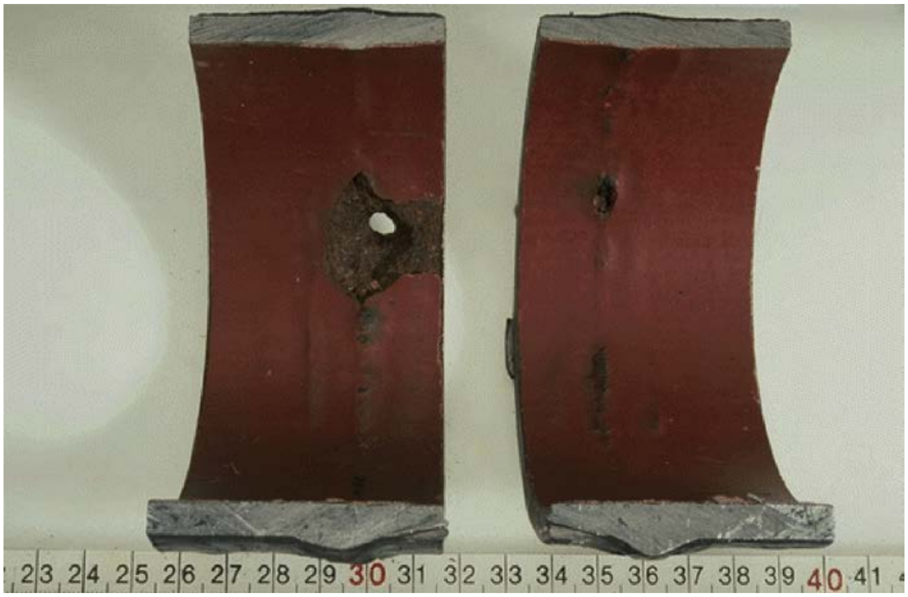
APPEARANCE	Severe localized attack at sites where the coating is damaged. On the right, ringworm corrosion at the upset extremity.
TIME IN SERVICE	2–4 years.
ENVIRONMENT	Carbon dioxide⁻ and salt-containing oil/water mixtures, temperature up to 50 °C.
CAUSE	Severe CO_2 corrosion at sites where the coating afforded no protection due to pinholes and/or damage present. Coating defects may be attributable to errors in pretreatment or coating application or to rough handling of the pipes.
REMEDY	• Improved inspection of coating quality by the manufacturer (spark testing for pinholes); • Careful handling of coating pipes, local conditions permitting; • Application of corrosion inhibitor; • Application of duplex stainless steel under highly corrosive conditions.

CORROSION ATLAS

CASE HISTORY

03.11.02.03

MATERIAL	Carbon steel with in situ applied epoxy-silica coating.
SYSTEM	Disposal water transport system.
PART	Pipe section (wall thickness 6 mm).
PHENOMENON	Carbon dioxide/oxygen corrosion.



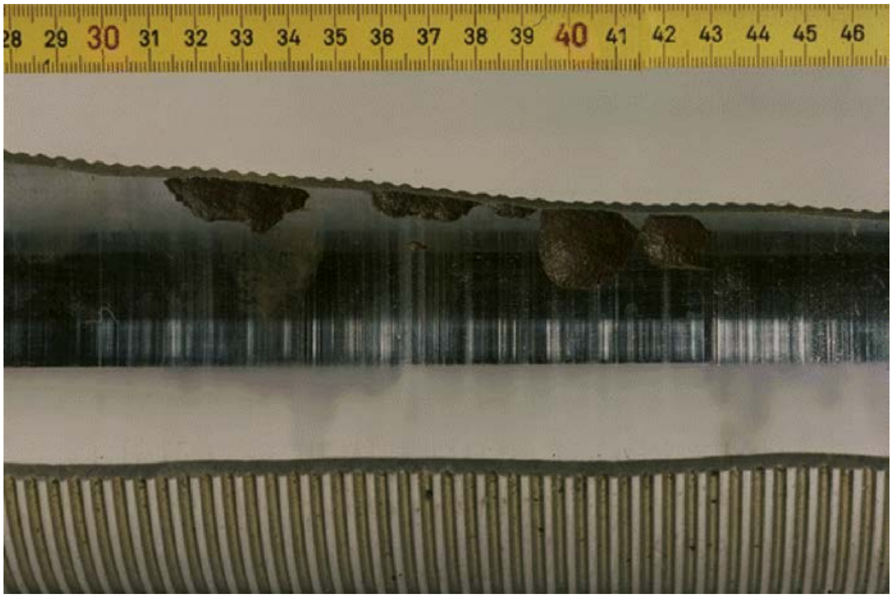
APPEARANCE	Pitting attack near the weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Oxygen¯ and carbon dioxide¯containing water of high salinity (15–20%), temperature about 30 °C.
CAUSE	In situ applied internal coating leaves holidays near the weld penetration. Corrosion in these places may lead to very rapid penetration, sometimes as high as 10 mm/year.
REMEDY	Change to glass fiber–reinforced epoxy piping.

CORROSION ATLAS

CASE HISTORY

03.11.12.01

MATERIAL	Nickel plated steel (St52) (40 μm Ni + 70 μm Cr).
SYSTEM	Margarine manufacture.
PART	Perfector tube for cooling margarine with ammonia (externally).
PHENOMENON	Chloride attack.



APPEARANCE	Severe pitting on the underside of the tube.
TIME IN SERVICE	1/2 year.
ENVIRONMENT	Margarine emulsion, in mixed form during the production process, in unmixed fat and water phase during shut down.
CAUSE	During operating shut down (at night), the water phase containing 8% salt settled out and caused pitting of the coating and next of the carbon steel (galvanic corrosion may have played a contributory role via pores in the coating).
REMEDY	• Prevent demixing by maintaining cooling at night. • Alternative: make the perfector tubes of Stellite 6 (a highly abrasion-resistant and chloride-resistant cobalt–chromium alloy).

CORROSION ATLAS

CASE HISTORY

03.11.12.02

MATERIAL	Glass-lined steel.
SYSTEM	Distillation unit.
PART	Equipment.
PHENOMENON	Fluoride attack.
	
APPEARANCE	Severe local attack of the enamel lining and the steel.
TIME IN SERVICE	5 months.
ENVIRONMENT	Solution of organic solvents and hydrochloric acid with 10–20 ppm fluoride; temperature: 80 °C.
CAUSE	Glass-lined steel, just like glass (see Case History 13.11.12.01), is not resistant to environments containing F^- at elevated temperatures. Even at room temperature, glassy materials are attacked in a diluted HF solution.
REMEDY	Use any chemical or physical techniques to ensure a minimum fluoride level.

CORROSION ATLAS

CASE HISTORY

03.11.14.01

MATERIAL	Tin-plated steel.
SYSTEM	Pasteurization installation.
PART	Food can.
PHENOMENON	Galvanic corrosion (reversal of potential).

APPEARANCE	Rust spots at one side of the can.
TIME IN SERVICE	Approximately 1 hour (pasteurization and cooling).
ENVIRONMENT	Water circulating over a cooling tower; heating by means of steam injection at the base of the autoclave, to 90°C; pH 8.7 (at 95 °C); chloride (Cl^-) 120 ppm; free chlorine (Cl_2) 2 ppm.
CAUSE	The oxygen is dispelled from the water by the steam injection. Under anaerobic conditions, reversal of potential of the tin/iron cell takes place, after which, at the side facing the wall of the basket, the tin enters anodically into solution. The steel of the baskets and autoclave acts as cathode. After the detinning process, rusting occurs upon entry of oxygen with the cooling water (the tin coating is now cathodic relative to the steel in the pores).
REMEDY	• Breaking the contact between the cans and the baskets by providing the latter with a plastic lining and/or placing the cans on plastic plates in the baskets. • Alternative: installing magnesium ribbon cable anodes in the autoclave, thereby protecting the cans cathodically.

CORROSION ATLAS

CASE HISTORY

03.11.14.02

MATERIAL	Tin-plated steel.
SYSTEM	Dairy.
PART	The inside of the base of a can.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Black corrosion patches and spots.
TIME IN SERVICE	1–2 months.
ENVIRONMENT	Low-fat pasteurized milk.
CAUSE	The porous tin coating is unable to prevent corrosion in contact with low-fat milk. In the case of other foods, the corrosion will only occur after an extended period or not at all because the products contain colloids which act as an inhibitor, or tin-complexing substances such as benzoic acid. In the latter case, the tin surface becomes less noble than the steel surface so that no corrosion occurs.
REMEDY	• Application of a sealed tin coating (very expensive), or • Application of a varnish coating over the tin coating (gives the latter a brown appearance and is less attractive).

CORROSION ATLAS

CASE HISTORY

03.11.24.01

MATERIAL	Coated carbon steel (35.8)
SYSTEM	Liquid ammonia transport system.
PART	Pipeline.
PHENOMENON	Atmospheric corrosion.

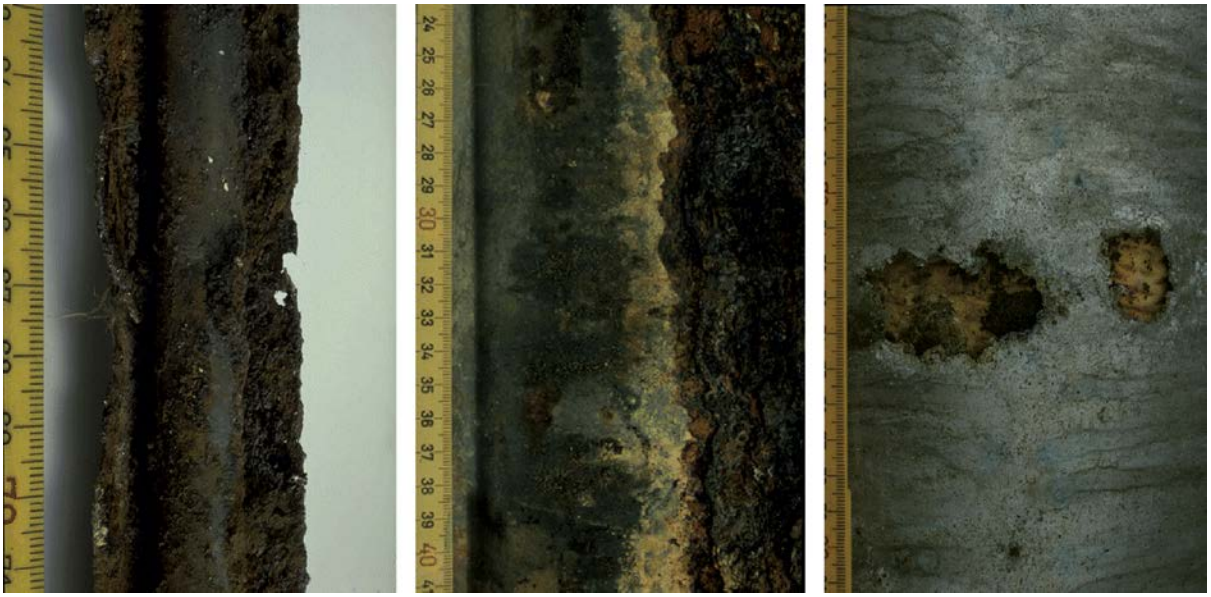
APPEARANCE	The coating flaked off at the I-beam support, and the steel pipe was attacked.
TIME IN SERVICE	15 years.
ENVIRONMENT	Industrial-marine atmosphere. Through the pipe: ammonia at 23 °C and 6.5 bar.
CAUSE	Moisture (in the form of acid chloride-containing rainwater and salt-containing droplets from the cooling towers installed in the direct vicinity) remains between the pipe and the I-beam.
REMEDY	Change the construction from supporting to suspension and provide the pipe with additional protection at the suspension point by means of tape.

CORROSION ATLAS

CASE HISTORY

03.11.25.01

MATERIAL	Coated carbon steel, continuous hot-dip galvanized steel, and aluminum.
SYSTEM	A 40-km-long product transport pipeline system equipped with steam tracing.
PART	Carbon steel pipe coated with zinc silicate paint, galvanized angle steel of copper steam tracing (secured to the pipe with stainless steel straps), and aluminum plating of the mineral wool insulation.
PHENOMENON	Corrosion under insulation.



APPEARANCE	Left: Angle steel with tracing, severely attacked and locally eroded. Center: Transport pipeline, severely attacked at the base. Right: Plating, locally eroded at the base.
TIME IN SERVICE	Product leakage identified after 11 years.
ENVIRONMENT	Insulation had become wet due to water ingress and gave alkaline reaction due to the dissolving of the sodium silicate-based heat-transfer cement present between the tracing and the angle steel.
CAUSE	Due to rainwater ingress, the insulation became wet especially at the base, so that the pipe and plating were attacked underneath. The highly alkaline reacting heat-transfer cement attacked the galvanized angle steel and reinforced the corrosion of the aluminum plating. The corrosion processes were, of course, strongly galvanically reinforced by the combination of so many different metals. Galvanized steel or zinc silicate–painted steel is moreover not applicable under insulation, since no protective patina coating is formed because of the inaccessibility to air.
REMEDY	There are a large number of options, including: • seal crevices with compound and make dewatering holes; • replace mineral wool by cellular glass; • use heat-transfer cement based on graphite and synthetic resin; • coat the pipe with epoxy or tape with Polyethylene (PE); • apply a different tracing design (at distance at four o'clock).

CORROSION ATLAS

CASE HISTORY

03.14.17.01

MATERIAL	Tape-wrapped carbon steel.
SYSTEM	Gas supply system.
PART	Underground pipe.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Severe local attack.
TIME IN SERVICE	2.5 years.
ENVIRONMENT	Groundwater with a high sulfate content (1300 ppm).
CAUSE	Owing to poor application (the result of poor workmanship), the bandage (X dur coat) had become detached at a number of points and water present underneath it probably became anaerobic, allowing sulfate-reducing bacteria to develop (sulfide detected in corrosion products). The resultant sulfide attacked the steel. Note: Any unprotected pipe will be attacked by groundwater without sulfate-reducing bacteria as well.
REMEDY	Affected sections should be replaced by properly wrapped pipe.

CORROSION ATLAS

CASE HISTORY

03.14.17.02

MATERIAL	Bitumen-coated nodular cast iron.
SYSTEM	Gas distribution grid.
PART	Pipe.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Severe localized attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Inhomogeneous soil, contaminated with slag, pH 7.2, resistivity 2300 Ω cm.
CAUSE	When the soil was compacted after the pipe was laid, the bitumen coating was damaged by the slag, after which the exposed cast iron was attacked by sulfide formed from sulfate by sulfate-reducing bacteria (see also Case History 03.10.17.01).
REMEDY	Pipe was replaced by a bitumen-coated steel pipe laid in a homogeneous sand bed.

CORROSION ATLAS

CASE HISTORY

03.14.26.01

MATERIAL	Bitumen-coated steel.
SYSTEM	Gas supply system.
PART	Underground pipe.
PHENOMENON	Stray current corrosion.

APPEARANCE	Severe local attack in part near home connection.
TIME IN SERVICE	10 years.
ENVIRONMENT	Soil (composition unknown).
CAUSE	The gas pipe was used for earthing electrical appliances in the home; the earthing currents left the pipe underground and caused local attack (see also Case History 01.05.26.01).
REMEDY	Installation of an isolating plastic insert at the gas meter.

CORROSION ATLAS

CASE HISTORY

03.14.26.02

MATERIAL	Bitumen-coated steel.
SYSTEM	Gas supply system.
PART	900 mm diameter, underground pipe section, just before socket connection.
PHENOMENON	Stray current corrosion.

APPEARANCE	Localized corrosion with many holes, before the socket connection.
TIME IN SERVICE	More than 100 years.
ENVIRONMENT	Soil; composition unknown.
CAUSE	The bitumen-coated pipe ran parallel with a tram-line. Absorbed stray currents left the pipe just before the socket connection (hemp and lead).
REMEDY	Pipeline removed. Prevention possible by draining the gas pipeline (see Case History 01.05.26.01).

CORROSION ATLAS

CASE HISTORY

03.16.24.01

MATERIAL	Painted steel.
SYSTEM	Pont Lizotte bridge, Quebec, Canada
PART	Crash barriers.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	The paint coating has flaked off due to under-rusting, the bare steel is uniformly corroded, but the galvanized steel bolts are corrosion-free.
TIME IN SERVICE	10 years.
ENVIRONMENT	Rural atmosphere.
CAUSE	Painting bare steel provides insufficient local protection against corrosion. The galvanized steel girders, gutters, angle plates, bolts, nuts, etc., however, exhibited no rust after 10 years (see also Case History 02.17.24.06).
REMEDY	The corrosion could have been prevented by subjecting all the steel bridge components plus attachment fittings to hot-dip galvanizing treatment.

CORROSION ATLAS

CASE HISTORY

03.16.40.01

MATERIAL	Polyamide epoxy coating (two coats, new untried formulation).
SYSTEM	Bridge over tidal river.
PART	Structural detail.
PHENOMENON	Coating failure (insufficient coverage on edges and in recessed areas).

APPEARANCE	General rusting on edges, bolt heads, flat, and recessed areas.
TIME IN SERVICE	2 years.
ENVIRONMENT	Marine atmosphere.
CAUSE	Poor application because the coating used was not adequate for the exposure. The coating surface tension pulls coatings away from sharp comers and edges, causing rapid penetration of edges and thin areas.
REMEDY	• Improve the application: if applied by brush, the coating should be pulled out over the edges, developing as thick a coating as possible on the edge; applied by spray, the coating should be targeted directly at the edge in order to help build up the coating there. • Apply multiple thin coats with drying in between. A fairly rapid-dry, high-build coating is a good aid to overcome edge problems. • In this case, it was necessary to reblast and recoat with a tested and effective two-coat epoxy. A better answer would have been to apply it over an inorganic zinc primer.

CORROSION ATLAS

CASE HISTORY

03.16.40.02

MATERIAL	Epoxy coating (two coats) on sand-blasted steel surface.
SYSTEM	Bridge structure over a tidal river.
PART	Beam.
PHENOMENON	Coating failure (poor selection).

APPEARANCE	General rust penetration through the coating. Failure on plane surfaces with severe undercutting of the coating.
TIME IN SERVICE	2 years.
ENVIRONMENT	Marine environment.
CAUSE	Inappropriate coating selection. This coating was new and had never been previously applied or tested. The first application of this coating failed within 2 years at both edges and plane surfaces. It was reapplied and failed similarly after 2 years. The photograph shows the second application (see also Case History 03.21.40.08).
REMEDY	Sand-blast and apply a coating which has been previously proven in this atmosphere.

CORROSION ATLAS

CASE HISTORY

03.17.40.01

MATERIAL	Alkyd top coat and unknown primer over steel surface.
SYSTEM	Street equipment.
PART	Highway sign.
PHENOMENON	Coating failure (checking or crazing).

APPEARANCE	General large checking overall: a crack system not penetrating to the substrate.
TIME IN SERVICE	Within 2 years.
ENVIRONMENT	Mild mid-western US climate, very cold winters.
CAUSE	Inappropriate coating selection. Checks are caused by weathering, oxidation, and polymerization. Excessive shrinkage of the alkyd top coat on curing over a softer less highly cured primer causes this type of coating failure over a period of time. Some pigments may stimulate the crazing process.
REMEDY	Select highly weather-resistant coatings which incorporate nonreactive and reinforcing pigments.

CORROSION ATLAS

CASE HISTORY

03.20.24.01

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat) over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Rain gutter.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Edge corrosion.
TIME IN SERVICE	1 year.
ENVIRONMENT	Normal road conditions.
CAUSE	Poor pretreatment before coating: Sharp edges on rain gutter due to poor deep-drawing and grinding activities in body shop prevented effective covering.
REMEDY	Remove sharp edges with special knife before painting.

CORROSION ATLAS

CASE HISTORY

03.20.24.02

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat) over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Seam sill box section to B-post.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Rust (water) bleeding from seams.
TIME IN SERVICE	1 year.
ENVIRONMENT	Normal road conditions.
CAUSE	Poor coating application: no extra corrosion protection between seams, poor seam sealing (see Case Histories 03.20.24.05/06/08/09).
REMEDY	• Use of zinc-coated steel sheet for sill box section. • Improved seam sealing with PVC plastisol on electrocoat.

CORROSION ATLAS

CASE HISTORY

03.20.24.03

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat) over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Door surroundings, van body.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Rust on damaged part(s).
TIME IN SERVICE	1 month.
ENVIRONMENT	Normal road conditions
CAUSE	Poor fit and finish caused paint damage.
REMEDY	Improve positioning of door in order to overcome paint damage on the body due to closing of the cab door.

CORROSION ATLAS

CASE HISTORY

03.20.24.04

MATERIAL	Coated mild steel (primer coat and stoving enamel).
SYSTEM	Automotive system.
PART	Support fuel tank (for trucks).
PHENOMENON	Atmospheric corrosion.

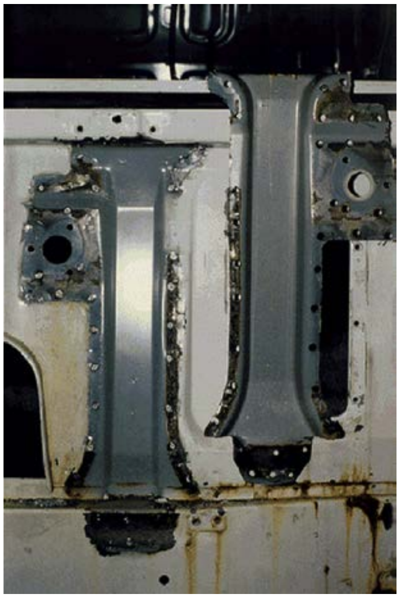
APPEARANCE	Rust on welded part; edge corrosion; rust on screw.
TIME IN SERVICE	Estimated: about 0.5 years under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test).
CAUSE	“Overall” corrosion, by a combination of dirt, road salts and humidity, caused by poor pretreatment and application: • scale on weld, paint damage due to distortion of the support (weight of fuel tank); • sharp edges (see also Case History 03.20.24.01); • paint damage due to screwing of bolts.
REMEDY	• Descaling of the weld. • Removing sharp edges before painting. • Application of wax-based corrosion protection after final assembly.

CORROSION ATLAS

CASE HISTORY

03.20.24.05

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat), over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Exterior of cab front panel.
PHENOMENON	Atmospheric corrosion.



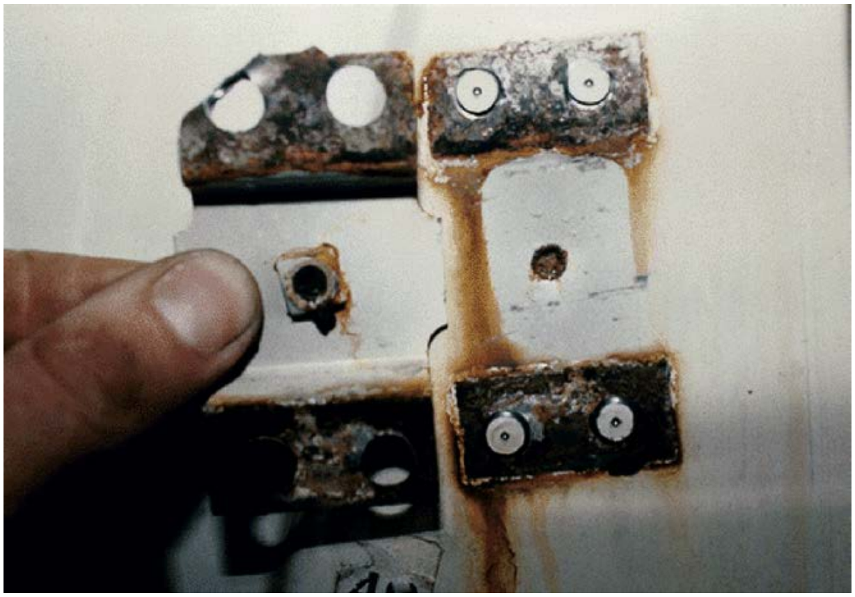
APPEARANCE	• Rusting of spot-welded seams. • Rust bleeding.
TIME IN SERVICE	Estimated: 2 years under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test).
CAUSE	• Insufficient protection of the spot-welded seams. • Crecive corrosion by a combination of dirt, road salts, and humidity.
REMEDY	• Use of zinc-coated steel. • Seam sealing with PVC plastisol. • Complementary protection (wax injection treatment).

CORROSION ATLAS

CASE HISTORY

03.20.24.06

MATERIAL	Coated mild steel (electrocoat, primer surfacer, and stoving top coat).
SYSTEM	Automotive system.
PART	Support bulkhead.
PHENOMENON	Atmospheric corrosion.



APPEARANCE	Rust in seam, rust bleeding from seam.
TIME IN SERVICE	Estimated: 1 year under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test). Combination of dirt, road salts, and humidity.
CAUSE	No corrosion protection on support caused crevice corrosion in seams (see Case History 03.20.24.09).
REMEDY	• Use continuous hot-dip zinc-coated (Senzimir process) steel sheet for the supports (zinc coating about 10–15 µm), in order to overcome problems with spot welding. • Complementary protection with coating.

CORROSION ATLAS

CASE HISTORY

03.20.24.07

MATERIAL	Coated steel (etch primer plus two-pack top coat).
SYSTEM	Automotive system.
PART	Stabilizer.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Stone chipping with rust.
TIME IN SERVICE	Estimated: 1 year under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test).
CAUSE	Paint damage due to stone chipping in combination with dirt, road salts, and humidity, resulting in rusting.
REMEDY	Increase film build, use electrocoat primer plus high-build two-pack top coat.

CORROSION ATLAS

CASE HISTORY

03.20.24.08

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat) over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Door.
PHENOMENON	Atmospheric corrosion.

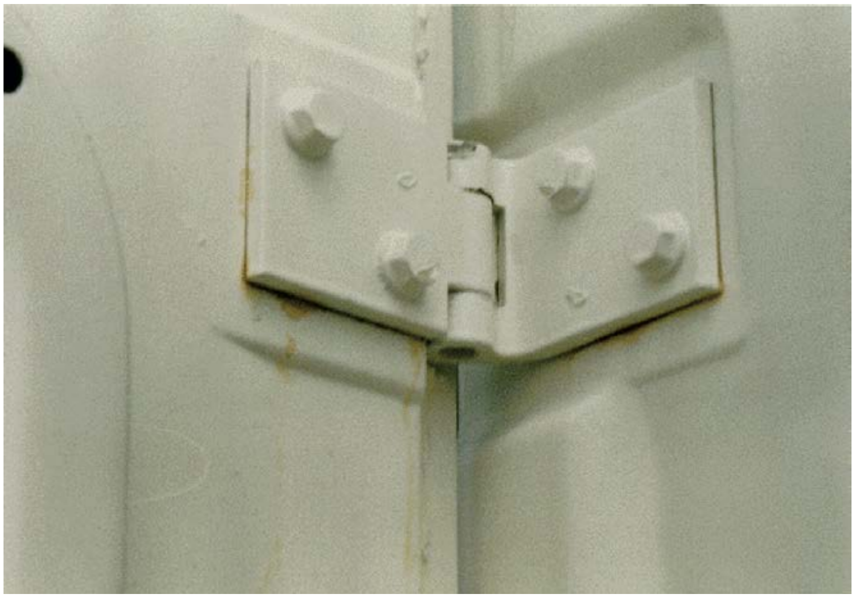
APPEARANCE	Rust bleeding from clinched seam.
TIME IN SERVICE	Estimated: about 0.5 years under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test).
CAUSE	Crevice corrosion in overlap seams, by a combination of dirt, road salts, and humidity. Poor painting of overlap, insufficient corrosion protection in overlap (see Case Histories 03.20.24.02/05/06).
REMEDY	• Improve application of adhesive in overlap, and use a more corrosion-resistant clinch adhesive. • Improve cavity waxing (after painting).

CORROSION ATLAS

CASE HISTORY

03.20.24.09

MATERIAL	Paint coating (electrocoat paint, primer/surfacer, stoving top coat) over mild cold-rolled steel.
SYSTEM	Automotive system.
PART	Door hinge.
PHENOMENON	Atmospheric corrosion.



APPEARANCE	Rust water coming from the overlap between hinge and cab, and hinge and door panel.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Normal road conditions.
CAUSE	Poor coating application: absence of paint in overlap between hinge and cab panel made this connection sensitive to crevice corrosion because of oxygen concentration cell formation (see also Case History 03.20.24.06).
REMEDY	• Zinc-plating with yellow passivation of the hinge. • Zinc-rich primer on cab and door panel (duplex system).

CORROSION ATLAS

CASE HISTORY

03.20.41.01

MATERIAL	Varnished steel.
SYSTEM	Automotive system.
PART	Light reflector, with clear enamel coating.
PHENOMENON	Filiform corrosion.

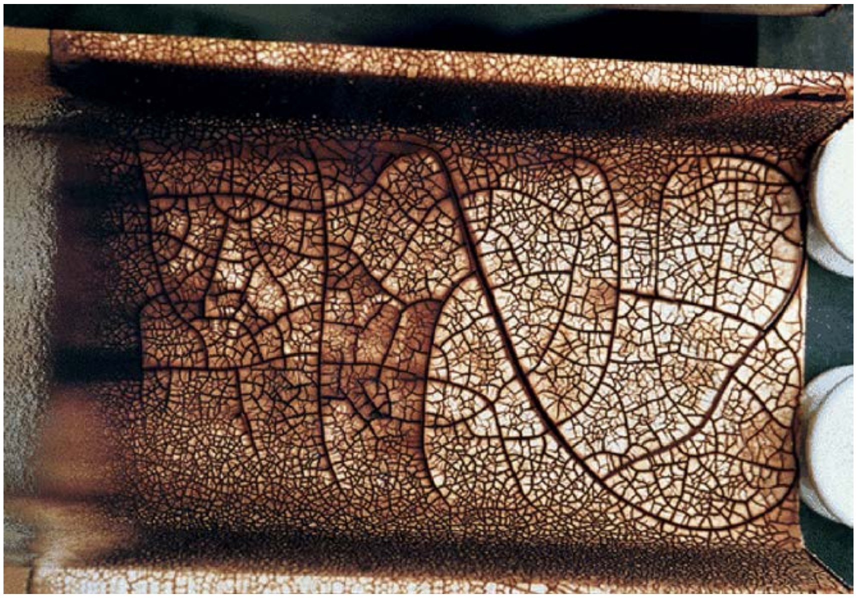
APPEARANCE	Corrosion of the steel under the coating in the form of hairlike filaments, starting from the edges.
TIME IN SERVICE	More than 10 years.
ENVIRONMENT	Storage in moist indoor atmosphere.
CAUSE	The discontinuity of the coating system at the edges and at defects elsewhere, allowing moisture to diffuse underneath coating, resulting in a filiform, fanning-out corrosion of the steel. Filiform corrosion is activated by chlorides. Oxygen concentration cells are formed between the moving end (head = anode) and the remainder of the track (tail = cathode). The pH at the head drops to 1.5–2.5 (see also Case Histories 03.24.41.01 and 12.20.41.01).
REMEDY	• Storage under less moist conditions (humidity below 65%). • Apply a different coating system (with at least two coats) after pretreatment of the steel surface. • Prevent the presence of chlorides and other salts by rinsing with demineralized water before coating.

CORROSION ATLAS

CASE HISTORY

03.21.40.01

MATERIAL	Heavy epoxy coat over steel.
SYSTEM	Steel structure.
PART	Gutter on an offshore installation.
PHENOMENON	Coating failure (cracking).



APPEARANCE	General long curved cracks overall. All cracks penetrate to the substrate. Corrosion starting at steel interface.
TIME IN SERVICE	Several months.
ENVIRONMENT	Marine.
CAUSE	Inappropriate coating selection. Poor expansion and contraction characteristics of the coating. Continued oxidation and polymerization over a long period of time leads to excessive coating shrinkage, causing cracks down to the bare metal. Improper pigmentation may aid in the weather-related cracking process (as with checking, see Case History 03.17.40.01). Oxidizing coatings are often more susceptible to cracking than are the fully polymerized thermoplastic-type resins.
REMEDY	Select a weather-resistant coating which incorporates reinforcing pigments and permanent plasticizers in order to add some extensibility and flexibility to the coating.

CORROSION ATLAS

CASE HISTORY

03.21.40.02

MATERIAL	Epoxy primer (red) followed by a top coat (grey).
SYSTEM	Tanker.
PART	Fore deck.
PHENOMENON	Coating failure (chalking).

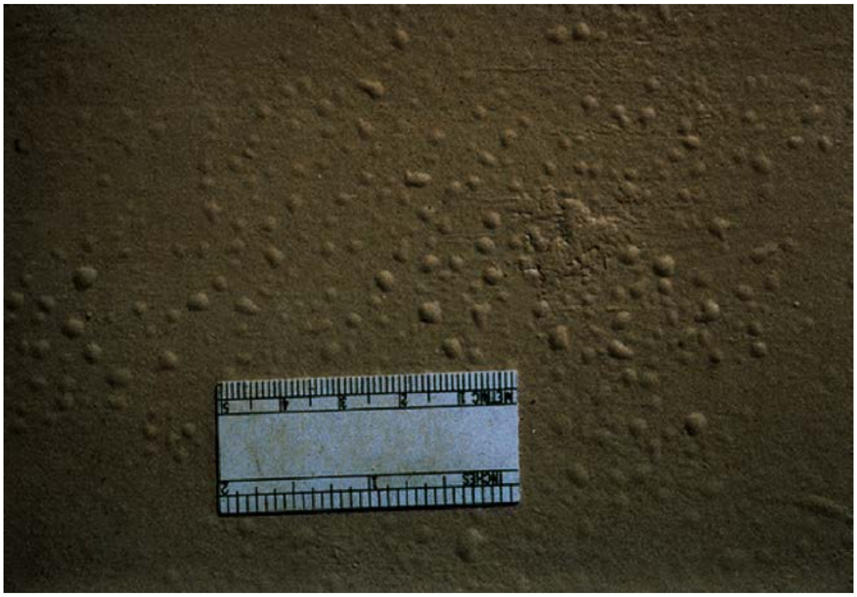
APPEARANCE	General soft, dusty surface. Only the top coat is attacked. The intact red epoxy primer shines through the powdered grey top coat.
TIME IN SERVICE	1 year.
ENVIRONMENT	Marine.
CAUSE	Inappropriate coating selection. Chalking is caused by disintegration of the binder resin by actinic solar rays, combined with the overall weathering process, leaving the pigment as a dust on the surface. Many pigments will catalyze or increase the chalking process.
REMEDY	Use a chalk-resistant resin coating which is not affected by solar rays (vinyl, acrylic, or urethane coating systems). Note: Sometimes chalking may be considered a favorable failure mechanism as an indicator for periodic maintenance of the coating system to prolong coating life.

CORROSION ATLAS

CASE HISTORY

03.21.40.03

MATERIAL	Epoxy coating (two coats) over steel.
SYSTEM	Tanker.
PART	Interior of a seawater ballast tank (coating thickness 200–250 μm).
PHENOMENON	Coating failure (blistering).



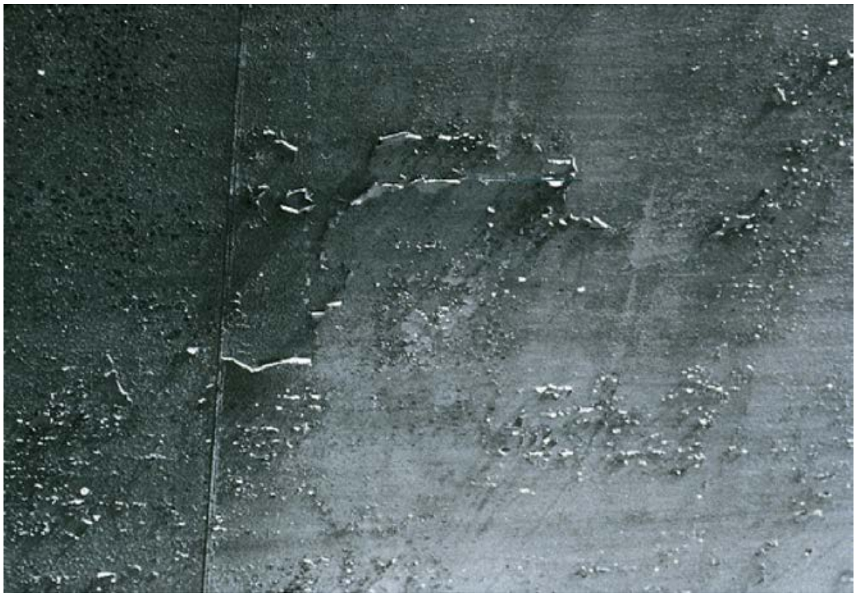
APPEARANCE	Severe fine blistering of the coating. After removal of the coating, corrosion was found.
TIME IN SERVICE	2 years.
ENVIRONMENT	Alternately dry and immersed in seawater.
CAUSE	Poor adhesion caused by contamination on the surface and questionable adhesion in immersion service because of excessive moisture vapor transmission rate of the coating. Osmosis and the thermal gradient across the coating are involved too. The coating lifts from the surface in spots due to gas or liquid beneath the coating (see also Case History 03.05.40.01).
REMEDY	• Improve the adhesion by more careful application to assure a clean surface before coating. • Select a coating with strong adhesion and a low moisture vapor transmission rate.

CORROSION ATLAS

CASE HISTORY

03.21.40.04

MATERIAL	Polyamide epoxy coating (two coats) on steel.
SYSTEM	Ship.
PART	Ship's hull (top coat thin: 25–50 μm).
PHENOMENON	Coating failure (peeling).



APPEARANCE	Scaling and peeling of one coat from another.
TIME IN SERVICE	A few weeks.
ENVIRONMENT	Marine atmosphere (coating was not submerged).
CAUSE	Poor adhesion caused by application of the second coat over contamination (either dirt or condensation) (see also Case History 03.24.04.03 for peeling from the substrate).
REMEDY	Make sure that the surface is clean, free of dirt or other contamination, and dry before application of the second coat.

CORROSION ATLAS

CASE HISTORY

03.21.40.05

MATERIAL	Epoxy coating (two coats) on steel.
SYSTEM	Tanker.
PART	Interior ballast tank.
PHENOMENON	Coating failure (underfilm corrosion).

APPEARANCE	Blisters and rust surrounding break in coating.
TIME IN SERVICE	Several months.
ENVIRONMENT	Seawater.
CAUSE	Poor adhesion because of break in film and possibly chlorides on surface before application. Water penetrates the coating at break or in area of poor adhesion, causing corrosion at break or possible osmotic blistering.
REMEDY	• Use an inorganic zinc coating as a primer to obtain maximum adhesion, or • Make sure the coating is applied over a perfectly clean, dry, and blasted surface.

CORROSION ATLAS

CASE HISTORY

03.21.40.06

MATERIAL	Epoxy coating (two coats) on steel.
SYSTEM	Ship.
PART	Interior seawater ballast tank.
PHENOMENON	Coating failure (overspray).

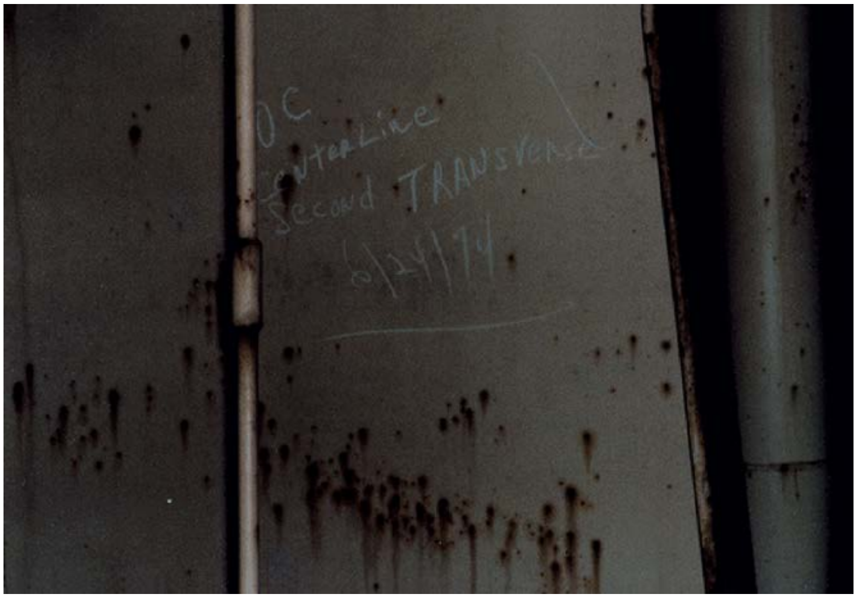
APPEARANCE	Rusty pinpoint area above clean area.
TIME IN SERVICE	6 months.
ENVIRONMENT	Seawater.
CAUSE	Poor application. Fast-drying or heavily pigmented coatings cause dry spray. Dry particles adhere to the surface and make a rough film. Improper spray techniques aggravate the problem. Overspray in itself is not a cause of coating failure. It is a condition which can lead to coating failure. If not wiped off, the overspray area becomes an area of porosity where rapid coating failure (pinholing) can take place. In this case, the first coat was partly applied as overspray. The second coat was applied over the first without removing the overspray. A continuous coating could never be formed.
REMEDY	• Better application procedure: proper gun adjustment and gun handling, removing overspray, closer application inspections. • Apply slower-drying coatings, such as oil-based materials or catalyzed epoxies.

CORROSION ATLAS

CASE HISTORY

03.21.40.07

MATERIAL	Epoxy coating (two coats) on steel.
SYSTEM	Tanker.
PART	Interior ballast tank.
PHENOMENON	Coating failure (pinholing).



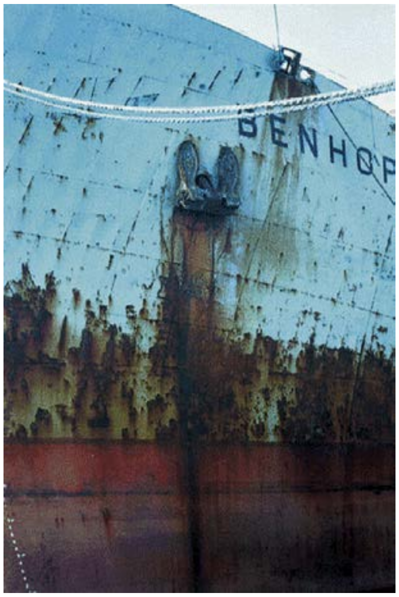
APPEARANCE	Small rusty tubercles in the coating. Note that the area between pinholes is relatively free of corrosion. Only the pinholes which penetrate to the substrate show corrosion.
TIME IN SERVICE	Very short.
ENVIRONMENT	Seawater.
CAUSE	Poor application. Pinholing may result from many causes. In this case, the probable cause is the spray gun adjustment or holding the spray gun too close to the surface in the single pass. In both cases, air bubbles will be entrained in the coating and, where the bubbles remain, leave voids providing a passage through the coating down to the substrate (pinholes).
REMEDY	• Better care in application. Close inspection of the coating as it is applied by both the painter and inspector. • Where pinholes appear, apply a coat by brush, working coating into the pinholes. Once formed, spraying over the surface will not fill the holes. • Apply slow-drying coatings with good flow characteristics.

CORROSION ATLAS

CASE HISTORY

03.21.40.08

MATERIAL	Alkyd coating (two to three coats) on steel.
SYSTEM	Ship.
PART	Ship's hull.
PHENOMENON	Coating failure.



APPEARANCE	General rusting and coating break-down.
TIME IN SERVICE	1 year.
ENVIRONMENT	Marine atmosphere.
CAUSE	Poor coating selection. Coating not suited for such environments. General failure due to water, oxygen, and salt penetration to the substrate.
REMEDY	Use a high-performance marine coating system with an inorganic zinc primer.

CORROSION ATLAS

CASE HISTORY

03.24.24.01

MATERIAL	Galvalum-coated steel (zinc/aluminum/silicon coating).
SYSTEM	Weathering test.
PART	Test plate.
PHENOMENON	Atmospheric corrosion.

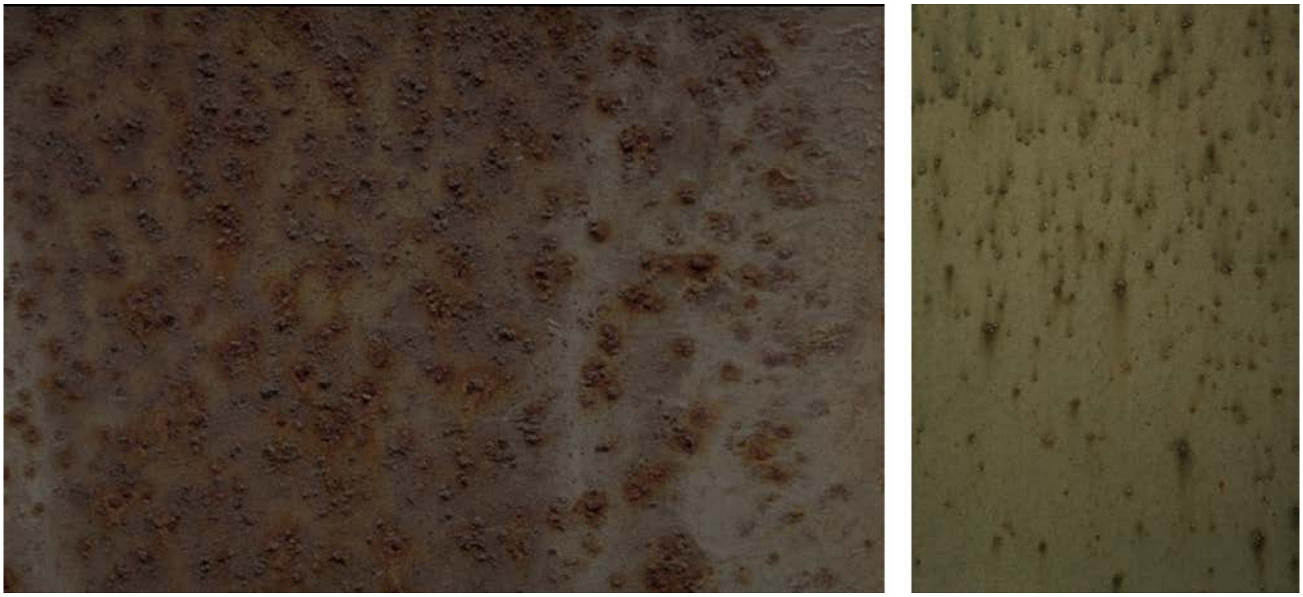
APPEARANCE	Locally the surface exhibits slight corrosion.
TIME IN SERVICE	15 years.
ENVIRONMENT	Marine-industrial atmosphere.
CAUSE	The underside of the test plate lying on the beams of the exposure rack was found to be corroded at the contact surfaces, as a result of the formation of differential aeration cells. The topside and also the free parts of the underside remained rust-free after 15 years. Coating thickness: 20 μm.
REMEDY	Not applicable.

CORROSION ATLAS

CASE HISTORY

03.24.24.02

MATERIAL	Left: Hot-dip aluminized steel. Right: Sprayed aluminum coating on steel.
SYSTEM	Weathering tests.
PART	Test panels.
PHENOMENON	Atmospheric corrosion.



APPEARANCE	Pitting corrosion over the entire surface.
TIME IN SERVICE	8 years and 12 years, respectively.
ENVIRONMENT	Industrial-marine atmosphere.
CAUSE	Left case: In this case, a 30-µm-thick aluminum layer, which is moreover cathodic in relation to the underlying steel surface due to the aluminum oxide formed, is unable to provide effective rust protection. Right case: The presence of pores in the 100-µm-thick aluminum coating, as a result of which local Al_2O_3/Fe elements were able to form leading to locally severe rusting of the iron surface.
REMEDY	Remove the layer by grit-blasting and then cross-spray a 150- to 200-µm-thick aluminum layer, optionally followed by one or two coats of chemical-resistant paint (epoxy, chlorinated rubber, polyurethane) in a total layer thickness of 100–200 µm.

CORROSION ATLAS

CASE HISTORY

03.24.40.01

MATERIAL	Coal tar coating (two coats) over steel substrate.
SYSTEM	Weathering test rig.
PART	Coated steel test plate.
PHENOMENON	Coating failure (alligatoring).

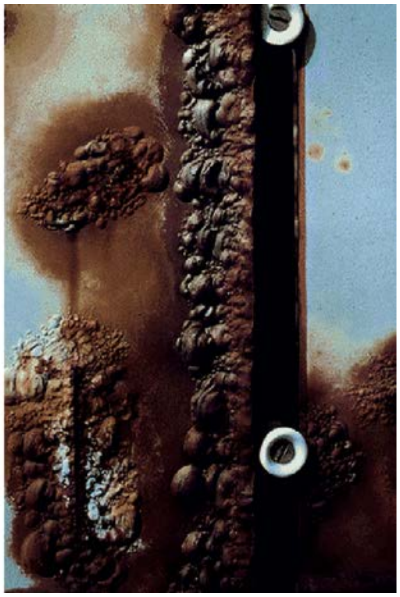
APPEARANCE	General large (some cm Ø) checking in an alligator (or dried mud) pattern in the top coat (not to the substrate).
TIME IN SERVICE	Several months.
ENVIRONMENT	Marine.
CAUSE	Inappropriate coating selection. When a coal tar coating is applied very thickly (>500 µm) and exposed to sunlight and weathering, the surface reacts to cause shrinkage over the lesser cured undercoat. The cracks may continue to substrate with time.
REMEDY	Prevent alligatoring by: • Use failure-sensitive coating systems only in areas protected from the sunlight, or • Apply an aluminum top coat. • Never apply hard coating over a soft extensible base.

CORROSION ATLAS

CASE HISTORY

03.24.40.02

MATERIAL	Epoxy polyamide coating (three coats) over steel.
SYSTEM	Weathering test rig.
PART	Coated steel panels (coating thickness 250–300 μm).
PHENOMENON	Coating failure (undercutting).



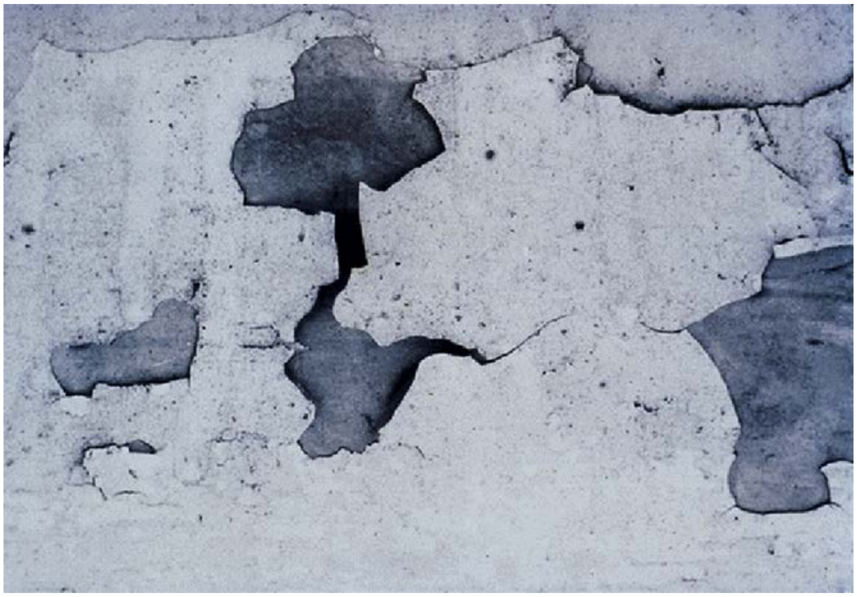
APPEARANCE	Severe rusting at the scribe (left photo) and at the edge (right photo) with penetration of the rust under the film to blistering. The plain surface is corrosion free.
TIME IN SERVICE	3 years (corrosion started almost immediately at the scribe).
ENVIRONMENT	Marine –15 m above high tide along the coast.
CAUSE	Poor coating adhesion caused by application of the coating over a contaminated surface (mill scale, rust, oil, dirt, and dust). Oxygen will penetrate under the film from a break in the coating, causing the growth of iron oxide underneath the film. As the oxide builds up, it expands under the coating, causing the blistering effect. Chloride in the atmosphere will accelerate the corrosion process.
REMEDY	• Use a very highly adherent coating over a properly abrasion-blasted surface which is perfectly clean and free of contamination, or • Apply the epoxy over an inorganic zinc primer.

CORROSION ATLAS

CASE HISTORY

03.24.40.03

MATERIAL	Heavy alkyd coating (three to four coats) on steel.
SYSTEM	Test rig.
PART	Steel test panel (coated with thorough drying in between).
PHENOMENON	Coating failure (peeling).



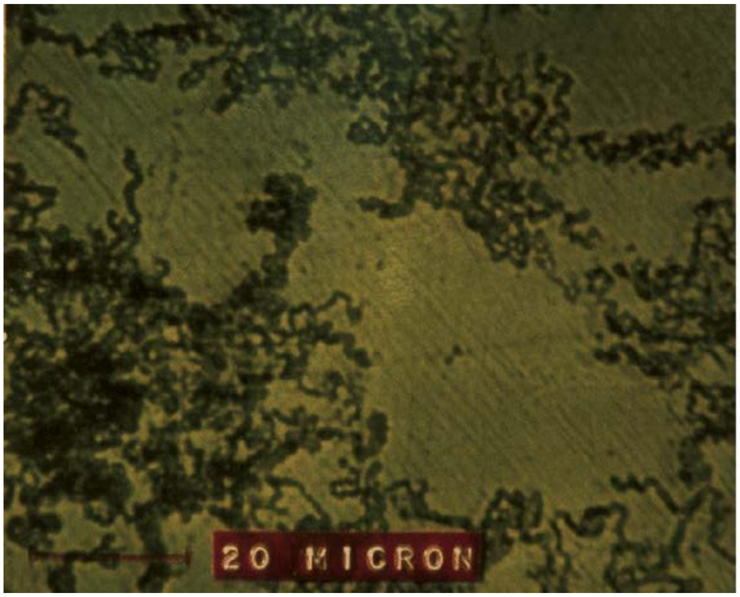
APPEARANCE	Coating is pulling away from the substrate.
TIME IN SERVICE	A few weeks.
ENVIRONMENT	Rural marine atmosphere.
CAUSE	Poor adhesion because the tensile strength of the coating is greater than adhesion to the surface. The strong thick film of alkyd which continues to cure over a period of time is therefore pulling away from the substrate. (For peeling between coats, see Case History 03.21.40.04.)
REMEDY	Use a more plastic coating (more extensible) which has high intrinsic adhesion or over a strongly adherent primer.

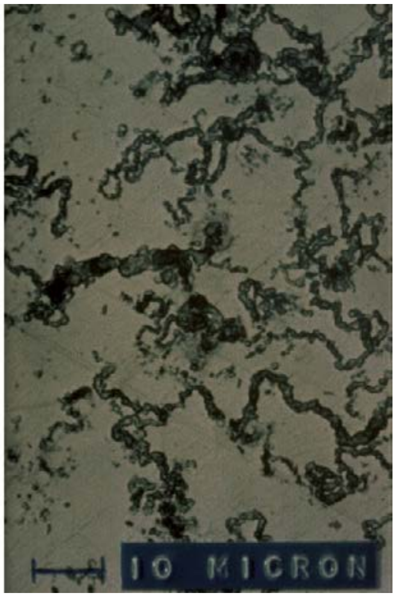
CORROSION ATLAS

CASE HISTORY

03.24.41.01

MATERIAL	Degreased, cold-rolled carbon steel, sprayed with an ethyl cellulose–based unpigmented coating.
SYSTEM	Test rig.
PART	Plates for instrument cabinets.
PHENOMENON	Filiform corrosion.





APPEARANCE	Corrosion under the coating in the form of hairlike filaments.
TIME IN SERVICE	1–2 years.
ENVIRONMENT	Humid indoor atmosphere, relative humidity 80–95%.
CAUSE	As a result of local differences in humidity on the smooth surface, differential aeration cells originated, and iron oxide hydrate begins to form from the edges, fanning out beneath the coating (filiform corrosion). The transparent coating allows locally intensified diffusion of moisture to occur, thereby creating initiation points for filiform corrosion (see also Case Histories 03.20.41.01 and 12.19.41.01).
REMEDY	• Keep the humidity below 65% if possible. • Apply a different coating system (with at least two coats).

CORROSION ATLAS

CASE HISTORY

04.01.04.01

MATERIAL	Proprietary hardenable stainless steel (similar to AISI 410).
SYSTEM	Condensing steam turbine.
PART	Blades from high-pressure condensing stage.
PHENOMENON	Acid corrosion.

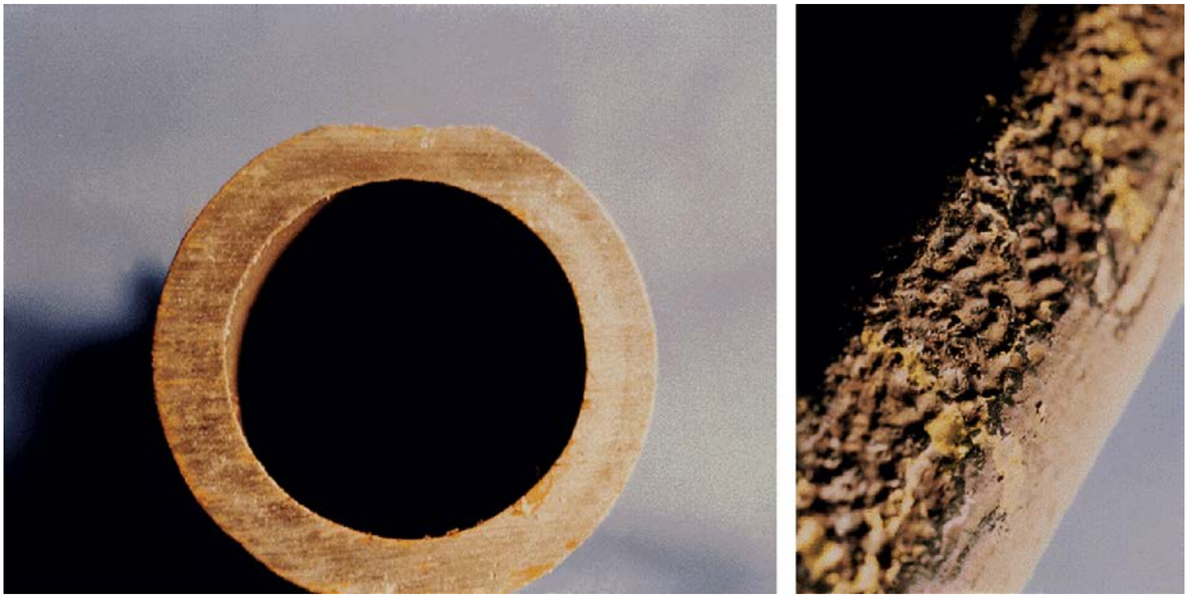
APPEARANCE	Severe pitting especially at the edges; parts are corroded away. Deposits were removed to reveal attack.
TIME IN SERVICE	Turbine stage was rebuilt 7 years before failure.
ENVIRONMENT	Salts containing steam, temperature between 71 and 43°C; pressure between 0.035 and 0.0069 MPa.
CAUSE	Because of vaporous carry-over, the steam contained salts from the boiler water. These salts (chlorides and sulfates) were deposited on the blades. Hydration caused severe corrosion due to hydrolysis (see also Case History 04.11.04.01).
REMEDY	Preventing carry-over by good boiler-water conditioning and the best possible steam/water separation equipment.

CORROSION ATLAS

CASE HISTORY

04.01.06.01

MATERIAL	Austenitic stainless steel (AISI 321; W.-Nr. 1.4541).
SYSTEM	Coal-fired water-tube boiler (pressure: 17.2 MPa).
PART	Secondary superheater outlet tube (OD 5.4 cm).
PHENOMENON	High-temperature corrosion (oxidation, in this case also known as coal-ash corrosion).



APPEARANCE	Pock-marked surface in a 2.5cm-wide band as a result of severe corrosion along one side of the tube. The tube-wall thickness had been reduced by 2.2 mm.
TIME IN SERVICE	3 years continuous operation.
ENVIRONMENT	Flue-gases with fly-ash, from combustion of coal Analysis: ash 10%; O_2 3%–4%; S 7%; SO_2 1200 ppm; CO_2 15%; SO_3 1 ppm; CO 300 ppm.
CAUSE	Deposit of fly-ash on the superheater tubes. With time, the volatile alkali and sulfur compounds forming from the coal combustion condense on the fly-ash and react with it to form complex alkali sulfates such as $K_3Fe(SO_4)_3$ and $Na_3Fe(SO_4)_3$ at the metal–deposit interface. The molten slag fluxes the protective oxide covering of the tube, exposing the metal beneath to accelerated oxidation: coal-ash corrosion (see also Case History 01.01.06.01).
REMEDY	• Corrosion monitoring by ultrasonic thickness surveys. • If corrosion is not severe, periodic tube replacement, specification of thicker tube walls, or use of thermal spray coatings may be economic solutions. • Where coal-ash corrosion is severe, cladding of tubes with a resistant alloy may be required. Fuel additives have not been economically successful. It may be valuable to blend coals to reduce the percentage of corrosive constituents and to lower metal temperatures.

CORROSION ATLAS

CASE HISTORY

04.01.14.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Boiler feedwater system.
PART	Float of feedwater deaerator tank.
PHENOMENON	Galvanic corrosion (deposition corrosion).

APPEARANCE	Pitting under blue-green deposits.
TIME IN SERVICE	2 years.
ENVIRONMENT	Boiler feedwater with low oxygen concentration.
CAUSE	Copper originating from the copper condensate lines has deposited on the stainless steel surface of the float. Since this surface was activated because of low oxygen content, it was less noble than the copper particles. As a result of this, galvanic corrosion took place by cathodic contamination of the anode (see also Case History 02.05.14.04).
REMEDY	Because copper deposition caused problems in the boiler too, a cation exchanger was placed to eliminate the copper from the condensate.

CORROSION ATLAS

CASE HISTORY

04.01.15.01

MATERIAL	Stainless steel (W.-Nr. 1.4521).
SYSTEM	Boiler feedwater tank equipped with steam heating.
PART	Steam coil.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Pitting attack concentrated at upper part of coil.
TIME IN SERVICE	2 years.
ENVIRONMENT	Mixture of steam condensate and softened make-up water, pH 6.1; chloride (Cl^-) 132 ppm.
CAUSE	Deposition of iron oxide from the condensate caused pitting by forming differential aeration cells (a form of crevice corrosion) (see also Case Histories 04.06.15.01/02/03).
REMEDY	Feeding of the iron-containing condensate directly into the deaerator; the presence of iron oxide in the condensate indicates corrosion in the condensate system, and measures should be taken to prevent this.

CORROSION ATLAS

CASE HISTORY

04.01.18.01

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Steam pipe.
PART	Flange.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracking on seal surface.
TIME IN SERVICE	4 years.
ENVIRONMENT	Steam at 125°C, pressure 1 bar.
CAUSE	Stress corrosion due to bonding the seal with chloride-containing adhesive (the seal was bonded in order to prevent crevice corrosion!) (see also Case Histories 04.02.18.01/02 and 04.11.18.01 and following).
REMEDY	Use of chloride-free adhesive or compound to treat the seal.

CORROSION ATLAS

CASE HISTORY

04.01.18.02

MATERIAL	Stainless steel (AISI 321).
SYSTEM	Steam system.
PART	Valve bolts.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Fracture in screw thread at parts under highest loads.
TIME IN SERVICE	2 years.
ENVIRONMENT	Rainwater.
CAUSE	Near the coast, rainwater always contains chloride, which is capable of causing stress corrosion above 60°C.
REMEDY	Use of bolts made from low-alloyed steel (see also Case History 01.11.20.05).

CORROSION ATLAS

CASE HISTORY

04.01.18.03

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Waste-gas water-tube boiler (pressure 4.1 MPa).
PART	First-stage vertical superheater tube (OD 3.8 cm).
PHENOMENON	Stress-corrosion cracking (intergranular, caustic stress-corrosion cracking see also Case History 04.25.18.01).

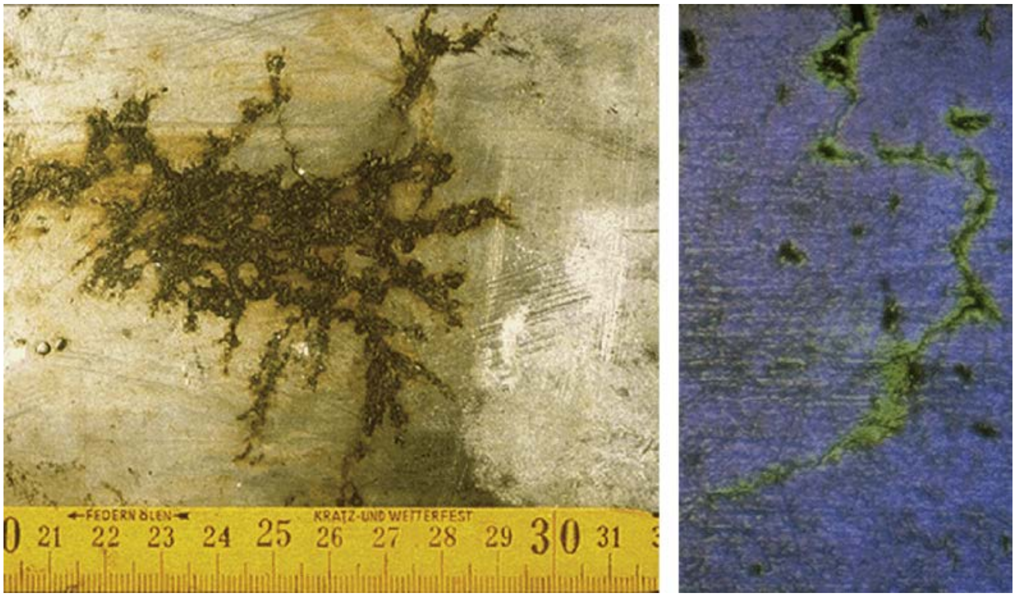
APPEARANCE	Transverse highly branched crack in a bent tube. Note small "window" that has been blown out of the wall.
TIME IN SERVICE	3 weeks (the original carbon steel tubes cracked after 9 months in service).
ENVIRONMENT	Superheated steam contaminated with alkaline boiler water. Water treatment: phosphate.
CAUSE	The joint action of concentrated sodium hydroxide and tensile stresses: • The steam drum lacked adequate devices for separation of steam and water and load swings were frequent, possible causing carry-over of boiler water. • The tubes had been moderately cold-bent during installation and were not stress relief annealed, so residual stresses were present in the tube bends.
REMEDY	• Improving the steam/water separation equipment and avoiding load swings. • Replacement of the stainless steel tubes by carbon steel tubes (stainless steel superheater tubes in a boiler of this pressure are unusual).

CORROSION ATLAS

CASE HISTORY

04.01.18.04

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Boiler feedwater deaerator.
PART	Deaerator cascade jacket.
PHENOMENON	Stress-corrosion cracking (transgranular) under insulation.



APPEARANCE	Branched cracking.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Internally: softened water, at 105°C.
CAUSE	Evaporation of boiler feedwater which had penetrated underneath the insulation through a leaking flange connection caused local high salt content, which led to transgranular stress corrosion (see also Case History 04.11.18.05).
REMEDY	Replacement of the affected plate. N.B.: in such a case, corrosion can be prevented by providing the stainless steel with an external coating.

CORROSION ATLAS

CASE HISTORY

04.01.18.05

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Steam system.
PART	Orifice plate in steam line.
PHENOMENON	Stress-corrosion cracking (transgranular) under insulation.

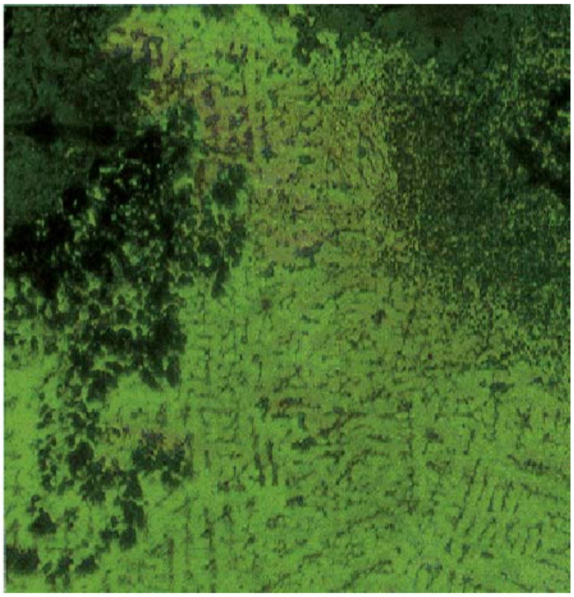
APPEARANCE	Parts dislodged by extensive cracking.
TIME IN SERVICE	Unknown, several years.
ENVIRONMENT	Atmosphere, pipe wall temperature underneath insulation 220°C.
CAUSE	Ingress of chloride-containing rainwater, after which the salinity increased by evaporation, in conjunction with the mounting stresses present lead to stress-corrosion cracking (see also Case Histories 04.01.18.04 and 04.11.18.16).
REMEDY	• Improved insulation to prevent rainwater ingress (see Case Histories 01.02.25.01, 03.11.25.01, and 04.11.25.01). • Use of improved mounting/assembly techniques.

CORROSION ATLAS

CASE HISTORY

04.01.19.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Production plant
PART	Welded bend in steam coil.
PHENOMENON	Intergranular corrosion (weld decay).



APPEARANCE	Attacked zones approximately 1 cm from the welds.
TIME IN SERVICE	A few years.
ENVIRONMENT	Steam, maximum 190°C through the pipe; glycol around the pipe.
CAUSE	Maintaining stainless steel in a temperature range from 600 to 850°C results in precipitation of chromium carbides ($M_{23}C_6$) at the grain boundaries. This carbide formation impoverishes locally the chrome content of the austenitic matrix and the corrosion resistance of the steel decreases as a result. This process takes place, e.g., at the heat affected zones during the welding treatment. Selective attack of these zones takes place at a distance of approximately 1 cm from the weld (see also Case Histories 04.08.19.01 and 04.11.19.02/04/07).
REMEDY	• Application of seamless pipe and avoiding the use of welded bends; or • Normalizing welds (Post Weld Heat Treatment, PWHT); or • Use of stainless steel alloy with low carbon content (≤0.03%) or stabilized with titanium or niobium.

CORROSION ATLAS

CASE HISTORY

04.01.28.01

MATERIAL	Stainless steel (AISI 413, W.-Nr. 1.4000).
SYSTEM	Steam system.
PART	Ball from ball tap.
PHENOMENON	Fatigue.

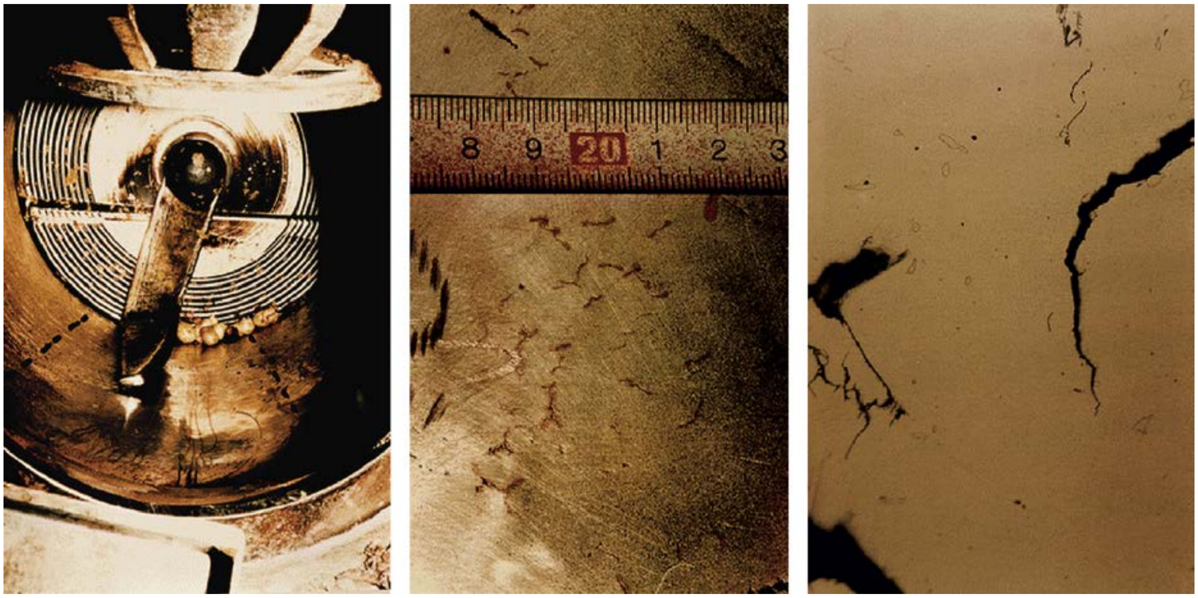
APPEARANCE	At positions “12 o’clock, 3 o’clock and 6 o’clock,” three 15–20-mm-long straight cracks running perpendicularly downwards. The cracks gape about 0.5 mm.
TIME IN SERVICE	Several years.
ENVIRONMENT	Steam with some condensate.
CAUSE	The present martensitic stainless steel is strong, hard, and scarcely tough. These properties in combination with the shape and site of the cracks point to the occurrence of fatigue cracking due to, e.g., water hammer or by the ball tap opening too fast, so that it receives a sudden impact from the steam pressure.
REMEDY	Manufacture the ball tap from a tougher stainless steel, e.g., AISI 316, which is also resistant to chloride attack resulting from wet steam.

CORROSION ATLAS

CASE HISTORY

04.01.28.02

MATERIAL	Cast austenitic stainless steel.
SYSTEM	Steam drum of a potato peeler.
PART	Inner wall.
PHENOMENON	Thermomechanical corrosion fatigue.



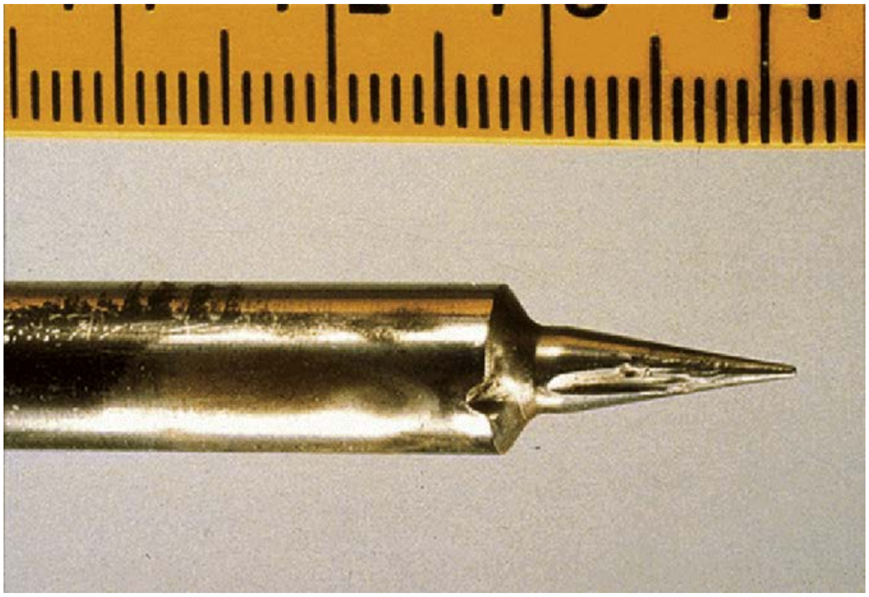
APPEARANCE	Randomly oriented short surface cracks filled with corrosion products.
TIME IN SERVICE	Approximately 8 years.
ENVIRONMENT	Steam at 250°C, pressure 1.5 MPa, and potatoes.
CAUSE	The hot inner wall is periodically in contact with cold running water used to clean the seats of the lid of the filling opening of the drum. The resultant alternating thermal stresses in the surface caused the cracking (internal stresses) (see also Case Histories 01.04.28.01 and 01.11.28.03).
REMEDY	Prevent contact of cold running water with the hot inner wall of the vessel.

CORROSION ATLAS

CASE HISTORY

04.01.32.01

MATERIAL	Stainless steel (316 Ti).
SYSTEM	High-pressure boiler.
PART	Spindle of high-pressure reducing valve for the sampling of boiler water.
PHENOMENON	Erosion.



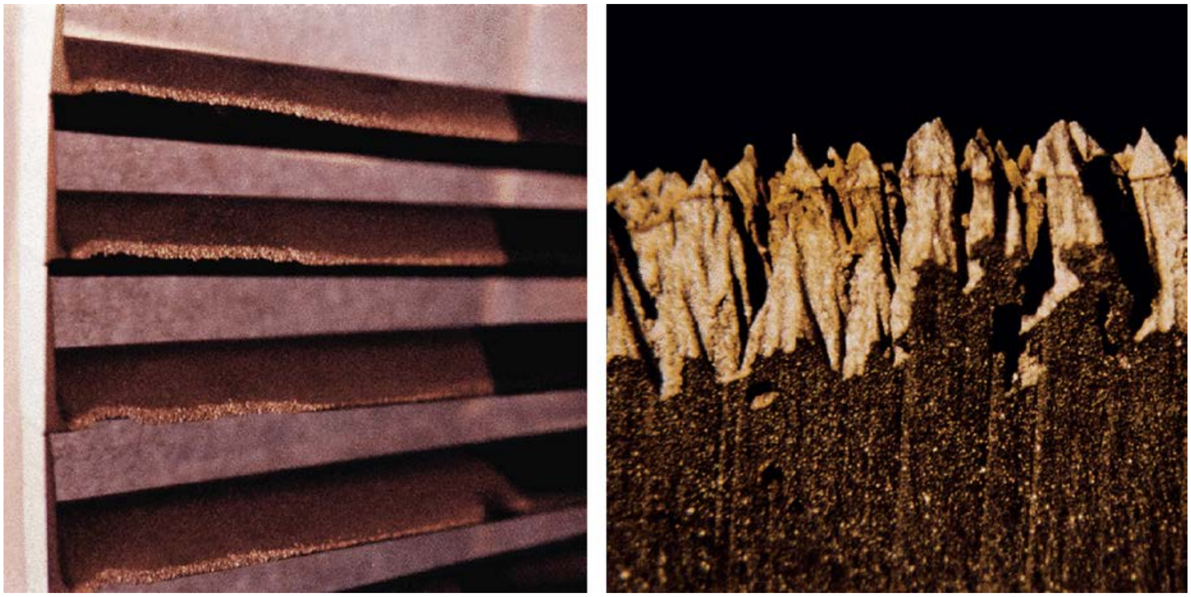
APPEARANCE	The spindle point is severely worn and no longer makes a seal.
TIME IN SERVICE	A few days.
ENVIRONMENT	Boiler water with magnetite (Fe_3O_4) particles.
CAUSE	According to the supplier's specifications, the spindle point was made of Satellite (a cobalt-chromium alloy), which is highly resistant to erosion. Analysis showed it to be made of highly deformed austenitic steel (see above), which is insufficiently erosion-resistant to the boiler water flowing past at high speed (see also Case Histories 04.11.32.01/02/03/04).
REMEDY	Use of spindle and seat made from an appropriate Satellite type.

CORROSION ATLAS

CASE HISTORY

04.01.32.02

MATERIAL	Stainless steel (AISI 403).
SYSTEM	Steam turbine (45 MW, 3600 rpm).
PART	Final-stage turbine blades, condensing section. Horizontal turbine shaft
PHENOMENON	Erosion (water-droplet impingement).



APPEARANCE	Left: ragged leading edges of buckets. Right: fine, striated grooves on front face (magnification ×7.5).
TIME IN SERVICE	6 years.
ENVIRONMENT	Superheated steam (450°C).
CAUSE	Water-droplet impingement (see also Case Histories 01.01.32.02/04). A 0.45 MPa steam-extraction, non-return valve failed to seat properly during an electrical turbine trip. The 0.45 MPa header emptied through the turbine (vacuum condition). The turbine speed increased to 5000 rpm (design 3600 rpm) before manual shutdown.
REMEDY	Ensure proper functioning of non-return valves by periodic testing and timely repair procedures.

CORROSION ATLAS

CASE HISTORY

04.01.34.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Carbon dioxide deodorizer in brewery.
PART	Ball valve in outlet pipe.
PHENOMENON	Erosion corrosion.

APPEARANCE	Severe erosion of ball and valve house.
TIME IN SERVICE	1.5 months.
ENVIRONMENT	CO_2-containing steam; pressure: 1 MPa; temperature: 180°C.
CAUSE	A near-closed ball valve causes high steam velocity, resulting in erosion corrosion.
REMEDY	• Place a throttle plate ahead of the ball valve, or • Replace the ball valve by one constructed of Satellite.

CORROSION ATLAS

CASE HISTORY

04.02.18.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Steam condensate system.
PART	Uninsulated underground pipeline.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracking.
TIME IN SERVICE	2 years.
ENVIRONMENT	Chloride-containing groundwater.
CAUSE	Chloride in the groundwater coupled with high temperature (90°C) of the condensate pipe and stresses present (see also Case Histories 04.11.18.01 and following).
REMEDY	• In view of the small quantity of condensate, it was decided not to replace the pipeline and to discharge the condensate into the sewer. • Alternatively: a new condensate pipeline could be constructed as a double-walled pipe system with a carbon steel inner pipe and a plastic jacket, with insulation in between.

CORROSION ATLAS

CASE HISTORY

04.02.18.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Steam condensate system.
PART	Uninsulated pipeline.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Longitudinal cracks, pipe fractured open.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Internal: salt-free condensate, 95°C; external: rainwater.
CAUSE	Regular external wetting with chloride-containing acid rainwater which evaporates on the hot pipe (see also Case Histories 04.11.18.01 and following).
REMEDY	Wrap the stainless steel pipeline with aluminum foil and then insulate it; the aluminum gives cathodic protection to the stainless steel.

CORROSION ATLAS

CASE HISTORY

04.05.12.01

MATERIAL	Stainless steel (bolt AISI 304, plate AISI 316L).
SYSTEM	Hot water system.
PART	Bolt with plate.
PHENOMENON	Chloride attack.

APPEARANCE	Pitting attack on the bolt, none on the plate.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hot water (80°C) with 140 ppm CI.
CAUSE	Stainless steel AISI 304 is not resistant, whereas AISI 316L is resistant in the chloride-containing medium at 80°C. In view of the slight potential differential between the two types of stainless steel, there is no question of galvanic corrosion (see also Case History 04.11.12.03).
REMEDY	Construct the bolts of AISI 316 as well.

CORROSION ATLAS

CASE HISTORY
04.05.12.02

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Drinking water system in brewery.
PART	Pipe section (outside surface).
PHENOMENON	Chloride attack and stress-corrosion cracking.

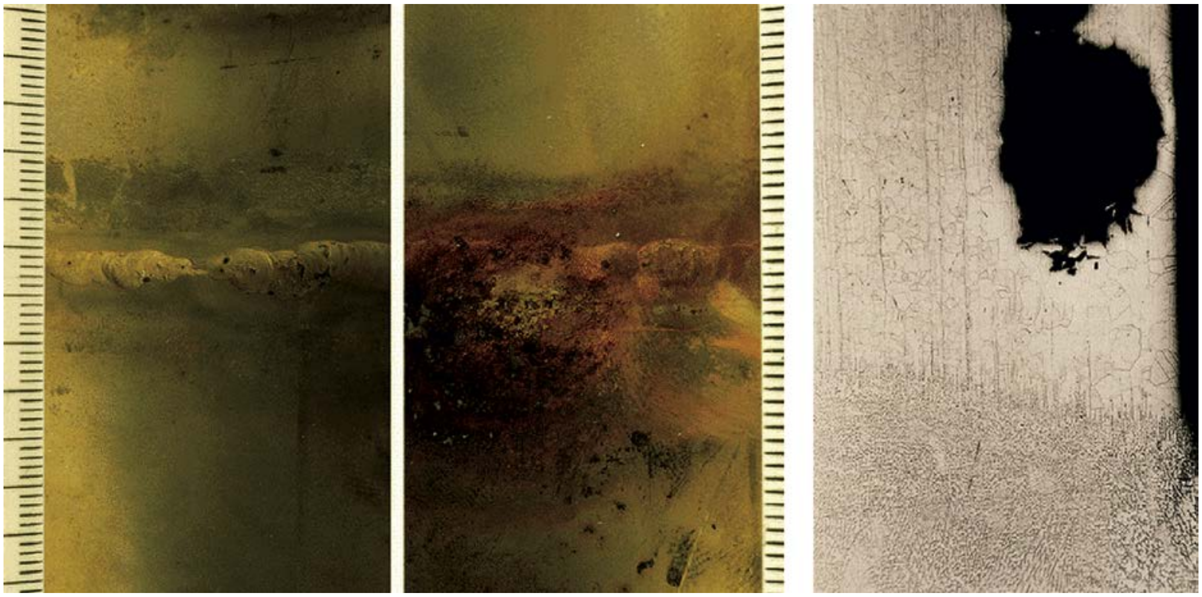
APPEARANCE	Many pits and some cracks.
TIME IN SERVICE	3 weeks.
ENVIRONMENT	Inside: drinking water. Outside: Contaminated with hydrochloric acid.
CAUSE	Leakage of an HCl conveyor line, located overhead the affected pipe (see also Case History 04.11.12.08).
REMEDY	The HCl conveyor line was relocated.

CORROSION ATLAS

CASE HISTORY

04.05.17.01

MATERIAL	Stainless steel (316L).
SYSTEM	Sealing water supply system.
PART	Pipe section with shop-applied butt weld (argon-arc welding procedure with backing gas).
PHENOMENON	Microbiologically induced corrosion.



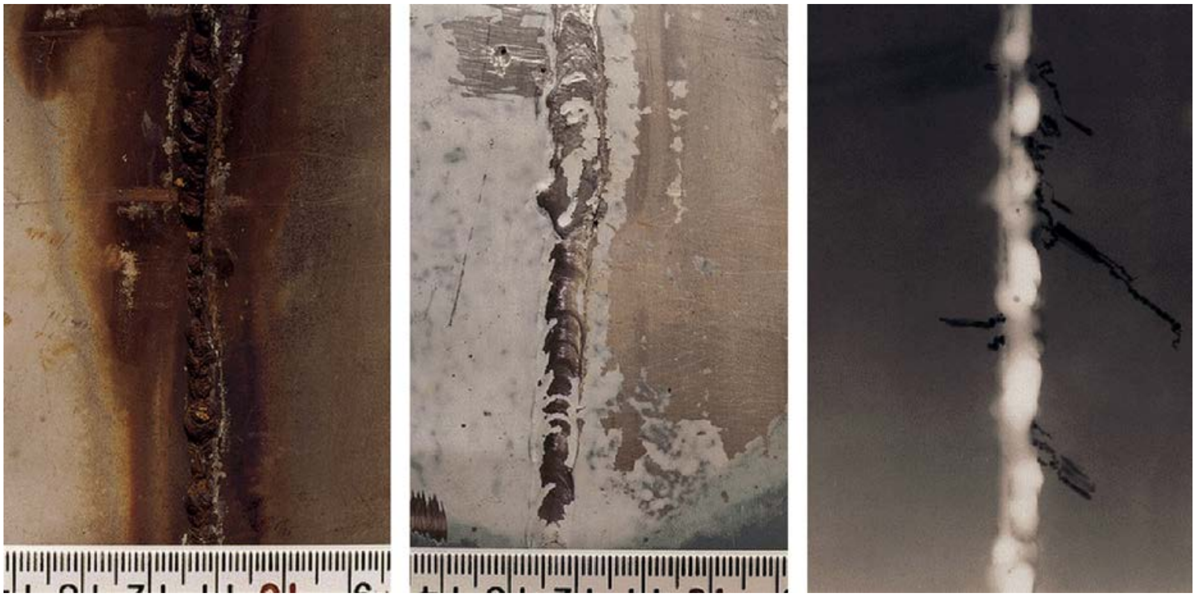
APPEARANCE	Macro: small black tinted pits and brown modules on the weld seam and in the HAZ. Micro: small penetration leading to larger cavity with tunneling.
TIME IN SERVICE	3 months.
ENVIRONMENT	Pre-purified river water with the following analysis: conductivity 80–100 mS/m; chloride 140–200 ppm; sulfate 60–85 ppm; hardness 4.7–5.8 meq/L (235–290 ppm CaCO$_3$); nitrate 10–19 ppm; iron content < 0.06–0.23 ppm; temperature 13–24°C; micro-organisms (Aeromonas spp.) 1100–5600/100 mL.
CAUSE	Colonization of iron bacteria on the weld bead allows the formation of oxygen concentration cells on the weld seam, leading to pitting attack on the welds and in the HAZ, where the corrosion resistance has been reduced by chromium carbide precipitation. In view of the microscopic corrosion picture and the water analysis – also taking into account published literature on this form of corrosion – this is a case of microbiological corrosion of the weld seams. The temperature increase and the iron concentration of the water have strongly promoted this corrosion. This form of corrosion also occurs when Fe-containing water is used for pressure-testing purposes (see also Case History 04.08.17.01).
REMEDY	• After disassembly and X-ray inspection, the affected welds in the system should be replaced, and after reassembly, the line should be flushed with water dosed with a biocide, e.g. chlorine, to kill any remaining bacteria. • When pressure-testing with Fe-containing water, flush with demineralized water and then dry with hot air.

CORROSION ATLAS

CASE HISTORY

04.05.17.02

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Drinking water pumping station.
PART	Transmission line (outer diameter 50 and 70 cm).
PHENOMENON	Microbiologically induced corrosion.



APPEARANCE	Red-brown corrosion products at both sides of the weld. Pinholes through pipe wall near weld, tunneling in pipe wall (see X-ray print).
TIME IN SERVICE	A few months to a year.
ENVIRONMENT	Iron traces containing drinking water made from well water. Temperature: 15–18°C.
CAUSE	Iron bacteria colonized weld surface and induced pitting attack and typical tunneling through pipe wall (see also Case Histories 04.05.17.01 and 04.08.17.01).
REMEDY	• Repair of the system where necessary and clean with nitrite acid, improve operation of the deferrization installation, and prevent biological deposits by increasing the water velocity, or • Replace the stainless steel pipes by glass-fiber reinforced epoxy pipes.

CORROSION ATLAS

CASE HISTORY

04.05.18.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Hot tap water system.
PART	Electrically heated coil.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracking.
TIME IN SERVICE	A few months.
ENVIRONMENT	At first hard, later softened, mains water; chloride (Cl^-) 135 ppm; temperature 80°C.
CAUSE	Stress corrosion resulting from stresses in the coil caused by temperature fluctuations at high chloride and high environment temperature. Once the leak has occurred, water which penetrates during down period is converted into steam after the coil is switched on, and the resultant pressure build-up causes the element to fracture longitudinally (see also Case History 04.02.18.01).
REMEDY	At first the coils were constructed of nickel-coated steel, but these also fractured after 3 months because of pitting via the pores in the nickel. Advice: construct the coils of copper and use completely softened water (passed through a sodium exchanger).

CORROSION ATLAS

CASE HISTORY

04.05.26.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Level switch of water trough.
PART	Electrode.
PHENOMENON	Stray current corrosion.

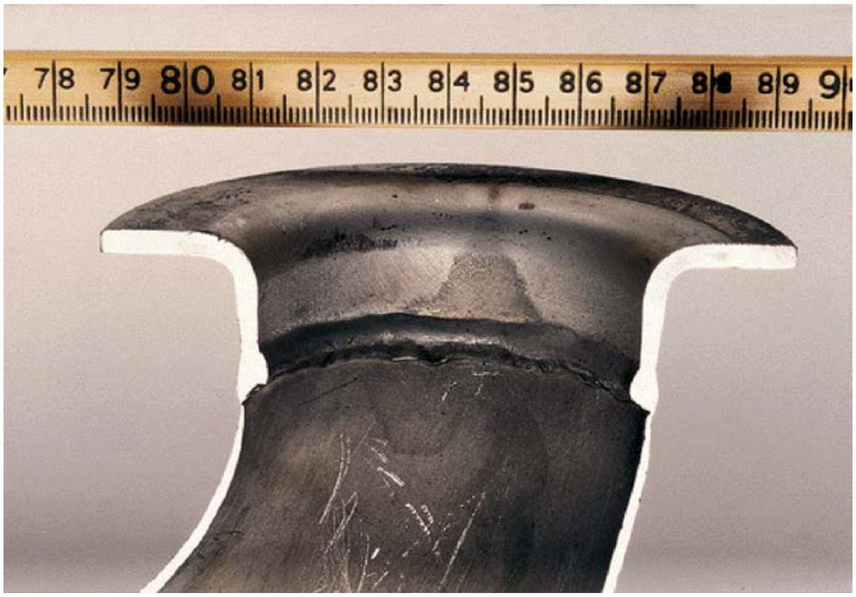
APPEARANCE	Severe attack of electrode.
TIME IN SERVICE	Within 1 year.
ENVIRONMENT	Surface water at ambient temperature.
CAUSE	The water level inside the basin was maintained by a battery-powered pump. As this 12 V source (DC) was also used for the level switch, the middle electrode (minimum level) was severely attacked by stray current corrosion. The upper electrode, limiting the upper level by switching of the pump, was attacked to a somewhat lesser extent (see also Case Histories 04.11.26.01 and 04.12.26.01).
REMEDY	• Change the electrical circuit in such a way that the voltage and especially the current will be significantly reduced. • Alternatively, a more corrosion-resistant material (e.g. titanium) should be selected.

CORROSION ATLAS

CASE HISTORY

04.05.34.01

MATERIAL	Stainless steel (straight section: AISI 316; bend: AISI 304), welding wire: 19 Crl2Ni 2.5Mo).
SYSTEM	Water supply system.
PART	Pipe bend.
PHENOMENON	Erosion corrosion.



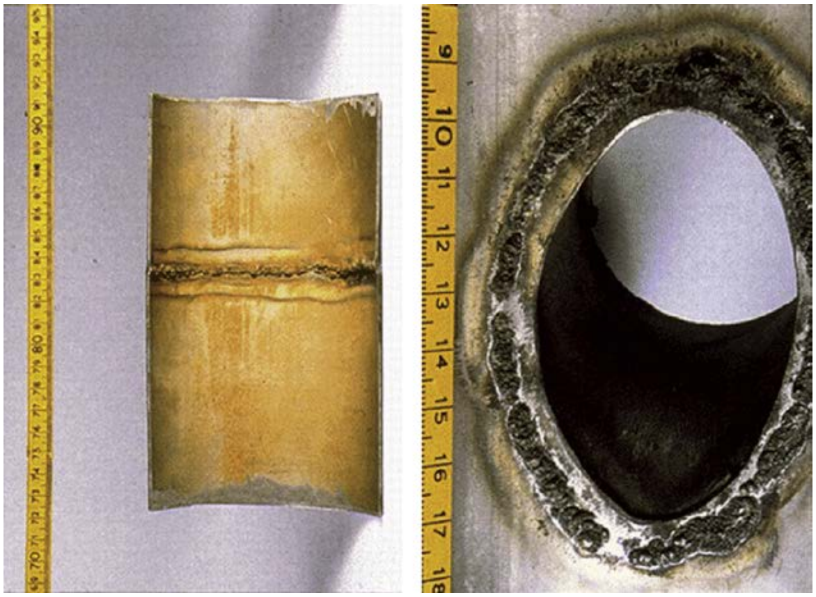
APPEARANCE	Severe attack of the weld at the side of the bend section, and gradual loss of wall thickness of the bend after the weld (in the direction of the weld).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Mains water.
CAUSE	Turbulence in the flow downstream from the weld causes erosion, so that locally no protective oxide skin is built up (in view of the small voltage differential between AISI 304 and 316 galvanic corrosion must be ruled out) (see also Case History 04.06.34.01).
REMEDY	Avoid excessive root fusion.

CORROSION ATLAS

CASE HISTORY

04.05.38.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Hot tap water system.
PART	Pipe sections.
PHENOMENON	Weld defect.



APPEARANCE	Pitting attack in the welds.
TIME IN SERVICE	5 years.
ENVIRONMENT	Dealkalized water, heated to 90°C; pH 7.2; chloride (Cl^- 30 ppm)
CAUSE	Poor weld quality due to poor workmanship (irregular with crevices, annealing colors caused by working without a gas shield).
REMEDY	Application of new and better welds (working under gas shield, using 316L electrodes).

CORROSION ATLAS

CASE HISTORY

04.06.12.01

MATERIAL	Stainless steel (17% chromium steel; AISI 430).
SYSTEM	Gas cooler.
PART	Pipe.
PHENOMENON	Chloride attack.

APPEARANCE	Pitting attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	Through the pipe, gas at 150–200°C; around the pipe, cooling water with 100 ppm Cl^-.
CAUSE	Chromium steel is insufficiently resistant to the chloride-containing cooling water (see also Case Histories 04.08.12.01 and following, and 04.11.12.01 and following).
REMEDY	Use of a more chloride-resistant stainless steel (W.-Nr. 1.4539) for the gas cooler pipes.

CORROSION ATLAS

CASE HISTORY

04.06.12.02

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Power station condenser.
PART	Step inside water header.
PHENOMENON	Chloride attack.

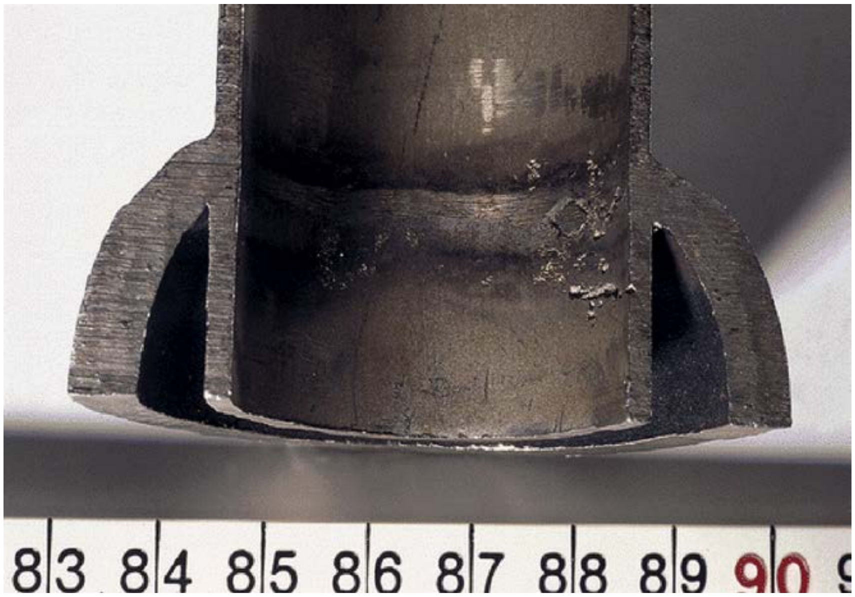
APPEARANCE	Pitting attack.
TIME IN SERVICE	2 months.
ENVIRONMENT	Cold seawater.
CAUSE	The high chloride content of the seawater caused the pitting, accelerated by fouling with acorn barnacles and the galvanic action due to the electrical connection with the titanium condenser, via the rubberized header (see also Case History 04.06.15.02).
REMEDY	• Rubberize the steps as well. • In this case, the step was removed and a separate wooden ladder is used for inspection purposes.

CORROSION ATLAS

CASE HISTORY

04.06.12.03

MATERIAL	Stainless steel (AISI 304L, W.-Nr. 1.4306).
SYSTEM	Nitrous gas absorber.
PART	Cooling water coil.
PHENOMENON	Chloride attack.



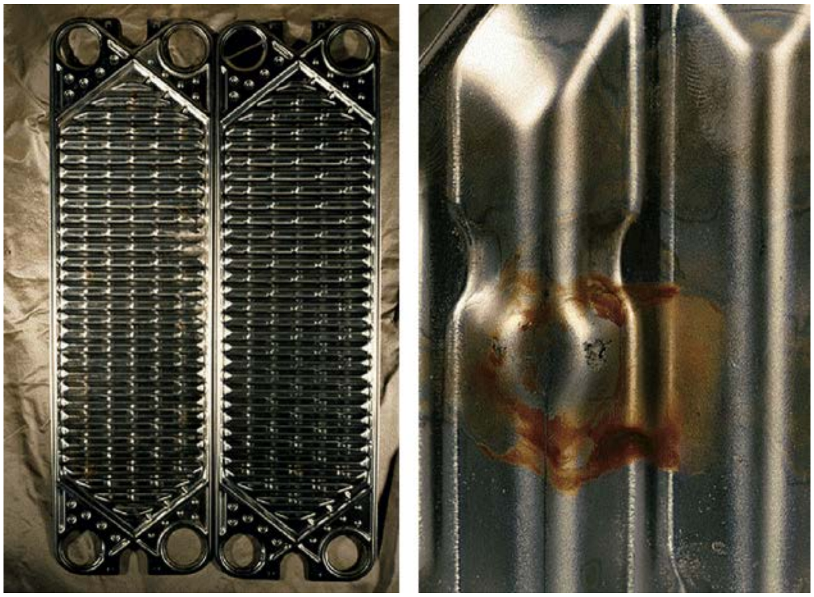
APPEARANCE	Pitting attack of the weld and the HAZ.
TIME IN SERVICE	6 months after test run.
ENVIRONMENT	Cooling water with 100 ppm CL^-; temperature: 5 months ambient temperature and 1 month 30–40°C.
CAUSE	The weld and the HAZ are more sensitive to chloride attack than the pipe due to insufficient pickling and passivation.
REMEDY	Ensure better weld treatment. Porous oxide layers resulting from heat treatment like welding should be removed.

CORROSION ATLAS

CASE HISTORY

04.06.13.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Oil cooler.
PART	Heat exchanger plates.
PHENOMENON	Crevice corrosion.



APPEARANCE	Rust patches surround small pits on the stainless steel cooling water side.
TIME IN SERVICE	1 year.
ENVIRONMENT	Oxygen-containing surface water with 100 ppm Cl^-.
CAUSE	Because of the presence of crevices in the heat exchanger (at the pressure points of the plates), the construction is sensitive to pitting caused by chloride, as a result of differential aeration. The rust is formed by oxidation of ferrous iron ejected from tiny pits. In such cases, this pitting is known as crevice corrosion.
REMEDY	• The use of a different construction, for example, a tube heat exchanger, was impossible for lack of room. It was therefore decided, for both constructional and price reasons, to construct the plate heat exchanger of titanium. • Alternative: construction using a more crevice corrosion–resistant alloy, e.g., 254 SMO.

CORROSION ATLAS

CASE HISTORY

04.06.13.02

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Power station cooling system.
PART	Sieve from steam condenser cooling water system.
PHENOMENON	Crevice corrosion.

APPEARANCE	Local attack underneath seal.
TIME IN SERVICE	2 years.
ENVIRONMENT	Flowing seawater, maximum temperature 40°C.
CAUSE	Because of the presence of a crevice between the seal and the stainless steel, the construction is locally extra sensitive to attack by chloride (see also Case History 04.11.13.01).
REMEDY	Use a plastic sieve, or seal the crevice with compound.

CORROSION ATLAS

CASE HISTORY

04.06.15.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Condenser cooler in nitric acid plant.
PART	Cooler jacket.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Pitting developing into vertical grooves.
TIME IN SERVICE	About 5 years.
ENVIRONMENT	Chloride-containing cooling water (500–600 ppm Cl^-), at max. 40°C at the jacket side.
CAUSE	Deposition of corrosion products originating from elsewhere owing to the low flow velocity. Underneath the deposits, an oxygen deficit occurs, as a result of which the passive layer is attacked by chloride and further corrosion takes place (as in crevice corrosion).
REMEDY	• Increase the flow velocity (>1.5 m/s), alternatively passing the cooling water *through* the pipes; or • Construct the cooler with a coated jacket.

CORROSION ATLAS

CASE HISTORY

04.06.15.02

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Heat exchanger provided with a fluid bed of 2-mm glass beads to prevent fouling.
PART	Riser pipes.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Inside pipe surface clean and uncorroded at the fluid bed. The upper section fouled by deposition of barnacles, including pitting attack (see right-hand photograph for more detail).
TIME IN SERVICE	Trial lasted 1.5 years.
ENVIRONMENT	Seawater (unhealed).
CAUSE	Chloride attack underneath deposit, as a result of the formation of differential aeration cells (as in crevice corrosion) (see also Case History 04.06.12.02).
REMEDY	Result of trial: provided heat exchangers constructed of stainless steel 316 are equipped with a fluid bed; fouling and corrosion can be prevented at the present temperature.

CORROSION ATLAS

CASE HISTORY

04.06.15.03

MATERIAL	Stainless steel (AISI 321).
SYSTEM	Through-flow cooling water system.
PART	Cooler tube.
PHENOMENON	Under-deposit corrosion.

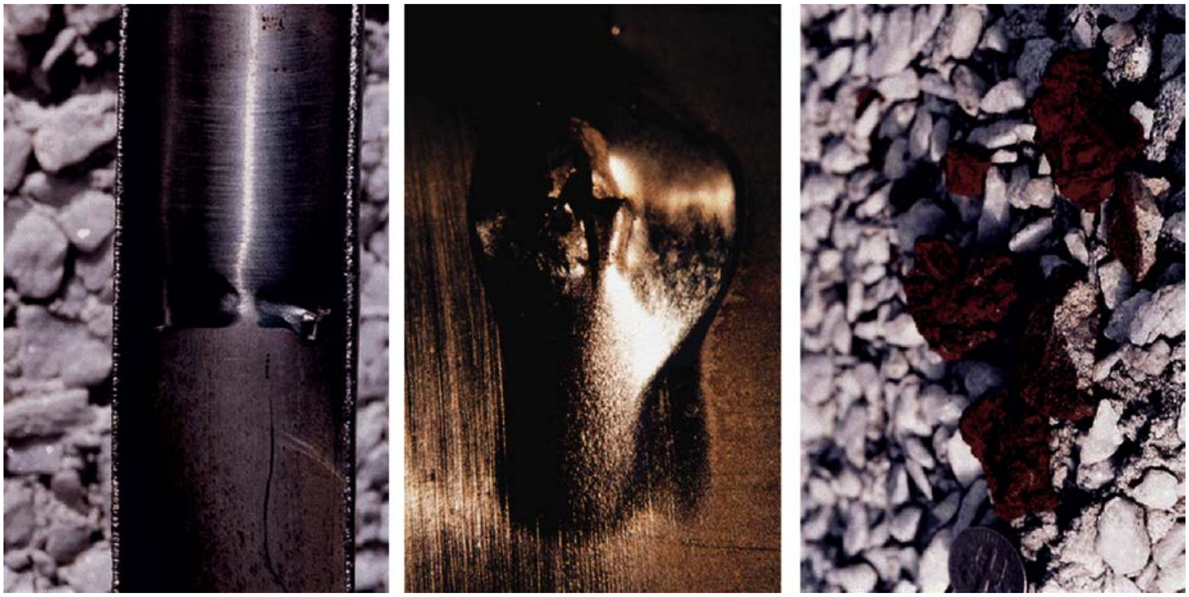
APPEARANCE	Local attack under deposits.
TIME IN SERVICE	3 years.
ENVIRONMENT	Brackish cooling water.
CAUSE	Particles from the cooling water deposit on the metal surface, causing corrosion due to galvanic effects (formation of anodic sites under the deposits) resulting in local corrosion (see also Case Histories 04.01.15.01, 04.11.15.01, and 05.06.15.01/02).
REMEDY	• Prevent formation of deposits by higher cooling water velocity; or • Use better pitting corrosion-resistant material (AISI 316) provided with a baked coating.

CORROSION ATLAS

CASE HISTORY

04.06.34.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Circulating cooling-water system.
PART	Inlet end of horizontal condenser tube (OD 2.5 cm).
PHENOMENON	Erosion corrosion.



APPEARANCE	Severe gouging on internal surface with close-up of perforated gouge (magnification ×7.5). Concrete chips covered with orange iron oxide (tubes and chips are placed on gravel).
TIME IN SERVICE	4 years.
ENVIRONMENT	Internal: treated cooling water adjusted with sulfuric acid for pH control and sodium hypochlorite added as a biocide; temperature 38–49°C, water velocity 2.1 m/s, pH 8.0–8.4, sulfate 500–1000 ppm, chloride 100–450 ppm, total hardness 500 ppm. External: Steam and condensate.
CAUSE	The gouging was caused by the lodgment of concrete chips at the inlet end of the tubes (chips exfoliated from large-diameter, concrete-lined pipes delivering make-up water to the cooling towers). Intense turbulence downstream of the lodged debris was sufficient to cause highly localized erosion. Microstructural examinations of the gouged regions revealed that plastic deformation of the metal had not occurred (see also Case History 06.06.34.02).
REMEDY	Prevent lodgment of foreign objects on the tube-sheet face or within tubes by improved filtration by screens or filters and by periodic cleaning of the exchanger itself.

CORROSION ATLAS

CASE HISTORY

04.08.04.01

MATERIAL	Stainless steel (12% chromium steel; AISI 410).
SYSTEM	Wastewater pipe.
PART	Ball valve ball.
PHENOMENON	Acid corrosion.

APPEARANCE	Entire surface of the ball attacked; locally, the material is totally eaten away.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Wastewater contaminated with fatty acids; temperature 50–80°C.
CAUSE	Chromium steel is insufficiently resistant to corrosion in this environment.
REMEDY	Replacement of ball valve by a glass-lined membrane valve with a polytetrafluoroethylene membrane.

CORROSION ATLAS

CASE HISTORY

04.08.12.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Water treatment system (ion exchanger).
PART	Drainage pipe.
PHENOMENON	Chloride attack.

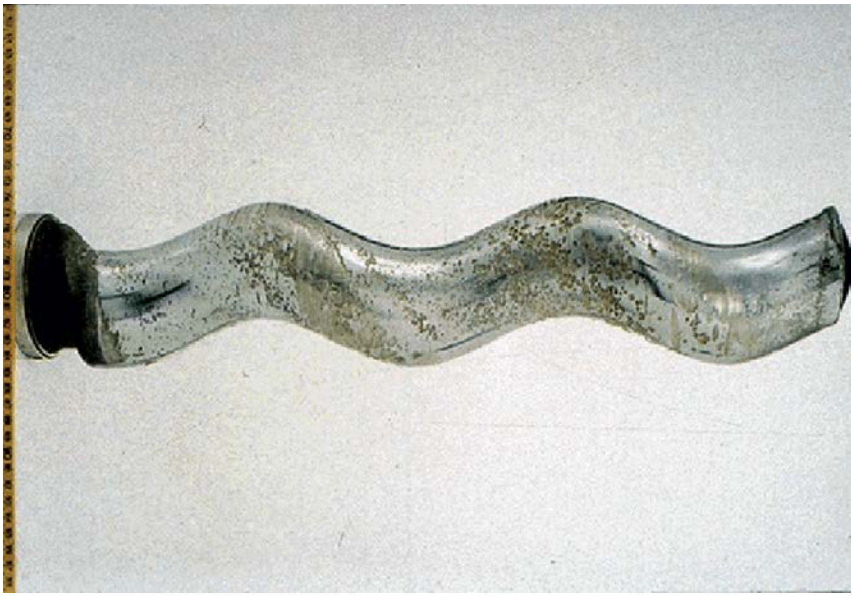
APPEARANCE	Pitting attack over the entire surface.
TIME IN SERVICE	Approximately 1 year.
ENVIRONMENT	Regularly 6% hydrochloric acid (during regeneration).
CAUSE	Stainless steel is not resistant to hydrochloric acid (high chloride concentration with low pH) (see also Case History 04.08.12.06).
REMEDY	Use drainage system made Monel or plastic.

CORROSION ATLAS

CASE HISTORY

04.08.12.02

MATERIAL	Stainless steel (type unknown).
SYSTEM	Sewage treatment plant.
PART	Worm from worm gear pump.
PHENOMENON	Chloride attack and erosion.



APPEARANCE	Pitting attack, with grooves.
TIME IN SERVICE	A few months.
ENVIRONMENT	Sludge from the sewage treatment plant, to which ferric chloride was dosed just upstream of the pump to control stench (H_2S). Overall pH approximately 7, but it may have been lower locally inside the pump.
CAUSE	$FeCl_3$ is well known as a pitting initiator in stainless steel; erosion is caused by the sludge.
REMEDY	Dosing point was moved downstream of the pump, with the application of a plastic static mixer or mixing flange in order to ensure thorough mixing.

CORROSION ATLAS

CASE HISTORY

04.08.12.03

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Chemical-physical wastewater purification plant.
PART	Mixing flange in wastewater pipeline.
PHENOMENON	Chloride attack.

APPEARANCE	Severe pitting attack.
TIME IN SERVICE	6 years.
ENVIRONMENT	Wastewater at 25–30°C into which a 43% $FeCl_3$ solution was dosed 15 cm upstream of the mixing flange to give a concentration of 500–1000 ppm in the wastewater.
CAUSE	Pitting due to the combination of a high chloride content with a low pH (see also Case History 04.08.12.02).
REMEDY	Replacement with a mixing flange constructed of plastic.

CORROSION ATLAS

CASE HISTORY

04.08.12.04

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Sewage treatment plant.
PART	Section of the support construction of the canvas cover of the sand trap.
PHENOMENON	Chloride attack.

APPEARANCE	Reddish-brown, rusty exterior with slight pitting (<0.5 mm).
TIME IN SERVICE	$1\frac{1}{2}$ years.
ENVIRONMENT	Humid atmosphere above the sand trap. The condensation formed on the stainless steel contained 270 ppm Cl at a pH of 4.6.
CAUSE	HCl vapors from aluminum chloride dosed in the sand trap (the corrosion products contained 20,000 ppm Cl).
REMEDY	• Stripping the structure and then pickling and passivating it by immersion, in addition to repositioning the aluminum chloride storage tank outside the sand trap, and dosing it below the water level in the trap, or coating or painting the stainless steel. • Alternative: making the structure out of timber or plastic.

CORROSION ATLAS

CASE HISTORY

04.08.12.05

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Sewage treatment plant.
PART	Extractor duct and fan housing of the extraction system for all the sub-processes.
PHENOMENON	Chloride pitting.

APPEARANCE	Pitting attack with corrosion nodules and fanned-out corrosion products.
TIME IN SERVICE	2 years.
ENVIRONMENT	Humid air contaminated with chloride, H_2S, and other gases of putrefaction. Temperature 5–20°C. Successive condensation and evaporation.
CAUSE	Pitting due to rising chloride content caused by evaporation, in a reducing atmosphere.
REMEDY	The extractor system was constructed of plastic (see also Case History 04.08.12.04).

CORROSION ATLAS

CASE HISTORY
04.08.12.06

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Regeneration system of cation exchangers.
PART	Pipeline.
PHENOMENON	Chloride attack.

APPEARANCE	General corrosion and pitting.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Warm hydrochloric acid (approximately 10% at 40–50°C).
CAUSE	Stainless steel is not resistant in such reducing environments (see also Case History 04.08.12.01).
REMEDY	Apply a more appropriate material, like PVC.

CORROSION ATLAS

CASE HISTORY

04.08.17.01

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Swimming pool water filter installation.
PART	Filter wall (thickness 3 mm).
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Red-brown corrosion products at the inside of the wall, with pinholes tunneling through wall (see right photograph: the holes at the edge).
TIME IN SERVICE	1–2 years. After replacement of attacked wall section, leakage recurred after 1–1.5 years.
ENVIRONMENT	Swimming pool water with 1.3 ppm chlorine.
CAUSE	Most likely iron bacteria from iron-containing drinking water with which pool was replenished weekly (see also Case History 04.05.17.01).
REMEDY	• Circulation pattern in filter had been changed, but did not prevent re-attack. • Optimizing the cleaning and disinfection methods (a periodic concentration of 20 ppm chlorine during 12 h is necessary to kill the iron bacteria), or • Replace stainless steel with glass-fiber reinforced plastic.

CORROSION ATLAS

CASE HISTORY

04.08.19.01

MATERIAL	Stainless steel (base metal AISI 304; weld metal AISI 347).
SYSTEM	Water demineralization plant.
PART	Part of filter wall.
PHENOMENON	Intergranular corrosion (weld decay) and acid corrosion.

APPEARANCE	Severe corrosion along the weld in the HAZ and etching of the base metal.
TIME IN SERVICE	6 months.
ENVIRONMENT	During regeneration: diluted sulfuric acid (6%); temperature: 40°C.
CAUSE	Selection of inadequate base metal for given conditions: AISI 304 has too high a carbon content that causes chromium depletion as a result of welding (see Case Histories 04.01.19.01 and 04.11.19.02). Moreover, this alloy is not resistant to diluted sulfuric acid at this temperature.
REMEDY	• Use of suitable stainless steel, i.e., AISI 316L or 316 Ti, or • Construct cation exchanger filter of carbon steel coated with ebonite, or of plastic.

CORROSION ATLAS

CASE HISTORY

04.08.42.01

MATERIAL	Stainless steel (AISI 308).
SYSTEM	Water demineralization plant.
PART	Part of structure in cation exchanger.
PHENOMENON	End grain attack.

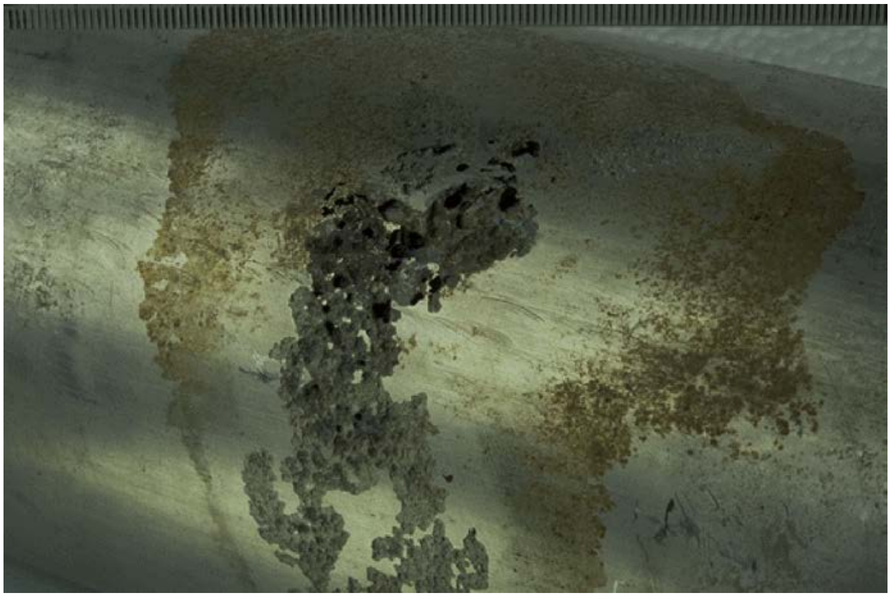
APPEARANCE	Pitting at the edge.
TIME IN SERVICE	3 months.
ENVIRONMENT	During generation: diluted sulfuric acid (6%); temperature: 40°C.
CAUSE	Selective corrosion took place at the edges of the non-metallic inclusions in the metal. These were rolled out and elongated into long stringers during the rolling action. When the end grain is exposed to a strong corrodent, end grain attack starts at the end of the stringers and can aggressively proceed down into the steel (see also Case Histories 01.12.42.01 and 05.11.42.01).
REMEDY	• Use clean steel without non-metal inclusions. • Butter the edges with weld metal. • Manufacture the structure of plastic (PVC). Note: AISI 316 has a better resistance in diluted sulfuric acid at this temperature, but it will not prevent end grain attack.

CORROSION ATLAS

CASE HISTORY

04.10.15.01

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Fire-extinguisher system.
PART	Underground pipe.
PHENOMENON	Under-deposit corrosion.



APPEARANCE	The pipe exhibited wide local zones of severe pitting corrosion, surrounded by iron oxide deposits (see also Case History 04.06.13.01).
TIME IN SERVICE	2 years.
ENVIRONMENT	Soil consisting of a mixture of sand and lumps of clay with bog iron ore. Analysis of the clay: pH 7.6; chloride 550 ppm; iron 1.5% wt; sulfide positive. The pipe lay above the groundwater level.
CAUSE	Inhomogeneous soil: the uneven aeration and the reducing environment underneath the lumps of clay with bog ore rendered the pipe surface locally sensitive to pitting.
REMEDY	• An uncoated stainless steel pipe should be laid in a clean, homogenous sand bed to guarantee sufficient aeration. • Alternative: use a well-coated stainless steel or carbon steel pipe, or use a plastic pipe.

CORROSION ATLAS

CASE HISTORY

04.11.04.01

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Vinyl chloride system.
PART	Strainer.
PHENOMENON	Acid corrosion.

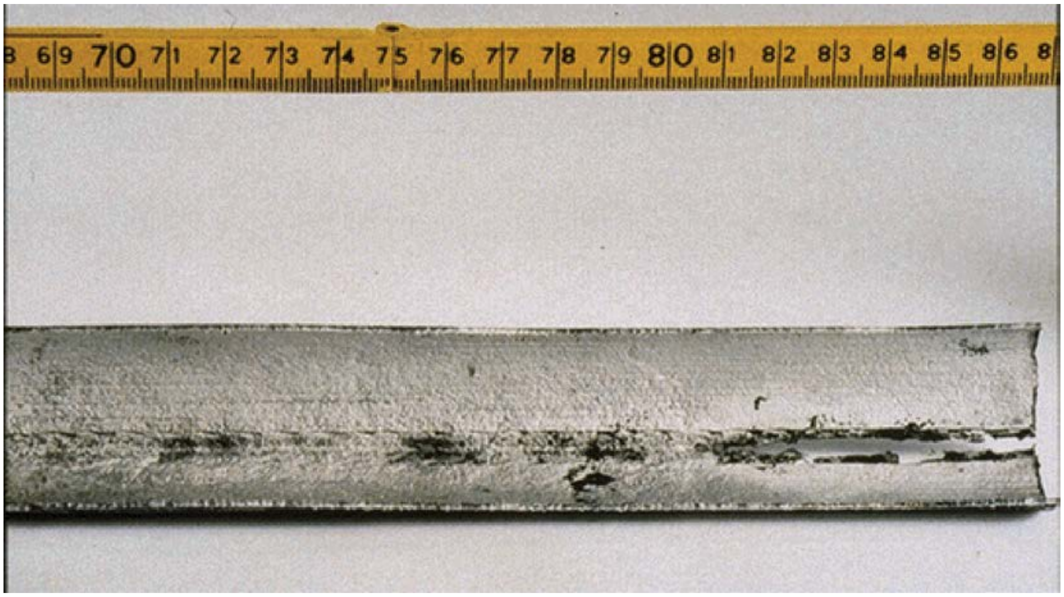
APPEARANCE	Pits on surface, growing bigger below the surface.
TIME IN SERVICE	4 years.
ENVIRONMENT	Vinyl chloride and water.
CAUSE	In the presence of water/condensation from the outside, vinyl chloride hydrolyses into hydrochloric acid. Acid droplets corrode the passive film on the AISI 316L, causing pitting (see also Case History 04.01.04.01).
REMEDY	Prevent water ingress.

CORROSION ATLAS

CASE HISTORY

04.11.04.02

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Glue plant.
PART	Autoclave charge pipe.
PHENOMENON	Acid corrosion.



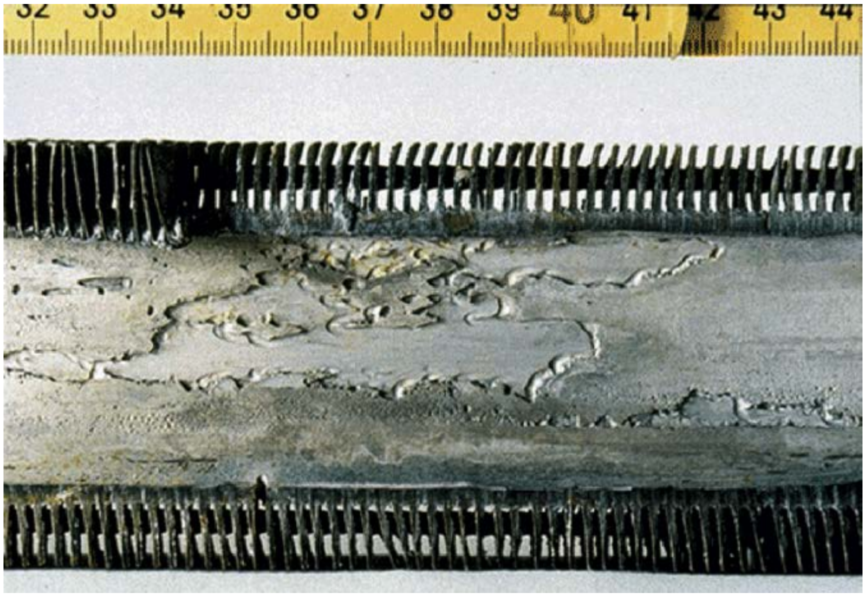
APPEARANCE	Etched surface, uniform attack with preferent attack of the weld.
TIME IN SERVICE	4 months (2000 operating hours).
ENVIRONMENT	75% phosphoric acid; temperature 20–110°C
CAUSE	Stainless steel 316L is not resistant to 75% phosphoric acid at 110°C (see also Case History 04.11.04.16).
REMEDY	Construct the pipe from more resistant stainless steel (W.-Nr. 1.4563).

CORROSION ATLAS

CASE HISTORY

04.11.04.03

MATERIAL	Stainless steel (AISI 316 Ti).
SYSTEM	Sulfuric acid plant.
PART	Cooling element of air-cooled sulfuric acid heat exchanger.
PHENOMENON	Acid corrosion.



APPEARANCE	Local uniform attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	96%–98.5% H_2SO_4; temperature 80–85°C; velocity approximately 1 m/s.
CAUSE	316 Ti stainless steel is not resistant to 98.5% sulfuric acid at 80°C.
REMEDY	• Construction of the cooler from Cr and Mo alloyed nickel-based alloys, e.g., Hastelloy C (expensive!), or • Application of anodic protection to the present system.

CORROSION ATLAS

CASE HISTORY

04.11.04.04

MATERIAL	Stainless steel (AISI 316 Ti).
SYSTEM	Heat exchanger.
PART	Attacked tube from bundle, with a new tube below it for comparison.
PHENOMENON	Acid corrosion.
	
APPEARANCE	Uniform attack to entire surface.
TIME IN SERVICE	14 days.
ENVIRONMENT	Around the pipe: steam, 140°C; through the pipe: synthetic detergent, sulfonic acid and occasional traces of sulfuric acid, pH < 1.
CAUSE	AISI 316 Ti is not resistant to sulfuric acid traces at the present temperature. Attack took place at the steam inlet, where the temperature is highest (for the resistance of stainless steel in diluted sulfuric acid, see also Case Histories 04.11.04.06/09 and 04.12.04.05).
REMEDY	• Reduction of the temperature if possible, and • Improvement of the sulfuric acid neutralization, or • Use of a more corrosion-resistant material, e.g., Hastelloy B-2.

CORROSION ATLAS

CASE HISTORY

04.11.04.05

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Distillation tower.
PART	Belleville washers (top specimen unused, bottom specimen corroded).
PHENOMENON	Acid corrosion.

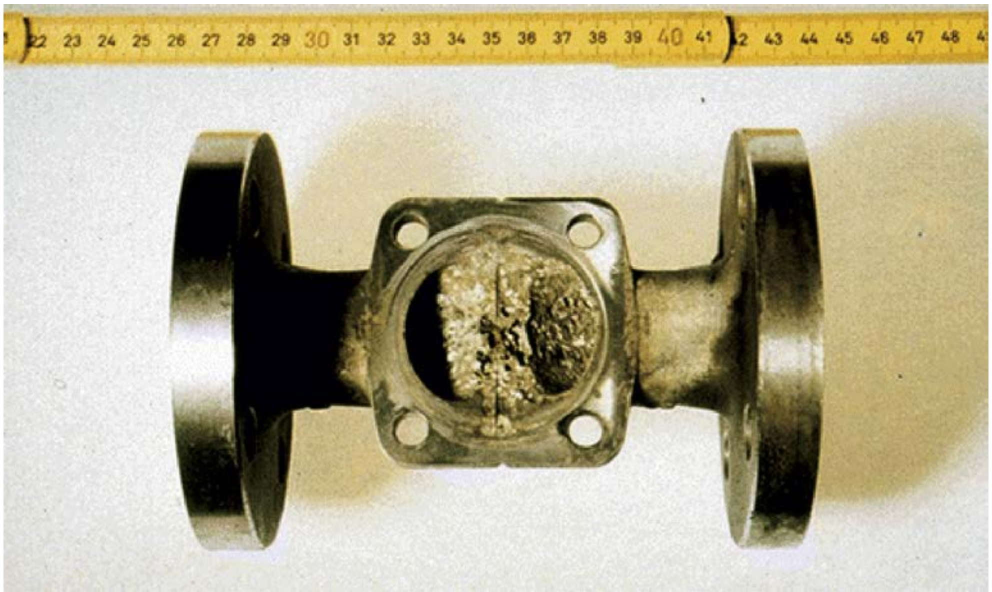
APPEARANCE	Uniform attack, leaving the material wafer-thin.
TIME IN SERVICE	A few years.
ENVIRONMENT	Acetic acid with some formic acid and propionic acid; temperature approximately 120°C.
CAUSE	At this temperature, the stainless steel is attacked by the formic acid and propionic acid.
REMEDY	The cheapest solution is periodic replacement of the tray washers during shutdown.

CORROSION ATLAS

CASE HISTORY

04.11.04.06

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Sulfuric acid transport system.
PART	Valve.
PHENOMENON	Acid corrosion.



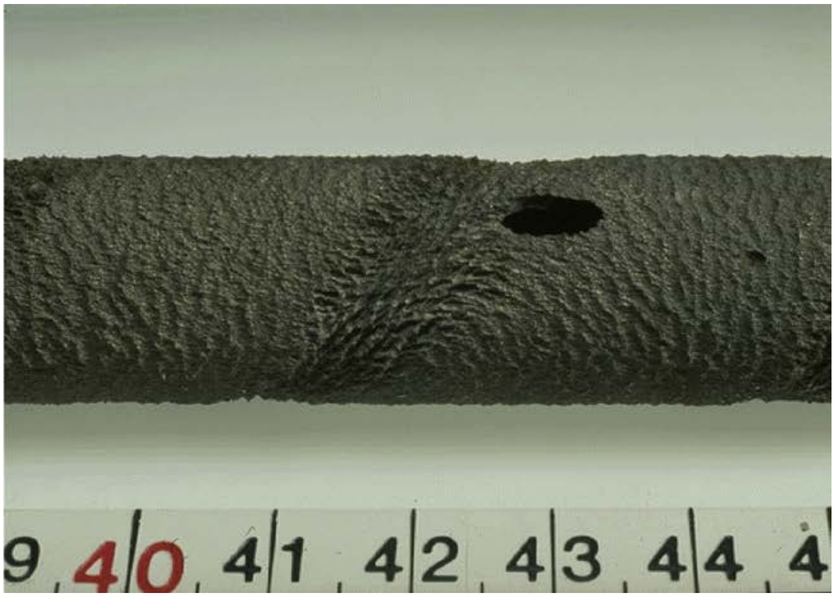
APPEARANCE	Severe attack to interior.
TIME IN SERVICE	4 months.
ENVIRONMENT	20%–25% H_2SO_4; temperature 15–20°C.
CAUSE	The stainless steel valve was used as an ad hoc solution to replace a glazed specimen which had corroded through owing to a hole in the glazing.
REMEDY	Use of valves coated with PTFE (polytetrafluoroethylene).

CORROSION ATLAS

CASE HISTORY

04.11.04.07

MATERIAL	Stainless steel (Uranus B6; W.-Nr. 1.4539).
SYSTEM	Mixing reactor in metal plant.
PART	Heating pipe.
PHENOMENON	Acid corrosion.



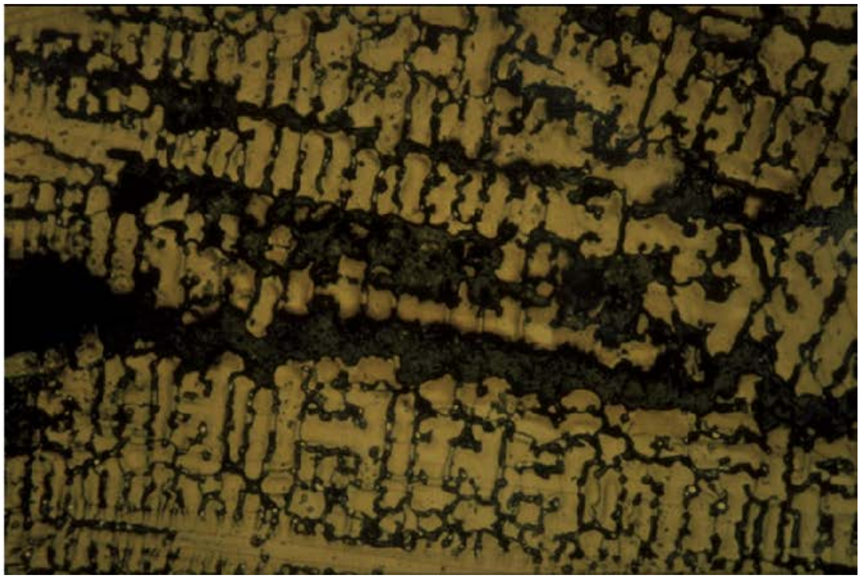
APPEARANCE	General roughening and local penetration at the dark-colored, spiral-shaped, more severe area of attack.
TIME IN SERVICE	3–4 years.
ENVIRONMENT	Internal: steam. External: a mixture of nitric acid and other oxidizing mineral acids. Temperature 110–115°C. Elevated oxygen pressure.
CAUSE	This material is not resistant to the present medium. Due to the lead wrapping of a thermocouple, a crevice was present at that site whilst moreover the heat transmission was lower and the wall temperature was therefore higher, so that intensified corrosion took place there (for the resistance of stainless steel in nitric acid, see also Case Histories 04.11.04.08, 04.12.04.04, 04.11.19.05, and 04.11.34.02).
REMEDY	• Do not wrap the thermocouple spiral around the tube. • Periodic replacement of the bundle because of the general attack (roughening), which cannot be prevented.

CORROSION ATLAS

CASE HISTORY

04.11.04.08

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Mixing vessel of a nitriding plant.
PART	Piece of the cast propeller blade of the immersion stirrer.
PHENOMENON	Acid corrosion.



APPEARANCE	Outwardly, the material does not appear corroded. However, it can be deformed by hand as if it were a piece of rubber.
TIME IN SERVICE	Several weeks.
ENVIRONMENT	Nitriding acid, consisting of 80% nitric acid 98% and 20% fuming sulfuric acid. Temperature 25°C.
CAUSE	The interdendritic material, which was the last to solidify and therefore contains quite a variety of constituents, was found (see microphoto) to have been almost totally eroded. Because dendrites interlock, the integrity of the propeller was retained, but because each of the remaining dendrites acts as an independent hinge, the material can be moved to and fro as if it were rubber. Conclusion: selective attack of the connective interdendritic material.
REMEDY	Stainless steel AISI 304 is per se resistant to the present acid mixture. For casting purposes, however, the purest possible material should be used in order to prevent the formation of a less corrosion-resistant interdendritic phase. Alternative: construct the propeller blade of enameled cast iron.

CORROSION ATLAS

CASE HISTORY

04.11.04.09

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Reactor for the manufacture of catalysts.
PART	Stirrer support.
PHENOMENON	Acid corrosion.

APPEARANCE	Projecting edge uniformly attacked and totally eroded; the pipe section and welded-on strips are not attacked.
TIME IN SERVICE	Several years.
ENVIRONMENT	Aluminum–silica slurry with a small proportion of sulfuric acid. pH about 3. Temperature 50°C.
CAUSE	Incorrect choice of material: like the pipe section and strips, the rim should also have been made of stainless steel AISI 316. The components concerned had been manufactured by the plant itself.
REMEDY	Prevent incorrect selection of material by correct labeling of the materials in the store, effective entry control, and, if possible, standardization to a single material (AISI 316).

CORROSION ATLAS

CASE HISTORY

04.11.04.10

MATERIAL	Stainless steel (AISI 420; EPI L80 tubing).
SYSTEM	Natural gas well.
PART	Section from well tubing.
PHENOMENON	Acid corrosion.

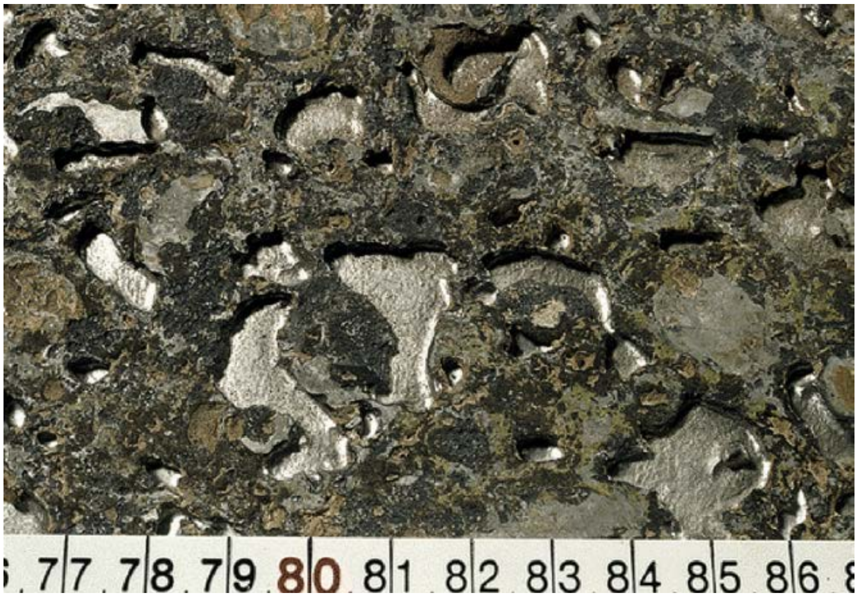
APPEARANCE	Localized attack in the longitudinal direction.
TIME IN SERVICE	Some days after contact with acid.
ENVIRONMENT	Normally wet CO_2-containing natural gas, but some days in contact with mineral acids (HCl and HF) during well stimulation.
CAUSE	Failure of the acid corrosion inhibitor due to excessive exposure duration at elevated reservoir temperature (70–80°C). This caused local breakdown of the inhibitor film (see also Case Histories 04.12.12.02 and 01.01.04.04).
REMEDY	Improved acid stimulation techniques to avoid protracted exposures of the tubing to acid.

CORROSION ATLAS

CASE HISTORY

04.11.04.11

MATERIAL	Stainless steel (AISI 347, W.-Nr. 1.4550).
SYSTEM	Fertilizer plant.
PART	Reactor vessel wall.
PHENOMENON	Acid corrosion.



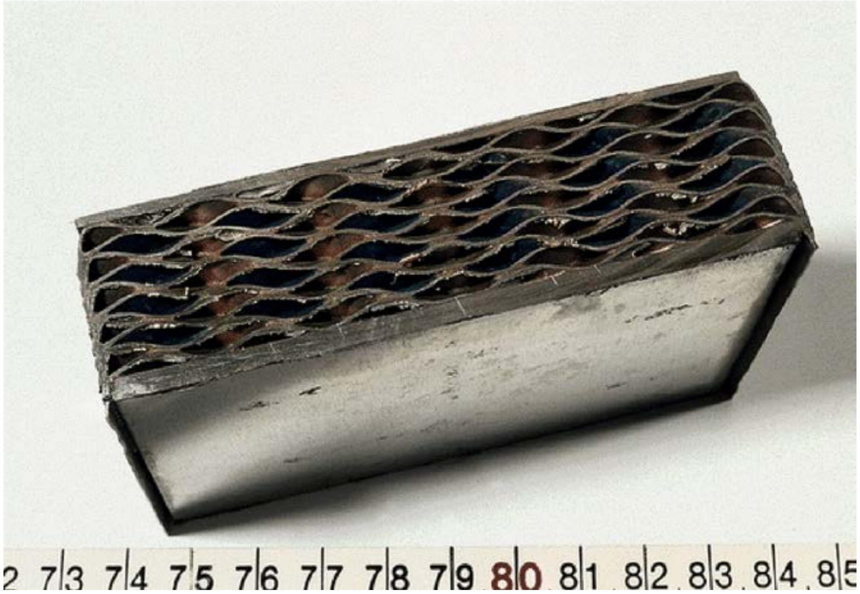
APPEARANCE	Local overall corrosion.
TIME IN SERVICE	A couple of days.
ENVIRONMENT	A mixture of: H_3PO_4, HNO_3, $(NH)_2SO_4$, and $CaSO_4$, with traces of Cl^- and F^- as contamination; temperature approximately 65°C.
CAUSE	The presence of amidosulfonic acid in the acidic nitrate phosphate solution in combination with traces of chloride and fluoride.
REMEDY	The corrosion was halted by using an alternative material of construction: AISI 316L.

CORROSION ATLAS

CASE HISTORY

04.11.04.12

MATERIAL	Stainless steel (AISI 316), copper-brazed.
SYSTEM	Ethylene oxide reactor.
PART	Sample cooler.
PHENOMENON	Acid corrosion.



APPEARANCE	Uniform attack of the copper solder. At some places the copper has totally disappeared, at other places the copper is blue-colored.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Inside: A condensing gas flow (pressure = 1.4 MPa, temperature = 60°C, flow rate 50 L/h), consisting of 85% methane, 8% ethylene oxide, ethylene, oxygen, carbon dioxide, water, and organic acids. Outside: Air for cooling.
CAUSE	The cooler leakage was caused by the condensing organic acids attacking the copper solder joints between the plates. This also caused the blue color. As a result of the attack, the stainless steel plates were no longer connected and deformation of the cooler took place, resulting in leakage.
REMEDY	Replace the copper-brazed plate cooler by a cooler with aluminum-finned stainless steel tubes.

CORROSION ATLAS

CASE HISTORY

04.11.04.13

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Sulfuric acid storage tank.
PART	Horizontal outlet piping (OD 1.3 cm, wall thickness: 0.76 mm).
PHENOMENON	Acid corrosion.

APPEARANCE	Internal severe general corrosion with dark tenacious corrosion products. Near the failure, the remaining metal was paper-thin.
TIME IN SERVICE	One year.
ENVIRONMENT	Sulfuric acid containing excessive water (20%–30%).
CAUSE	Water entered the storage tank due to condensation of moisture-laden air that was sucked into the tank. Air-drying systems were not in good working order. Stainless steel 316 is attacked by sulfuric acid with so much water (for the corrosion resistance of stainless steel in concentrated sulfuric acid, see Case Histories 04.11.04.03 and 04.11.19.01/03 and 04.11.34.03).
REMEDY	Keep the air-drying systems in a good working order, or if the acid contains 10% water or more, add acid to reduce water concentration to below 5%.

CORROSION ATLAS

CASE HISTORY

04.11.04.14

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Chemical plant.
PART	Safety bellows of HCl gas pipeline.
PHENOMENON	Acid corrosion.

APPEARANCE	Uniform attack from the inside, holes in the bellows.
TIME IN SERVICE	0.5 years.
ENVIRONMENT	Dry HCl gas, ambient temperature.
CAUSE	Material exchange. The bellows were made from AISI 316 instead of Hastelloy C. Hydrochloric acid was formed as a result of the entrance of moisture and attacked the bellows.
REMEDY	Retrofitting a Hastelloy C bellows.

CORROSION ATLAS

CASE HISTORY

04.11.04.15

MATERIAL	Stainless steel (AISI 430).
SYSTEM	Scrubber.
PART	Column packing rings.
PHENOMENON	Acid corrosion.

APPEARANCE	Wall thinning by uniform attack.
TIME IN SERVICE	One year.
ENVIRONMENT	Hot glycol and water, temperature: 220°C.
CAUSE	Oxidized glycol at high temperature gives an acidic environment by forming glycolic acid.
REMEDY	Select stainless steel AISI 316.

CORROSION ATLAS

CASE HISTORY

04.11.04.16

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Cumene plant.
PART	Tank drain line.
PHENOMENON	Acid corrosion.

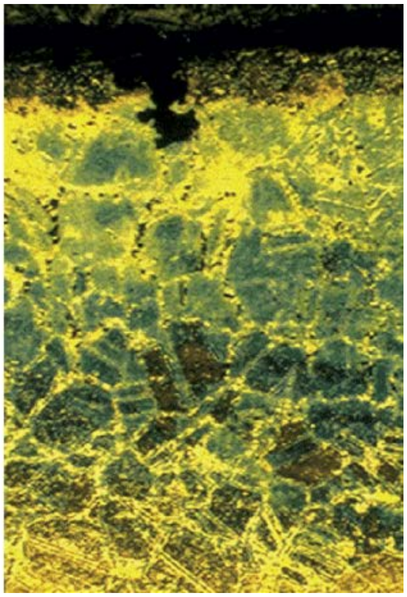
APPEARANCE	Vertical grooves.
TIME IN SERVICE	3 years.
ENVIRONMENT	Phosphoric acid sludge.
CAUSE	Inappropriate initial material choice (see also Case History 04.11.04.02).
REMEDY	Replaced by Hastelloy C276.

CORROSION ATLAS

CASE HISTORY

04.11.06.01

MATERIAL	Stainless steel (253 MA; AISI 309).
SYSTEM	Welding wire annealing system.
PART	Wall of annealing furnace.
PHENOMENON	High-temperature corrosion (carburization).



APPEARANCE	Uniform attack.
TIME IN SERVICE	4 years.
ENVIRONMENT	Nitrogen atmosphere at 850°C (temperature of welding wire 1070°C); traces of propene and propane; welding wire externally contaminated with soap residues and oil.
CAUSE	From the oil and hydrocarbons, carbon is formed which produces chromium and iron carbides in the stainless steel (carburization) (see also Case History 05.11.06.01). As a result, the material loses its ductility and the furnace collapses as a result of embrittlement. Formation of nitrides (nitriding) may also have played a role.
REMEDY	Construction of the furnace from titanium or RA 330 (W.-Nr. 1.4333) materials which are insensitive, or much more resistant, to carburization and nitriding.

CORROSION ATLAS

CASE HISTORY

04.11.06.02

MATERIAL	Chromium steel (W.-Nr. 1.4772; X10 CrSi 29).
SYSTEM	Heat recovery plant.
PART	Pipe.
PHENOMENON	High-temperature corrosion (oxidation).

APPEARANCE	Excessive wall thickness reduction and formation of a thick, yellowish scale with penetration of the pipe wall.
TIME IN SERVICE	$1\frac{1}{2}$ years.
ENVIRONMENT	Combustion gases from a glass melting furnace; temperature 600–1000°C.
CAUSE	Loss of corrosion protection by the chromium because, in the presence of chlorine in the combustion gases, chromium oxidizes to form yellowish alkali chromates. The chlorine accelerates the oxidation.
REMEDY	Application of base materials with a very low content of chlorine compounds.

CORROSION ATLAS

CASE HISTORY

04.11.06.03

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Synthetic resin plant.
PART	Heating coil.
PHENOMENON	High-temperature corrosion (nitriding).

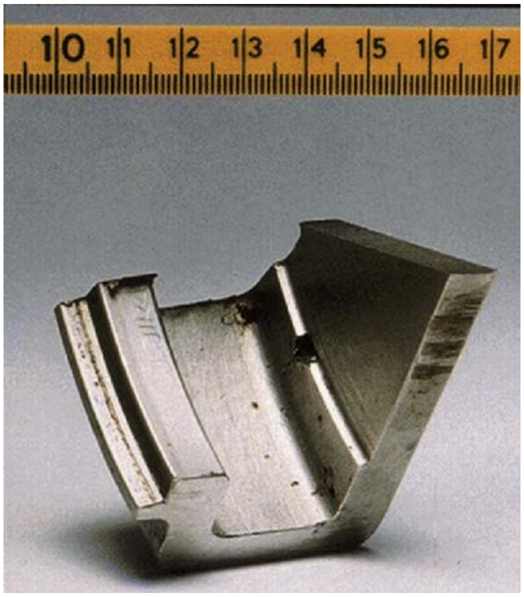
APPEARANCE	Severe overall and annular corrosion; 2–3 mm of the wall thickness had disappeared.
TIME IN SERVICE	Some years.
ENVIRONMENT	NH_3 and CO_2 gas mixture; temperature 450°C.
CAUSE	Decomposition of ammonia produces atomic nitrogen that diffuses into the steel, followed by the formation of nitrides resulting in scaling of the nitride layer. In the case of a high nitriding potential, stainless steel has a limited lifetime (see also Case Histories 01.11.06.03 and 05.03.06.01).
REMEDY	Lower stress levels by avoiding thermal shocks during start-up and shut-down.

CORROSION ATLAS

CASE HISTORY

04.11.12.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Ketchup plant.
PART	Part of cast pump casing.
PHENOMENON	Chloride attack.



APPEARANCE	Severe pitting attack.
TIME IN SERVICE	6 months.
ENVIRONMENT	Ketchup; pH 3.5; 3.8% NaCl; temperature 90°C (see also Case History 04.11.18.06).
CAUSE	Pitting corrosion is caused by the high chloride content together with the low pH and high temperature of the product. The pump casing was slightly magnetic, indicating ferrite precipitation in the casting process, and this increased its sensitivity to chloride.
REMEDY	The casing was constructed of a more chloride-resistant steel (e.g., W.-Nr. 1.4539 or Sanicro 28).

CORROSION ATLAS

CASE HISTORY

04.11.12.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Dairy factory, whey manufacturing unit.
PART	Whey transport pipeline.
PHENOMENON	Chloride attack.

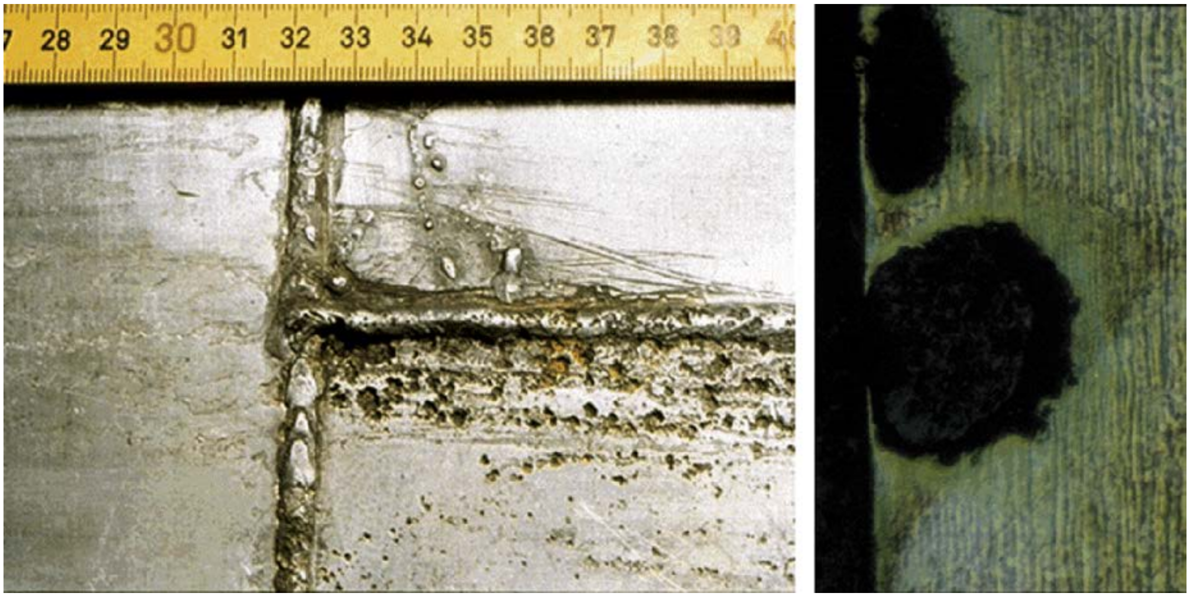
APPEARANCE	Pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Humid atmosphere with chloride and chlorine due to periodical spraying with a solution of sodium hypochlorite for disinfection purposes.
CAUSE	Chloride pitting as a result of evaporation of the chloride-containing water on the pipe, reinforced by the oxidizing action of the sodium hypochlorite (see also Case History 04.08.12.04).
REMEDY	Change-over to spraying a solution of hydrogen peroxide in salt-free water (e.g., condensate).

CORROSION ATLAS

CASE HISTORY

04.11.12.03

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Distillation plant.
PART	Bottom plate of benzene storage tank.
PHENOMENON	Chloride attack.



APPEARANCE	Internal pitting attack of the plate, lower right.
TIME IN SERVICE	6 years.
ENVIRONMENT	Benzene-containing organic compound with a small quantity of water and traces of SO_2. Temperature 50°C.
CAUSE	Under the prevailing conditions (reducing chloride-containing environment at 50°C), stainless steel AISI 304 is susceptible to chloride particularly in the neighborhood of the welds. The pitting attack only appeared, however, at some places in the plant, constructed completely in stainless steel 304. Systematic analysis of a great number of metal samples showed that all the attacked plates had a Mo-content of <0.1% (which is normal for AISI 304). The plates with some tenths of 1% Mo (as contaminant) showed no pitting (see also Case History 04.05.12.01).
REMEDY	Construct tank from AISI 316 stainless steel.

CORROSION ATLAS

CASE HISTORY

04.11.12.04

MATERIAL	Duplex stainless steel.
SYSTEM	Centrifuge.
PART	Drum.
PHENOMENON	Chloride attack.

APPEARANCE	Small pinhole defects.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Solution of a mixture of salts mainly chlorides, 10^5 ppm Cl^-, temperature 40°C.
CAUSE	Aggressive environment caused pitting with preferential attack of ferrite phase.
REMEDY	Use of more resistant material, for instance, Hastelloy C22.

CORROSION ATLAS

CASE HISTORY

04.11.12.05

MATERIAL	SAF 2205 (duplex stainless steel), Sanicro 28 (super-austenitic stainless steel), and E-Brite 26/1 (super-ferritic stainless steel).
SYSTEM	Monochlorbenzene recovery system.
PART	Heat exchanger pipes.
PHENOMENON	Chloride attack.

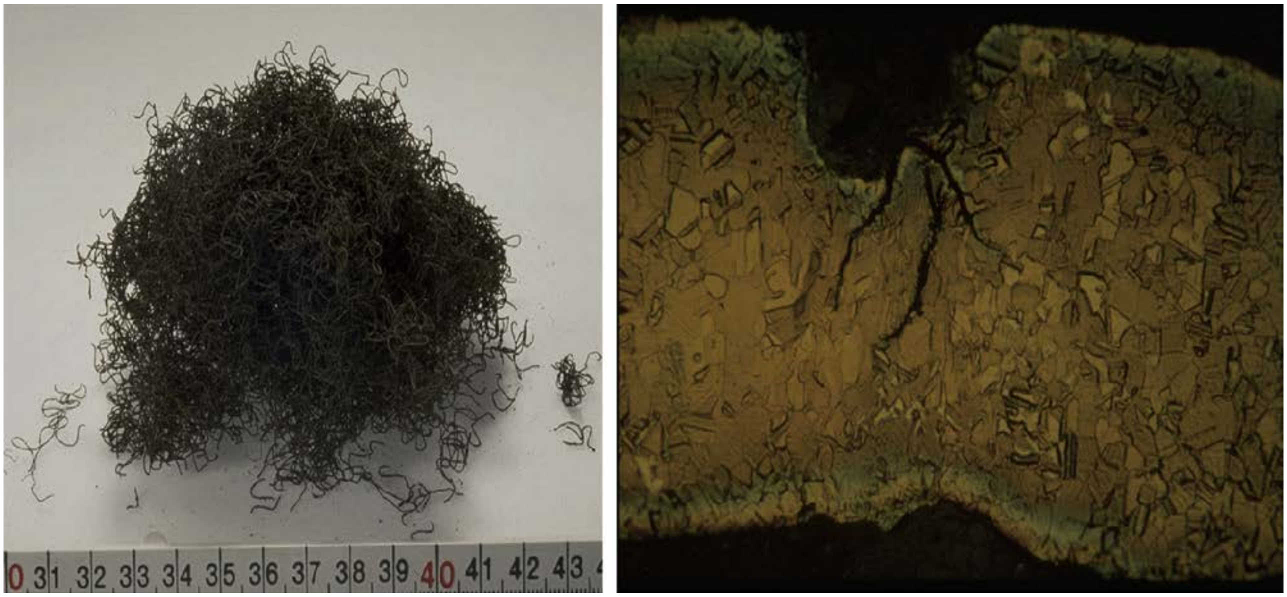
APPEARANCE	Pitting corrosion, left: SAF 2205, center; Sanicro 28, right: E-Brite 26/1.
TIME IN SERVICE	SAF 2205 and Sanicro 28: 1 year. E-Brite 26/1: 3 years.
ENVIRONMENT	Through the pipes: monochlorbenzene with a few percent of chloride, heated from 21 to 75°C. Around the pipes: the purified, low-chloride product which is cooled from 103 to 49°C.
CAUSE	None of the alloys used are sufficiently resistant to chloride attack.
REMEDY	Use 254 SMO, with periodic inspections.

CORROSION ATLAS

CASE HISTORY

04.11.12.06

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Vacuum tower demister.
PART	Demister material.
PHENOMENON	Chloride attack.



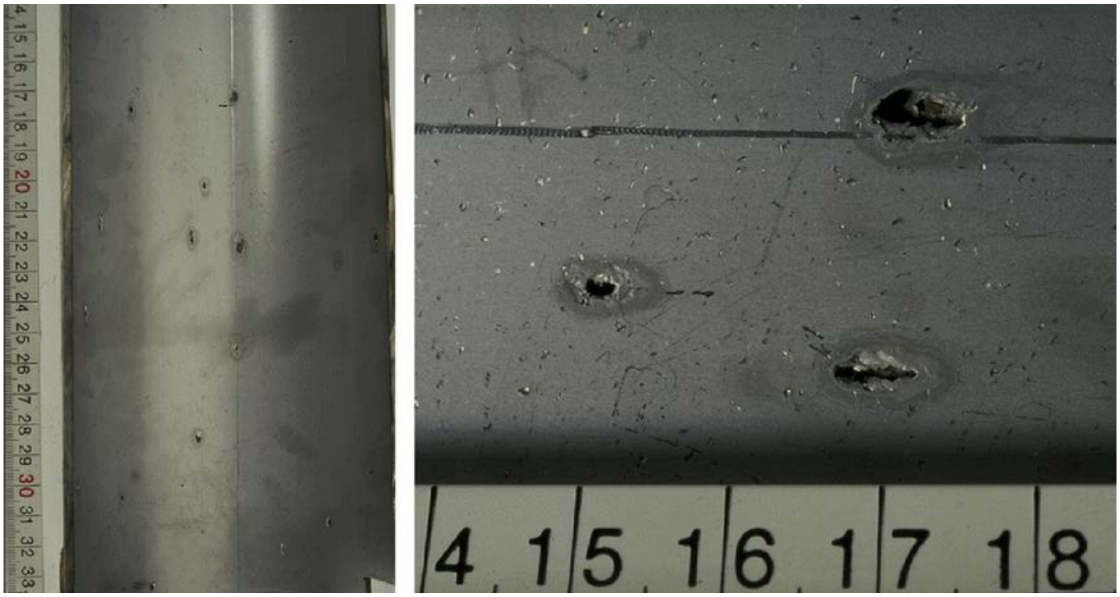
APPEARANCE	Under the microscope: pitting with a few transgranular cracks. The material itself was totally embrittled.
TIME IN SERVICE	About 4 years.
ENVIRONMENT	Hydrocarbons (59%) mixed with water vapor. Temperature 60–98°C. Contaminants present: Cl 12 ppm (average) to 24 ppm (maximum); H_2S 750 ppm, total S 5450 ppm; O_2 840 ppm.
CAUSE	The corrosion of the stainless steel wires was caused by the presence of chloride in the medium, which led to pitting. Although the chloride content was low, enrichment of the content takes place at the surface in crevices and underneath hydrocarbon deposits. The transgranular cracking may have been caused by the presence of sulfides.
REMEDY	Application of a more resistant material, e.g., AISI 316, or even better stainless steel W.-Nr. 1.4439 (17 Cr 13 Ni 5 Mo).

CORROSION ATLAS

CASE HISTORY

04.11.12.07

MATERIAL	Stainless steel (AISI 316 L).
SYSTEM	Centrifuge for organic products.
PART	Feed line.
PHENOMENON	Bromide attack.



APPEARANCE	Pitting attack at scratches and other sites.
TIME IN SERVICE	1 year.
ENVIRONMENT	Slurry consisting of a mixture of terephthalic acid and acetic acid, and a bromide-containing catalyst as contaminant. Temperature 100°C.
CAUSE	At the high temperature in this acid environment, the bromide contaminant causes pitting of stainless steel 316 L, corresponding to pitting by chloride and other halides.
REMEDY	• Use a more resistant alloy, e.g., stainless steel AISI 904 L (25 Cr, 20 Ni, 5 Mo). • Modify the process equipment design in order to limit catalyst carry over.

CORROSION ATLAS

CASE HISTORY

04.11.12.08

MATERIAL	Stainless steel AISI 316 (housing: W.-Nr. 1.4581, valve; W.-Nr. 1.4572).
SYSTEM	Modified starch plant
PART	Nonreturn valve from reactor dosing pipe.
PHENOMENON	Chloride attack.

APPEARANCE	Severe pitting.
TIME IN SERVICE	Approximately 3 months.
ENVIRONMENT	Starch slurry with acetic anhydride and hydrochloric acid; pH 4.5–0.9; temperature 48°C.
CAUSE	Stainless steel AISI 316 is not resistant to hydrochloric acid at any concentration or temperature (see also Case History 04.05.12.02).
REMEDY	Piping inside the reactor was already made of Hastelloy C with good results, so the nonreturn valve had been made from this material as well (housing: W.-Nr. 2.4883, valve: W.-Nr. 2.4819). The most resistant nickel base alloys in hydrochloric acid are Hastelloy B-2 and Hastelloy C-276.

CORROSION ATLAS

CASE HISTORY

04.11.12.09

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Desulfurization plant.
PART	Bursting heat exchanger disk.
PHENOMENON	Chloride attack.

APPEARANCE	Pitting under deposits.
TIME IN SERVICE	One year.
ENVIRONMENT	Outside: industrial atmosphere. Inside: Gas consisting of polycyclic aromates with sulfur compounds.
CAUSE	The corrosion at the outside of the plate was caused by contamination with dirt, iron oxide from the carbon steel standpipe above the bursting plate, and chloride-containing rainwater. This results in premature collapse of the disk.
REMEDY	Provide the bursting disk with a stainless steel standpipe, sealed with a plastic foil at the top.

CORROSION ATLAS

CASE HISTORY

04.11.12.10

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Filter press for filtration of metal hydroxides.
PART	Reducer in feed line.
PHENOMENON	Chloride attack.

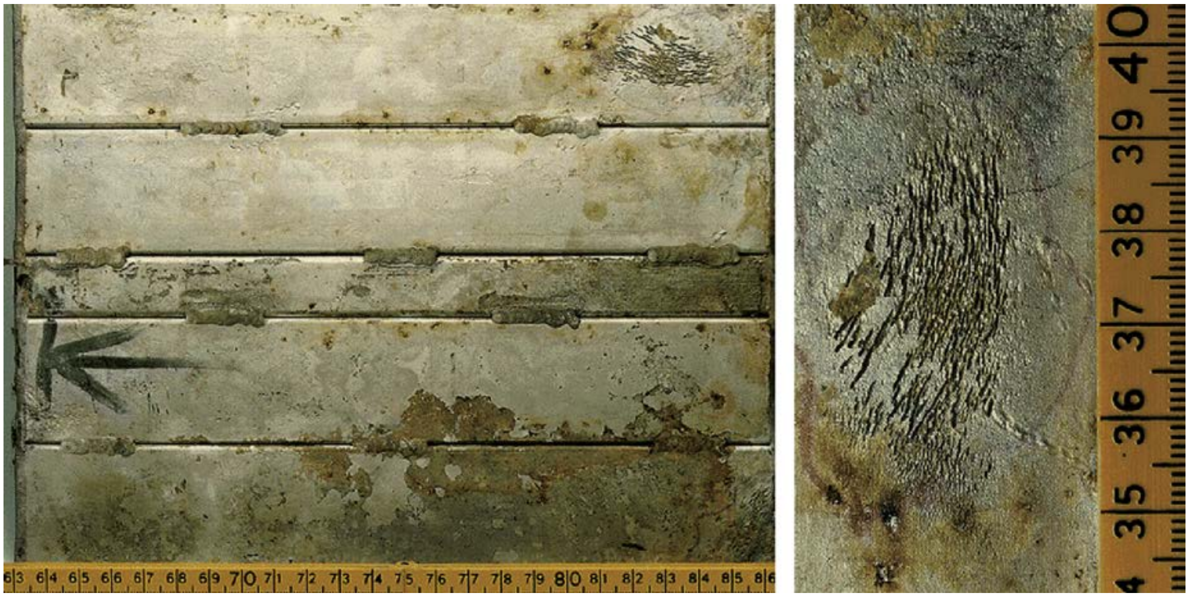
APPEARANCE	Pitting attack.
TIME IN SERVICE	14 months.
ENVIRONMENT	Water with various metal hydroxides and calcium chloride; temperature 70˚C, pH≈3.5.
CAUSE	Stainless steel AISI 316 is not resistant to high chloride concentrations at the present temperature and pH (see also Case History 04.11.12.01).
REMEDY	Replace with a Glass Fiber Reinforced Polypropylene (GFR/PP)-lined steel line.

CORROSION ATLAS

CASE HISTORY

04.11.12.11

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Synthetic fiber spinning mill.
PART	Water-cooled radiant heat shield.
PHENOMENON	Fluoride attack.



APPEARANCE	Pitting attack; attack more severe at the damaged oxide skin.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hydrofluoric acid vapors in a moist environment (relative humidity 75%–80%).
CAUSE	Stainless steel AISI 304 has poor HF resistance. As a result of condensation, the shields were etched by dilute HF.
REMEDY	Shields were constructed of stainless steel AISI 316, which has a serviceable HF resistance at room temperature in concentrations <10%.

CORROSION ATLAS

CASE HISTORY

04.11.13.01

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Reactor.
PART	Flange.
PHENOMENON	Crevice corrosion.

APPEARANCE	Severe uniform attack with clearly visible steel structure.
TIME IN SERVICE	2 years.
ENVIRONMENT	Amine hydrochloride 50%.
CAUSE	The crevice-corrosion resistance of AISI 316 is insufficient (see also Case History 04.06.13.02).
REMEDY	Replaced by duplex stainless steel W.-Nr. 1.4462 (SAF 2205).

CORROSION ATLAS

CASE HISTORY

04.11.14.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Paper mill.
PART	Pulp transport pipeline.
PHENOMENON	Galvanic corrosion. (Pitting due to contamination with carbon steel particles.)

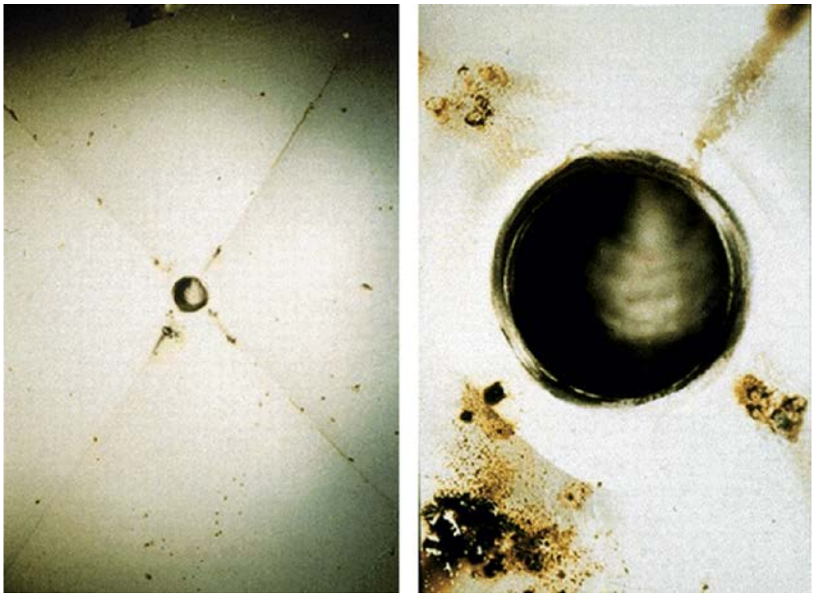
APPEARANCE	Pitting attack with rust particles.
TIME IN SERVICE	3 years.
ENVIRONMENT	Humid atmosphere around the pipe; pulp (water with 3% paper content) at 50°C through the pipe.
CAUSE	When a carbon steel pipeline situated above the stainless steel pipeline was being cut off, cuttings landed on the stainless steel pipe. The carbon steel particles caused pitting by cell formation.
REMEDY	Stainless steel pipelines should be covered when performing such operations.

CORROSION ATLAS

CASE HISTORY

04.11.15.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Lactic acid storage tank.
PART	Base (with drain).
PHENOMENON	Under-deposit corrosion.



APPEARANCE	Pitting attack.
TIME IN SERVICE	The corrosion took place within 3 weeks in a 3-month-old tank.
ENVIRONMENT	During operation: 17% lactic acid.
CAUSE	During the holiday period, the tank, uncleaned and closed, was stored in the open air; after 3 weeks it exhibited severe pitting caused by evaporation of lactic acid (low pH) underneath dirt residues; no problem was noted during normal use and cleaning. The pitting was the result of negligence.
REMEDY	Cleaning after use.

CORROSION ATLAS

CASE HISTORY

04.11.17.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Paper-mill strainer.
PART	Plate.
PHENOMENON	Microbiologically influenced corrosion.

APPEARANCE	Pitting under deposits.
TIME IN SERVICE	Plate had been in service several years, but no damage was noticed 1 year previously (last scheduled outage).
ENVIRONMENT	Water with large amounts of sulfate, fiber, and dissolved minerals; temperature: 49°C; pH ≈ 7–8.
CAUSE	Clumps of fiber and deposit accumulated on surface. Beneath the deposit colonies of sulfate reducers grew, causing severe pitting (see also Case History 01.11.17.01).
REMEDY	Maintenance of biocidal control is mandatory as deposits are endemic.

CORROSION ATLAS

CASE HISTORY

04.11.17.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Chemical process industry (synthetic fiber manufacturing).
PART	Heat-exchanger tube end (OD 5.1 cm).
PHENOMENON	Microbiologically influenced corrosion.

APPEARANCE	Many small hemispherical pits on the tube end.
TIME IN SERVICE	Several years. The exchanger was removed from service several years before being reemployed. It was during the idle period that the pitting occurred.
ENVIRONMENT	Atmosphere.
CAUSE	The heat exchanger was removed from service and stored vertically outside and exposed to the elements for several years. Deposits accumulated at the lower tube ends where sulfate reducers flourished (see also former case).
REMEDY	Effective cleaning before storing and/or (dry) layup procedures.

CORROSION ATLAS

CASE HISTORY

04.11.18.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Product transport system.
PART	Pipeline section.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Pipe burst open, branch fracturing under salt deposition with green patches.
TIME IN SERVICE	Unknown.
ENVIRONMENT	The pipe had become wet externally due to a leaking tap located above the pipe, from which mains water was dripping. Temperature of the medium internally was 50–60°C.
CAUSE	The sharply elevated chloride concentration due to the evaporation effect at the surface of the pipe caused stress corrosion at the present temperature. The green patches consist of trivalent chromium chloride (green iron) and in this case are a characteristic feature of chloride attack to stainless steel.
REMEDY	Prevent warm stainless steel transport pipelines becoming wet externally with chloride-containing water, by providing the pipelines with a proper insulation (see also Case History 04.11.25.01).

CORROSION ATLAS

CASE HISTORY

04.11.18.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Product transport system.
PART	Pipe.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracking at the steam tracing.
TIME IN SERVICE	8 years.
ENVIRONMENT	Chloride-containing product; wall temperature maximum 140°C.
CAUSE	The wall temperature at the steam tracing regularly rose too high, due to standing product. This, in combination with the chloride, led to stress-corrosion cracking.
REMEDY	• Reduce the wall temperature by installing the steam tracing at a distance or replacing it by a self-regulating electric tracing, or • Use duplex steel.

CORROSION ATLAS

CASE HISTORY

04.11.18.03

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Gas piping system.
PART	Inside wall section.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracks in and adjacent to the welds.
TIME IN SERVICE	5 years.
ENVIRONMENT	Chlorine-containing gas; temperature >95°C.
CAUSE	Locally, the pipe temperature had fallen below the dew point of the gas, owing to inadequate insulation. Chloride attack occurred at the most sensible place, in the weld and the HAZ.
REMEDY	Application of appropriate insulation so that the wall temperature remains above the dew point of the gas.

CORROSION ATLAS

CASE HISTORY

04.11.18.04

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Hydrochloric acid transport pipe.
PART	Metal strengthener around plastic bellows.
PHENOMENON	Stress-corrosion cracking (transgranular).

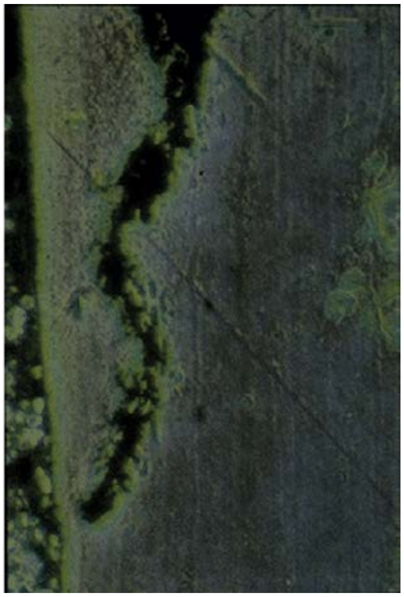
APPEARANCE	Pitting attack with cracks.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Leaked hydrochloric acid with water vapor (atmosphere).
CAUSE	Error in choice of material: instead of a Monel strengthener, a stainless steel strengthener was used. From the product side, hydrochloric acid gas diffused through the plastic (PTFE). Together with atmospheric moisture, this gas formed concentrated hydrochloric acid, which attacked the stainless steel.
REMEDY	• Replacement by a Monel strengthener. • Improved checks on the material selection.

CORROSION ATLAS

CASE HISTORY

04.11.18.05

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Textile steamer.
PART	Guide bar in textile conveyor system.
PHENOMENON	Stress-corrosion cracking (transgranular).



APPEARANCE	Transverse cracking.
TIME IN SERVICE	About 3 years.
ENVIRONMENT	Steam at 100°C, saturated by injection with softened water (at a later stage, with condensate).
CAUSE	Stress corrosion took place as a result of the simultaneous presence of: • tensile stresses in the bar, • high chloride content in the dyes in the textile, • high temperature.
REMEDY	Use of chloride-free dyes and injection with chloride-free condensate if the present 304 stainless steel construction is retained. Otherwise, construction of duplex steel (ferritic–austenitic stainless steel) if a chloride-free environment cannot be guaranteed.

CORROSION ATLAS

CASE HISTORY

04.11.18.06

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Ketchup plant.
PART	Product pipelines.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Cracking with some pitting.
TIME IN SERVICE	1 year.
ENVIRONMENT	Ketchup (pH 3.5–3.8; 3.7%–3.8% NaCl); temperature 45–90°C (see also Case History 04.11.12.01).
CAUSE	Stress corrosion and pitting caused by the combination of the high salt concentration, the low pH, and the high temperature of the product (see also Case History 04.11.18.11).
REMEDY	Construction of the ketchup pipes from duplex stainless steel (e.g., W.-Nr. 1.4462) that is more resistant to stress-corrosion cracking.

CORROSION ATLAS

CASE HISTORY

04.11.18.07

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Ureum stripper.
PART	Gas pipe.
PHENOMENON	Stress-corrosion cracking (transgranular).

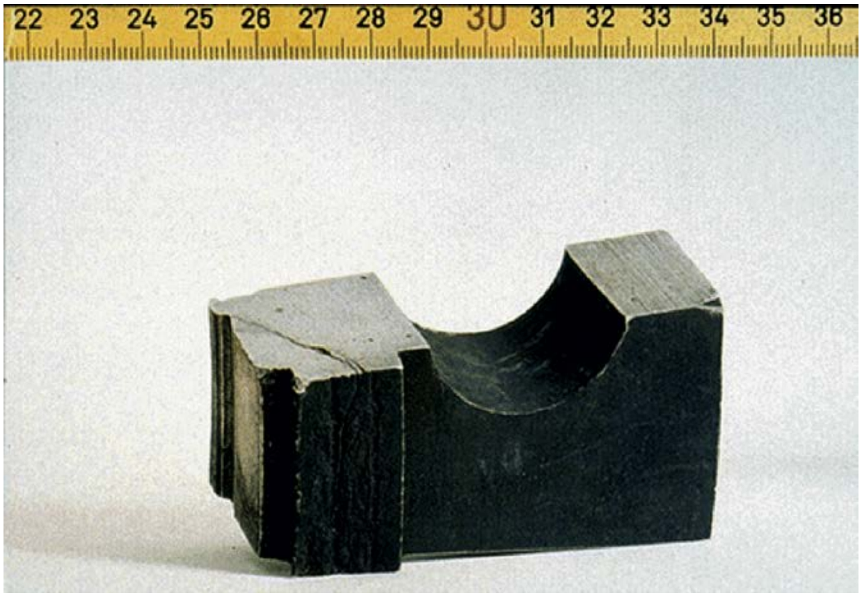
APPEARANCE	Cracking.
TIME IN SERVICE	2 years.
ENVIRONMENT	Internal: Urea synthesis solution (carbamate); temperature 80°C. External: Atmosphere.
CAUSE	The stainless steel pipe was marked with a chloride-containing marker (the number 357 or 857 is visible) (see also Case History 04.22.18.01).
REMEDY	Use of chloride-free markers when marking stainless steel.

CORROSION ATLAS

CASE HISTORY

04.11.18.08

MATERIAL	Stainless steel (AISI 321).
SYSTEM	Ammonium nitrate reactor.
PART	Flange.
PHENOMENON	Stress-corrosion cracking (transgranular).



APPEARANCE	Cracking.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Ammonium nitrate melt at 140°C in the pipe; flange provided with braided Teflon seal.
CAUSE	In combination with stresses present in the stainless steel flange, chlorides present in the seal cause stress corrosion at the present temperature.
REMEDY	Use of chloride-free seal material.

CORROSION ATLAS

CASE HISTORY

04.11.18.09

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Margarine plant.
PART	Separator tray for purifying the fat phase.
PHENOMENON	Stress-corrosion cracking (transgranular).
	
APPEARANCE	Cracks in the radius of the discharge channels.
TIME IN SERVICE	2 years.
ENVIRONMENT	Fat phase with 16,000 ppm Cl. Temperature 85°C.
CAUSE	The build-up of local stresses during rotation of the trays caused stress corrosion in the present medium.
REMEDY	• Modify the structure by replacing the channels with round holes. • Alternative: use less stress-sensitive stainless steel, e.g., duplex steel (W.-Nr. 1.4462)

CORROSION ATLAS

CASE HISTORY

04.11.18.10

MATERIAL	Stainless steel 316 L cladding on carbon steel.
SYSTEM	Cyclohexane oxidation reactor of a caprolactam plant.
PART	Wall section.
PHENOMENON	Intergranular stress corrosion (nitrate stress-corrosion cracking).

APPEARANCE	Cracking.
TIME IN SERVICE	6 weeks after sprinkling the reactor with cooling water.
ENVIRONMENT	Salt deposition underneath the insulation with 8000 ppm of nitrate. Reactor temperature 150°C, pressure 25 bar.
CAUSE	In order to reduce the explosion risk due to a gas leakage, this reactor was sprinkled with (nitrate-containing) cooling water which penetrated into the insulation and caused salt deposition. The high nitrate content caused intergranular stress-corrosion cracks in the stainless steel cladding and in the carbon steel as well (see also Case History 01.11.18.02).
REMEDY	Do not use nitrate-containing water in such a situation.

CORROSION ATLAS

CASE HISTORY

04.11.18.11

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Calcium chloride dosing line.
PART	Injection section.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	A perforating crack.
TIME IN SERVICE	1 week.
ENVIRONMENT	A solution of 30% calcium chloride in water. Temperature 15–20°C.
CAUSE	The high chloride content in combination with the temperature caused stress corrosion cracking (see also Case History 04.11.18.06).
REMEDY	The injection section is constructed of Polytetrafluoroethylene (PTFE).

CORROSION ATLAS

CASE HISTORY

04.11.18.12

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Crystal drier.
PART	Paddle.
PHENOMENON	Stress-corrosion cracking (transgranular).

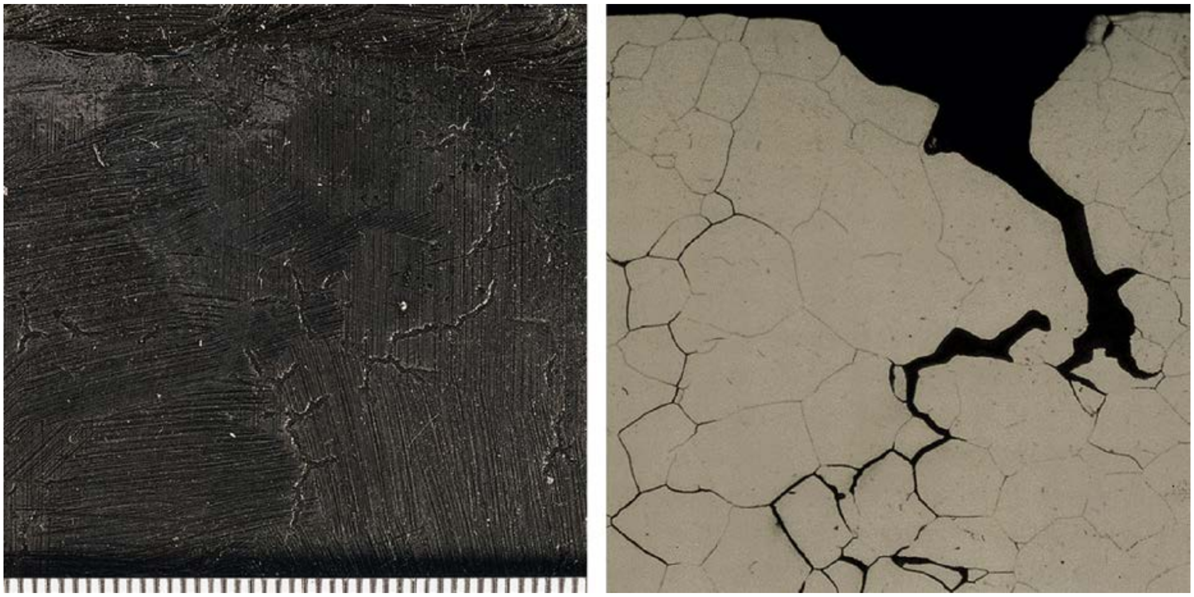
APPEARANCE	Transverse cracking over the paddle.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Chloride-containing crystals with hot air (injected for drying purposes).
CAUSE	Stress-corrosion cracking was able to occur due to the presence of moisture formed by condensation. The other conditions for stress corrosion cracking in stainless steel had been met, namely: presence of chloride, temperature > 60°C, and the presence of stresses in the material.
REMEDY	Prevent condensation by supplementary heating and use of predried air. If this is ineffective, construct paddles of stainless steel W.-Nr. 1.4539.

CORROSION ATLAS

CASE HISTORY

04.11.18.13

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Hydrodesulfurization unit.
PART	Rolled bond cladding of reactor.
PHENOMENON	Polythionic acid stress-corrosion cracking.



APPEARANCE	Intergranular cracking.
TIME IN SERVICE	The corrosion took place during shutdown.
ENVIRONMENT	During operation sulfides are formed in the reducing H_2/H_2S environment. Upon shutdown, these sulfides are transformed into polythionic acids with ingress of both oxygen and water.
CAUSE	Production of polythionic acid in combination with sensitization of the rolled bond clad layer (see also Case History 04.11.18.15).
REMEDY	Neutralization by washing with a soda ash solution in accordance with NACE-RP-01-70.

CORROSION ATLAS

CASE HISTORY

04.11.18.14

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Brew-water tank.
PART	Tank discharge line.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Small cracks in the tank wall.
TIME IN SERVICE	2 years.
ENVIRONMENT	Brew-water, pH 5.8; chloride approximately 120 ppm.
CAUSE	• This medium is too aggressive for SS 304 L. • Stresses in the SS caused by welding and processing.
REMEDY	• The problem was solved by raising the pH to approximately 7 and lowering the chloride content to almost 0. • Alternative: use duplex stainless steel.

CORROSION ATLAS

CASE HISTORY
04.11.18.15

MATERIAL	Stainless steel (AISI 304 H).
SYSTEM	Cracking furnace.
PART	Nozzle on inlet header of a radiant coil outside furnace.
PHENOMENON	Polythionic acid stress-corrosion cracking.

APPEARANCE	Irregular intergranular cracking, causing a rough surface.
TIME IN SERVICE	80,000 h.
ENVIRONMENT	Polythionic acid formed by sulfides, water, and oxygen during idle periods.
CAUSE	Condensation of water in the inlet header, in which the polythionic acid dissolves. For this polythionic acid stress corrosion, the stainless steel must be sensitized due to chromium carbide precipitation at the grain boundaries (see Case Histories 04.01.19.01 and 04.11.18.13) and tensile stresses must be present. The rough surface is caused by loss of the metal grains.
REMEDY	Use of stainless steel AISI 321 H, which is not susceptible to sensitization.

CORROSION ATLAS

CASE HISTORY

04.11.18.16

MATERIAL	Stainless steel (AISI 316).
SYSTEM	PVC plant.
PART	Process pipeline.
PHENOMENON	Stress-corrosion cracking (transgranular) under insulation.

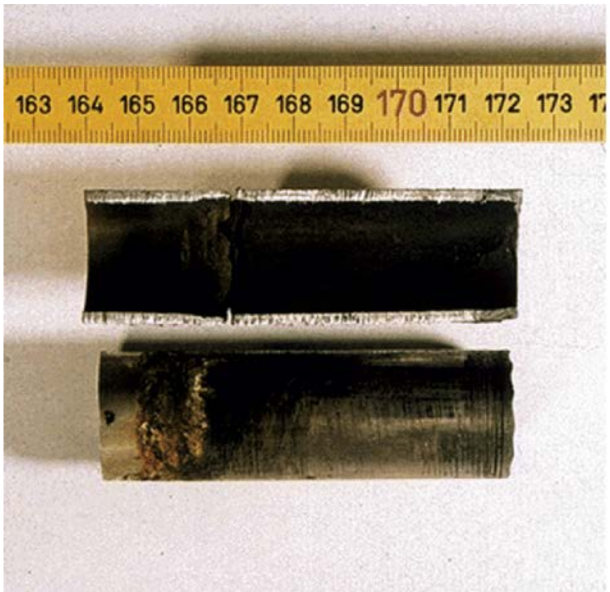
APPEARANCE	Finely branched cracking pattern.
TIME IN SERVICE	A few months.
ENVIRONMENT	Penetrated wash water with a chloride content of 60 ppm; temperature of process stream 50–9°C.
CAUSE	The insulated pipeline is regularly wetted by the penetrated wash water. The water reaches the pipe via imperfections in the insulation, leading to evaporation. The combination of stresses, chloride, and temperature then gives rise to stress corrosion (see also 04.01.18.04).
REMEDY	• Render the insulation impermeable to water (e.g., tamp crevices with compound). • Wrap pipe in aluminum foil before applying the insulation.

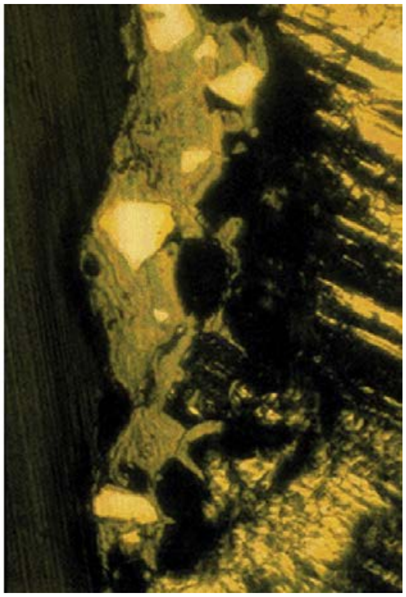
CORROSION ATLAS

CASE HISTORY

04.11.19.01

MATERIAL	Stainless steel (2RE51).
SYSTEM	Nitric acid condenser.
PART	Condenser tubes.
PHENOMENON	Intergranular corrosion internally, crevice corrosion externally.





APPEARANCE	Grooved attack internally, pitting attack externally.
TIME IN SERVICE	6 months.
ENVIRONMENT	Internally: HNO_3 vapor supersaturated with NO_x, 220°C, 8 bar; externally: cooling water with 400 ppm Cl^-, temperature 70°C, 6 bar.
CAUSE	This material is susceptible to intergranular corrosion under the present circumstances, and to crevice corrosion of the tubes in the tube plate [the latter was manufactured of 3RE60 (W.-Nr. 1.4417) and displayed stress corrosion]; moreover the weld contained inclusions, as can be seen on the microphoto. In addition, pipes made of 304, 410, W.-Nr. 1.4465, and 316 L stainless steel had a short service life.
REMEDY	Use of titanium longitudinal seam welded tubes and Inconel 600 tube plate provided with titanium cladding.

CORROSION ATLAS

CASE HISTORY

04.11.19.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Nitric acid plant
PART	Vessel wall section (on both sides).
PHENOMENON	Intergranular corrosion (weld decay).

APPEARANCE	Local attack at a short distance from the weld.
TIME IN SERVICE	Unknown.
ENVIRONMENT	54% nitric acid; temperature approximately 80°C.
CAUSE	Inappropriate material selection: in the present grade of stainless steel, chromium carbide precipitation occurs in the heat-affected zone (600–850°C) beside the weld, as a result of which the material becomes sensitive to corrosion owing to chromium depletion at the grain boundaries (see also Case History 04.01.19.01).
REMEDY	Application of stainless steel with a lower carbon content (AISI 304 L: C, 0.03%) or of stainless steel stabilized with Nb (AISI 347) or Ti (AISI 321).

CORROSION ATLAS

CASE HISTORY

04.11.19.03

MATERIAL	Stainless steel (Uranus B6; W.-Nr. 1.4539).
SYSTEM	Contaminated sulfuric acid transport pipeline.
PART	Plate in a butterfly valve.
PHENOMENON	Intergranular corrosion.

APPEARANCE	Severe uniform attack with a network of cracks on both sides of the plate.
TIME IN SERVICE	15 months.
ENVIRONMENT	A solution of 7% H_2SO_4, 4% $ZnSO_4$, 1% $MgSO_4$, and 0.5% $MnSo_4$, temperature 30°C; pressure 2.8 bar; velocity 1.6 m/s.
CAUSE	The used alloy is not resistant to this solution (see also Case History 05.11.19.01).
REMEDY	Construction of the valve from Incoloy 825 (W.-Nr. 2.4858).

CORROSION ATLAS

CASE HISTORY

04.11.19.04

MATERIAL	Stainless steel (AISI 321 above the weld and AISI 316 underneath the weld).
SYSTEM	Mixing reactor in a metal plant.
PART	Wall with weld.
PHENOMENON	Two forms of intergranular corrosion near the weld: knife-line attack and weld decay.

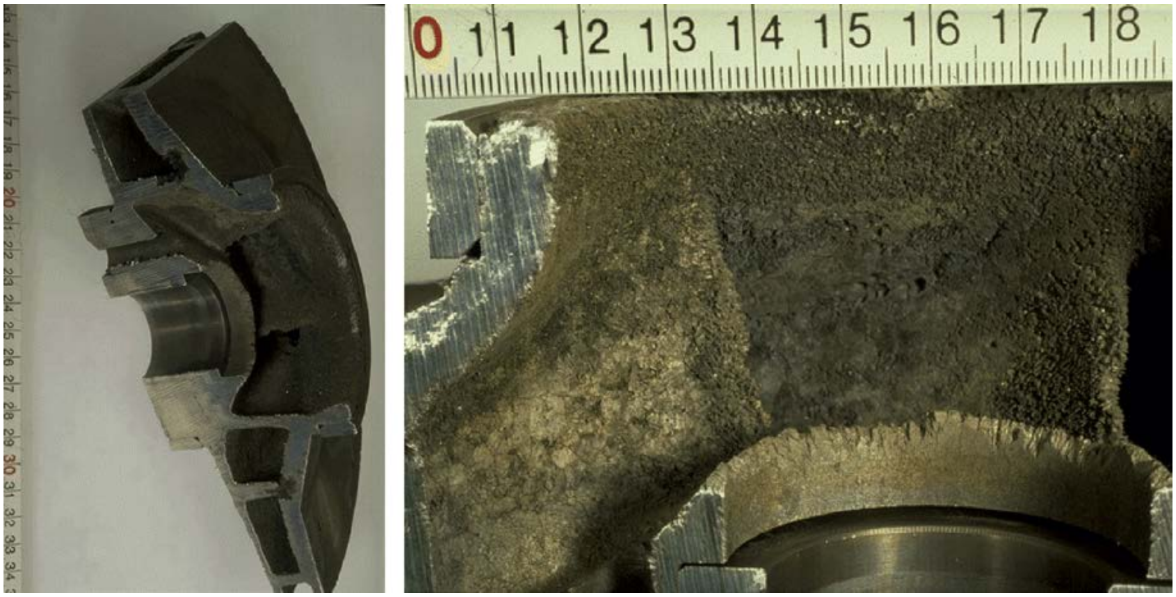
APPEARANCE	Selective attack: Above, right along the weld: knife-line attack; below, at some distance from the weld: weld decay; below, also uniform attack.
TIME IN SERVICE	About 2 years.
ENVIRONMENT	A mixture of nitric acid and other oxidizing mineral acids. Temperature 110–115°C. Elevated oxygen pressure.
CAUSE	Weld decay: see Case Histories 0401.19.01 and 04.11.19.02. When stainless steel stabilized with niobium or titanium is welded, in the zone immediately around the weld, all the carbides enter into solution (temperature >1225°C) and remain so during rapid cooling. When the weld is heated in the critical temperature area (e.g., in stress-relief annealing or multilayered welding), precipitation of chromium carbide occurs. Consequently, this zone becomes sensitive to intergranular corrosion (see also Case History 04.18.12.01).
REMEDY	Prevent knife-line attack to stabilized stainless steel by: • Post-weld heat treatment to 1065°C, so that the chromium carbide dissolves and titanium carbide forms. Thereafter, the cooling rate is no longer an important factor. • Alternative: select different material. Prevention of weld decay: see Case Histories 04.01.19.01 and 04.11.19.02.

CORROSION ATLAS

CASE HISTORY

04.11.19.05

MATERIAL	Stainless steel (AISI 316 cast; ACI-12M).
SYSTEM	Pump.
PART	Impeller.
PHENOMENON	Intergranular corrosion.



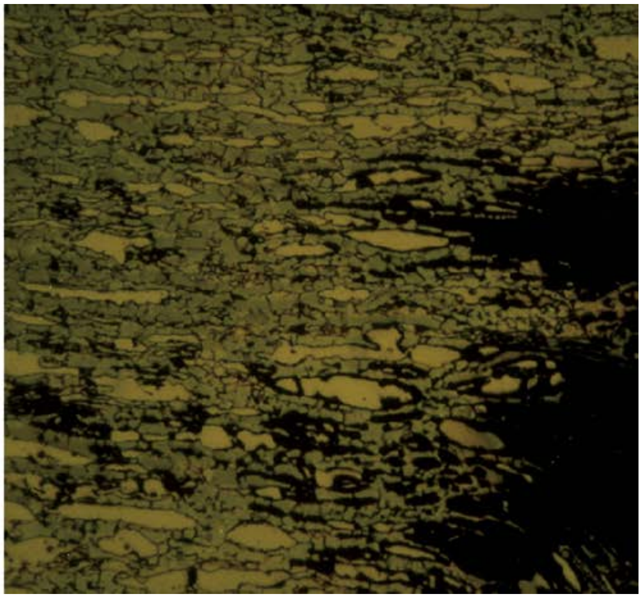
APPEARANCE	Partly a granular surface with loose grains, and partly a network of cracks.
TIME IN SERVICE	5 years.
ENVIRONMENT	57% nitric acid. Temperature 30–60°C.
CAUSE	The present type of stainless steel contains molybdenum and is relatively high in carbon content. The presence of both elements accelerates intergranular corrosion of stainless steel in concentrated nitric acid (see also Case History 04.11.19.10).
REMEDY	In this specific environment, use stainless steel of type ACI CF-3 (AINSI 304 L cast), which is low in carbon and molybdenum content.

CORROSION ATLAS

CASE HISTORY

04.11.19.06

MATERIAL	Duplex stainless steel (X2 CrNiMoN 25 6).
SYSTEM	Partial condenser for ammonium carbamate (see also Case History 09.11.20.01).
PART	Hold-down plate.
PHENOMENON	Intergranular corrosion and selective austenitic attack.



APPEARANCE	Nothing is visible to visual inspection, but microscopic examination discloses both selective attack to the austenitic phase and intergranular corrosion along the ferrite–austenite grain boundaries.
TIME IN SERVICE	3 years.
ENVIRONMENT	Condensing oxygen-free ammonium carbamate. temperature 125°C; pressure 6 bar.
CAUSE	Poor quality duplex steel: a high content of austenite (60%–70%), a microstructure consisting of an austenite matrix with ferrite islands instead of a ferrite matrix with austenite. Under these conditions, repassivation of the austenite does not occur. As a result, a brittle fracture occurs (see also Case History 04.11.19.11).
REMEDY	Switch to a better quality duplex steel with a good austenite–ferrite balance.

CORROSION ATLAS

CASE HISTORY

04.11.19.07

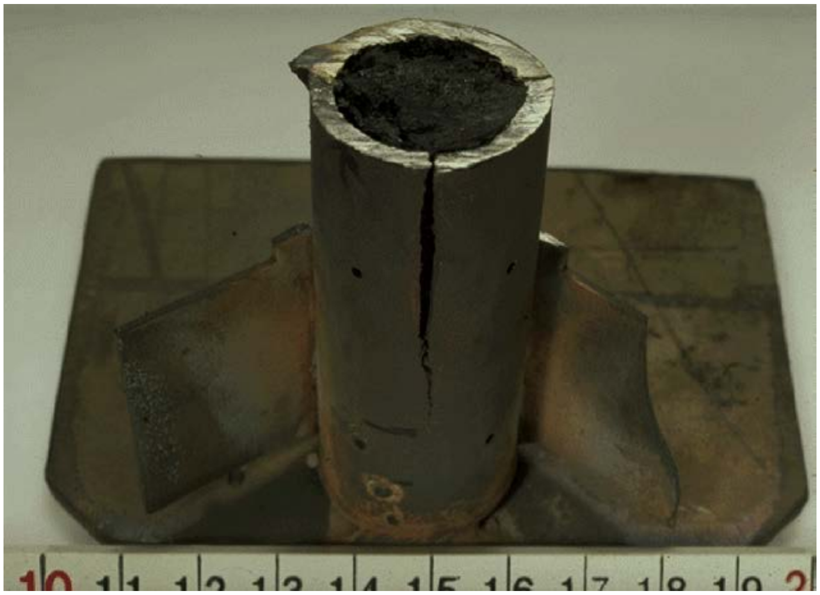
MATERIAL	Stainless steel (pipe: AISI 308, flange: AISI 304).
SYSTEM	Conveyor pipe system in pharmaceutical plant.
PART	Pipe with flange (joint welded by GTAW, Gas Tungsten Arc Welding process).
PHENOMENON	Intergranular corrosion (weld decay) with pitting.

APPEARANCE	Corrosion damage of fusion zone (HAZ, Heat affected Zone).
TIME IN SERVICE	2–3 years.
ENVIRONMENT	Solution with salt and acid; no further information available.
CAUSE	In the HAZ (600–850°C), chromium carbide precipitation occurs beside the weld, as a result of which the material becomes sensitive to corrosion owing to chromium depletion at the grain boundaries (see also Case History 04.08.19.01). With reference to the environment, chloride pitting has also taken place.
REMEDY	• For the present grade of stainless steel, application of PWHT (postweld heat treatment) to 1020–1150°C to dissolve the carbides, followed by rapid quenching. • Application of stainless steel with a low carbon content or stainless steel stabilized with Nb or Ti. With reference to the environment, stainless steel–containing molybdenum is recommended (AISI 316 Cb or 316 Ti).

CORROSION ATLAS

CASE HISTORY
04.11.19.08

MATERIAL	Stainless steel (AISI 310).
SYSTEM	Cracking furnace.
PART	Burner front of a low NOx burner.
PHENOMENON	Intergranular corrosion (sigma phase embrittlement).



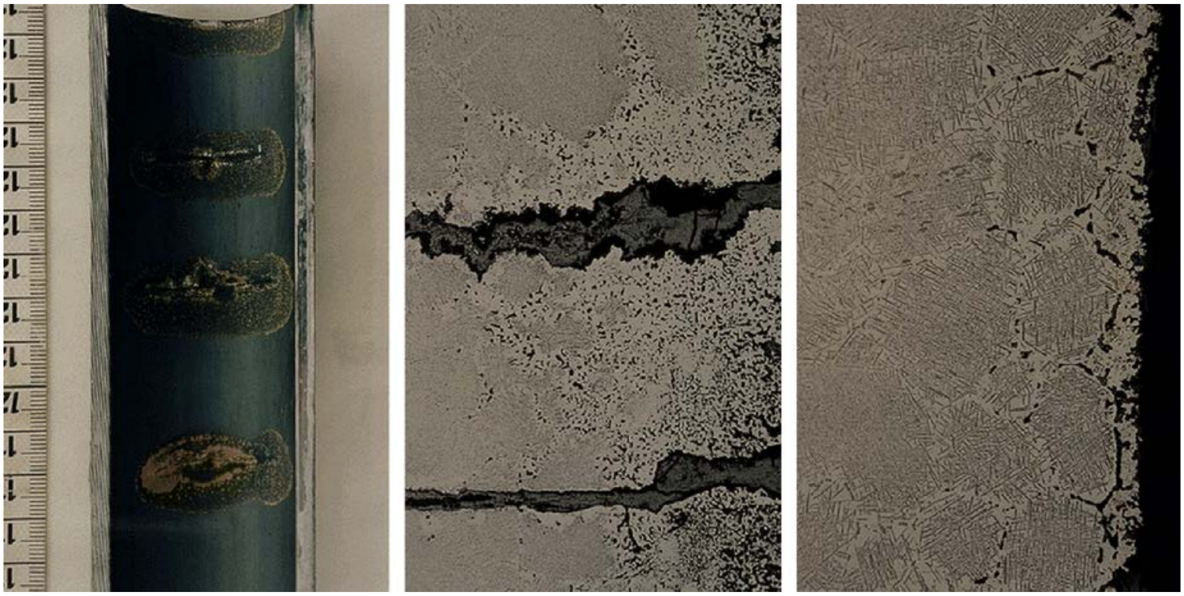
APPEARANCE	Longitudinal crack with plugging due to internal coking.
TIME IN SERVICE	1 year.
ENVIRONMENT	High-temperature gas atmosphere.
CAUSE	Coke formation caused plugging of the gas injection points, causing temperature rises into the sigma-phase formation range (500–900°C). The consequently embrittled metal cracked intergranularly due to stresses (see also Case Histories 04.11.19.09 and 04.12.19.01).
REMEDY	• Use of a material not susceptible to sigma-phase formation. In this case, Incoloy 800H was selected. • Enlarge the injection openings so that plugging tendency is reduced.

CORROSION ATLAS

CASE HISTORY

04.11.19.09

MATERIAL	Stainless steel (AISI 310, W.-Nr. 1.4841).
SYSTEM	Reactor air preheater.
PART	Shock tube.
PHENOMENON	Intergranular corrosion (sigma-phase embrittlement).



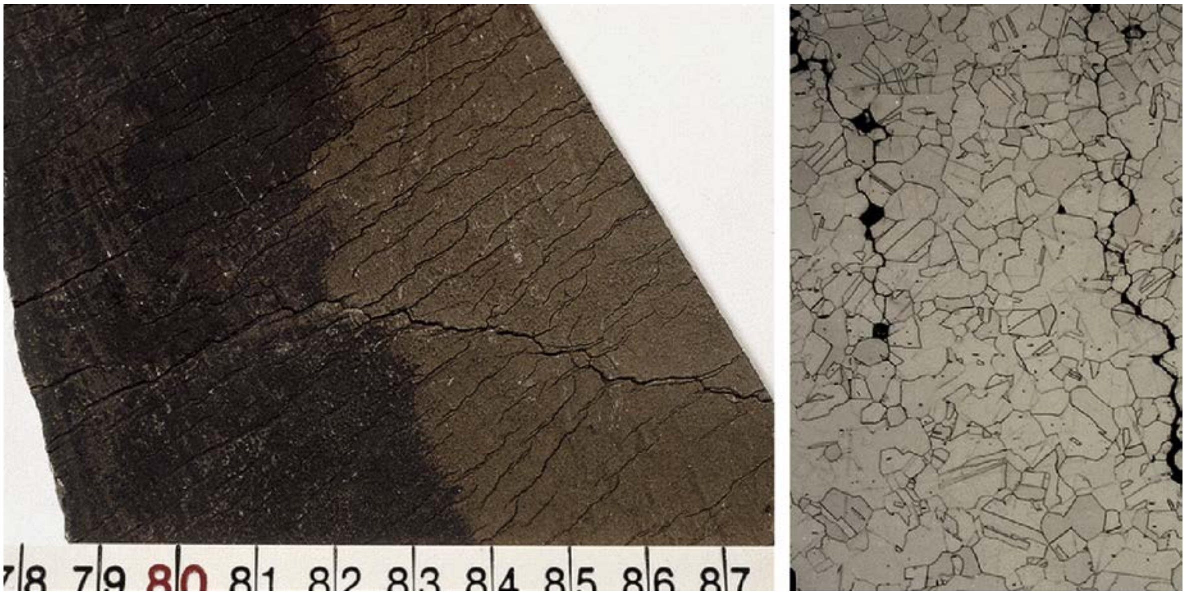
APPEARANCE	Brittle fracture.
TIME IN SERVICE	1 year.
ENVIRONMENT	Air is heated by flue gas from 325 to 690°C max. The air flows inside the tubes. The inlet temperature of the flue gas is 807°C maximum. The design temperature of the shock tubes is 570°C.
CAUSE	The temperature exceeded the design temperature by about 100°C for the entire operating period or at any rate for much of it. At this temperature, materials of the AISI 310 type are sensitive to embrittlement by the formation of sigma phase. In this condition, thermal stresses will provoke the formation of cracks (see also Case History 04.12.19.01).
REMEDY	Replacement of W.-Nr. 1.4841 by Rolled Alloy 330/333, which is not sensitive to the formation of sigma phase in the temperature range concerned.

CORROSION ATLAS

CASE HISTORY

04.11.19.10

MATERIAL	Stainless steel (W.-Nr. 1.4466).
SYSTEM	Neutralization section.
PART	Mist separator wall section.
PHENOMENON	Intergranular corrosion.



APPEARANCE	Intergranular cracking.
TIME IN SERVICE	4 years.
ENVIRONMENT	Off-gas, contaminated with mist and HNO_3; temperature 120°C; pressure: atmospheric.
CAUSE	Transpassive corrosion of Mo bearing alloy in strong oxidizing environment (see also Case Histories 04.11.19.01/05).
REMEDY	Mo-free duplex stainless steels like W.-Nr. 1.4362 give better performance.

CORROSION ATLAS

CASE HISTORY

04.11.19.11

MATERIAL	Stainless steel (AISI 316 L).
SYSTEM	Ammonia stripper in urea plant.
PART	Dip pipe.
PHENOMENON	Intergranular corrosion.

APPEARANCE	Except for the welds, the material is completely corroded away.
TIME IN SERVICE	>10 years.
ENVIRONMENT	Water with traces of ammonium carbamate.
CAUSE	Intergranular corrosion of 316L in carbamate solutions. Weld metal is more corrosion-resistant due to higher percentage of alloying components (see also Case History 04.11.19.06).
REMEDY	Alternative material of construction like duplex stainless steel W.-Nr. 1.4462 (UNS No. S31803).

CORROSION ATLAS

CASE HISTORY

04.11.20.01

MATERIAL	Stainless steel (martensitic).
SYSTEM	Mine water pump.
PART	Suction and discharge valve guides.
PHENOMENON	Hydrogen damage (hydrogen embrittlement).
	
APPEARANCE	Crumbling.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Acid and corrosive mine water.
CAUSE	Corrosion caused hydrogen development which embrittled the martensitic stainless steel (other parts of the pump were made of duplex stainless steel) (see also Case History 01.11.20.05).
REMEDY	Use a more ductile material with sufficient wear resistance (e.g., austenitic stainless steel).

CORROSION ATLAS

CASE HISTORY

04.11.26.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Electrolysis unit in zinc plant.
PART	Impeller cap in electrolyte pump.
PHENOMENON	Stray-current corrosion.

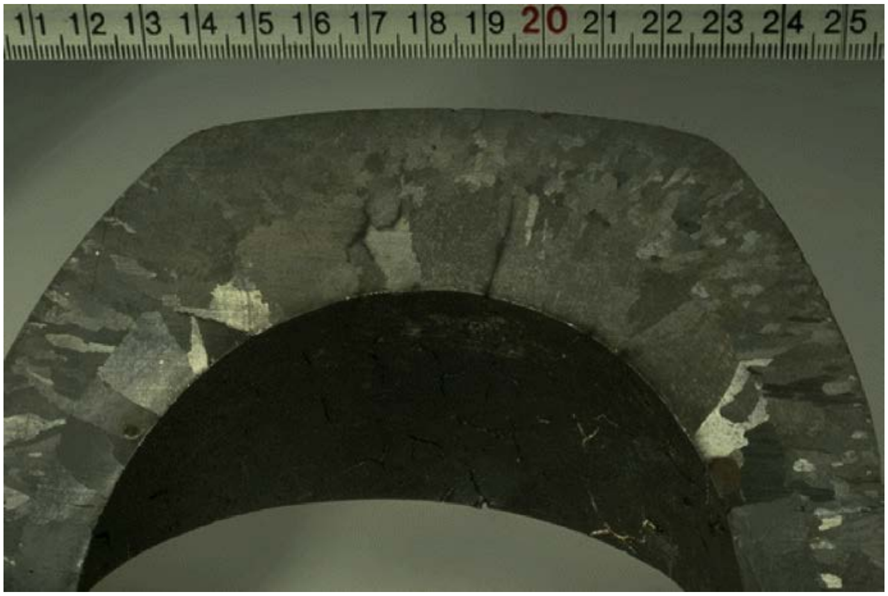
APPEARANCE	Severe pitting attack over the entire surface.
TIME IN SERVICE	3–4 months.
ENVIRONMENT	18% sulfuric acid.
CAUSE	In the present process, the liquids carry an electric voltage. To prevent leakage currents, the entire unit has to be installed free of earth. In this case, the pump concerned was insufficiently isolated from the foundation. Outgoing stray currents caused severe corrosion, concentrated on this cap in particular.
REMEDY	Ensure proper isolation (plastic) between the pump and the foundation.

CORROSION ATLAS

CASE HISTORY

04.11.28.01

MATERIAL	Stainless steel (AISI 310, cast).
SYSTEM	Furnace.
PART	Pipe bend.
PHENOMENON	Thermomechanical fatigue (intergranular).



APPEARANCE	Cracks.
TIME IN SERVICE	About 5 years.
ENVIRONMENT	Naphtha. Temperature 800–1050°C.
CAUSE	Thermomechanical fatigue due to fluctuating temperature.
REMEDY	Improvement of the casting quality and modification of the process conditions in order to prevent extreme temperature fluctuations.

CORROSION ATLAS

CASE HISTORY

04.11.28.02

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Mixing device.
PART	Mixer blade.
PHENOMENON	Corrosion fatigue.

APPEARANCE	One blade is ripped off. The remaining part contains several small cracks.
TIME IN SERVICE	Three years (8800 h' operation).
ENVIRONMENT	Liquid at 80–95°C, pH 7.7–8.1, 1400 ppm Cl^-.
CAUSE	Cracks were initiated by chloride-induced stress-corrosion cracking (SCC) in the most highly stressed area. These cracks grew by (corrosion) fatigue, which finally resulted in rupture of one of the blades (broken blade severely damaged the pump) (see also Case Histories 01.01.28.01, 01.21.28.01 and 04.11.28.03).
REMEDY	Use a more suitable material and/or apply additional protection.

CORROSION ATLAS

CASE HISTORY

04.11.28.03

MATERIAL	Stainless steel (AISI 316L).
SYSTEM	Mixing device.
PART	Shaft.
PHENOMENON	Fatigue or corrosion fatigue.

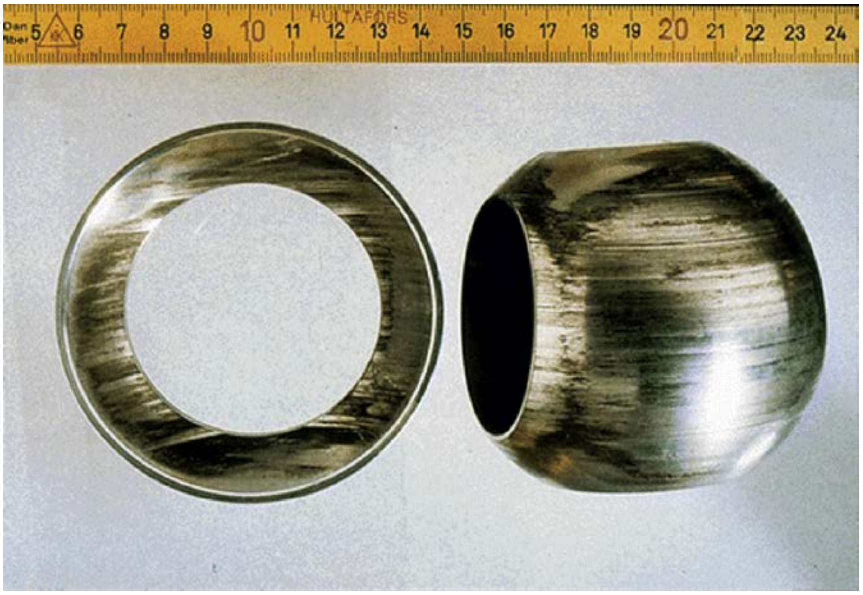
APPEARANCE	Crack growth lines which started at a drilled hole and small ductile fracture.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Uncertain (possibly chloride containing).
CAUSE	The slightly damaged (bent) shaft had to be straightened (no additional stress-relieving) (see also Case Histories 01.01.28.01, 01.21.28.01, and 04.11.28.02).
REMEDY	Avoid sharp stress raisers (such as drilled holes), especially at highly stressed areas. Note: The allowable fatigue strain in a corrosive environment is much lower than the known values which are usually obtained in a noncorrosive environment.

CORROSION ATLAS

CASE HISTORY

04.11.32.01

MATERIAL	Stainless steel (AISI 316), the seat is stellited.
SYSTEM	Platformer.
PART	Ball valve.
PHENOMENON	Erosion.



APPEARANCE	Ball and seat show grooves.
TIME IN SERVICE	A few months.
ENVIRONMENT	Catalyst on ceramic carrier.
CAUSE	The ceramic carrier is too hard in relation to the ball and seat, so that catalyst particles became embedded in the relatively soft material (see also the following Case Histories).
REMEDY	Use a harder material.

CORROSION ATLAS

CASE HISTORY

04.11.32.02

MATERIAL	Stainless steel (AISI 410).
SYSTEM	Catalytic cracking plant.
PART	Rod of a 42″ valve in the stripper stand pipe.
PHENOMENON	Erosion.

APPEARANCE	Material partly worn away, rod has become razor-sharp locally.
TIME IN SERVICE	3 years.
ENVIRONMENT	Steam with ceramic-based catalyst (see also Case History 04.11.32.01). Temperature 480°C.
CAUSE	Erosion followed by leakage past a gland, caused by the catalyst passing at high velocity. Steam is injected as floating medium in order to prevent valve-clogging coke formation.
REMEDY	Regular inspection in order to prevent leakage and replacement of the rod at set intervals (a different, harder, material failed to improve matters).

CORROSION ATLAS

CASE HISTORY

04.11.32.03

MATERIAL	Duplex stainless steel (3 RE 60).
SYSTEM	Natural gas well.
PART	Slotted liner (wall thickness 15 mm).
PHENOMENON	Erosion.

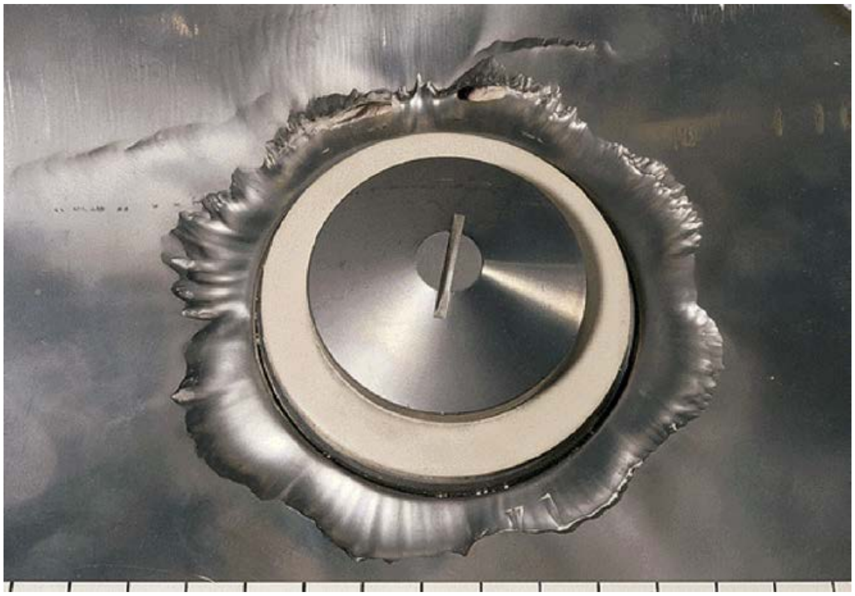
APPEARANCE	Material completely worn away near the slots.
TIME IN SERVICE	2 years.
ENVIRONMENT	Natural gas containing solids (sand, clay, etc.) originating from the formation.
CAUSE	High production velocities caused solids entrainment, resulting in erosion near the narrow slots.
REMEDY	Well repair to prevent solids entrainment.

CORROSION ATLAS

CASE HISTORY

04.11.32.04

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Kieselguhr (diatomaceous earth) tank in brewery.
PART	Air inlet valve in tank bottom.
PHENOMENON	Erosion.



APPEARANCE	Uniform eroded surface all around the valve.
TIME IN SERVICE	2 months.
ENVIRONMENT	Atomized kieselguhr in air.
CAUSE	Kieselguhr whirling in the air causes erosion around the inlet valve (see also Case Histories 04.01.32.01, 04.11.32.01/02/03).
REMEDY	Coat the tank with Teflon.

CORROSION ATLAS

CASE HISTORY

04.11.33.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Vacuum evaporation system for milk powder manufacture.
PART	Pump impeller.
PHENOMENON	Cavitation erosion.

APPEARANCE	Material worn away locally.
TIME IN SERVICE	1 year.
ENVIRONMENT	Skimmed milk; Temperature 70°C.
CAUSE	Steam bubble formation at the prevailing vacuum and high temperature; pressure build-up causes the bubbles to implode at the exit side of impeller (at a lower pump capacity for the processing of full-cream milk, no problems had been encountered; the lower capacity was set by throttling the delivery valve setting in action on an overfall valve in the short-circuit line from pressure side to suction side) (see also Case History 01.02.33.03).
REMEDY	After coating the impeller with a plastic lining proved incapable of preventing cavitation, the impeller was replaced by one made of Teflon PFA (perfluoroalkoxy).

CORROSION ATLAS

CASE HISTORY

04.11.34.01

MATERIAL	Stainless steel AISI 321.
SYSTEM	Product deaerator.
PART	Adapter (4″ → 2″).
PHENOMENON	Erosion corrosion.

APPEARANCE	Attack with pronounced flow pattern and severe attack to the weld.
TIME IN SERVICE	3 years.
ENVIRONMENT	Mixture of isocyanate and chlorbenzene, with traces of hydrochloric acid, no moisture! Temperature 170°C.
CAUSE	Corrosion due to the above-mentioned mixture combined with erosion due to the asymmetrical shape of the adapter, which creates additional turbulence.
REMEDY	Construct the adapter symmetrically of AISI 316 and install it vertically instead of horizontally.

CORROSION ATLAS

CASE HISTORY

04.11.34.02

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Acid pump.
PART	Impeller.
PHENOMENON	Erosion corrosion.

APPEARANCE	Impeller material partly eroded.
TIME IN SERVICE	3 months.
ENVIRONMENT	Nitric acid nitrate slurry with 40–50% nitric acid. Temperature 60–70°C.
CAUSE	Although stainless steel AISI 304 possesses outstanding resistance to nitric acid of the reported concentration and temperature, the presence of artificial fertilizer slurry coupled with the flow rate results in such erosion that the oxide skin formed is continuously removed (see also Case Histories 04.11.34.03/04).
REMEDY	Impeller made of Corrodur 30 (G-X 70 CrMo 29 2, W.-Nr. 1.4136), extending the lifetime to several years. Alternative (according to the literature): make impeller from Stellite No. 4.

CORROSION ATLAS

CASE HISTORY

04.11.34.03

MATERIAL	Stainless steel (AISI 317).
SYSTEM	Conveyor pump for Jarosite slurry.
PART	Impeller.
PHENOMENON	Erosion corrosion.

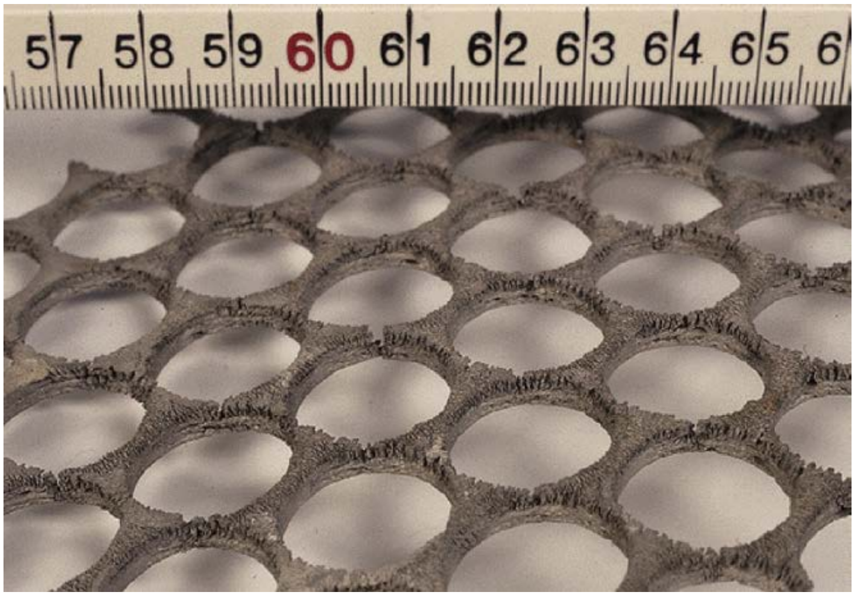
APPEARANCE	Impeller uniformly worn down from original 10 mm thickness to <1 mm.
TIME IN SERVICE	4 months.
ENVIRONMENT	Jarosite slurry consisting of contaminated sulfuric acid 7% (see Case History 04.11.18.01) with 400 g solids per liter, consisting of zinc, magnesium sulfate, and iron sulfate. Temperature 30°C.
CAUSE	Stainless steel AISI 317 is attacked by this slurry: the solid particles erode the impeller. Ni-based alloys, various polymers, and ceramic materials also failed to withstand this highly abrasive and acid medium.
REMEDY	Construct the impeller of steel and spray-weld a coating of Stellite 6 (a cobalt–chromium alloy) onto it. Stellite 6 is both acid and erosion resistant.

CORROSION ATLAS

CASE HISTORY

04.11.34.04

MATERIAL	Stainless steel (904L, W.-Nr. 1.4539).
SYSTEM	Heat exchanger in a fertilizer plant.
PART	Baffle.
PHENOMENON	Erosion corrosion.



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APPEARANCE	Severe general attack with many little cracks.
TIME IN SERVICE	5 years.
ENVIRONMENT	Phosphoric acid slurry with 42% P_2O_5, 0.1% solid particles ($CaSO_4 \cdot \frac{1}{2}H_2O$), 2% sulfuric acid, 800 ppm Cl^-, 1000 ppm F^-. Temperature: 95°C.
CAUSE	According to the literature, 904L has quite good resistance in this medium. A corrosion rate of 0.178 mm/year is given for this mixture without particles, i.e., almost 1 mm in 5 years. The presence of particles probably accelerated the erosion corrosion (see also the two previous Case Histories).
REMEDY	• In this case, the baffle is constructed of Hastelloy C276. • Alloy 20 CB-3 or Hastelloy 825 might also be useful.

CORROSION ATLAS

CASE HISTORY

04.11.34.05

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Ethanol amine plant.
PART	Rundown line from reboiler.
PHENOMENON	Erosion corrosion.

APPEARANCE	Material locally worn away.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Ethanol amines; temperature about 100°C.
CAUSE	Turbulence downstream from valves, measurement instruments, etc., combined with selective attack of nickel by ethanol amines (complexing) at this temperature.
REMEDY	• Reduce velocity by larger dimensioning of the pipe work. • Use more corrosion-resistant material, e.g., 12% chromium steel (AISI 405 or 410).

CORROSION ATLAS

CASE HISTORY

04.11.38.01

MATERIAL	Duplex stainless steel (W.-Nr. 1.4462).
SYSTEM	Pipeline system.
PART	Field weld.
PHENOMENON	Weld defect.

APPEARANCE	Selective attack inside the weld zone (left) leading to leakage and external attack to the pipe (right).
TIME IN SERVICE	Less than 6 months.
ENVIRONMENT	Stagnant aerated water used for hydrotesting.
CAUSE	The formation of oxide scale during welding causes crevices internally. Once the weld was penetrated, the corrosion continued underneath the externally applied coating.
REMEDY	Use of oxygen-free backing gas to prevent scale formation during welding, together with controlled hydrotest conditions.

CORROSION ATLAS

CASE HISTORY

04.11.38.02

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Brew-water system.
PART	T-piece at brew-water tank.
PHENOMENON	Weld defect.

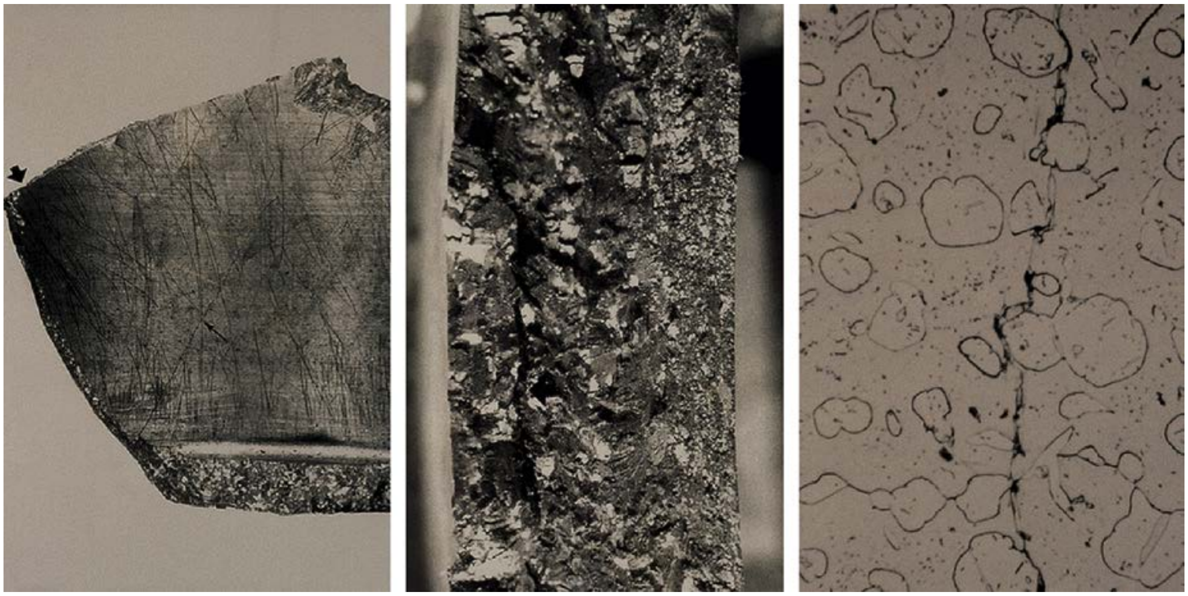
APPEARANCE	Cavity in weld (carried out with GTAW welding process).
TIME IN SERVICE	3 weeks.
ENVIRONMENT	Brew-water: pH approximately 6; chloride approximately 90 ppm; temperature 15–20°C.
CAUSE	Start-stop welding defect caused by abruptly starting or stopping the welding torch. This case is an example of poor workmanship.
REMEDY	Do not retract the torch suddenly at the end of the welding procedure, but hold it in the bath for uniform decrease of the electric current (this takes place automatically by activating the start/stop button).

CORROSION ATLAS

CASE HISTORY

04.11.44.01

MATERIAL	Stainless steel (Duplex, W.-Nr. 1.4590).
SYSTEM	Epicote resin plant.
PART	Epicote centrifuge bowl.
PHENOMENON	475°C embrittlement.



APPEARANCE	Left photograph: a piece from the underside of the bowl. Middle photograph: detail of the fraction at the arrow showing a crack parallel to the surface.
TIME IN SERVICE	2 years, of which 20 h at 420–450°C.
ENVIRONMENT	Fluidized bed at 420–450°C (quartz sand, air, and propane gas).
CAUSE	Cleaning every 2 months for 60 min in fluidized bed at 420–450°C. Embrittlement in seconds at 850°C, minutes at 475°C and hours at 420–450°C. Normal operating temperature 90°C. (The microphoto shows transgranular cracks in ferrite avoiding relatively tough austenite. Precipitates along the austenite boundaries and in the ferrite).
REMEDY	• Different cleaning method. • Attention for abnormal operating temperatures.

CORROSION ATLAS

CASE HISTORY

04.12.04.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Cleaning circuit.
PART	Pipe section.
PHENOMENON	Acid corrosion.

APPEARANCE	Etched surface, uniform attack, weld seam gone completely.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	Cleaning liquid (6% sulfamic acid, 20°C).
CAUSE	304 stainless steel is not resistant to 6% sulfamic acid. The preferential attack of the weld seam is probably due to use of the wrong weld metal (less noble than the pipe metal).
REMEDY	Cleaning circuit constructed of AISI 317 stainless steel, properly welded (weld metal equal to or more noble than the pipe metal).

CORROSION ATLAS

CASE HISTORY

04.12.04.02

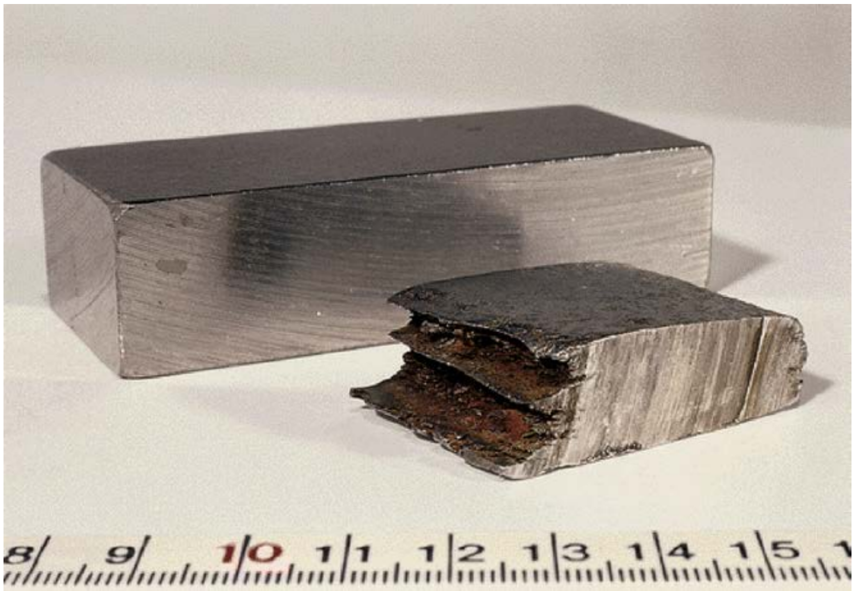
MATERIAL	Stainless steel (AISI 304).
SYSTEM	Cleaning system.
PART	Ball valve.
PHENOMENON	Acid corrosion.
	
APPEARANCE	Pitting attack.
TIME IN SERVICE	Several days.
ENVIRONMENT	Inhibited 10% hydrochloric acid. Temperature 20°C.
CAUSE	Standing acid remained after chemical cleaning; after degradation of the inhibitor, the stainless steel was attacked (for attack of stainless steel by hydrochloric acid, see also Case Histories 04.11.04.01/11/14).
REMEDY	Good through-flow during cleaning, and careful rinsing.

CORROSION ATLAS

CASE HISTORY

04.12.04.03

MATERIAL	Stainless steel (AISI 316 or 316Ti).
SYSTEM	Pickling installation in steel mill.
PART	Fixtures of spray system at the end of installation.
PHENOMENON	Acid corrosion.



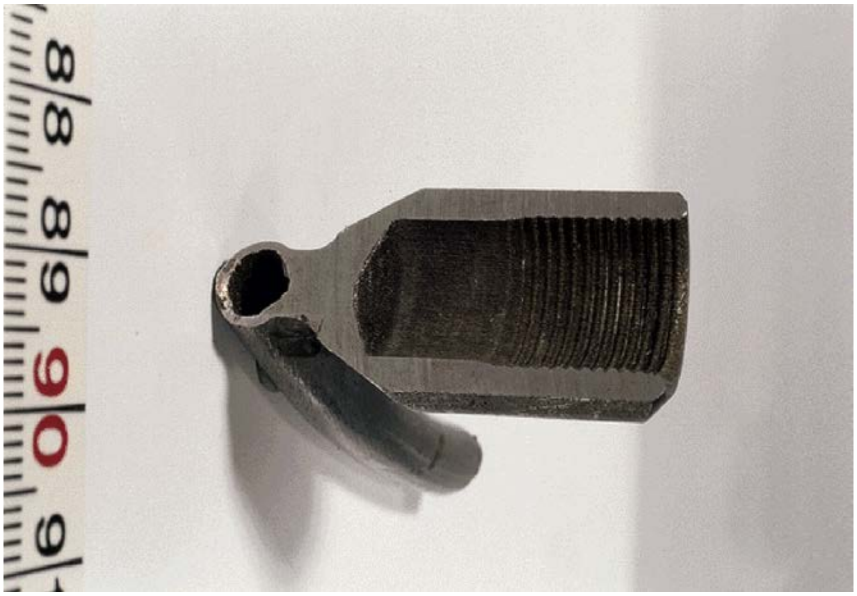
APPEARANCE	General attack (in the background a new sample).
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Condensing hydrochloric acid, at approximately 50°C.
CAUSE	Stainless steel is not resistant to hydrochloric acid. The previously applied carbon steel fixtures, provided with a protective coating, require some maintenance after a period of approximately 5 years, mainly due to mechanical wear of the coating (for the attack of stainless steel by hydrochloric acid, see also the Case Histories 04.11.04.01/14 and 04.12.04.02).
REMEDY	Provide the coated carbon steel fixtures with replaceable wear plates of a suitable nonmetallic material.

CORROSION ATLAS

CASE HISTORY

04.12.04.04

MATERIAL	Stainless steel (AISI 303 and 304).
SYSTEM	Spray system of a ventilator in a pickling installation (increasing the RH).
PART	Ring line with sockets for spray nozzles.
PHENOMENON	Acid corrosion.



APPEARANCE	General corrosion. Loss of screw thread.
TIME IN SERVICE	Several hours.
ENVIRONMENT	Pickling bath, 20% HNO_3 + 4% HF, 30–40°C.
CAUSE	Selection of a more easily machinable type of stainless steel for the sockets. As these types of stainless steels (usually with a higher sulfur content) have a much lower corrosion resistance, the threads dissolve during chemical cleaning (pickling).
REMEDY	Material selection should not be solely based on the (sometimes rather mild) working conditions only. (Free-machining types of stainless steels cannot be pickled together with the standard types of stainless steels.)

CORROSION ATLAS

CASE HISTORY

04.12.04.05

MATERIAL	Stainless steel (904 L).
SYSTEM	Pickling bath for steel.
PART	Heating pipe of pickling bath.
PHENOMENON	Acid corrosion.

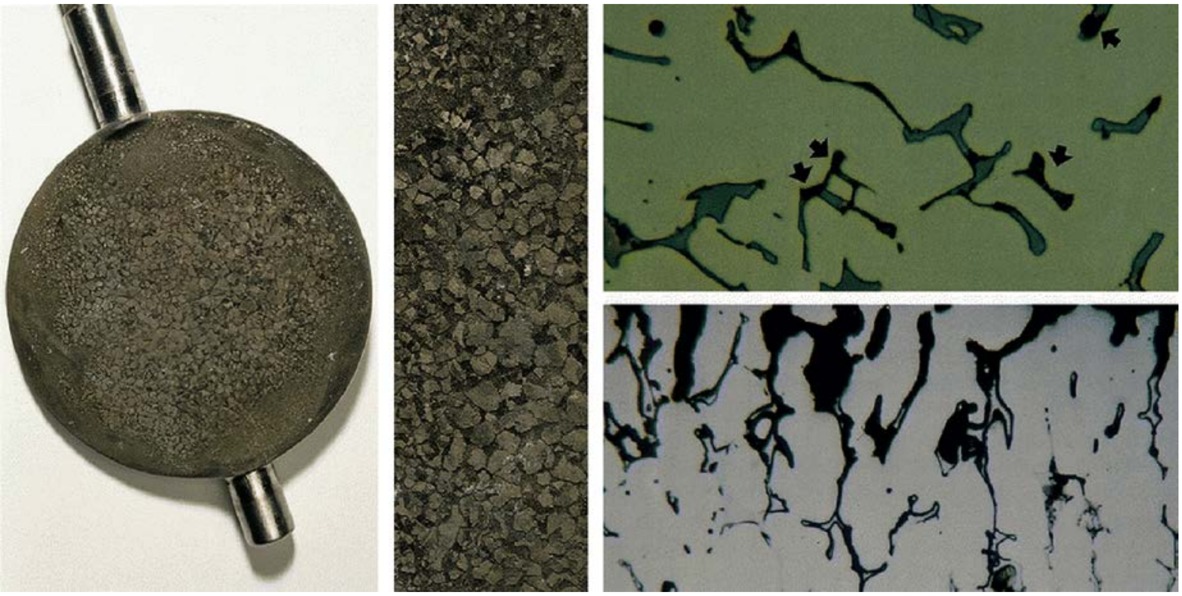
APPEARANCE	Strong reduction of wall thickness by uniform corrosion, with many superficial pits (wall reduction from 4.4 to 2.5 mm).
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Inside: superheated steam; temperature about 175°C. Outside: Sulfuric acid pickling bath: 12 w/w %, inhibited; temperature: 70°C. Temperature at the pipe surface: >100°C.
CAUSE	Stainless steel is slowly attacked by sulfuric acid at this concentration and temperature, despite the added inhibitor (see for the resistance of stainless steel in diluted sulfuric acid also the Case Histories 04.11.04.04/06/09).
REMEDY	Periodic inspection and renewal of heating pipes.

CORROSION ATLAS

CASE HISTORY

04.12.19.01

MATERIAL	Cast stainless steel (AISI 316 Nb).
SYSTEM	Cleaning system at a food manufacturing plant.
PART	Butterfly valve in circulation line.
PHENOMENON	Sigma-phase embrittlement.



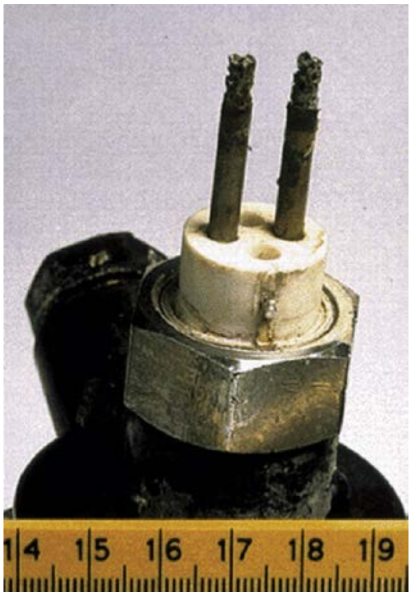
APPEARANCE	Overall attack, leaving the primary grain structure visible. Micro upper right: cast structure of austenite with delta-ferrite with conversion into sigma phase (see arrows). Micro lower right corrosion penetrates via the austenite–ferrite (sigma phase) into the material.
TIME IN SERVICE	3 years.
ENVIRONMENT	Flowing oxygen-rich water with 2% NaOH and 1% cleaner booster (EDTA) added; temperature 80–100°C. Analysis: conductivity 4640 mS/m, pH 13.1, P number 240 mEq/L, chloride content 22 ppm, EDTA 0.23%. The system is cleaned once a year with a 3% nitric acid solution.
CAUSE	Normally, AISI 316 Nb should be resistant to the above-mentioned chemical solutions. However, this was not the case due to the presence of sigma phase. This sigma phase forms during residence in a temperature range around 850°C, e.g., by excessively slow cooling during casting or inadequate heat treatment. The formation of this sigma phase, which consists of approximately equal parts of Cr and Fe, reduces the chromium content of the surrounding material and thereby makes it vulnerable to selective attack via these chromium-depleted zones. Microscopic examination shows that the attack has indeed travelled via these zones (see also Case Histories 04.11.19.08/09).
REMEDY	New butterfly valves made of the same material grade can be used, but the supplier will have to give guarantees on the material structure, namely an austenite cast structure with several per cent delta-ferrite, free of sigma phase.

CORROSION ATLAS

CASE HISTORY

04.12.26.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Cleaning circuit.
PART	Conductivity electrodes placed in the circuit.
PHENOMENON	Stray-current corrosion.



APPEARANCE	Electrodes completely dissolved.
TIME IN SERVICE	1 year.
ENVIRONMENT	An alternation of different cleaning liquids, namely: • mains water, • mains water with caustic soda and EDTA, • mains water with 20–30 ppm Cl_2.
CAUSE	Occurrence of a DC potential difference between the electrodes and the pipe wall as a result of difference in resistance of the earthing cables of electrodes and pipe wall. The exit current causes some kind of stray-current corrosion (see also Case History 04.05.26.01).
REMEDY	A DC potential difference between electrodes and pipe wall can be eliminated by improving the earthing.

CORROSION ATLAS

CASE HISTORY

04.16.12.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Housing for experimental animals.
PART	Wall panel.
PHENOMENON	Chloride attack.

APPEARANCE	Brown patches, no pitting apparent to visual inspection.
TIME IN SERVICE	1 week.
ENVIRONMENT	Atmosphere with 50% relative humidity, 25°C.
CAUSE	After completion, the walls were cleaned with a product which the supplier stated was based on phosphoric acid. The product was said to contain no chloride. However, analysis showed that the cleaning product contained hydrochloric acid instead of phosphoric acid. A chloride content of 1630 ppm and a pH of 0.9 was found in the diluted product. It was therefore unsuitable for cleaning stainless steel. Residues remaining after insufficient rinsing caused the corrosion.
REMEDY	• Clean the walls with a neutral, chloride-free product and then rinse them with plenty of desalted water. • When cleaning stainless steel, have the proposed product analyzed and do not rely fully on the supplier's specification.

CORROSION ATLAS

CASE HISTORY

04.18.12.01

MATERIAL	Stainless steel (AISI 316 Ti; W.-Nr. 1.4571).
SYSTEM	Sludge incinerator of a sewage treatment plant.
PART	Mineral wool-insulated stack, downstream from the gas scrubber.
PHENOMENON	Chloride attack and knife-line attack.

APPEARANCE	Left-hand photograph: external corrosion of aluminum plating. Center photo: severe pitting attack, most severe in the vicinity of the welds. Right-hand photograph: razor-sharp attack directly alongside the weld.
TIME IN SERVICE	3 years.
ENVIRONMENT	Wet chloride-containing flue gases, temperature 60–80°C.
CAUSE	Entrained scrubbing water with a chloride content of 560 ppm and a pH of 2.8 caused pitting of the stainless steel. The first leaks arose near the non-PWHT welds and also led to corrosion of the aluminum sheeting of the stack insulation. The occurrence of weld decay was prevented by adding titanium. But, now knife-line attack took place; for the cause of this form of attack (right-hand photograph) refer to Case History 04.11.19.04.
REMEDY	• The stack was no longer reliable and was replaced by an ebonited carbon steel stack. • Other possibilities: alkalization of the scrubbing water: installing a drop catcher downstream of the gas scrubber or constructing the stack of titanium. In view of the presence of HF in the flue gases, application of titanium or glass fiber- or glass flakes–reinforced plastic as lining was not an eligible measure.

CORROSION ATLAS

CASE HISTORY

04.18.12.02

MATERIAL	Stainless steel (316 Ti, W.-Nr. 1.4571).
SYSTEM	Waste incineration plant.
PART	Strip from stack cyclone.
PHENOMENON	Chloride attack.

APPEARANCE	Irregular uniform attack with pitting.
TIME IN SERVICE	3–8 years (depending on position in cyclone).
ENVIRONMENT	Wet chloride-containing flue-gases downstream from gas scrubber, pH 4–5, temperature 70°C.
CAUSE	The chloride in the entrained scrubbing water caused attack to the stainless steel, whilst erosion–corrosion also occurred in combination with the speed of the droplets.
REMEDY	Gas scrubber, cyclone, and stack made of rubberized carbon steel (see also Case History 04.18.12.01).

CORROSION ATLAS

CASE HISTORY

04.18.12.03

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Waste incineration plant.
PART	Inspection hatch.
PHENOMENON	Chloride attack.

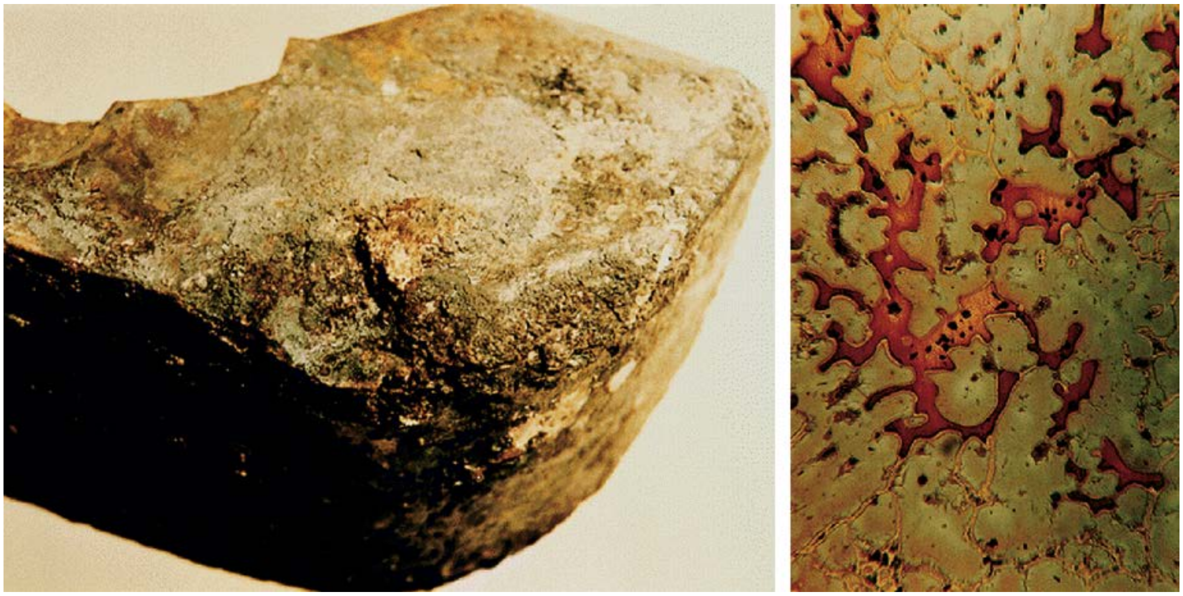
APPEARANCE	Pitting (hatch partly cleaned).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Wet combustion gases with chlorides.
CAUSE	Combustion of chloride-containing waste (e.g., PVC) results in the formation of hydrogen chloride gas which attacks the stainless steel when condensing on the uninsulated inspection hatch (see also Case History 04.11.18.03).
REMEDY	Manufacture the inspection hatch from high-silicon cast iron (Si > 14.2% + Mo + Cr + Cu), which possesses good resistance to hydrochloric acid.

CORROSION ATLAS

CASE HISTORY

04.18.22.01

MATERIAL	Stainless steel (22% chromium steel).
SYSTEM	Municipal waste incinerator.
PART	Grid.
PHENOMENON	Liquid metal embrittlement.



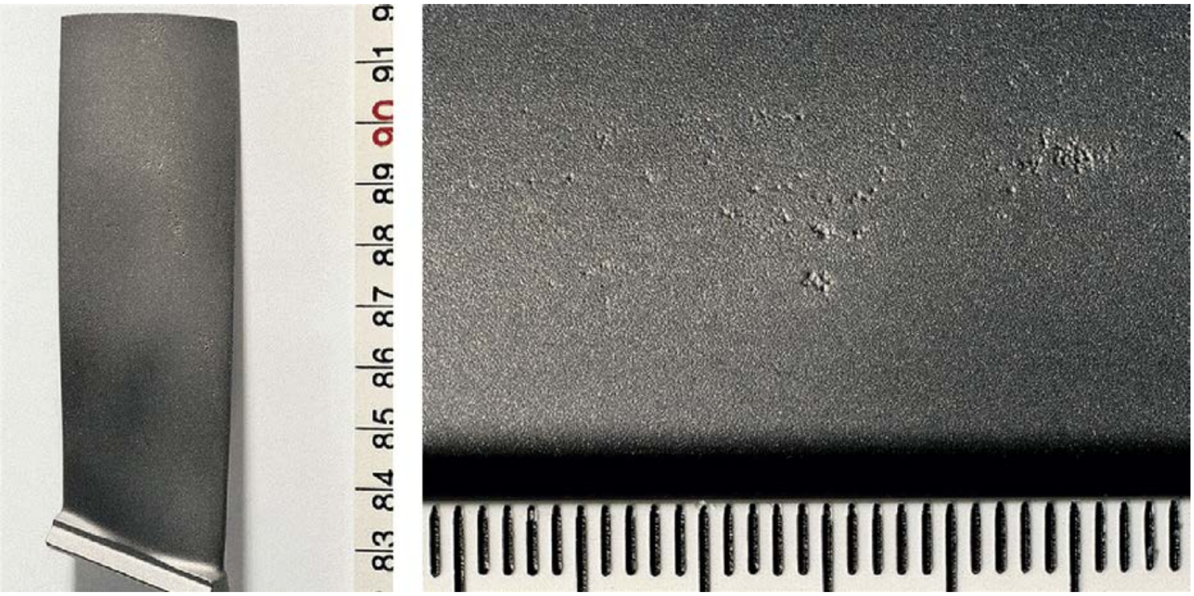
APPEARANCE	Copper-colored surface attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Municipal waste; temperature: 800–1200°C.
CAUSE	Presence of liquid copper caused penetration of copper into the material. The brittle phase formed could easily be removed (see also Case Histories 01.01.22.01/02)
REMEDY	Avoid copper in waste.

CORROSION ATLAS

CASE HISTORY

04.19.12.01

MATERIAL	Stainless steel (17-4 PH steel; 17 Cr 4 Ni 4 Cu).
SYSTEM	Turboprop engine from maritime patrol aircraft.
PART	Compressor blade.
PHENOMENON	Chloride attack.



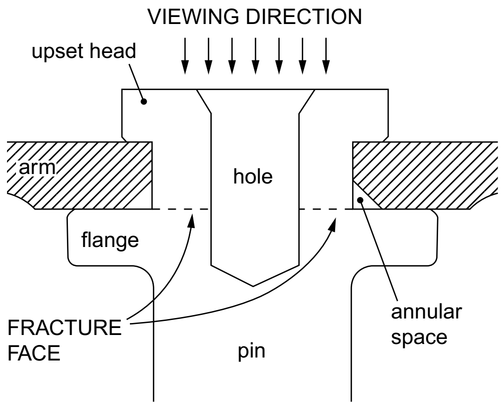
APPEARANCE	Isolated pits; depth in excess of rejection criterion.
TIME IN SERVICE	Rejected during scheduled inspection after 3000 service hours.
ENVIRONMENT	Marine atmosphere.
CAUSE	During service, sea salt is deposited. During shut-down periods, the deposits are wetted and acidified. The chlorides originating from the sea salt promote pitting corrosion. Blades with pits deeper than 250 μm are rejected in view of the danger of fatigue crack initiation.
REMEDY	• Frequent washing to remove sea salt, • Use more corrosion-resistant materials such as titanium alloys or nickel-based superalloys, or • Use a sacrificial coating.

CORROSION ATLAS

CASE HISTORY

04.19.18.01

MATERIAL	Stainless steel (Nitronic 60, nitrogen-containing stainless steel).
SYSTEM	Aircraft jet engine.
PART	Lever pin in compressor variable vane system.
PHENOMENON	SCC (transgranular).



APPEARANCE	SCC (brownish) surrounding overload fracture (whitish) introduced by tensile testing of pin after service.
TIME IN SERVICE	500 service hours, followed by destructive testing.
ENVIRONMENT	Air, sometimes salt-laden due to low-altitude flights over sea.
CAUSE	The three conditions for SCC were fulfilled: • upsetting the head-introduced residual tensile stresses; • salt deposits created a corrosive environment; • Nitronic 60 has poor resistance against SCC. After a flight accident, several hundred pins were tensile-tested; about 25% were found to suffer from SCC.
REMEDY	The pin material was replaced by a material immune to SCC.

CORROSION ATLAS

CASE HISTORY

04.21.13.01

MATERIAL	Stainless steel (W.-Nr. 1.4464).
SYSTEM	Ship.
PART	Sleeve of a ship's propeller shaft seal.
PHENOMENON	Crevice corrosion.

APPEARANCE	Severe pitting in a fixed path around the sleeve between the lip seals.
TIME IN SERVICE	9 months to 4–5 years.
ENVIRONMENT	Mixture of seawater and lubricating oil, temperature 60–65°C. The lubricating oil acidifies as time passes.
CAUSE	In view of the site where the sleeve corrosion occurs, i.e., only in the seawater–filled crevices directly adjacent to the contact face with the lip seals, and the absence of pitting on the free faces of the sleeves, the cause may be assumed to be crevice corrosion. The occurrence of this corrosion was promoted by the temperature increase of the bearing surfaces of the lip seals and by the reduction in pH caused by acidification of the lubricating oil.
REMEDY	• Manufacture the sleeves with a cladding of a wear-resistant castable alloy with a pitting resistance equivalent index of at least 40 (e.g., W.-Nr. 1.4469, Alloy 654 or Zeron 100), or • Modify the construction such that the seawater is sufficiently replenished between the contact surfaces of the lip seals.

CORROSION ATLAS

CASE HISTORY

04.22.18.01

MATERIAL	Stainless steel (AISI 304 with 0.8% Mo and 1.3–2.0% Mn).
SYSTEM	Central oil lubrication system.
PART	Pipes (12/10 mm dia.).
PHENOMENON	SCC (transgranular).

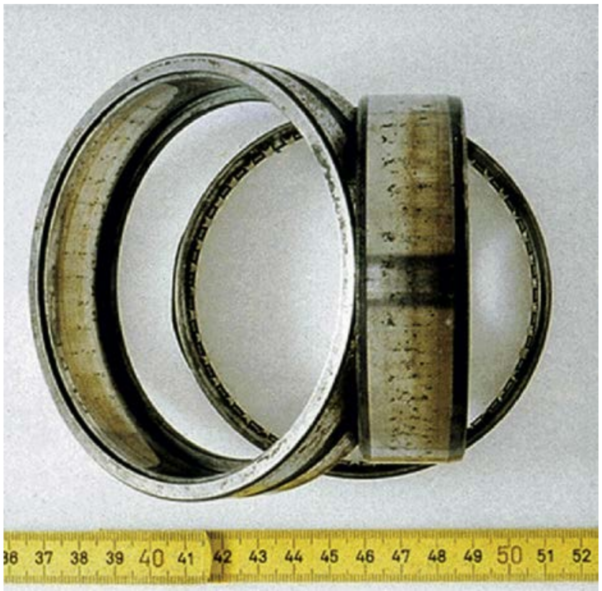
APPEARANCE	The pipes are locally cracked and broken off. In an area up to 2–10 mm from the cracks, the material exhibits pitting and cracking attack.
TIME IN SERVICE	Several months.
ENVIRONMENT	Internal: hot lubricating oil. External: atmosphere.
CAUSE	As a result of external markings being made on the pipes with a chloride-containing marker and tape, in combination with present tensile stresses and the elevated temperature, stress corrosion and pitting corrosion took place (see also Case History 04.11.18.07).
REMEDY	Markings should be applied to the pipes in a different way.

CORROSION ATLAS

CASE HISTORY

04.22.35.01

MATERIAL	Stainless steel (chromium steel).
SYSTEM	Pump.
PART	Roller bearing.
PHENOMENON	False brinelling.



APPEARANCE	Small pieces broken from the wearing surface.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Aerated lubricating oil.
CAUSE	During shutdown, the system is subject to slight vibration caused by rotating equipment in the vicinity. This allows a slight movement to take place between the rollers and the wearing surfaces, causing damage to the latter.
REMEDY	• Use of a lubricant with molybdenum sulfide. • Turning of the roller bearing regularly.

CORROSION ATLAS

CASE HISTORY

04.23.12.01

MATERIAL	Stainless steel (AISI 304L).
SYSTEM	Carbon-dioxide gas installation in brewery.
PART	Compressor suction pipe section.
PHENOMENON	Chloride attack.

APPEARANCE	Highly pitted.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	CO_2 gas with 72,0000 ppm chlorides.
CAUSE	The sodium hypochloride dosing in the CO_2 scrubber, situated before the CO_2 compressor, was set too high (see also Case History 04.11.12.02).
REMEDY	• The dosing was reduced, and • The suction pipe was constructed of polypropylene.

CORROSION ATLAS

CASE HISTORY

04.23.14.01

MATERIAL	Stainless steel (AISI 304).
SYSTEM	Activated charcoal filter.
PART	Wall section.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Local pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Activated charcoal; chlorinated hydrocarbons; condensing steam.
CAUSE	During regeneration of the activated charcoal filter with steam, condensation causes a liquid film on the cold wall, as a result of which a galvanic cell is formed between the charcoal and the stainless steel (see also Case History 05.23.14.01).
REMEDY	Line the steel vessel with a hot-hardened coating.

CORROSION ATLAS

CASE HISTORY

04.23.34.01

MATERIAL	Stainless steel (12% Cr steel; AISI 410).
SYSTEM	Carbon dioxide scrubbing tower.
PART	Pump shaft.
PHENOMENON	Erosion corrosion.

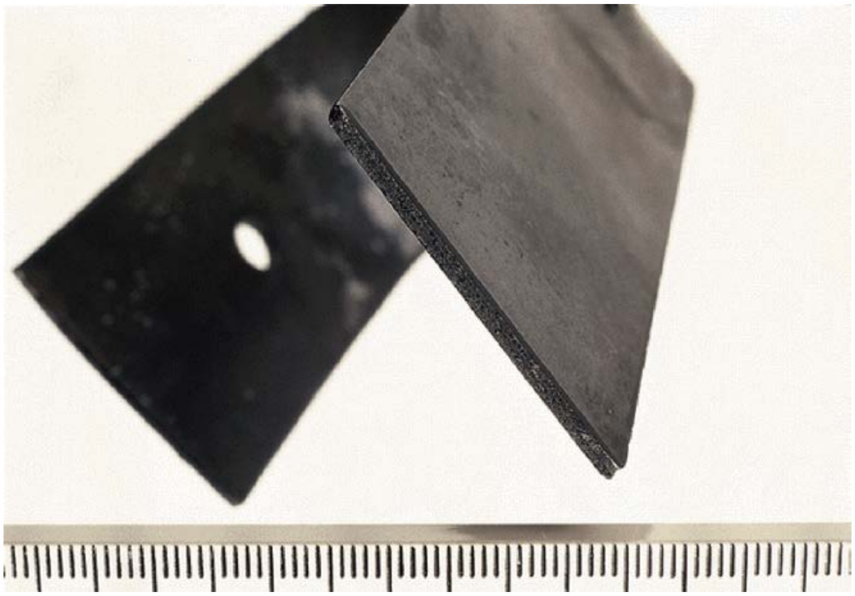
APPEARANCE	Severe local attack.
TIME IN SERVICE	At most 5 years.
ENVIRONMENT	Monoethanolamine solution in water, in which CO_2 is absorbed.
CAUSE	Contact with a corrosive solution at high velocity and turbulence (see also Case Histories 04.08.12.02 and 04.11.34.01).
REMEDY	On the basis of economic considerations, a choice can be made between: • the use of high-alloyed material, • constructional improvement, • acceptance of the service life in the present design.

CORROSION ATLAS

CASE HISTORY

04.24.04.01

MATERIAL	Stainless steel (AISI 316).
SYSTEM	Test rig.
PART	Stainless steel test plate (U-shaped, thickness 2.0 mm).
PHENOMENON	Acid corrosion.



APPEARANCE	Severe attack at the cutting edges, the plate surface itself is not corroded but only colored dark.
TIME IN SERVICE	About 20 days.
ENVIRONMENT	Sulfuric acid pickling bath: 12 w/w %, inhibited; temperature 70°C.
CAUSE	The stainless steel surface is not attacked by sulfuric acid at this concentration and temperature, but the edges show severe corrosion because of activation by the cutting process (see also Case History 01.24.04.01).
REMEDY	Passivation of edges after cutting.

CORROSION ATLAS

CASE HISTORY

04.25.18.01

MATERIAL	Stainless steel (AISI 316 L).
SYSTEM	Test autoclave.
PART	Wall.
PHENOMENON	SCC (inter- and transgranular).

APPEARANCE	Fracturing leading to leakage (inside left, outside right).
TIME IN SERVICE	2–3 days.
ENVIRONMENT	A nickel lining contained a 10% NaOH solution at 320°C.
CAUSE	Because the cover of the lining was leaking, caustic soda entered between the nickel lining and the stainless steel jacket. At a high pH and high temperature, stainless steel suffers intergranular attack as chromium dissolves, and transgranular fractures can also occur (see also Case History 04.01.18.03).
REMEDY	Provide a well-sealing nickel lining.

CORROSION ATLAS

CASE HISTORY

05.01.06.01

MATERIAL	Cronite ORD.
SYSTEM	Boiler.
PART	Burner deflector.
PHENOMENON	High-temperature corrosion (sulfidation).

APPEARANCE	Severe corrosion and cracking.
TIME IN SERVICE	Approximately 5000 h.
ENVIRONMENT	Flue gases from oil-fired burner; temperature 600–850°C.
CAUSE	Sulfidation of the material due to firing sulfur-containing fuel oil (see also Case Histories 01.11.06.04 and 05.19.06.01).
REMEDY	Use another material: • Cr–Ni 50/50 or Cr–Ni 60/40, or • pack aluminizing coating (by diffusion, aluminum forms a Ni/Al compound resistant to sulfidation), or • ceramic coating (plasma-sprayed).

CORROSION ATLAS

CASE HISTORY

05.01.06.02

MATERIAL	Incoloy 800H.
SYSTEM	Ammonia plant.
PART	Ferrule of entry/exit tubes (tube) plate of waste heat boiler downstream from secondary reformer.
PHENOMENON	High-temperature corrosion (metal dusting).

APPEARANCE	Pitting attack with powdery surface to the point of leakage.
TIME IN SERVICE	2 years.
ENVIRONMENT	Through the tubes: gas mixture CO, CO_2, H_2, and O_2 cooled from 850 °C to 540 °C. Around the tubes: cooling water.
CAUSE	Cr reacting with carbon components from the gaseous phase leads to the formation of excessive chromium carbide. This results in disintegration of the metal, which usually manifests itself as pitting (see also Case Histories 01.11.06.01/02 and 05.11.06.03).
REMEDY	Replacement with Inconel 601 tubes. Still no problems after 2.5 years.

CORROSION ATLAS

CASE HISTORY

05.01.18.01

MATERIAL	Inconel X 750.
SYSTEM	Steam system (pressure: 4 MPa).
PART	Part of spring ring of steam control valve.
PHENOMENON	Intergranular stress corrosion cracking (caustic stress-corrosion cracking).

APPEARANCE	Spring ring cracked at several points (brittle fracture).
TIME IN SERVICE	3 months.
ENVIRONMENT	Superheated steam at 4 MPa and 425 °C.
CAUSE	The steam had become contaminated with alkaline boiler water owing to a leak in the attemperator. Corrosion was caused by caustic deposition in combination with the stress in the spring ring (see also Case Histories 04.01.18.03 and 04.25.18.01).
REMEDY	• Use of steam control valves with an external spring. • Continuous monitoring of the steam quality using a conductivity meter.

CORROSION ATLAS

CASE HISTORY

05.02.18.01

MATERIAL	Nickel (≥ 99.5%).
SYSTEM	Steam/condensate system.
PART	Bursting disk (a dome-shaped membrane with a diameter of 47 mm and a thickness of 0.1 mm).
PHENOMENON	Stress corrosion cracking.
	
APPEARANCE	A piece of the material has torn loose. The color inside is metallic but dull, the outside is green-grey.
TIME IN SERVICE	A few months.
ENVIRONMENT	Outside: industrial climate, contaminated with SO_2, NOx, and chlorides because of the vicinity of the sea. Inside: Steam condensate, temperature 144 °C. The disk burst at a pressure of 0.32 MPa, although the designed bursting pressure of this disk is 1.7 MPa.
CAUSE	The oxidizing acids like sulfuric acid and nitric acid formed from the contaminants with moisture and lead to corrosion of nickel in the presence of air at higher temperatures (see also Case History 05.11.18.02). This corrosion process is promoted by the stresses in the bursting disk, which are present because the disk was cold-formed. In addition, conventional dome-shaped bursting disks are unsuitable for situations with cyclic or fluctuating pressures because of limitations like fragmentation, material fatigue, vacuum, and creep.
REMEDY	• The bursting disk should be made of a more resistant alloy such as Incoloy 825 or Inconel 625. • Furthermore, another type of disk should be chosen, based on the “reverse buckling” principle.

CORROSION ATLAS

CASE HISTORY

05.03.06.01

MATERIAL	Inconel 738 LC.
SYSTEM	Gas turbine.
PART	Stator blade.
PHENOMENON	High-temperature corrosion (Nitriding).

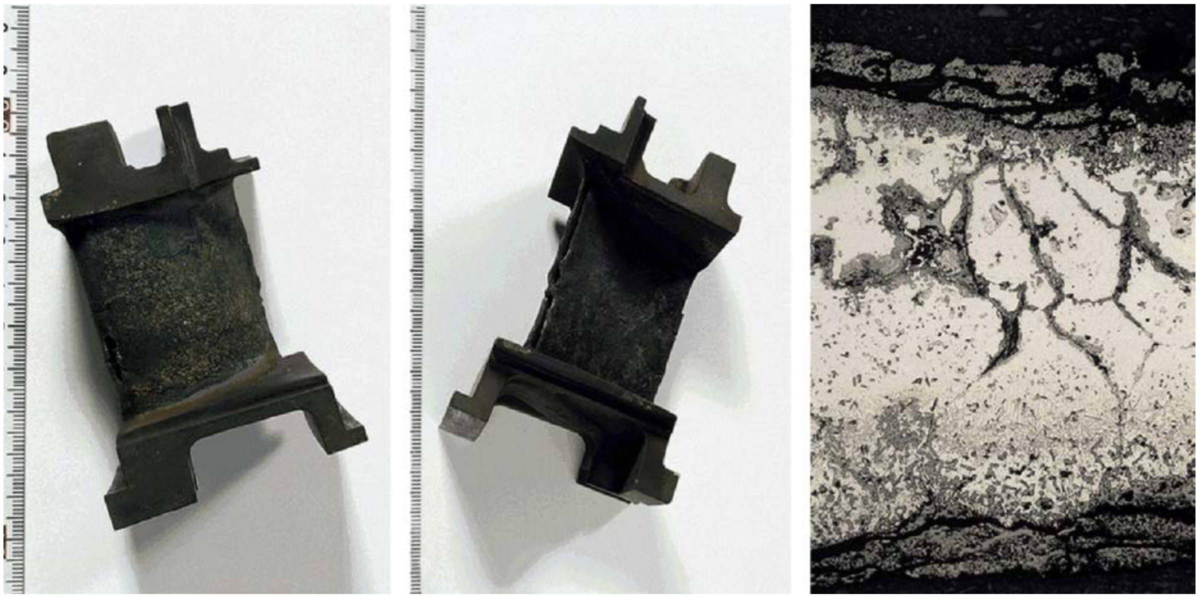
APPEARANCE	Attack where the highest wall temperature occurs.
TIME IN SERVICE	8000 hours.
ENVIRONMENT	Combustion gases (fuel: natural gas); temperature locally >900 °C.
CAUSE	A locally too low cooling efficiency of the turbine blade caused the wall temperature to exceed the allowable temperature for the material (830 °C) and diffusion of nitrogen followed by formation of nitrides to occur (see also Case History 04.11.06.03).
REMEDY	Application of an Al–Cr diffusion coating.

CORROSION ATLAS

CASE HISTORY

05.03.06.02

MATERIAL	Inconel 939.
SYSTEM	Gas turbine.
PART	First-stage vane.
PHENOMENON	High-temperature corrosion (oxidation and nitriding).



APPEARANCE	Uniform attack with dark-green corrosion products.
TIME IN SERVICE	4 years (30,000 hours and about 200 starts).
ENVIRONMENT	Around the vane: combustion gases; temperature 970 °C. Through the vane: cooling air; temperature 320 °C.
CAUSE	Probably lack of cooling allowed an excessive temperature increase of the vane, so that it was severely attacked by oxidation both externally (lower part of microphotograph) and internally. Cracking initiated from the cooling side (upper part of microphotograph). Externally, needle-shaped precipitations in the material are visible, presumably nitrides. The green corrosion products were found to consist mainly of nickel oxide.
REMEDY	• Ensure improved cooling, or • Provide new vanes with a duplex coating (chromium/aluminum diffusion coating), as was done in this case.

CORROSION ATLAS

CASE HISTORY

05.03.06.03

MATERIAL	Rene 77.
SYSTEM	Gas turbine.
PART	Vanes.
PHENOMENON	High-temperature corrosion (sulfidation).

APPEARANCE	Uniform attack.
TIME IN SERVICE	A few years.
ENVIRONMENT	Combustion gases (fuel: natural gas), contaminated with sodium sulfate particles. Temperature ~ 900 °C.
CAUSE	Malfunctioning of the air filters allowed sodium sulfate powder to be entrained with the combustion air. The sodium sulfate was emitted by the plant. A liquid sodium sulfate layer is formed on the surface of the vane. The sulfur is released from the layer and diffuses into the material, where it forms chromium sulfides. This phenomenon is also known as high-temperature hot corrosion.
REMEDY	Improved operation of air filters and detailed inspection.

CORROSION ATLAS

CASE HISTORY

05.06.15.01

MATERIAL	Monel.
SYSTEM	Steam condenser.
PART	Pipe.
PHENOMENON	Underdeposit corrosion.

APPEARANCE	Severe local attack on external surface, with green copper corrosion products.
TIME IN SERVICE	Unknown.
ENVIRONMENT	External: brackish cooling water; internal: condensing steam.
CAUSE	Formation of differential aeration cells owing to sludge deposition (see also Case History 04.06.15.03 and next case).
REMEDY	• Use aluminum brass pipes, or • Prevent formation of deposits by higher cooling water velocity.

CORROSION ATLAS

CASE HISTORY

05.06.15.02

MATERIAL	Incoloy 825.
SYSTEM	Through-flow cooling water system.
PART	Heat exchanger tube.
PHENOMENON	Under-deposit corrosion.

APPEARANCE	Local attack under deposits.
TIME IN SERVICE	8 years.
ENVIRONMENT	Brackish cooling water through the pipes.
CAUSE	Particles in the cooling water deposit on the metal surface of the pipes, causing galvanic effects (formation of anodic sites under the deposits) and resulting in local corrosion (see also Case History 04.06.15.03).
REMEDY	• Prevent deposits by higher cooling water velocity, or • Apply a baked coating inside the tubes.

CORROSION ATLAS

CASE HISTORY

05.06.17.01

MATERIAL	Inconel alloy 600.
SYSTEM	Through-flow cooling system of a chemical production unit.
PART	Pipe sections from a heat exchanger bundle.
PHENOMENON	Microbiologically induced corrosion.

APPEARANCE	Wide, deep pitting attack to leakage.
TIME IN SERVICE	Four weeks after stopping the dosing of sodium hypochlorite.
ENVIRONMENT	Internal: product, cooling from 160 °C to 45 °C, pressure 3.3 MPa. External: brackish cooling water, heating from 8 °C to 15 °C (winter); flow velocity 0.7–0.8 m/sec; composition: conductivity 3190 mS/m; pH 7.6; chloride 1.3%; sulfate 1710 ppm.
CAUSE	After dosing of chlorine bleach was stopped, the pipes became subject to biological contamination, stimulated by the low flow. The development of sulfate-reducing bacteria in the anaerobic environment underneath the deposition caused attack of the nickel in the alloy by sulfide (see also Case History 05.11.05.01 and next case). Metallographic examination showed the presence of nickel sulfides and intergranular attack of the pipes.
REMEDY	• Construct the pipe bundle from Inconel alloy 625, which is more corrosion resistant. • Resume the dosing of chlorine bleach in order to prevent biological growth. • Increase the flow velocity to 2.5 m/sec to prevent deposition.

CORROSION ATLAS

CASE HISTORY

05.06.17.02

MATERIAL	Carpenter 20.
SYSTEM	Oil refinery overhead condenser.
PART	Horizontal condenser tube (OD 1.6 cm).
PHENOMENON	Microbiologically influenced corrosion.

APPEARANCE	Pitting.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Shell side: condensing hydrocarbon and H_2SO_4 vapors. Tube side: cooling water, temperature ≈ 49 °C; water pH ≈ 8.2
CAUSE	Sulfate-reducing bacteria. Considerable sliming of the internal surfaces of the tube was noted during routine inspection. Furthermore, nondestructive testing confirmed deep pitting in more than 60% of tubes examined which was caused by sulfide attacking the nickel in the alloy. (See also former case.)
REMEDY	After cleaning the condenser, the cooling water was treated with high total free chlorine (>0.5 ppm).

CORROSION ATLAS

CASE HISTORY

05.08.12.01

MATERIAL	Hastelloy B_2.
SYSTEM	Waste treatment plant.
PART	Tube.
PHENOMENON	Chloride attack.

APPEARANCE	Severe craterlike attack.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	Sodium hypochlorite solution; ambient temperature.
CAUSE	This nickel-based alloy is not resistant to a strongly oxidizing environment like sodium hypochlorite.
REMEDY	Construction of the pipe of a more suitable material, for instance, Ferralium 255.

CORROSION ATLAS

CASE HISTORY

05.11.02.01

MATERIAL	Nickel 200.
SYSTEM	Oxidation reactor (see also Case History 0.5.11.18.02).
PART	Reactor internal tube.
PHENOMENON	Carbon dioxide corrosion (sweet corrosion).

APPEARANCE	General corrosion and deep pits in the material.
TIME IN SERVICE	8 years.
ENVIRONMENT	Carbon dioxide and disposal water. Temperature: 325 °C; pressure: 230 bar.
CAUSE	In certain parts of the reactor, the temperature falls below the dew point; this causes the CO_2 to dissolve in the water formed. At the present temperature, the resultant carbonic acid attacks the nickel.
REMEDY	Use of a CO_2 corrosion–resistant material (stainless steel AISI 316).

CORROSION ATLAS

CASE HISTORY

05.11.04.01

MATERIAL	Hastelloy C-22.
SYSTEM	Reactor in a fertilizer plant.
PART	Plate of butterfly valve mounted on the reactor.
PHENOMENON	Acid corrosion.

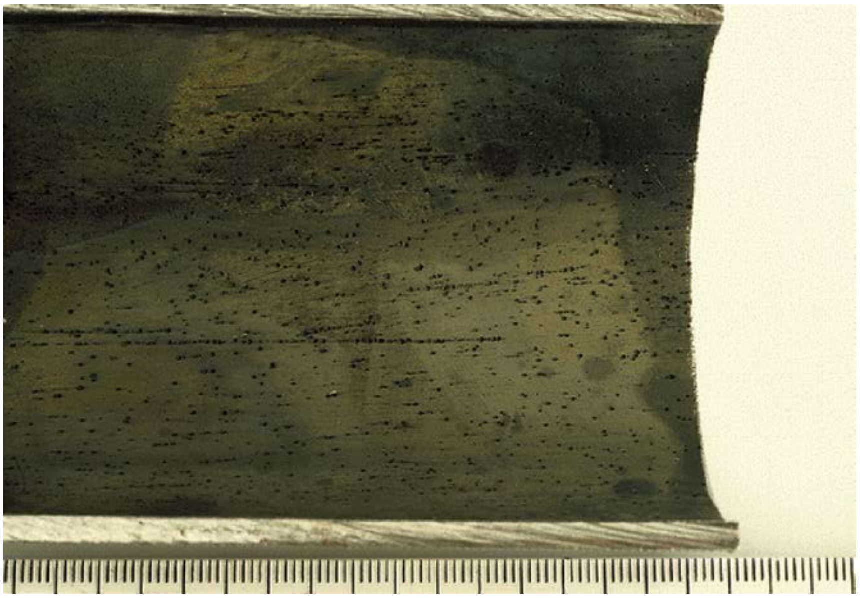
APPEARANCE	Pitting, overall attack, and mechanical damage.
TIME IN SERVICE	11 months.
ENVIRONMENT	Calcium sulfate-saturated phosphoric acid slurry with 42% P_2O_5, 33% solid particles ($CaSO_4$ 0,5 H_2), 2% sulfuric acid, 2500 ppm Cl^-, 1000 ppm F^-, temperature 100 °C.
CAUSE	Hastelloy alloy C-22 is resistant to pure phosphoric acid at 100 °C, but contamination with sulfuric acid, chloride, and fluoride substantially decreases this resistance. Mechanical damage is caused by periodical cleaning of the plate by mechanical force, to remove the calcium sulfate scale. This cleaning is necessary to guarantee a good sealing performance.
REMEDY	Application of a coating did not solve this problem, so the corrosion is accepted and the plate is regularly replaced.

CORROSION ATLAS

CASE HISTORY

05.11.04.02

MATERIAL	Alloy 20 (UNS-Nr. N08020; W.-Nr. 1.4660).
SYSTEM	Neutralization unit.
PART	Seamless line (OD 60.3 mm, wall thickness 2.8 mm).
PHENOMENON	Acid corrosion.



APPEARANCE	The internal surface became shallow pitted by numerous small pits, diameter 0.5–0.7 mm, maximum depth 0.8 mm. Some pits lie in a row.
TIME IN SERVICE	A few weeks.
ENVIRONMENT	Alternately: 99% sulfuric acid and 20% sodium hydroxide, so the pH varies between 0 and 13. Normally the temperature is equal to the outside temperature, but during reaction the temperature can reach at least about 65 °C. The medium may have been standing still in the line.
CAUSE	Alloy 20 is resistant to sodium hydroxide solutions. The isocorrosion diagram of Alloy 20 in sulfuric acid shows that generally this alloy is suitable up to 80 °C at concentrations up to 50%. For higher concentrations, good corrosion resistance is expected up to 40 °C. So, the conditions in the line of the neutralization unit are rather critical for extended use of Alloy 20. The line is damaged, first by erosion corrosion and second by the pitting influence of contaminating halides, i.e., chloride.
REMEDY	Another nickel alloy should be selected, with: a. a higher nickel content to withstand general corrosion and erosion corrosion; b. a higher molybdenum content for enough passivity against pitting. The recommended alloy is Alloy B_2 (UNS-nr. N 10665; W.-Nr. 2.4617)

CORROSION ATLAS

CASE HISTORY

05.11.04.03

MATERIAL	Hastelloy C.
SYSTEM	Mixing trough.
PART	Nozzle of dip pipe.
PHENOMENON	Acid corrosion.

APPEARANCE	Uniform attack, material partly disappeared.
TIME IN SERVICE	6 months.
ENVIRONMENT	Inside: 10% NaOH for neutralizing, ambient temperature. Outside: Initially 15% HCl, later on in the process a reaction mixture with inter alia aniline hydrochloride. Temperature: 30–90 °C.
CAUSE	Hastelloy C is not resistant to HCl at 90 °C.
REMEDY	Improved process temperature control (maximum 50 °C).

CORROSION ATLAS

CASE HISTORY

05.11.05.01

MATERIAL	Hastelloy B.
SYSTEM	Plastic plant.
PART	Guide roller for plastic film.
PHENOMENON	Sulfide corrosion.

APPEARANCE	Severe pitting attack.
TIME IN SERVICE	1–2 months.
ENVIRONMENT	A bath containing H_2S, sulfonates and flower of sulfur. In order to remove the flower of sulfur, the rollers were briefly immersed in a Na_2S bath to dissolve the flower of sulfur. Then the rollers were rinsed with water and air-dried (see also Case History 05.06.17.01).
CAUSE	Sulfide residues remaining after rinsing attack the nickel in the alloy during the drying period. Nickel is sensitive to attack by sulfide, and intergranular corrosion occurs.
REMEDY	If the rollers were polished after rinsing, as was done elsewhere, no corrosion occurred.

CORROSION ATLAS

CASE HISTORY

05.11.06.01

MATERIAL	Nickel alloy ASTM H P40 (25Cr 35Ni 0.4C + Nb), centrifugally cast.
SYSTEM	Cracking furnace.
PART	Radiant coil.
PHENOMENON	High-temperature corrosion (carburization).

APPEARANCE	Bulging with cracking.
TIME IN SERVICE	40,000 hours.
ENVIRONMENT	Cracked hydrocarbons. Temperature just above 1100 °C.
CAUSE	At temperatures above 950 °C, diffusion of carbon starts, causing carburization (see also Case History 04.11.06.01) and the formation of $M_{23}C_6$ and M_7C_3 carbides. If the temperature exceeds the oxidation resistance temperature of 1100 °C, the carburization becomes more severe and more M_7C_3 carbides are formed from the $M_{23}C_6$ carbide. The conversion of $M_{23}C_6$ into M_7C_3 carbides causes an increase in volume, and the material bulges and cracks.
REMEDY	Operate below oxidation resistance temperature.

CORROSION ATLAS

CASE HISTORY

05.11.06.02

MATERIAL	Thermalloy T66 (Ni 35; Cr 25; Co 15; W 5; C 0.50; Fe bal).
SYSTEM	Oxygen furnace (heater).
PART	Coil.
PHENOMENON	High-temperature corrosion (oxidation).

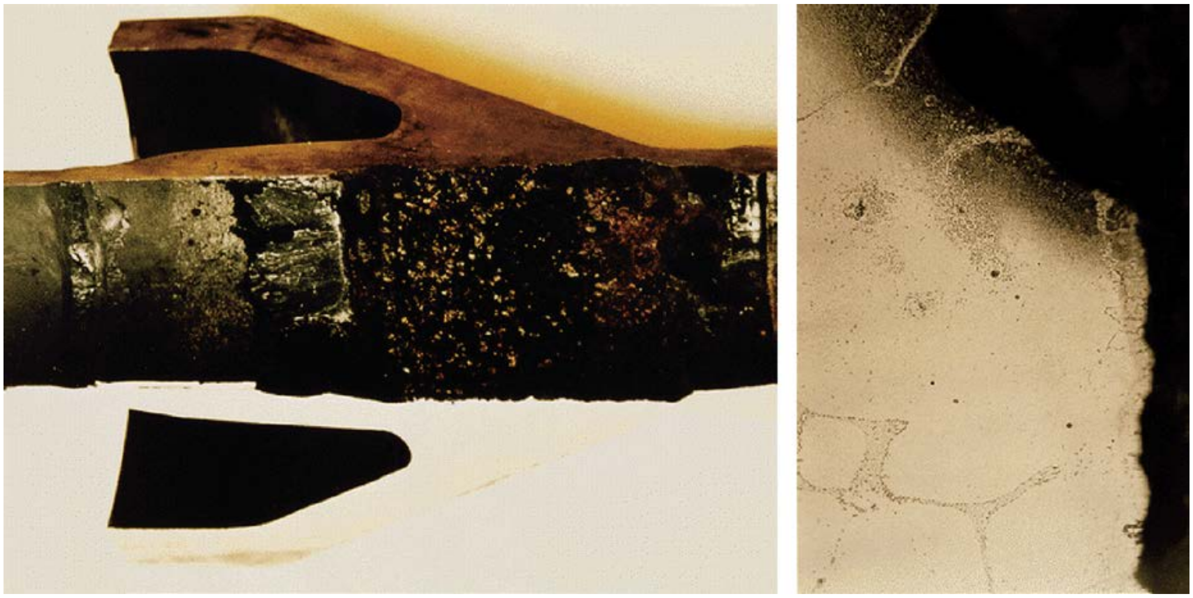
APPEARANCE	Uniform attack with cracking; reduction of wall thickness by 3–5 mm.
TIME IN SERVICE	4 years.
ENVIRONMENT	Oxygen gas flowing through the coil, temperature 1000–1050 °C. Combustion gases around the coil.
CAUSE	The damage to the coil was caused by oxidation of the medium present (oxygen) at the high operating temperature. The microphotograph of the internal surface of the coil shows intergranular and general oxidation. The carbides have coalesced and form paths along the dendrite grain boundaries, leading to material embrittlement. The cracks ultimately formed as a result of overloading.
REMEDY	The new coil is constructed of alloy HP 40 Nb (Ni 35; Cr 25; Nb 0.8; C 0.40; Ti 0.20; Zr 0.20). Tungsten (W) and yttrium (Y) may also be present in this alloy. Some suppliers add these elements. Typical contents are 0.1–0.5 W and max. 0.1 Y.

CORROSION ATLAS

CASE HISTORY

05.11.06.03

MATERIAL	Alloy 800.
SYSTEM	Furnace tube.
PART	Cone.
PHENOMENON	High-temperature corrosion (metal dusting).



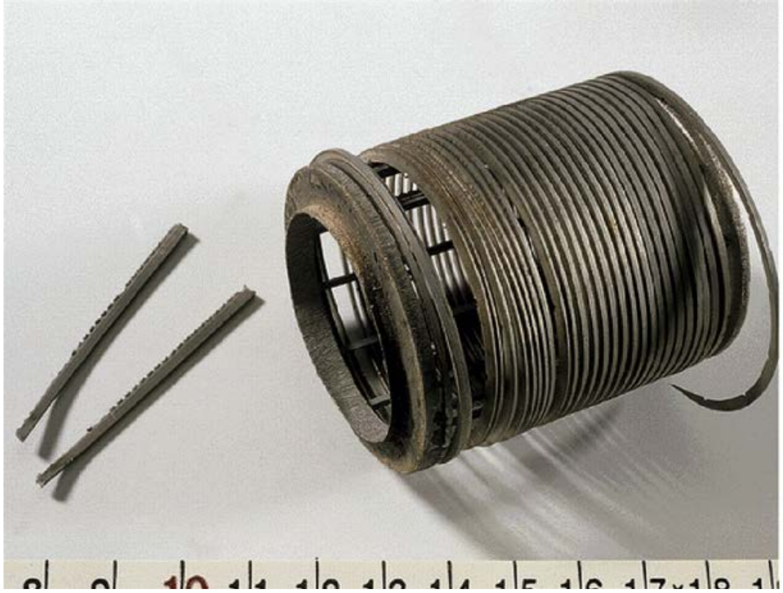
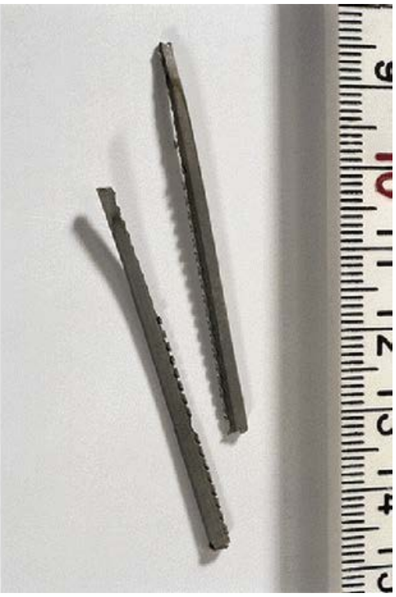
APPEARANCE	Local pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Gaseous atmosphere containing H_2 and CO, temperature: about 650 °C.
CAUSE	Local internal carburization (forming of chromium carbides) followed by Fe_3C precipitation, growth, and finally decomposition to iron and graphite. These corrosion products are easily removed by the gas flow, leaving pits behind. Alloy 800 is especially sensitive to metal dusting because of the low chromium diffusion ability (see also Case Histories 01.11.06.01/02 and 05.01.06.02).
REMEDY	• Use more resistant material, e.g., 20Cr15Ni, that forms a stable Cr_2O_3-scale. Guide for resistance against metal dusting: %Cr + 2x %Si > 24. • Inhibit reaction by adding traces of sulfur to the gas.

CORROSION ATLAS

CASE HISTORY

05.11.14.01

MATERIAL	Hastelloy C22.
SYSTEM	Chemical storage tank.
PART	Strainer.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Severe uniform corrosion, mainly at the vessel side of the strainer. The opening of the strainer has widened and the friction weldments of the rods and the wire are also corroded.
TIME IN SERVICE	6 months.
ENVIRONMENT	Sulfuric acid 90% at 95 °C.
CAUSE	The strainer was mounted in a Hastelloy C276 vessel and both end parts of the strainer were made of C276. The wire and rods were made of Hastelloy C22. Both materials have a good corrosion resistance in sulfuric acid. In combination, however, there will be galvanic corrosion of Hastelloy C22.
REMEDY	• Use one single material for the strainer: Hastelloy 276. • Solution annealing followed by water quench of the strainer after fabrication will enlarge the corrosion resistance of the friction weldments.

CORROSION ATLAS

CASE HISTORY

05.11.15.01

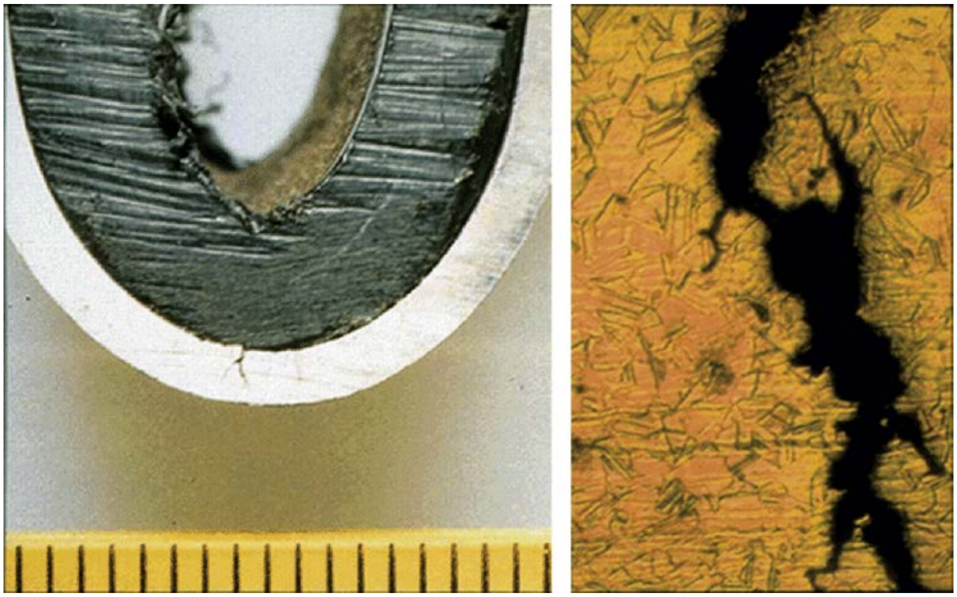
MATERIAL	Incoloy 825.
SYSTEM	Heat exchanger.
PART	Expansion bellows.
PHENOMENON	Underdeposit corrosion.
	
APPEARANCE	Local pits, varying in depth from 0.5 to 1.0 mm.
TIME IN SERVICE	4 years.
ENVIRONMENT	External: oil, contaminated with water and dirt; pressure 6 bar; temperature 160–200 °C.
CAUSE	Owing to insufficient through-flow in the dead end of the heat exchanger, dirt remained behind in the corrugations. This allows differential aeration cells to form, to which inter alia this alloy is sensitive (a form of crevice corrosion, see also Case Histories 05.06.15.01/02).
REMEDY	• Improvement of the through-flow. • Construction of the bellows from an alloy which is less sensitive to crevice corrosion, e.g., 254 SMO (ASTM S31254).

CORROSION ATLAS

CASE HISTORY

05.11.18.01

MATERIAL	Hastelloy C, lined with polytetrafluorethylene (PTFE).
SYSTEM	Hydrochloric acid recovery unit.
PART	Bellows.
PHENOMENON	Stress-corrosion cracking (intergranular).



APPEARANCE	Cracks at an outer convolution.
TIME IN SERVICE	Several years.
ENVIRONMENT	18% HCl; temperature approximately 160 °C.
CAUSE	Over the years, the HCl diffused through the PTFE coating. Hastelloy C is not resistant to the present environment.
REMEDY	Use solid PTFE bellows.

CORROSION ATLAS

CASE HISTORY

05.11.18.02

MATERIAL	Inconel 625.
SYSTEM	Oxidation reactor.
PART	Branch pipes of heat exchanger feed rundown.
PHENOMENON	Stress-corrosion cracking (intergranular).

APPEARANCE	Cracks.
TIME IN SERVICE	About 3 months.
ENVIRONMENT	Aerated disposal water; temperature approximately 350 °C; pressure approximately 200 bar.
CAUSE	High nickel alloys are sensitive to this attack in aerated water under high pressure and temperature. This results in oxygen stress-corrosion cracking (see also Case History 05.02.18.01).
REMEDY	Use carbon steel with stainless steel plating.

CORROSION ATLAS

CASE HISTORY

05.11.19.01

MATERIAL	Carpenter 20.
SYSTEM	Sulfuric acid transport system.
PART	Pump impeller.
PHENOMENON	Intergranular corrosion.

APPEARANCE	Severe local attack and the material worn away.
TIME IN SERVICE	Unknown.
ENVIRONMENT	80% H_2SO_4; temperature approximately 100 °C.
CAUSE	Carbide formation occurred at the grain boundaries owing to the high temperature of the sulfuric acid environment. Moreover, the material had not received proper heat treatment (see also Case History 04.11.19.03).
REMEDY	• Keep the temperature below 80 °C. • Improve the casting quality by means of heat treatment (e.g., ASTM A 744–CN-7M).

CORROSION ATLAS

CASE HISTORY

05.11.32.01

MATERIAL	Incoloy 800H overlay welded-on with Stellite 6.
SYSTEM	Cracking furnace.
PART	Thermocouple from outlet of radiant coil.
PHENOMENON	Erosion.

APPEARANCE	Material wear, original shape cylindrical. Left: the unaffected side; right: the eroded side perpendicular to the direction of flow.
TIME IN SERVICE	Approximately 6 months.
ENVIRONMENT	Steam with coke particles at a temperature of 500–600 °C.
CAUSE	During decoking, the high velocity of the steam carrying coke particles causes erosion of the thermocouple; first the welded-on Stellite 6 and then the Incoloy 800H wears away.
REMEDY	Use a cast Stellite 6 thermocouple, because this material is more wear resistant.

CORROSION ATLAS

CASE HISTORY

05.11.34.01

MATERIAL	Monel.
SYSTEM	Margarine manufacture.
PART	Back-pressure control valve of the mixing chamber of the pump of a margarine cooler.
PHENOMENON	Erosion corrosion.

APPEARANCE	Severe grooved attack of the used specimen (an unused specimen is shown for comparison).
TIME IN SERVICE	5 years.
ENVIRONMENT	Margarine emulsion (80% fat, 20% water). Temperature 45 °C. Aqueous phase: pH; 8% sodium chloride.
CAUSE	Attack by the salt-containing product combined with high local velocity caused erosion corrosion.
REMEDY	• Regular replacement, or alternatively • Make the back-pressure control valve from Stellite (see Case History 03.11.12.01).

CORROSION ATLAS

CASE HISTORY

05.11.34.02

MATERIAL	Hastelloy C276.
SYSTEM	Mixer trough in chemical plant.
PART	Mixer tube.
PHENOMENON	Erosion corrosion.

APPEARANCE	Wall thinning by uniform attack, material partly eroded away.
TIME IN SERVICE	6 months.
ENVIRONMENT	Initially 15% HCl, later on in the process a reaction mixture with inter alia aniline hydrochloride. Temperature 90 °C.
CAUSE	Hastelloy C276 has a rather good corrosion resistance in all HCl concentrations up to 50 °C (corrosion rate <0.5 mm/year). Erosion corrosion was caused by high local velocities combined with attack by HCl at this high temperature.
REMEDY	• Design change, or • use lower velocities.

CORROSION ATLAS

CASE HISTORY

05.11.42.01

MATERIAL	Hastelloy C4.
SYSTEM	Mixing reactor at a metal plant.
PART	Bolts and nuts of agitator.
PHENOMENON	End grain attack and crevice corrosion.

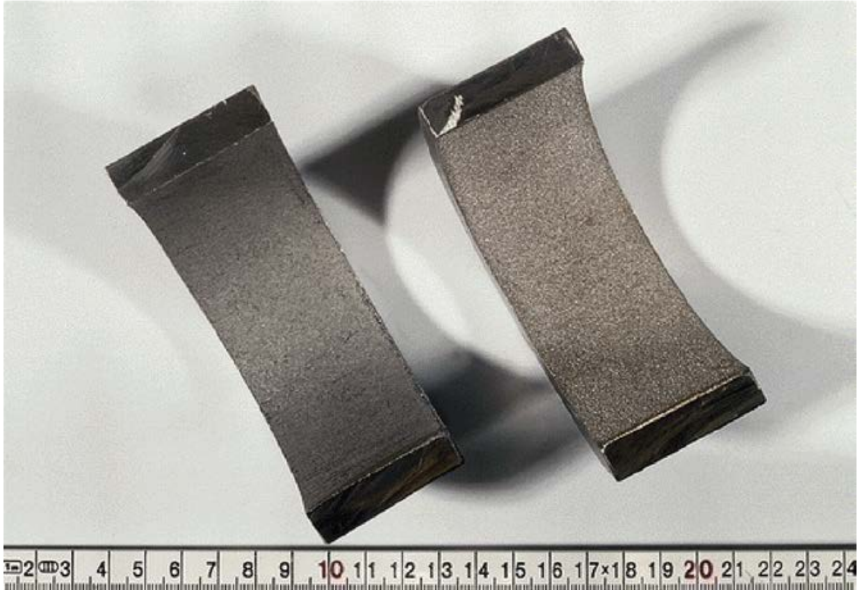
APPEARANCE	Nuts: grooved attack in the crevice of the seat; pitting corrosion on the upper surface. Bolts: surface attack in the crevice of the shaft.
TIME IN SERVICE	1 year.
ENVIRONMENT	A mixture of nitric acid and other oxidizing mineral acids. Temperature 110–115 °C. Elevated oxygen pressure.
CAUSE	Topside of nuts: selective corrosion of the nonmetallic inclusions in the metal, rolled out and elongated into long “stringers” during the rolling action. When the end grain is exposed to a strong corrodent, end grain attack starts at the end of the stringers and can aggressively proceed down into the steel (see also Case Histories 01.12.42.01 and 04.08.42.01). The sides, on the other hand, do not corrode. Bolts and underside of nuts: formation of differential aeration cells due to the presence of crevices.
REMEDY	• Providing end grain protection by “buttering” the end grain with weld metal. Weld metal is not susceptible to this form of attack; or • Manufacture bolts and nuts from polyvinylidene fluoride (PVDF).

CORROSION ATLAS

CASE HISTORY

05.12.19.01

MATERIAL	Incoloy 800 H.
SYSTEM	Piping system.
PART	Bends (Ø 107 mm, 10 mm thick).
PHENOMENON	Intergranular corrosion.



APPEARANCE	A very rough internal surface.
TIME IN SERVICE	Approximately 20 hours.
ENVIRONMENT	Pickling bath (15% HNO_3 + 2% HF at approximately 20 °C).
CAUSE	Removal of the thick scale, formed during annealing after hot bended of the pipe, made it necessary to prolong the pickling treatment. However, as the bends had become sensitized during annealing, they became severely corroded.
REMEDY	Sensitized components should not be pickled and definitely not with the commonly used pickling solutions. They should be solution-annealed prior to the cleaning treatment.

CORROSION ATLAS

CASE HISTORY

05.19.06.01

MATERIAL	Cobalt alloy.
SYSTEM	Aircraft turbine.
PART	Vane.
PHENOMENON	Sulfidation.

APPEARANCE	Pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Combustion gases. Temperature 1100–1200 °C.
CAUSE	The fuel was found to be contaminated with vanadium and sulfur. Vanadium reduces the melting point of sodium sulfate. The resultant sodium sulfate melt attacks the cobalt alloy (see also Case History 05.01.06.01). The corrosion products were entrained by the combustion gases.
REMEDY	Use uncontaminated fuel.

CORROSION ATLAS

CASE HISTORY

05.23.14.01

MATERIAL	Hastelloy B_2.
SYSTEM	Activated charcoal filter.
PART	Thermometer bulb.
PHENOMENON	Galvanic corrosion.

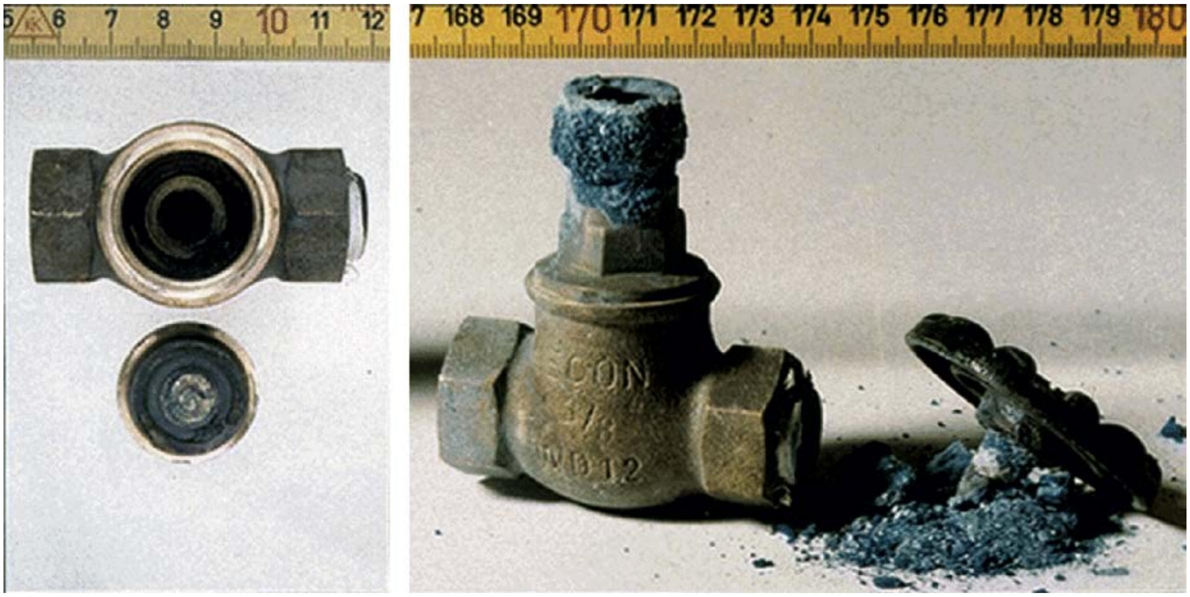
APPEARANCE	Pitting attack in the form of carbon grains.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Activated charcoal; residual gas from vinyl chloride; condensing steam.
CAUSE	During regeneration of the activated charcoal filter with steam at 130–140 °C, condensation leaves water vapor in the grains, forming acid decomposition products with the vinyl chloride, which causes galvanic attack to the metal at the grains (by couple action). (See also Case History 04.23.14.01.)
REMEDY	Application of a protective sprayed layer of Al_2O_3.

CORROSION ATLAS

CASE HISTORY

06.01.10.01

MATERIAL	Bronze.
SYSTEM	Shell-type boiler (1.0 MPa).
PART	Pressure gauge valve.
PHENOMENON	Ammonia corrosion.



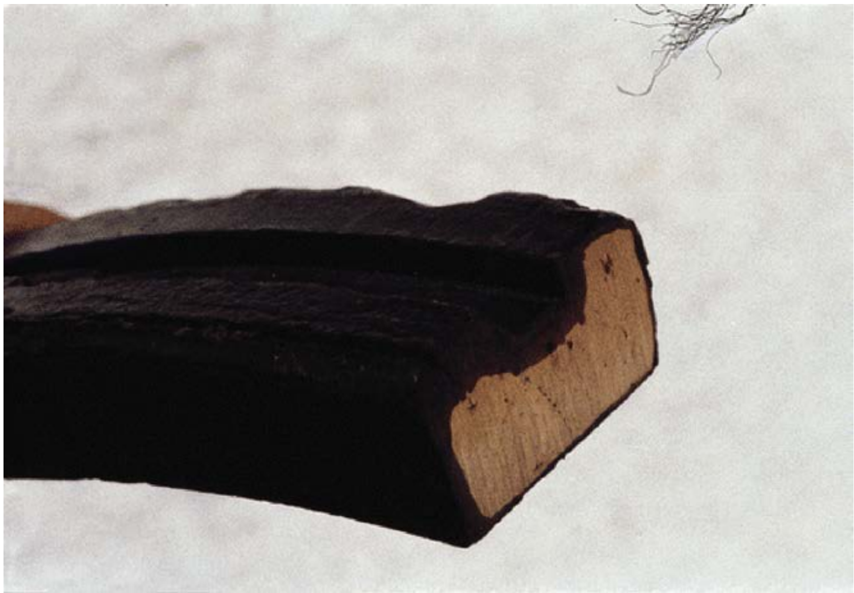
APPEARANCE	Internal: erosion corrosion to the point of leakage; external: uniform attack; with blue corrosion products (see also Case History 06.13.10.01).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Ammonium-containing boiler water (6 ppm NH_4^+), originating from ammonium in make-up water (from own well water supply).
CAUSE	Corrosion of bronze valve by ammonia together with oxygen in the boiler water. Upon leakage, boiler water escaped and caused salt deposition (blue color due to the formation of a copper–ammonia complex).
REMEDY	Replacement of the bronze valve by a stainless steel valve, or use of ammonium-free make-up water.

CORROSION ATLAS

CASE HISTORY

06.01.16.01

MATERIAL	Admiralty brass.
SYSTEM	Boiler feedwater system.
PART	Feedwater pump component (13.8 by 1.3 cm).
PHENOMENON	Selective leaching (layer-type dezincification, see also Case 06.20.16.01).



APPEARANCE	A copper layer wrapping around the brass inner of the component.
TIME IN SERVICE	The pump had been in service for 12 years, but the failure was discovered after a 3-month outage.
ENVIRONMENT	Contaminated boiler feedwater due to leaking condensers; temperature: 144 °C.
CAUSE	Probably high chloride concentration during prolonged outage (see also Case History 06.06.16.01).
REMEDY	Condenser leakage repaired (condenser replaced).

CORROSION ATLAS

CASE HISTORY

06.01.16.02

MATERIAL	Cupronickel (70/30).
SYSTEM	Boiler feedwater system.
PART	Horizontal inlet first pass of high-pressure feedwater heater (OD 1.6 cm).
PHENOMENON	Selective leaching (denickelification).

APPEARANCE	Exfoliation at the outside where sheets are peeling off, with 15% reduction of the wall thickness.
TIME IN SERVICE	7 years (the corrosion took place during the last 2 years).
ENVIRONMENT	Boiler feedwater.
CAUSE	Feedwater heater tubes were thinned by cyclic oxidation followed by reduction of oxides in service. During the previous 2 years, the boiler had experienced frequent outages during which air leaked into the heater shell and caused surface oxidation. Conversion of oxide to elemental copper occurred during normal operation.
REMEDY	• Outages should be as short as practical. • Air contact should be prevented by steam or nitrogen blanketing. • The boiler feedwater heater could be constructed of carbon steel.

CORROSION ATLAS

CASE HISTORY

06.01.32.01

MATERIAL	Copper.
SYSTEM	Heat exchanger of hot water system.
PART	Heating tubes.
PHENOMENON	Erosion (impingement attack).

APPEARANCE	Deep dents, always at the same sites (on the steam side).
TIME IN SERVICE	7 months.
ENVIRONMENT	Steam (around the pipes).
CAUSE	Presence of water in the steam caused impingement attack by water droplets on the surface of the copper tubes facing the steam inlet nozzle (even after replacement of the tubes, this damage reappears at the same sites) (see also Case History 06.02.32.02).
REMEDY	Installation of a drain with steam trap immediately upstream of the steam feed regulator of the heat exchanger.

CORROSION ATLAS

CASE HISTORY

06.01.32.02

MATERIAL	Copper.
SYSTEM	Sterilizer.
PART	Steam vent pipe.
PHENOMENON	Erosion.

APPEARANCE	Roughened surface of bare copper.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Steam with water droplets. Steam pressure 2.5 bar.
CAUSE	Erosion due to excessive velocity combined with droplets in the steam.
REMEDY	• Bend section was dimensioned larger and water droplets were drained away by a steam trap. • Alternative: construct of a less erosion-sensitive material, e.g., stainless steel.

CORROSION ATLAS

CASE HISTORY

06.01.34.01

MATERIAL	Bronze.
SYSTEM	Boiler-feed system.
PART	Impeller of feedwater pump.
PHENOMENON	Erosion corrosion.

APPEARANCE	The material wore away until it was paper-thin and then crumbled away.
TIME IN SERVICE	2 years.
ENVIRONMENT	Deaerated feedwater, temperature 105 °C.
CAUSE	Feedwater was contaminated with ammonia which, in the presence of (traces of) oxygen, attacks copper and copper alloys. Together with the high velocity of the feedwater in the pump, this caused erosion corrosion (see also Case History 06.11.34.01).
REMEDY	Because the ammonia contamination in the feedwater was unavoidable, the impeller was constructed of nickel cast iron.

CORROSION ATLAS

CASE HISTORY

06.02.02.01

MATERIAL	Copper.
SYSTEM	Steam condensate system of air conditioning installation with steam humidification.
PART	Condensate pipe.
PHENOMENON	Carbonic acid corrosion.

APPEARANCE	Uniform corrosion.
TIME IN SERVICE	10 years.
ENVIRONMENT	Corrosive oxygen-containing condensate; temperature 90–100 °C (low-pressure steam is produced by steam generators fed with softened, non-deaerated water; heating medium: hot water at 150 °C).
CAUSE	Copper is not resistant to corrosive oxygen-containing condensate (see also Case History 06.02.02.02).
REMEDY	Deaeration of the feedwater. Alternatives: dosing of sodium sulfite as oxygen scavenger, or alkalinity reduction of the make-up water. In the present case, however, in view of the small quantity of condensate it was decided to discharge the condensate to the nearest sewer instead of recycling it to the boiler house via a new, long copper line.

CORROSION ATLAS

CASE HISTORY

06.02.02.02

MATERIAL	Copper.
SYSTEM	Steam condensate system.
PART	Condensate pipe extremity.
PHENOMENON	Carbonic acid corrosion.

APPEARANCE	Severe irregular attack.
TIME IN SERVICE	About $1\frac{1}{2}$ years.
ENVIRONMENT	Corrosive oxygen-containing condensate, about 90 °C; boiler fed with deaerated feedwater (mixture of softened make-up water and condensate).
CAUSE	Copper is well resistant to carbonic acid or oxygen alone in the condensate, but not to the combination of these two gases.
REMEDY	In view of the limited length of the condensate line, it was decided to construct it of stainless steel (AISI 304) (under different conditions, alkalinity reduction of the make-up water may be preferable).

CORROSION ATLAS

CASE HISTORY

06.02.10.01

MATERIAL	Admiralty brass.
SYSTEM	Steam condensate system.
PART	Condenser tube (OD: 2.54 cm).
PHENOMENON	Ammonia corrosion.

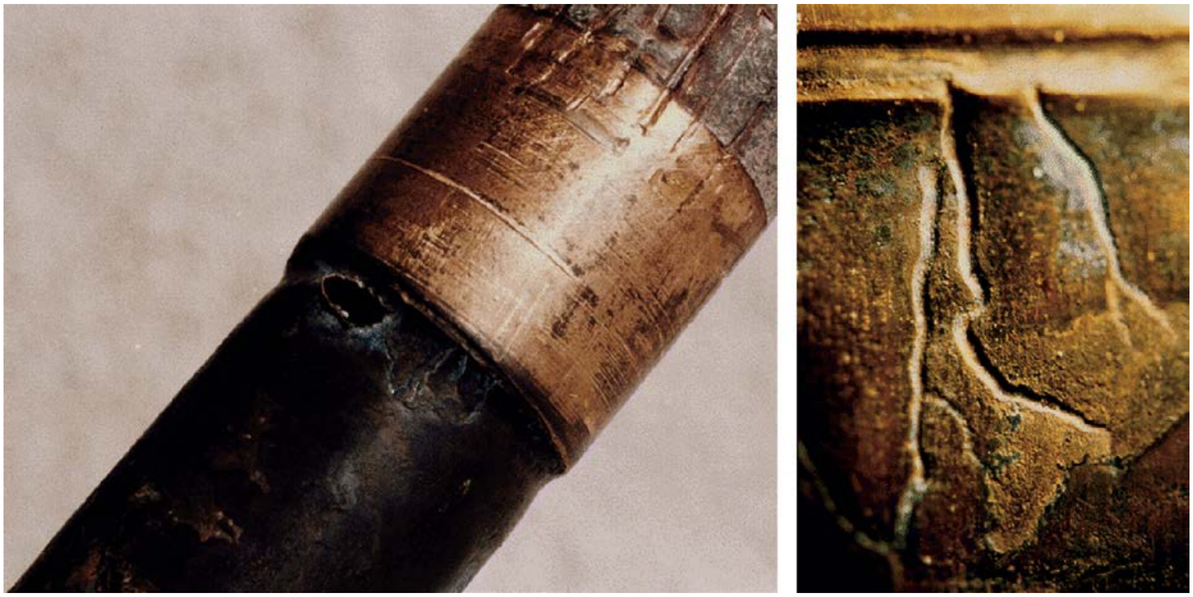
APPEARANCE	General attack with fine grooves.
TIME IN SERVICE	18 months since last inspection, which found no significant damage.
ENVIRONMENT	Ammonia-containing steam.
CAUSE	Wastage took place by condensing ammonia-containing steam. The ammonia was produced by breakdown of hydrazine and carry-over in steam (see also next Case History).
REMEDY	Start-up procedures were improved and gas venting increased in air removal section of exchangers.

CORROSION ATLAS

CASE HISTORY

06.02.10.02

MATERIAL	Admiralty brass.
SYSTEM	Steam condensate system (low-pressure turbine condenser).
PART	Inlet just outside tube sheet (OD 2.5 cm).
PHENOMENON	Ammonia corrosion.



APPEARANCE	Severe grooving in the direction of gravity. A thin dark oxide layer, replaced in places by a dark green patina.
TIME IN SERVICE	14 years.
ENVIRONMENT	Saturated steam 41–54 °C. Analysis: During normal service: NH_3 <0.3 ppm, pH 8.7–9.0, dissolved oxygen 10–20 ppb; during start-up (once or twice a year): NH_3 up to 75 ppm, pH 8.7–9.4, dissolved oxygen up to 3500 ppb, hydrazine 10–20 ppb.
CAUSE	Wastage was caused by condensate containing high concentrations of ammonia, carried over in steam from boiler-water treatment. The ammonia-rich condensate ran down the tube sheet and collected at tube ends, causing pronounced localized wastage.
REMEDY	Basically, improve gas removal during start-ups. Much damage is caused during start-ups, when NH_3 concentrations may exceed several hundred parts per billion.

CORROSION ATLAS

CASE HISTORY

06.02.10.03

MATERIAL	Copper.
SYSTEM	Steam condensate system (carpet drying tubes).
PART	Horizontal condensate line.
PHENOMENON	Ammonia corrosion.

APPEARANCE	Severe internal general thinning along the bottom of the pipe.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Ammonia-containing condensate; temperature 54–71 °C; pH >9.5.
CAUSE	The ammonia in the condensate caused general attack of the copper condensate lines. Ammonia was carried over from boiler-water treatment chemicals.
REMEDY	Start-up procedures were improved and gas venting increased in air removal section of exchangers.

CORROSION ATLAS

CASE HISTORY

06.02.18.01

MATERIAL	Aluminum brass (Cu 2 Al Mn).
SYSTEM	Turbine condenser.
PART	Bolt.
PHENOMENON	Stress-corrosion cracking (transgranular).

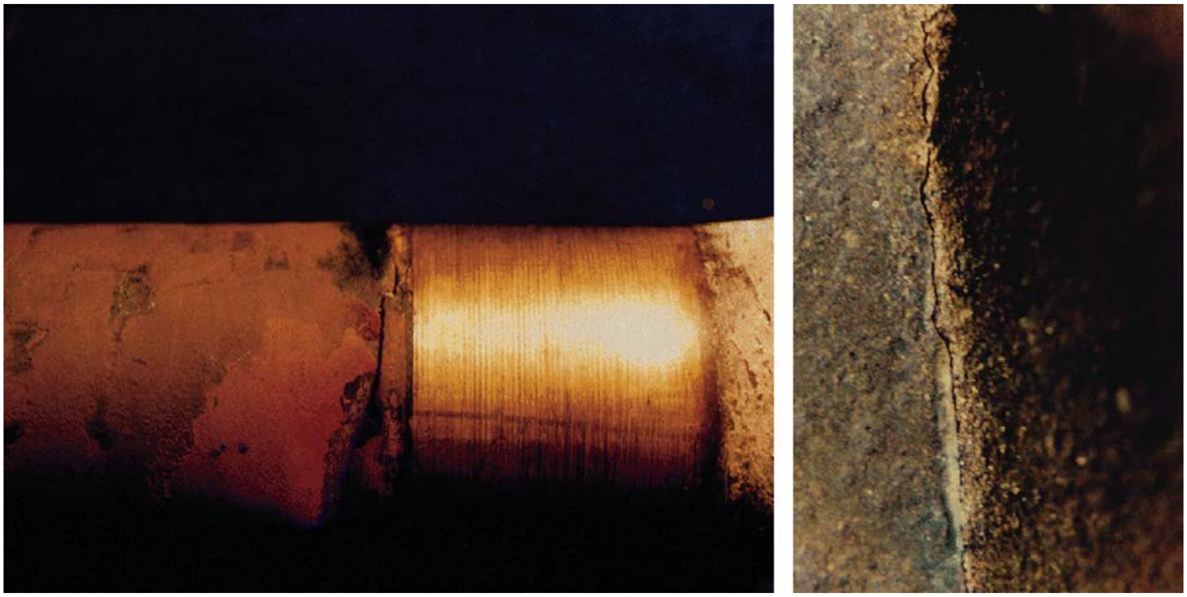
APPEARANCE	Brittle fracture plane.
TIME IN SERVICE	$3\frac{1}{2}$ years.
ENVIRONMENT	Condensing steam with traces of ammonia.
CAUSE	In combination with present material stresses, ammonia leads to stress-corrosion cracking in brass (season cracking) (see also Case Histories 06.06.18.01, 06.15.18.01, and 06.25.18.01).
REMEDY	Construct the bolts from a material that is not susceptible to ammonia attack, e.g., stainless steel.

CORROSION ATLAS

CASE HISTORY

06.02.28.01

MATERIAL	Admiralty brass (inhibited).
SYSTEM	Steam condensate system.
PART	Inlet end condenser tube (OD 2.5 cm).
PHENOMENON	Corrosion fatigue.



APPEARANCE	Circumferential crack adjacent to location of tube sheet. Microprint (magnification ×33) shows straight unbranched crack.
TIME IN SERVICE	25 years (the failure had occurred in a much shorter time).
ENVIRONMENT	Internal: circulating cooling water pH 7.8–8.2. External: Steam and condensate treated with an oxygen scavenger and ammonia, pH 7.8–9.2, temperature ambient to 66 °C.
CAUSE	The condenser had lastly been in cyclic service. Microstructural examinations revealed straight, unbranched transgranular cracks, typical of corrosion fatigue. The cracks originated on the external surface where the corrosion was superficial. In view of the circumferential appearance of the crack, the cyclic stresses responsible for this failure were apparently bending stresses, associated with cyclic thermal expansion and contraction (for longitudinal fatigue crack in copper, see Case History 06.06.28.01).
REMEDY	Eliminate cyclic stresses by avoiding cyclic service.

CORROSION ATLAS

CASE HISTORY

06.02.32.01

MATERIAL	Copper.
SYSTEM	Steam condensate system.
PART	Condensate pipe.
PHENOMENON	Erosion (deformation by water hammer).

APPEARANCE	Bulging material, worn to the point of leaking.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Condensate at 90–100 °C.
CAUSE	Installation error: equal-diameter pipes were connected by reducing the diameter of one pipe by means of hammering. External deformation due to water hammer until leakage occurred. This is obviously a case of poor workmanship (see also Case Histories 06.01.32.01 and 06.02.32.01).
REMEDY	Assembly by means of socket connection.

CORROSION ATLAS

CASE HISTORY

06.02.32.02

MATERIAL	Admiralty brass.
SYSTEM	Turbine steam condensate system (pressure 5.9 MPa).
PART	Horizontal condenser tube (OD 1.9 cm).
PHENOMENON	Erosion (impingement attack).

APPEARANCE	A pattern of erosion spots on the external surface facing the turbine exhaust inlet. The close-up (magnification ×7.5) shows a small forest of erosion cones.
TIME IN SERVICE	15 years.
ENVIRONMENT	Internal: cooling water treated with phosphate, dispersant, and bleach; temperature 21–38 °C, pH 6.8–7.2. External: Steam and condensate, pH 8.0.
CAUSE	Erosion was caused by the impingement of high-velocity steam probably mixed with droplets of condensate. The tube had been removed from a position directly in line with the turbine exhaust inlet. The circular, equally spaced erosion sites apparently reproduced corresponding equally spaced circular openings in the exhaust inlet (see also Case History 06.01.32.01).
REMEDY	• Separate moisture from the steam before it enters the condenser (mechanically or by means of pressure reduction, which causes superheating). • Install a deflector shield to protect the area experiencing corrosion. • Specify metals that are more resistant to erosion, such as cupronickel, Monel, or stainless steel.

CORROSION ATLAS

CASE HISTORY

06.02.34.01

MATERIAL	Copper.
SYSTEM	Steam condensate system (0.15 MPa).
PART	Bends in heating tubes of hot water storage boiler.
PHENOMENON	Erosion corrosion.

APPEARANCE	Grooved attack.
TIME IN SERVICE	$1\frac{1}{2}$ to 2 years.
ENVIRONMENT	Steam–condensate mixture, corrosive due to the presence of carbon dioxide (130 ppm).
CAUSE	The combination of corrosive condensate and strong turbulence in the bends (local high velocity) (see also next case).
REMEDY	• The cheapest solution was found to be constructing the heating tubes of AISI 316 stainless steel, which is resistant to carbon dioxide. • Alternatives: copper tubes with straight pipes, reversal of media, alkalinity reduction of make-up water (dosing of chemicals into the steam was impossible in view of the steam used).

CORROSION ATLAS

CASE HISTORY

06.02.34.02

MATERIAL	Copper.
SYSTEM	Condensate system.
PART	Bend section.
PHENOMENON	Erosion corrosion.

APPEARANCE	Pipe wall totally eroded away locally.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Aggressive condensate.
CAUSE	Erosion corrosion was caused by the combination of high velocity and aggressiveness (see also former case).
REMEDY	• Reduce condensate aggressiveness by means of appropriate boiler feedwater treatment (dealkalization and deaeration). • New copper bend sections should be dimensioned larger, or • Replace copper pipes with stainless steel pipes.

CORROSION ATLAS

CASE HISTORY

06.04.10.01

MATERIAL	Copper.
SYSTEM	Central heating water system.
PART	Thermometer bulb.
PHENOMENON	Ammonia corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hot softened water, 70–90 °C, to which hydrazine was added as an oxygen scavenger.
CAUSE	The presence of ammonia in the water, originating from the partial decomposition of hydrazine, in addition to traces of oxygen. Oxygen accelerates the attack of copper and copper alloys by ammonia (see also Case Histories 06.02.10.01/02).
REMEDY	Combining the make-up and the hydrazine dosing, thereby preventing the presence of oxygen in the system water.

CORROSION ATLAS

CASE HISTORY

06.04.16.01

MATERIAL	Brass (>20% Zn).
SYSTEM	Central heating system.
PART	Temperature sensor tube.
PHENOMENON	Selective leaching (layer type dezinkification).

APPEARANCE	Above: tube covered with bluish-black coating (1–1.5 mm thick). Center: tube with bluish-back coating tapped off. Below: the bluish-black coating that surrounded the tube like a shell.
TIME IN SERVICE	13 years.
ENVIRONMENT	Central heating water at 70–90 °C. Analysis: pH 9.4, conductivity 46.4 mS/m, chloride 122 ppm. Deposit: 87% CuO; 8.2% Fe_3O_4.
CAUSE	Deposition of the more noble magnetite on the brass pipe caused dezinkification, with the formation of a nonadhesive layer of copper oxide and iron oxide on the surface. The magnetite originates from the steel line work.
REMEDY	Construct the tubes of copper.

CORROSION ATLAS

CASE HISTORY

06.04.16.02

MATERIAL	Brass (35% Zn–Cu).
SYSTEM	Hot-water heating system in commercial building.
PART	Horizontal pipe.
PHENOMENON	Selective leaching (dezincification).

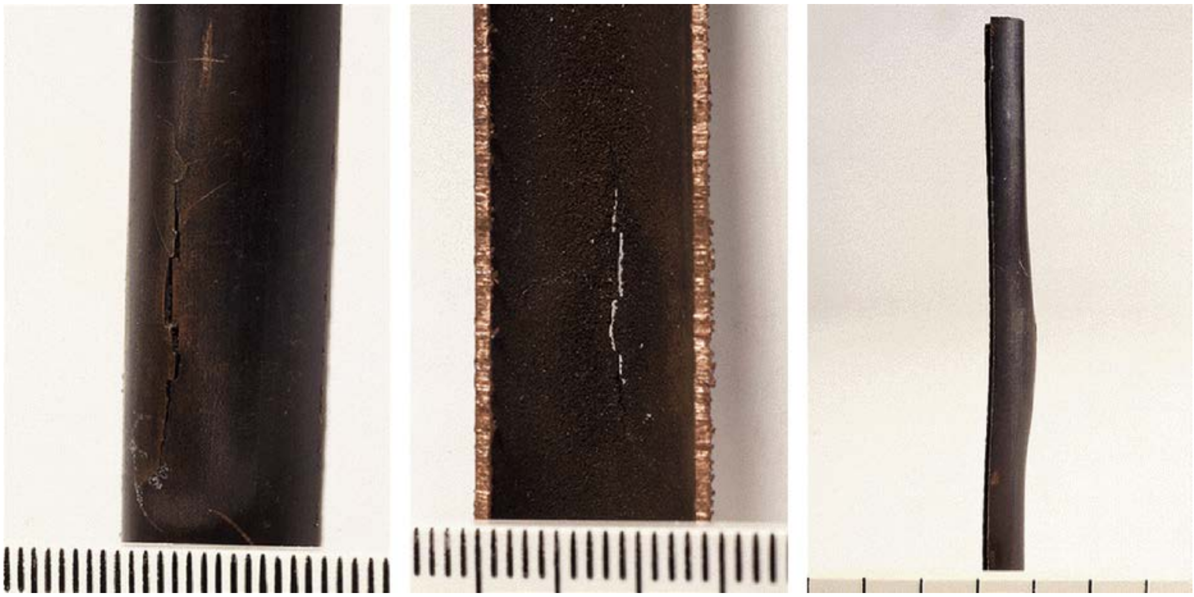
APPEARANCE	Plug-type dezincification beneath a deposit.
TIME IN SERVICE	>60 years.
ENVIRONMENT	Untreated city water with high hardness and silica content; temperature 49–66 °C.
CAUSE	Brass is sensitive to dezincification under deposits. Deposits were disloged in a vertical adjoining pipe and came to rest on the bottom surface of the pipe. Also, two phase brasses, not inhibited, are more susceptible to dealloying (see also Case History 06.05.16.03).
REMEDY	• Prevent deposit formation by improved water treatment or by maintaining higher flow rate, or • Replace with inhibited brass and/or copper.

CORROSION ATLAS

CASE HISTORY

06.04.32.01

MATERIAL	Copper.
SYSTEM	Central heating system.
PART	Tube section (15 mm Ø OD; 1 mm wall thickness) from the upper tube of a horizontal bank in heat exchanger.
PHENOMENON	Erosion (deformation by water hammer).



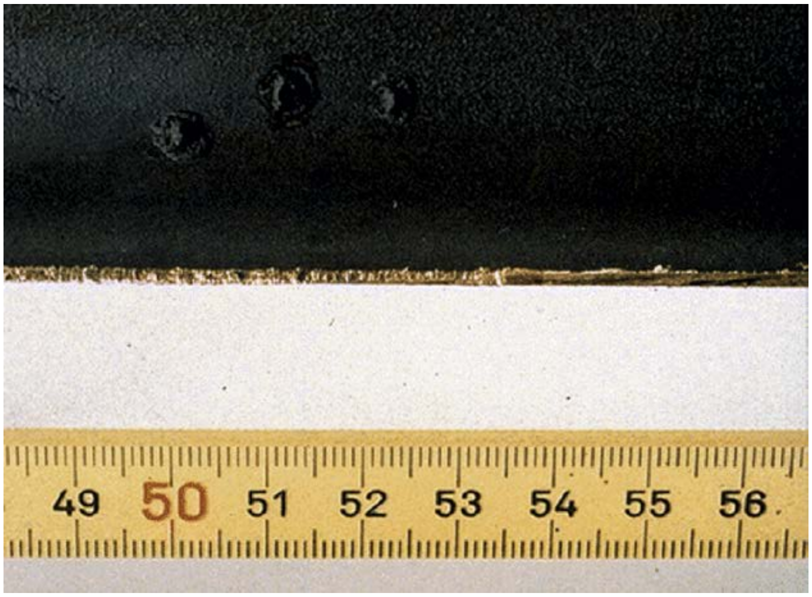
APPEARANCE	Bulging with cracking starting from inside; photographs on the left and in the middle: cracking outside and inside; photograph on the right: bulging outside.
TIME IN SERVICE	1–3 months.
ENVIRONMENT	Around the tubes, system water heated from 70 °C to 90 °C. Through the tubes, steam at 0.25 MPa and 135 °C.
CAUSE	On the steam side, the heat exchanger is controlled by a motorized on/off valve in response to the temperature of the outflowing water. The condensate is discharged to the condensate system via a steam trap below the heat exchanger. When the valve in the steam delivery line is closed, the pressure in the tube bundle is reduced to vacuum so that condensate is drawn in from the condensate circuit and water hammer occurs in the upper tubes.
REMEDY	Fit a self-closing return valve in the condensate discharge line downstream from the steam trap.

CORROSION ATLAS

CASE HISTORY

06.05.02.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Pitting by copper-aggressive water.



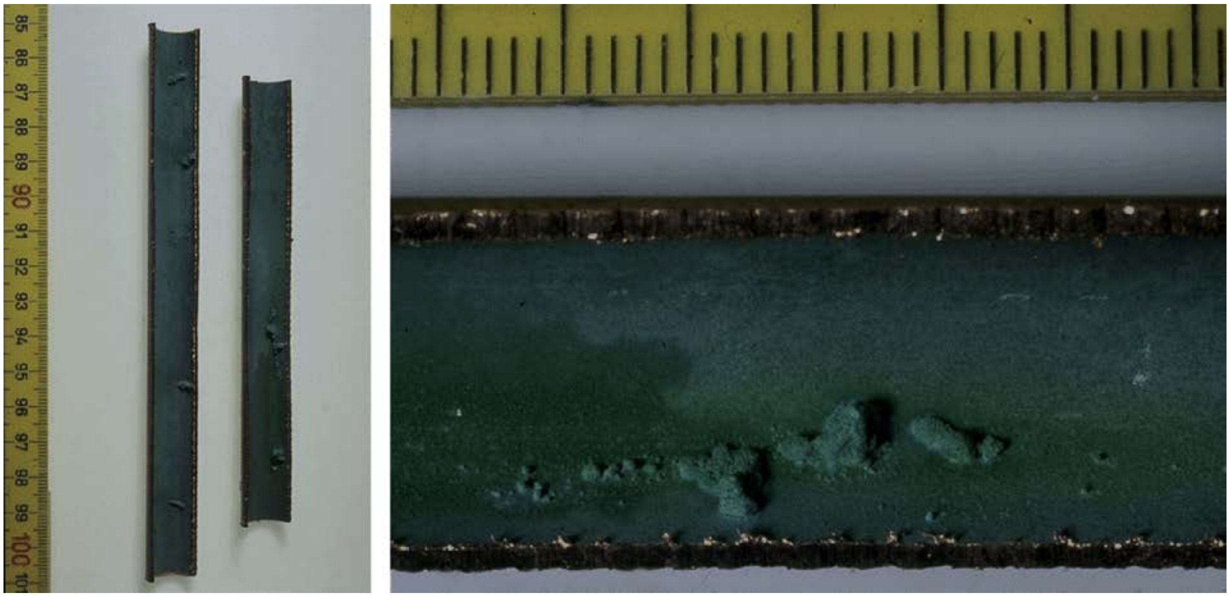
APPEARANCE	Pitting attack underneath corrosion nodules.
TIME IN SERVICE	8 years.
ENVIRONMENT	Flowing hot water, 70 °C; pH 6.8–7.2; HCO_3^- 0.3–2 mEq/l (15–100 ppm $CaCO_3$); Cl^- 100–220 ppm; SO_4^{2-} 5–80 ppm
CAUSE	The present water type leads to type II pitting corrosion of copper in hot water >60 °C. In relation to the quantities of sulfate and chloride and the pH, the water has too low a content of bicarbonate (see also next case).
REMEDY	• Chemical cleaning of the system for removing the corrosion products. • Increasing the water hardness by the admixture of different water or by filtration over activated dolomite.

CORROSION ATLAS

CASE HISTORY

06.05.02.02

MATERIAL	Copper.
SYSTEM	Cold and hot tap water system.
PART	Pipes.
PHENOMENON	Pitting by copper-aggressive water.



APPEARANCE	Pitting corrosion underneath corrosion nodules only at the upper side in pipes often containing standing water.
TIME IN SERVICE	8 months to 2 years (leakages).
ENVIRONMENT	Deferrized well water, saturated with oxygen. pH 7.5; aggressive CO_2 7 ppm; total hardness 4.8 mEq/l (240 ppm $CaCO_3$); m-alkalinity 2.88 mEq/l (144 ppm $CaCO_3$); chloride 36 ppm; sulfate 76 ppm, and nitrate 142 ppm Organic material absent. Temperature around 20 °C.
CAUSE	Type I corrosion due to the present water composition, initiated by oxygen bubbles originating from the standing water. The corrosion products consisted of malachite and atakamite. Calcium carbonate was also present (see also former case).
REMEDY	• Assure as far as possible sufficient flow through the lines, with improvement of the water composition (increased pH and decreased O_2 content), or • Replace by mains water (no problems with copper pipes, according to local experience), or • Use plastic pipes.

CORROSION ATLAS

CASE HISTORY

06.05.05.01

MATERIAL	Copper.
SYSTEM	Drinking water system.
PART	Underground pipeline.
PHENOMENON	Sulfide corrosion.

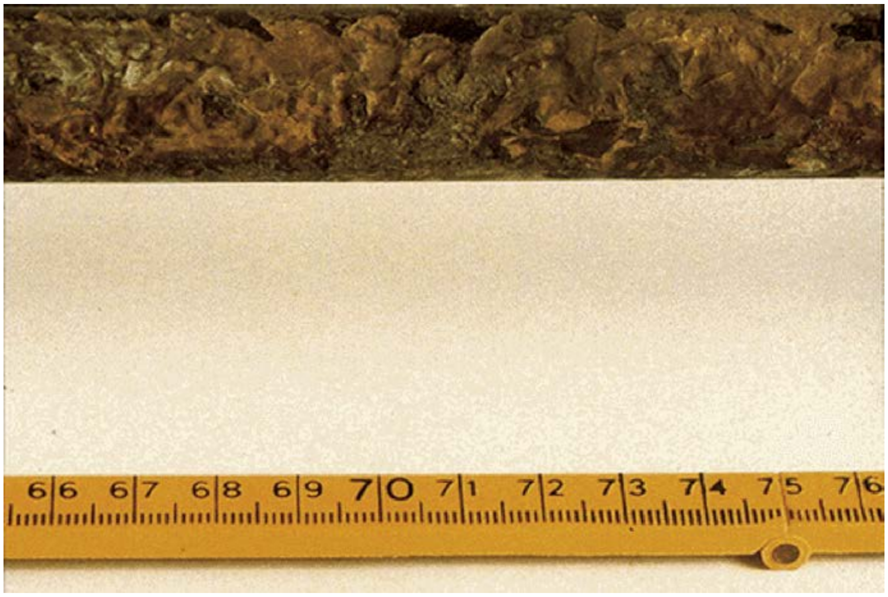
APPEARANCE	Irregular general attack, with black corrosion products.
TIME IN SERVICE	5 years.
ENVIRONMENT	H_2S-containing groundwater.
CAUSE	Copper is attacked by sulfide, with the formation of black copper sulfide (CuS).
REMEDY	Use of impermeable plastic pipe.

CORROSION ATLAS

CASE HISTORY

06.05.10.01

MATERIAL	Copper.
SYSTEM	Drinking water system.
PART	Pipe.
PHENOMENON	Ammonia corrosion.



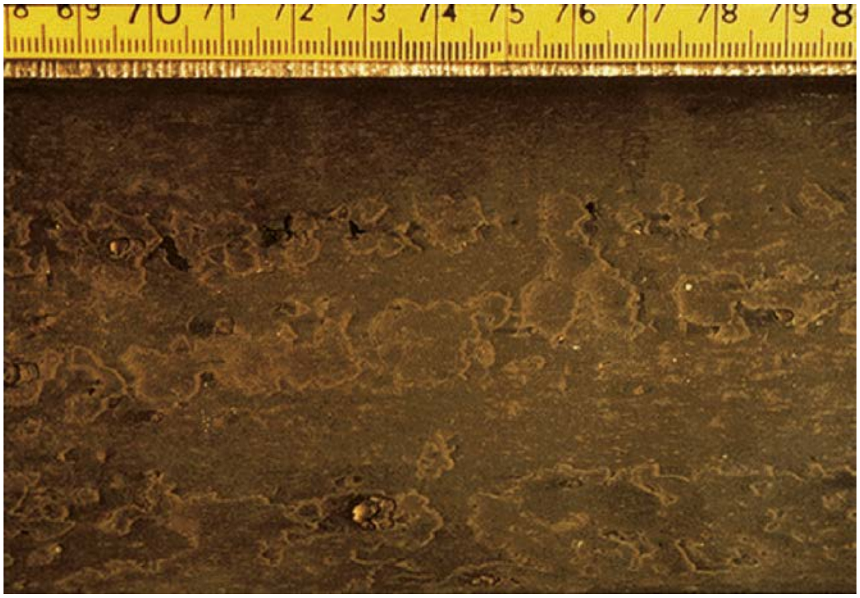
APPEARANCE	Blotchy blue-green appearance due to irregular attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Atmosphere in cow-shed.
CAUSE	Ammonia originating from cow manure attacks copper (see also Case History 06.13.10.01).
REMEDY	Use of impermeable plastic pipe.

CORROSION ATLAS

CASE HISTORY

06.05.14.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Circulation pipe.
PHENOMENON	Galvanic corrosion.



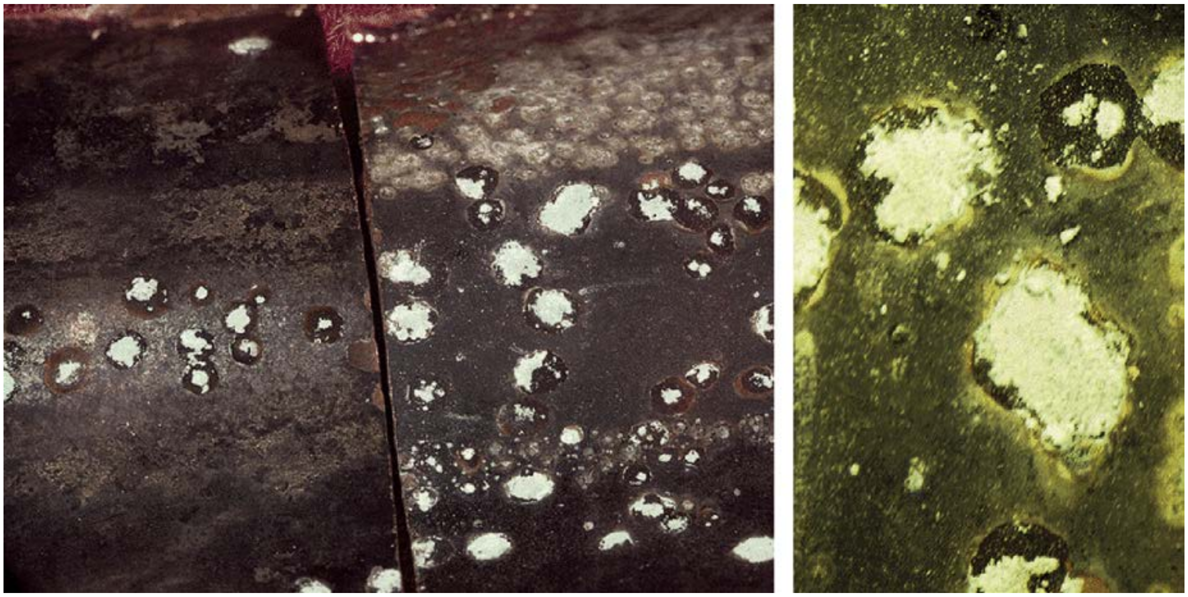
APPEARANCE	Pitting attack.
TIME IN SERVICE	6 years.
ENVIRONMENT	Circulating oxygen-containing hot tap water; temperature 80 °C; pH 7.5; chloride (Cl^-) 38 ppm; bicarbonate (HCO_3^-) 4.2 mEq/l (210 ppm $CaCO_3$).
CAUSE	Damage to the oxide skin by air bubbles (erosion) followed by galvanic corrosion due to local Cu/Cu_2O cell formation.
REMEDY	• Fit an air vent on the hot water storage tank, or • Construct the circulation pipe of AISI 316 L stainless steel.

CORROSION ATLAS

CASE HISTORY

06.05.14.02

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Circulation pipe.
PHENOMENON	Galvanic corrosion (deposition corrosion).



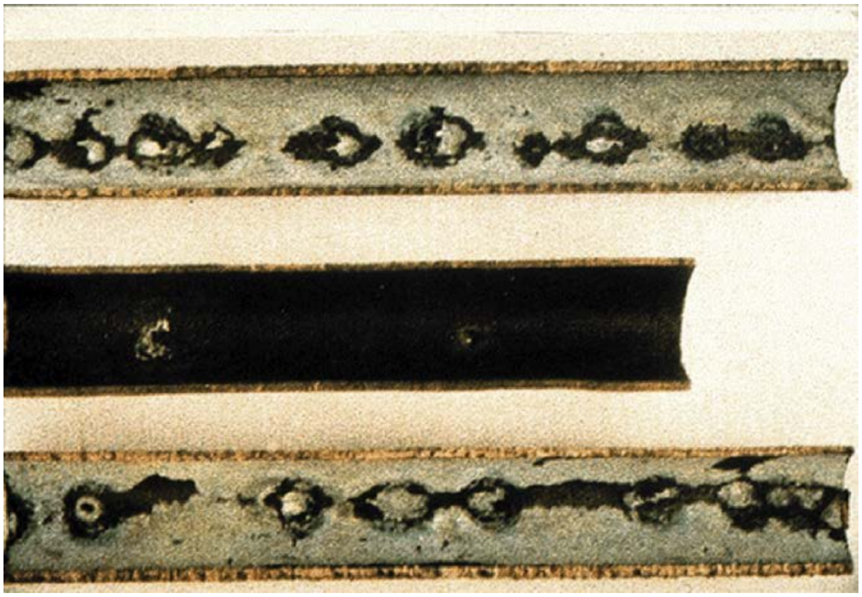
APPEARANCE	Little pits covered with black, green, and blue white deposits and corrosion products.
TIME IN SERVICE	Unknown.
ENVIRONMENT	City water, 60 °C.
CAUSE	Deposition corrosion caused by deposit of graphite, liberally used as lubricant during the construction of the system. The presence of graphite is explicitly shown by the energy dispersive X-ray (EDX) analysis of the corrosion products (performed by HMC Technology, Leiden, the Netherlands).
REMEDY	Degreasing and cleaning the system. Do not use graphite-containing materials in copper systems.

CORROSION ATLAS

CASE HISTORY

06.05.15.01

MATERIAL	Copper.
SYSTEM	Cold tap water system
PART	Pipe section.
PHENOMENON	Underdeposit corrosion.



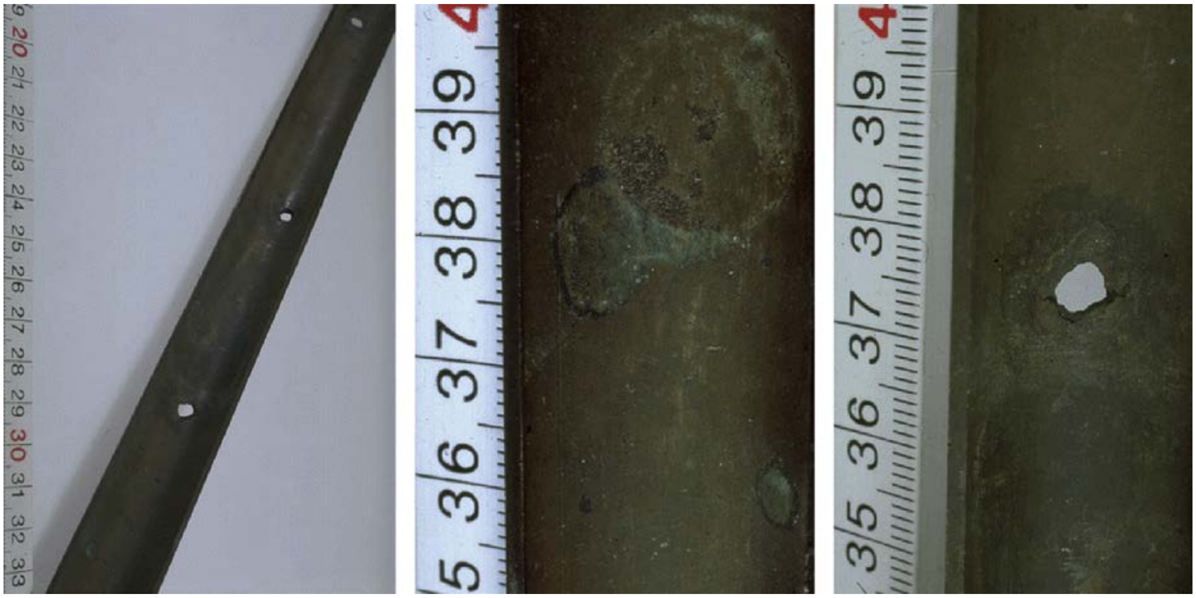
APPEARANCE	Pitting attack.
TIME IN SERVICE	9 months.
ENVIRONMENT	Aggressive mains water (originating from well water).
CAUSE	The system, originally constructed of galvanized steel, had to be replaced after 2 years as a result of serious corrosion by the aggressive mains water, and it was then constructed of copper. The subsequent pitting corrosion of the copper indoor pipe was caused by deposition of iron oxide originating from the upstream steel pipes of the urban water pipeline network. Underneath the iron oxide deposit, the copper surface will become anodic. (See also Case Histories 06.05.15.02/03/04 and 06.06.15.01/02).
REMEDY	• Installation of filters to catch rust particles >0.01 mm. • Elimination of the corrosion in the steel mains water pipes by neutralization of the well water.

CORROSION ATLAS

CASE HISTORY

06.05.15.02

MATERIAL	Aluminum brass (arsenic-containing).
SYSTEM	Drinking water distribution system.
PART	Pipe.
PHENOMENON	Underdeposit corrosion.



APPEARANCE	Pitting attack.
TIME IN SERVICE	1 year.
ENVIRONMENT	Mains water, composition: unknown. Temperature: 10–20 °C. Flow rate: 15 cm/sec.
CAUSE	Due to the low flow rate, rust particles settled out as a result of which the brass was attacked by the formation of differential aeration cells.
REMEDY	The pipe was replaced and the flow rate raised to 1 m/sec.

CORROSION ATLAS

CASE HISTORY

06.05.15.03

MATERIAL	Copper (Cu-ETP).
SYSTEM	Drinking water system.
PART	Indoor pipe.
PHENOMENON	Underdeposit corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	15 years.
ENVIRONMENT	Cold flowing drinking water.
CAUSE	Contamination of the surface of the copper pipes causes the formation of active corrosion cells. Electrolytic tough pitch copper is more sensitive for pitting than deoxidized copper.
REMEDY	• Use a pipe made of deoxidized high-residual phosphorus copper (Cu-DHP), which is less sensitive to pitting, and • Take measures to prevent contamination of the pipes.

CORROSION ATLAS

CASE HISTORY

06.05.15.04

MATERIAL	Copper.
SYSTEM	Hot water system.
PART	Pipe.
PHENOMENON	Underdeposit corrosion.

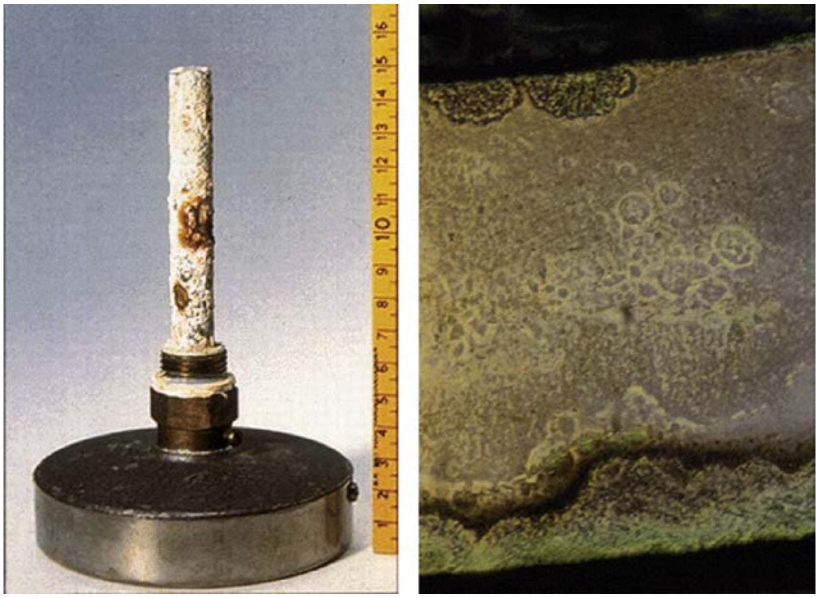
APPEARANCE	Local uniform attack at underside of the horizontal pipe (after blasting).
TIME IN SERVICE	17 years.
ENVIRONMENT	Deferrized well water at 80 °C.
CAUSE	Ineffective deferrizing procedure allowed deposition of iron oxide (Fe_2O_3) on the underside of the pipe. Differential aeration led to the formation of galvanic cell, attacking the copper underneath the deposit (see also the preceding three cases).
REMEDY	Optimize the performance of the deferrizing installation.

CORROSION ATLAS

CASE HISTORY

06.05.16.01

MATERIAL	Brass.
SYSTEM	Copper-lined hot water storage boiler with copper tubes.
PART	Thermometer bulb.
PHENOMENON	Selective leaching (plug-type dezincification).



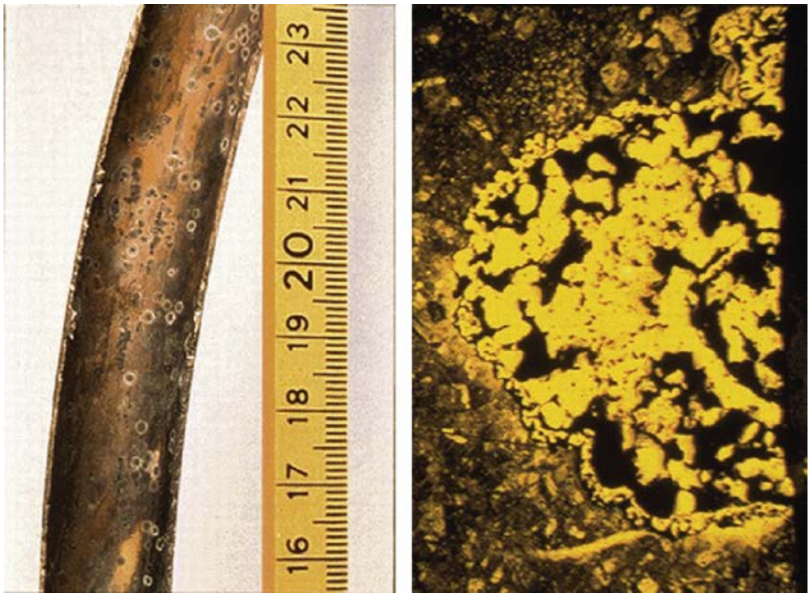
APPEARANCE	Pitting underneath white deposition.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hot tap water, 60 °C, with hardness sediment.
CAUSE	Dezincification of the brass occurs underneath the formed deposit and is additionally promoted by the potential difference between copper and brass (see also the next three cases).
REMEDY	Use of copper bulb.

CORROSION ATLAS

CASE HISTORY

06.05.16.02

MATERIAL	Brass.
SYSTEM	Mains water system.
PART	Tap component.
PHENOMENON	Selective leaching (plug-type dezincification).



APPEARANCE	Pitting attack.
TIME IN SERVICE	Approximately 1 year.
ENVIRONMENT	Mains water with a low bicarbonate content (0.4 mEq/l; 20 ppm $CaCO_3$).
CAUSE	Copper-aggressive water caused dezincification of the brass taps (the copper pipes were also attacked by pitting corrosion; see also Case Histories 06.05.02.01/02).
REMEDY	Raising the water hardness to a bicarbonate content ≥1.5 mEq/l (75 ppm $CaCO_3$).

CORROSION ATLAS

CASE HISTORY

06.05.16.03

MATERIAL	Brass.
SYSTEM	Hot tap water system.
PART	Valve and pipe sections.
PHENOMENON	Selective leaching (plug-type dezincification).

APPEARANCE	Severe contamination with a white deposit, underneath which the brass was locally red-colored and brittle.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hot water, 70 °C; pH 7.6; bicarbonate (HCO_3^-) 1.8 mEq/l (90 ppm $CaCO_3$); aluminum (Al^{3+}) 2.0 ppm; deposit 90% $Al(OH)_3$.
CAUSE	As a result of deposition of aluminum hydroxide (originating from the cathodic protection present in the boilers owing to aluminum anodes with impressed DC current), severe dezincification of the brass occurred (see also Case History 06.04.16.02).
REMEDY	Cleaning of the system and performing the cathodic protection with inert anodes (e.g., platinum-coated titanium anodes), not only to prevent dezincification of the brass fittings but also to prevent blockage of the pipe system and, from the health point of view, intolerable contamination of the water with aluminum.

CORROSION ATLAS

CASE HISTORY

06.05.16.04

MATERIAL	Brass.
SYSTEM	Drinking water system.
PART	Mixing tap orifice.
PHENOMENON	Selective leaching (plug-type dezincification).

APPEARANCE	Local pitting attack.
TIME IN SERVICE	3 years.
ENVIRONMENT	Drinking water, flowing and standing, varying temperature; pH 7.7; conductivity 62 mS/m; chloride (Cl^-) 61 ppm; bicarbonate (HCO_3^-) 56 mEq/l (280 ppm $CaCO_3$).
CAUSE	In view of the site of the attack, namely near the soldered joint, the attack is most likely attributable to the use of an excessively aggressive solder due to poor workmanship.
REMEDY	Use of an approved solder.

CORROSION ATLAS

CASE HISTORY

06.05.25.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Underground pipe section.
PHENOMENON	Corrosion under insulation.

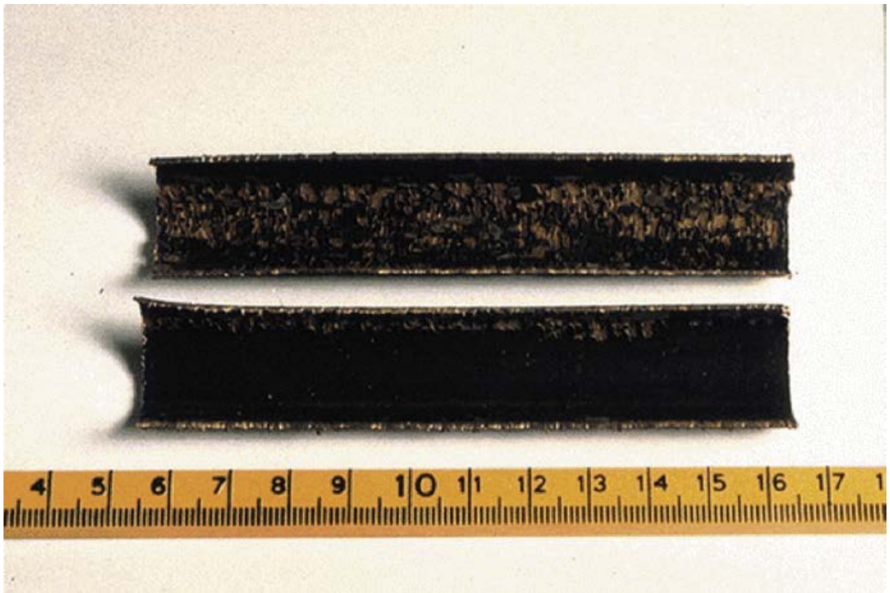
APPEARANCE	Severe local attack to the point of leakage.
TIME IN SERVICE	12 years.
ENVIRONMENT	Wet polyurethane (PUR) foam insulation (pipe lay above the groundwater level).
CAUSE	The insulation became wet as a result of leakage, through a fractured soldered connection; at the prevailing temperature of 80 °C, the fire-retardant substance trichloroethyl phosphate present in the insulation thereby decomposed into phosphoric acid and hydrochloric acid, which attacked the copper pipe.
REMEDY	• Use of PUR without fire-retardant substance or a different insulation. • Application of modern pipe-in-pipe systems which are supplied ready for installation ex-factory, so that in-situ insulation is unnecessary and good water-tight connections can be made.

CORROSION ATLAS

CASE HISTORY

06.05.32.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Pipe section downstream from air vent.
PHENOMENON	Erosion.



APPEARANCE	Material locally worn away over approximately $1\frac{1}{2}$ m.
TIME IN SERVICE	3 months.
ENVIRONMENT	Hot tap water; temperature 70 ˚C.
CAUSE	Partial blockage of the boiler due to hardness deposition caused under pressure in the system; this caused aeration by the air vent; the air bubbles sucked in causing local erosion (see also Case History 06.05.34.02).
REMEDY	• Replacement of the attacked pipe section. • Cleaning the boiler and avoiding future hardness deposition by partial softening of the water. • Maintain constantly sufficient pressure in the whole system.

CORROSION ATLAS

CASE HISTORY

06.05.32.02

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Heat exchanger tube sections.
PHENOMENON	Erosion (impingement attack).

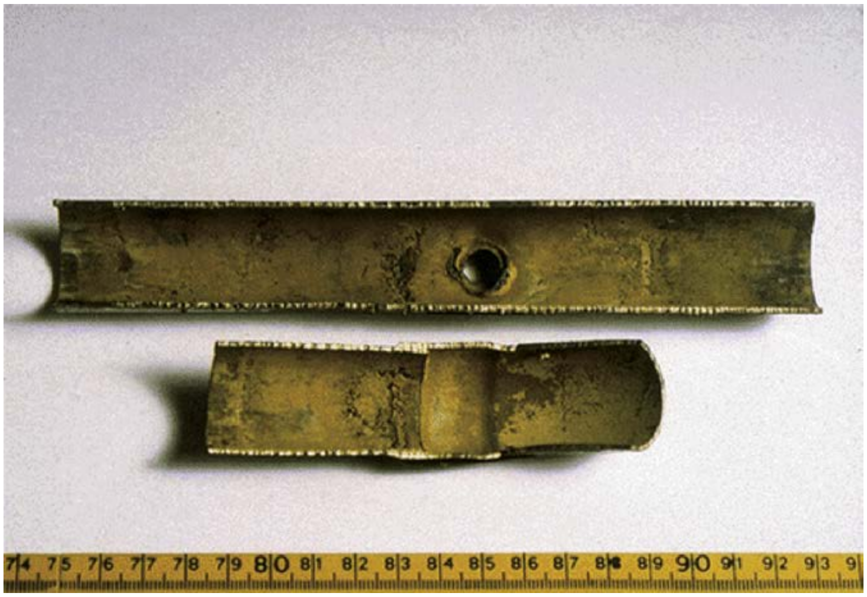
APPEARANCE	Eroded surface.
TIME IN SERVICE	15 years.
ENVIRONMENT	Steam through the tubes; softened tap water (oxygen-rich) around the tubes; temperature 32–55 °C; flow velocity 2 m/s.
CAUSE	The water inlet was set at 90° relative to the tubes, thereby causing impingement.
REMEDY	• Enlarge inflow orifice from 4″ to 6″ to reduce inflow velocity. • Alternative: fit an antisplash plate underneath the inflow orifice.

CORROSION ATLAS

CASE HISTORY

06.05.33.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Cavitation erosion.



APPEARANCE	Local attack downstream of irregularities.
TIME IN SERVICE	10 years.
ENVIRONMENT	Mains water heated to 65 °C.
CAUSE	Eddies owing to irregularities in pipes at connections.
REMEDY	• Reduction of water velocity (≤0.8 m/s) and/or increasing the pressure. • Prevent irregularities at assembly.

CORROSION ATLAS

CASE HISTORY

06.05.34.01

MATERIAL	Copper.
SYSTEM	Hot tap water system.
PART	Pipe section.
PHENOMENON	Erosion corrosion.

APPEARANCE	Attack in a distinct flow pattern (horseshoe attack).
TIME IN SERVICE	5 years.
ENVIRONMENT	Flowing hot tap water; temperature 80 °C; velocity 6 m/s.
CAUSE	Erosion corrosion resulting from excessively high water velocity (see also Case Histories 06.06.34.01/03).
REMEDY	• Replace the pipes by larger-diameter copper pipe, thereby reducing the velocity to ≤0.8 m/s, or alternatively • Construct them of stainless steel.

CORROSION ATLAS

CASE HISTORY

06.05.34.02

MATERIAL	Copper.
SYSTEM	Water transport pipeline.
PART	Bend section.
PHENOMENON	Erosion corrosion.

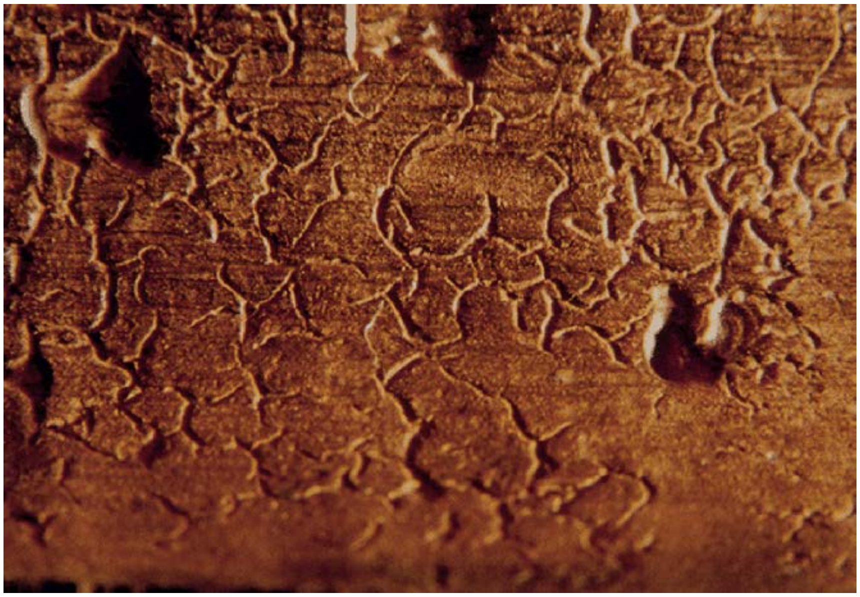
APPEARANCE	Severe internal eroded, particularly at the outside of the bend.
TIME IN SERVICE	1 year.
ENVIRONMENT	Cold deferrized well water; hardness approximately 1 mEq/l (50 ppm $CaCO_3$); CO_2 6 ppm; pH 7.3; conductivity 16 mS/m.
CAUSE	The presence of many air bubbles in the water (“white” water), originating from the pressurized aeration at the iron-removing filters (see also Case History 06.05.32.01).
REMEDY	Installation of a pure water tank downstream of the filters, in which the bubbles can escape.

CORROSION ATLAS

CASE HISTORY

06.06.04.01

MATERIAL	Copper.
SYSTEM	Cooling water system from 6.17 MPa power boiler in a paper mill.
PART	Condenser tube from main condenser.
PHENOMENON	Acid corrosion.



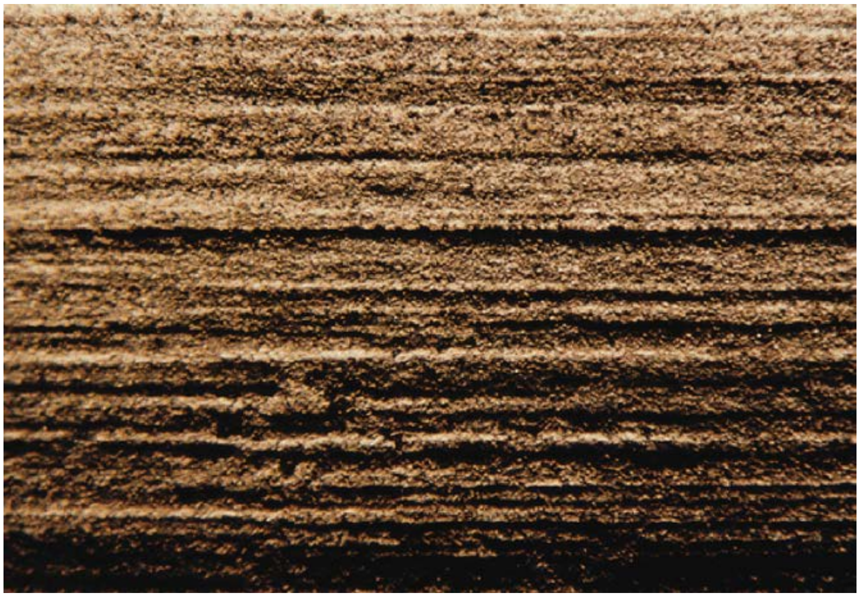
APPEARANCE	Network of shallow ditches.
TIME IN SERVICE	All wastage occurred during one 24-hour cleaning period.
ENVIRONMENT	2–4% hydrochloric acid at 43–66 °C.
CAUSE	Condensation of acidic fluids during acid cleaning. The acid was used to remove calcium carbonate deposits. The resultant foaming prevented complete filling of the topmost tube and allowed dropwise condensation of acids on horizontal surfaces; topmost tubes were not cleaned at all. This indicates lack of experience by the cleaning firm (see also next case and the Case Histories 01.01.04.01/04).
REMEDY	The procedures of proper condenser venting, limiting exposure period, and decreasing acid concentration reduce attack.

CORROSION ATLAS

CASE HISTORY

06.06.04.02

MATERIAL	Admiralty brass.
SYSTEM	Cooling water system for utility main condenser.
PART	Condenser tube.
PHENOMENON	Acid corrosion.



APPEARANCE	Striations on the internal surface (magnification ×15).
TIME IN SERVICE	During one 36-hour cleaning period.
ENVIRONMENT	Hydrochloric acid; 5% by volume at ambient temperature.
CAUSE	Excessive exposure time and high residual stresses. Frequently, deposits are nonuniform. This necessitates excessive cleaning time in order to remove all deposits. Hence, lightly deposited surfaces are exposed to acid for longer periods than are heavily deposited surfaces.
REMEDY	Limit cleaning time.

CORROSION ATLAS

CASE HISTORY

06.06.11.01

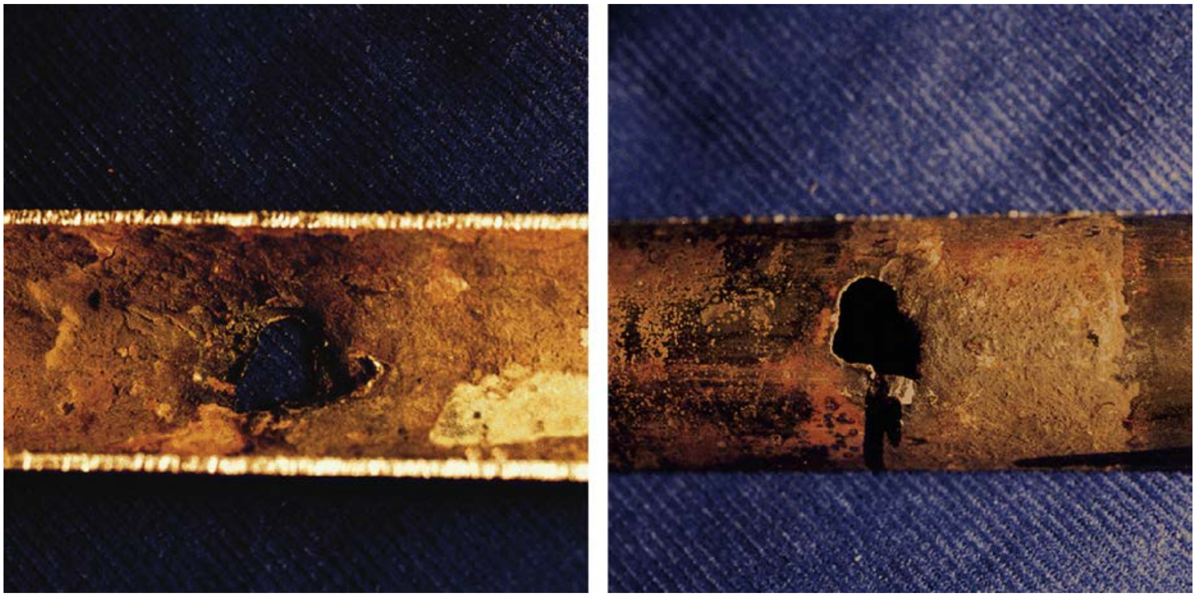
MATERIAL	Copper.
SYSTEM	Once-through compressor cooling system.
PART	Pipe section.
PHENOMENON	Corrosion caused by solder.
	
APPEARANCE	Local attack at the solder joints.
TIME IN SERVICE	1 year.
ENVIRONMENT	Oxygen-containing well water.
CAUSE	In view of the bowl-shaped appearance of the corrosion and the site of the attack (near the solder joints), the presumable cause is corrosion resulting from the use of an incorrect or excessive solder, i.e., a case of poor workmanship (see also Case History 06.15.11.01).
REMEDY	• Replacement of the copper cooling water pipes by plastic pipes was found to be the cheapest solution in this case. • Copper pipes have to be soldered by means of noncorrosive solder.

CORROSION ATLAS

CASE HISTORY

06.06.14.01

MATERIAL	Cupronickel (90/10).
SYSTEM	Once-through cooling-water system.
PART	Horizontal turbine condenser tube (OD 2.2 cm).
PHENOMENON	Galvanic corrosion (by thermogalvanic cell).



APPEARANCE	Perforation originating from the internal surface along the bottom of the tube where it rested on the steel baffle.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Internal: cooling water. External: steam and condensate.
CAUSE	Tube metal temperatures were higher in the area of contact with the baffle than at adjacent locations. The hotter tube metal at the baffle established a thermogalvanic cell with the surrounding cooler metal, causing metal wastage in the hotter region.
REMEDY	Thermally isolate tube from baffle.

CORROSION ATLAS

CASE HISTORY

06.06.15.01

MATERIAL	Copper.
SYSTEM	Once-through cooling water system.
PART	Oil cooler tube.
PHENOMENON	Underdeposit corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Softened oxygen-containing water (not corrosive to copper).
CAUSE	Deposition of iron oxide originating from corrosion of untreated steel transport pipelines (underneath the iron oxide deposit, the copper surface will become anodic) (see also Case History 06.05.15.01).
REMEDY	Use of polymer transport pipelines, also to prevent corrosion of the pipelines themselves.

CORROSION ATLAS

CASE HISTORY

06.06.15.02

MATERIAL	Cupronickel 90/10.
SYSTEM	Coolant water system for oil cooler.
PART	Oil cooler pipes.
PHENOMENON	Underdeposit corrosion.

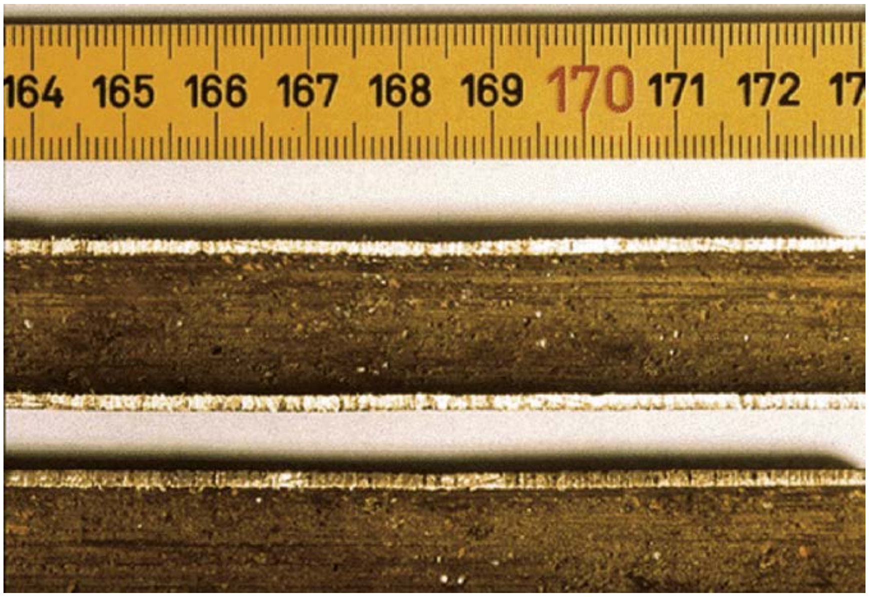
APPEARANCE	Pitting corrosion to the point of leakage underneath a brownish-green sludge layer (the glittering particles are copper, resulting from sawing-through of the pipe).
TIME IN SERVICE	1 year.
ENVIRONMENT	Around the pipes: oil for testing ball bearings. Through the pipes: river water, heated from 20 to 25–35 °C, flow rate <<1 m/sec. Water analysis: conductivity 84 mS/m; pH 8.1; total hardness 5.1 mEq/l (255 ppm $CaCO_3$); chloride 153 ppm; sulfate 70 ppm. Sludge analysis: Malachite ($Cu_2(OH)_2(CO_3)$), iron oxide, and sand particles.
CAUSE	Due to too low a flow velocity, sand particles entrained with the river water deposited in the pipes, causing aeration cells to form; leading to pitting attack.
REMEDY	In view of the presence of sand particles, increasing the flow velocity would probably lead to erosion corrosion. Possible options are: • filtration of the river water; • selection of a less sensitive material for the cooler pipes, e.g., 254 SMO or graphite.

CORROSION ATLAS

CASE HISTORY

06.06.16.01

MATERIAL	Brass.
SYSTEM	150-kV plant transformer cooler.
PART	Cooling pipe.
PHENOMENON	Selective leaching (plug-type dezincification).



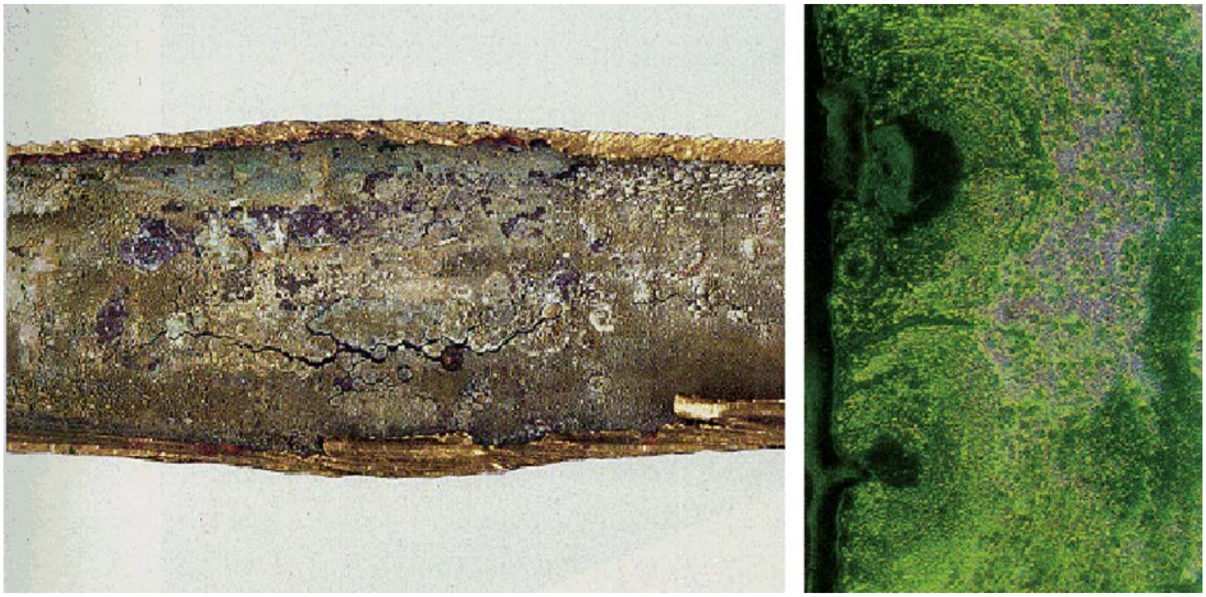
APPEARANCE	Pitting attack, with red copper spots.
TIME IN SERVICE	Half a year.
ENVIRONMENT	Brackish water, stagnant.
CAUSE	The formation of deposits in the stagnant water caused dezincification to take place, accelerated by the high salt content of the cooling water.
REMEDY	• When the cooler is shut down, it should first be purged with mains water and then put away dry; • Or allow the brackish cooling water to circulate normally (in the aerated state).

CORROSION ATLAS

CASE HISTORY

06.06.16.02

MATERIAL	Brass.
SYSTEM	Circulating cooling water system.
PART	Pipe.
PHENOMENON	Selective leaching (plug-type dezincification).



APPEARANCE	Pitting attach with red spots.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Cooling water dosed with sodium hypochlorite to control bacterial growth.
CAUSE	Excessively high pH (>9) caused by uncontrolled dosing of sodium hypochlorite.
REMEDY	• Improved monitoring of sodium hypochlorite dosing, or • Use of an organic bactericide.

CORROSION ATLAS

CASE HISTORY

06.06.17.01

MATERIAL	Admiralty brass.
SYSTEM	Once-through cooling-water system.
PART	Horizontal condenser tube (OD 2.5 cm).
PHENOMENON	Microbiologically influenced corrosion (ammonia attack).

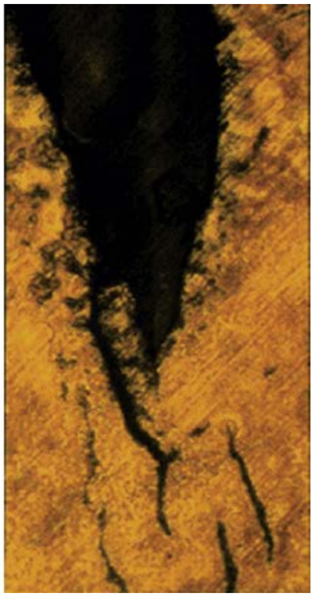
APPEARANCE	Longitudinal branched cracks, thick-walled.
TIME IN SERVICE	7 years.
ENVIRONMENT	Cooling water. Temperature: inlet ≈ 21 °C, outlet ≈ 26 °C; pH = 7.4–8.3.
CAUSE	Decomposition of dead organisms at the bottom of the tube generated ammonia locally, high enough to produce stress-corrosion cracking of the brass condenser tubes. The tubes contained considerable residual hoop stress (see also Case Histories 06.06.18.01, 06.15.18.01, and 06.25.18.01).
REMEDY	Avoid low flow and dose biocides.

CORROSION ATLAS

CASE HISTORY

06.06.18.01

MATERIAL	Aluminum brass (76-22-2 + As).
SYSTEM	Circulating cooling water system with cooling tower.
PART	Outer jacket around unalloyed steel cooling pipe in cooling tower (see also Case History 01.11.20.01).
PHENOMENON	Stress-corrosion cracking (transgranular).



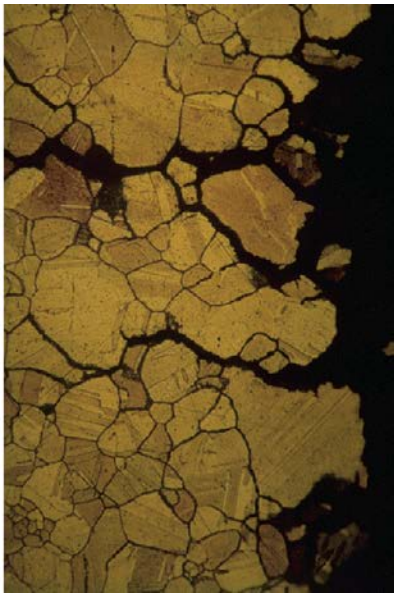
APPEARANCE	Cracks.
TIME IN SERVICE	A couple of months.
ENVIRONMENT	Around the pipe: chloride-containing cooling water temporarily contaminated with ammonia owing to leakage.
CAUSE	In combination with stresses in the brass, ammonia attack causes stress-corrosion cracking (also called: season cracking) (see also Case Histories 06.15.18.01 and 06.25.18.01).
REMEDY	• Leakage of ammonia should be prevented, or • Use an ammonia-resistant material.

CORROSION ATLAS

CASE HISTORY

06.06.18.02

MATERIAL	Aluminum brass (ASTM B 111; CDA 687; UNS C 68700). Composition: Cu 76–79%, Al 1.8–2.5%, Zn remainder, As traces).
SYSTEM	Once-through cooling system.
PART	Fuel oil cooler pipes.
PHENOMENON	Stress-corrosion cracking (intergranular).



APPEARANCE	Cracking, with pipe fractured on the left and intergranular attack on the right.
TIME IN SERVICE	About 20 years.
ENVIRONMENT	Internally, brackish cooling water conductivity 463 mS/m; pH 7.8; total hardness 13 mEq/l (650 ppm $CaCO_3$); chloride 1460 ppm; sulfate 235 ppm; ammonium 0.1 ppm. Externally, fuel oil: water <0.05%; sulfur 5.3%; acid number 0.50; total N 1000 ppm.
CAUSE	The aluminum brass showed a phosphorus content of 0.064% at an arsenic content of 0.018%. This rendered it sensitive to intergranular attack in the brackish cooling water, leading to stress corrosion. Transgranular stress corrosion due to ammonium could not be demonstrated and was also less probable in the present environment.
REMEDY	Construct the pipes of the heat exchanger of cupronickel 30 (CuNi 30 Fe, W.-Nr. 2.0882, UNS C 71500) with the average composition of Cu 69.5, Ni 30.0, and Fe 0.5. This material possesses good resistance to both stress corrosion and intergranular attack.

CORROSION ATLAS

CASE HISTORY

06.06.28.01

MATERIAL	Copper.
SYSTEM	Circulating cooling water system for an oxygen plant aftercooler.
PART	Horizontal heat-exchanger tube (OD 1.6 cm).
PHENOMENON	Corrosion fatigue.

APPEARANCE	Longitudinal crack, originating on the external surface.
TIME IN SERVICE	5 years.
ENVIRONMENT	Internal: oxygen. External: Cooling water at 35 °C; water treatment: phosphate and zinc.
CAUSE	Microstructural examinations revealed intergranular, low-branched cracks. The longitudinal orientation of the cracks revealed that the cyclic stresses were induced by fluctuations in internal pressures. (Intergranular corrosion-fatigue cracks in copper may be difficult to differentiate from stress-corrosion cracking.)
REMEDY	Avoid pressure fluctuations and complete the water treatment with a copper inhibitor.

CORROSION ATLAS

CASE HISTORY

06.06.32.01

MATERIAL	Bronze.
SYSTEM	Cleaning installation of a cooling water system using ceramic-coated rubber balls.
PART	Pump impeller.
PHENOMENON	Erosion.

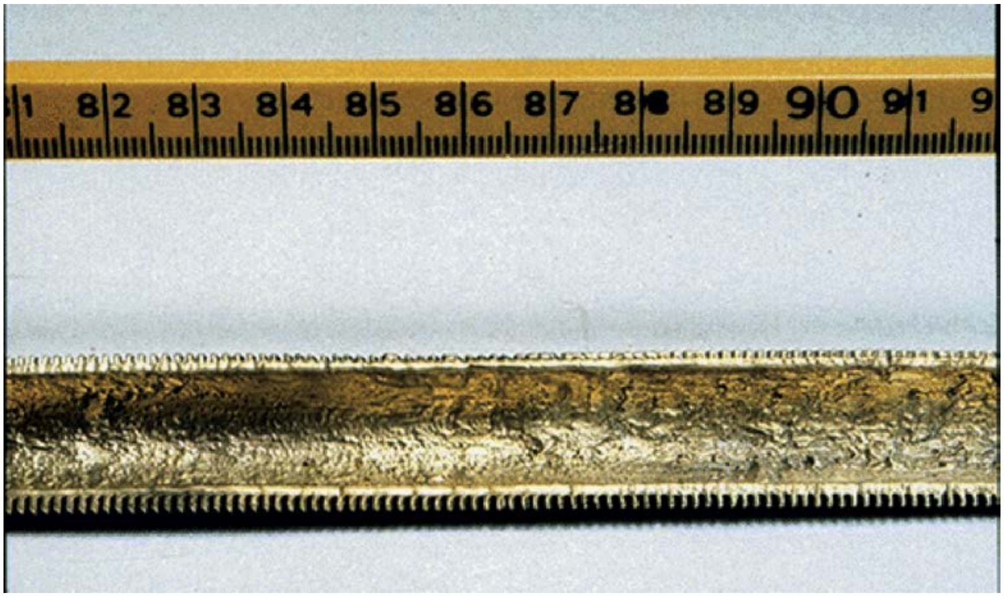
APPEARANCE	Bronze locally worn away.
TIME IN SERVICE	About 1 year after ferrosulfate dosing was discontinued.
ENVIRONMENT	Seawater.
CAUSE	Discontinuation of the protective effect of the ferrosulfate dosing, allowing erosion by the ceramic-coated rubber balls to take place. The ferrosulfate dosing was used to protect the aluminum brass condenser from erosion corrosion. The dosing was stopped after replacement of the condenser by a titanium one. The cleaning installation was kept in operation for cleaning the bundle of contamination.
REMEDY	Provide impeller with a wear-resistant coating.

CORROSION ATLAS

CASE HISTORY

06.06.34.01

MATERIAL	Naval brass (70 Cu, 29 Zn, 1 Sn)
SYSTEM	Propane condenser.
PART	Condenser tubes.
PHENOMENON	Erosion corrosion.



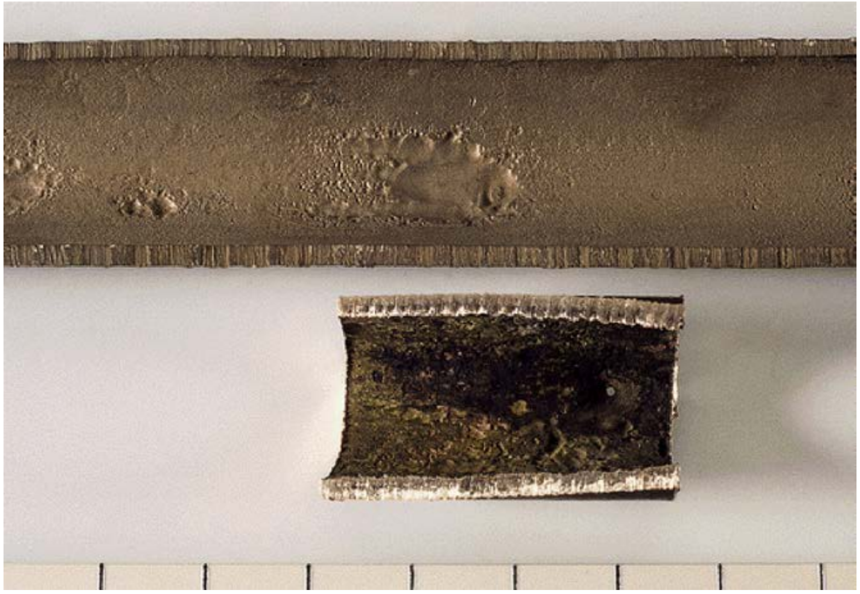
APPEARANCE	Irregular attack over the entire surface, showing a distinct flow pattern.
TIME IN SERVICE	8 years.
ENVIRONMENT	Brackish cooling water with dosing of phosphonates and sodium hypochlorite; NaCl: 2500 ppm; conductivity 450 mS/m; pH 7.9; hardness: 13 mEq/l (650 ppm $CaCO_3$); velocity of cooling water in tubes 2.0 m/s.
CAUSE	The present velocity is too high for this grade of brass (maximum allowable 1.5 m/s) (see also Case Histories 06.05.34.01 and 06.06.34.03).
REMEDY	• Use of tubes of aluminum brass (CuZn 20 Al) with a maximum allowable velocity of 2.5 m/s, or even better of cupronickel 30 (CuNi 30 Fe_2 Mn_2) with a maximum velocity of 3.5 m/s. • Alternative: dose ferrosulfate.

CORROSION ATLAS

CASE HISTORY

06.06.34.02

MATERIAL	Cupronickel 90/10.
SYSTEM	Once-through cooling-water system.
PART	Exchanger tubes.
PHENOMENON	Erosion corrosion.



APPEARANCE	Some dents. The leakages are located at 350 and 5550 mm from the inlet tube plate. Except for around these holes, the inside surface of the tubes is completely smooth.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Seawater.
CAUSE	Maritime obstacles, e.g., a mussel shell clamped in the tube, cause local high seawater velocity. Plastic brush holders installed as a trial in the seawater inlet of the tubes to prevent mussel shells clamping in the tubes, which are too weak. The plastic brush-holders could not dislodge the mussel shells (see also Case History 06.06.34.04).
REMEDY	• Modification of the existing brush holders: 1. to prevent mussel shells entering the tubes 2. reinforcement of the brush holder • Design of a mussel shell filter for installation in the seawater inlet of the exchanger. • Prevent mussel shells clamping in the tubes during back-flushing.

CORROSION ATLAS

CASE HISTORY

06.06.34.03

MATERIAL	Admiralty brass.
SYSTEM	Cooling-water system of overhead condenser in a refinery.
PART	Heat-exchanger tube.
PHENOMENON	Erosion corrosion.

APPEARANCE	Horseshoe-shaped depressions on the internal surface.
TIME IN SERVICE	10 weeks.
ENVIRONMENT	Cooling water, temperature 45 °C; pH 8.4.
CAUSE	Erosion may occur when a rapid or turbulent fluid impinges upon the surface of a susceptible metal. Flow rate through this exchanger was increased in the months prior to failure (see also Case Histories 06.05.34.01 and 06.06.34.01).
REMEDY	• Diminish coolant flow rate. • Specify a replacement metal having greater resistance to erosion, such as 70/30 cupronickel. • Reduce corrosivity of coolant by increasing the dosage of the inhibitor.

CORROSION ATLAS

CASE HISTORY

06.06.34.04

MATERIAL	Cupronickel (90/10).
SYSTEM	Once-through cooling-water system.
PART	Horizontal condenser tube, inlet end (OD 2.5 cm).
PHENOMENON	Erosion corrosion.

APPEARANCE	Irregularly shaped patterns of highly localized metal loss.
TIME IN SERVICE	6 years (the leaks arose over a 3-month period).
ENVIRONMENT	Internal: cooling water at 38 °C, pH 7.8–8.4, conductivity 80–300 mS/m. External: Steam and condensate, pH 8.2–9.2.
CAUSE	The sites were located at the inlet end and resulted from the lodgment of debris at the mouth of the tube. Highly localized turbulence created by this debris caused the erosion. In this case, the erosion was the main cause of the damage, the corrosion was of less importance (see also Case History 06.06.34.02).
REMEDY	Prevent lodgment of foreign objects on the face of the tube sheet or within tubes by improved filtration by screens or filters and by periodic cleaning of the exchanger itself.

CORROSION ATLAS

CASE HISTORY

06.07.10.01

MATERIAL	Bronze.
SYSTEM	Brine circulation of absorption cooling system.
PART	Pump impeller.
PHENOMENON	Ammonia corrosion.

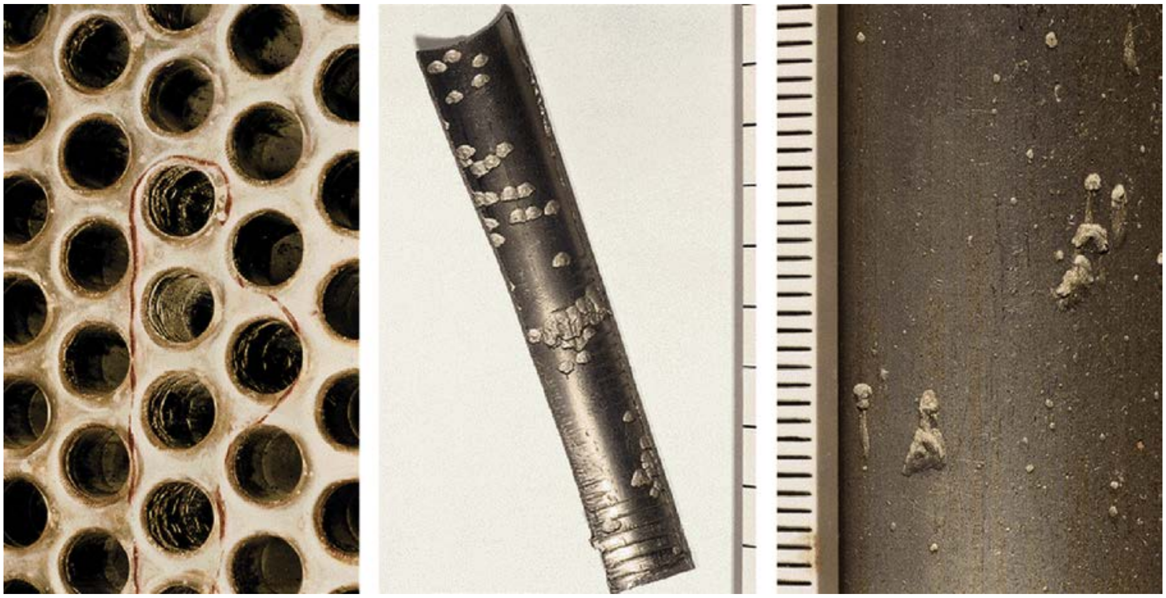
APPEARANCE	Severe local attack.
TIME IN SERVICE	12 months operation in all; damage occurred 2 months after ammonia contamination took place.
ENVIRONMENT	Brine: water with approximately 20% sodium chloride; 0.3% potassium bichromate; 0.1% caustic soda, and contaminated with 2.5% ammonia originating from the leaking evaporator of the absorption cooling machine.
CAUSE	Bronze is not resistant to ammonia; the evaporator leak was caused by corrosion by the brine due to poor maintenance of the inhibitor level (potassium bichromate) because of regular brine loss in the plant (see also Case History 06.01.34.01).
REMEDY	Bronze impeller replaced by a cast iron one; subsequently the brine, which caused numerous problems elsewhere as well, was replaced by a glycol–water mixture as cooling liquid.

CORROSION ATLAS

CASE HISTORY

06.07.34.01

MATERIAL	Cunifer 70/30 (Cu Ni 30 Mn 1 Fe).
SYSTEM	Reboiler in the food and beverage industry.
PART	Tube of shell-and-tube heat exchanger (Ø 32 × 1.65 mm).
PHENOMENON	Erosion corrosion.



APPEARANCE	Left photograph: tubes located in tube plate; middle photograph: the inner surface of a tube; right photograph: detail of the corrosion, attack horseshoe-shaped.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Saturated brine at boiling point (50–55 °C in vacuum).
CAUSE	After replacement of the previous boiler, which had been used for more than 15 years, the temperature was slightly raised to enhance process efficiency. As the boiling now started in the reboiler, previously in the evaporator, the velocity increased dramatically.
REMEDY	Reduce the velocity inside the tubes or use an even more erosion-resistant material.

CORROSION ATLAS

CASE HISTORY

06.10.34.01

MATERIAL	Bronze (80 Cu, 18.5 Sn, 1.5 Zn).
SYSTEM	Fire-extinguishing system.
PART	Delivery valve.
PHENOMENON	Erosion corrosion.

APPEARANCE	Material locally worn away at sealing edge.
TIME IN SERVICE	2–3 weeks.
ENVIRONMENT	Seawater, temperature 25 °C.
CAUSE	The delivery valve, sealing at the system pressure of 8 atm, failed to seal sufficiently because of the bronze-to-bronze contact. This, combined with the corrosive quality of the water, led to local erosion corrosion on leakage.
REMEDY	Fitting of the valves with a plastic (Teflon) seat, thereby obtaining a better seal.

CORROSION ATLAS

CASE HISTORY

06.11.03.01

MATERIAL	Copper.
SYSTEM	Sodium hydroxide storage tank.
PART	Float ball.
PHENOMENON	Caustic attack.

APPEARANCE	Uniform severe wall thickness reduction. Covered with a black copper oxide layer (CuO).
TIME IN SERVICE	10 years.
ENVIRONMENT	33% sodium hydroxide solution; temperature 20–40 °C.
CAUSE	Normally copper is not attacked by concentrated sodium hydroxide. Presumably, this case involved hypochlorite-contaminated sodium hydroxide solution, as produced by the diaphragm process.
REMEDY	Construct the float ball of steel or plastic (PTFE possesses both alkali and oxidant resistance).

CORROSION ATLAS

CASE HISTORY

06.11.04.01

MATERIAL	Bronze.
SYSTEM	Pump forming part of a cleaning system.
PART	Pump impeller.
PHENOMENON	Acid corrosion.

APPEARANCE	Severe uniform attack, material largely disappeared.
TIME IN SERVICE	A few hours.
ENVIRONMENT	1% sulfamic acid; temperature 30 °C.
CAUSE	Bronze is not resistant to sulfamic acid; previously another chemical was used for cleaning purposes and when the use of sulfamic acid had begun, its effect on the bronze impeller was overlooked.
REMEDY	Use of an impeller constructed from AISI 316 L stainless steel.

CORROSION ATLAS

CASE HISTORY

06.11.16.01

MATERIAL	Brass.
SYSTEM	Stainless steel outdoor product tank.
PART	Bolt of a stainless steel flange connection.
PHENOMENON	Selective leaching (plug-type dezincification).

APPEARANCE	Red discoloration on bolt head, with fracture underneath the head.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Industrial atmosphere.
CAUSE	Dezincification of the brass caused by potential difference between brass and stainless steel, the remaining copper being responsible for the red discoloration.
REMEDY	Use bolts also made from stainless steel.

CORROSION ATLAS

CASE HISTORY

06.11.16.02

MATERIAL	Aluminum bronze (86 Cu, 10 Al, 1 Fe, 1 Ni).
SYSTEM	Reactor for the production of isopropyl alcohol.
PART	Internal reactor.
PHENOMENON	Selective leaching (dealuminification).

APPEARANCE	Red color of yellow plate at product side. General and intergranular attack α-granules with transformed eutectic β-areas (dark).
TIME IN SERVICE	A few years.
ENVIRONMENT	Approximately 50% phosphoric acid as catalyst; temperature: 200 °C.
CAUSE	Aluminum leaches out of the matrix in the presence of 50% H_3PO_4 at 200 °C.
REMEDY	Since the dealuminification itself did not cause the failure, no measures have been taken.

CORROSION ATLAS

CASE HISTORY

06.11.18.01

MATERIAL	Aluminum brass.
SYSTEM	Propylene condenser.
PART	Pipe.
PHENOMENON	Stress-corrosion cracking (transgranular).

APPEARANCE	Transverse cracking.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Through the pipe: ammonia-containing propylene.
CAUSE	Traces of excess ammonia in the propylene in combination with stresses in the present material cause stress-corrosion cracking (see also Case History 06.06.18.01). Ammonia is added in order to neutralize acid residues in the propylene.
REMEDY	Manufacture the pipes from superferritic material, e.g., Monit.

CORROSION ATLAS

CASE HISTORY

06.11.25.01

MATERIAL	Copper.
SYSTEM	Product transport pipe.
PART	Electric tracing.
PHENOMENON	Corrosion under insulation.

APPEARANCE	Local melting of copper sheathing.
TIME IN SERVICE	15 years.
ENVIRONMENT	Rainwater.
CAUSE	Rainwater penetrated into the insulation and attacked the copper sheathing, causing short-circuiting and the copper to melt.
REMEDY	Water-tight insulation of the system.

CORROSION ATLAS

CASE HISTORY

06.11.33.01

MATERIAL	Phosphorous de-oxided copper.
SYSTEM	Vessel for boiling alcohols.
PART	Pipe from the heating bundle in the vessel.
PHENOMENON	Cavitation erosion.

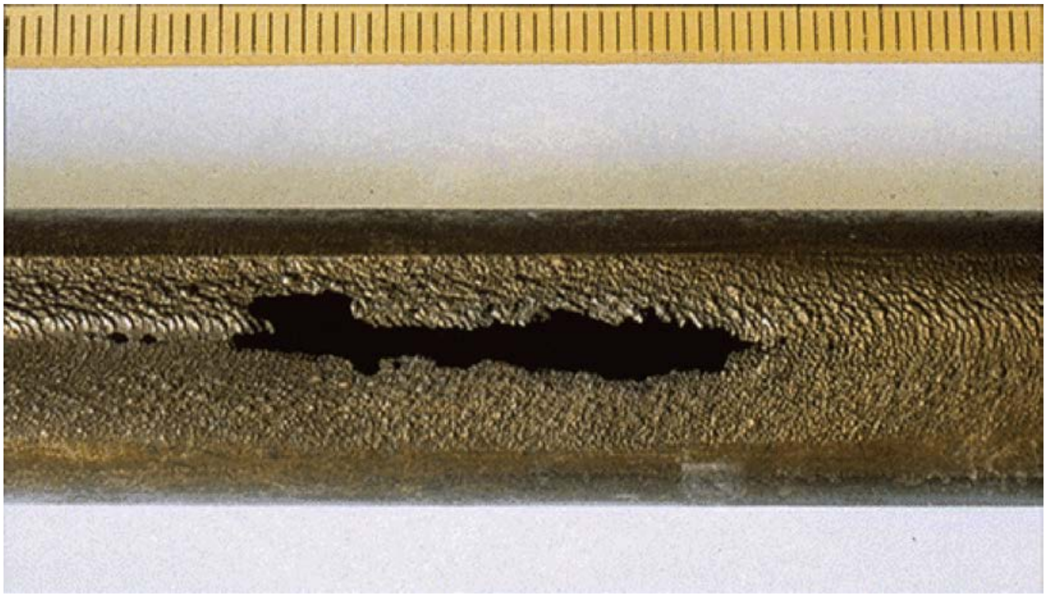
APPEARANCE	All along the upper part of the pipe, a strip of material 1.5–3 cm wide was worn away to the point of leakage.
TIME IN SERVICE	2 weeks.
ENVIRONMENT	Internal: steam. External: Organic product with alcohols. Temperature: 60 °C.
CAUSE	Flash-boiling occurred as a result of boiling point retardation, as a result of which the oxide skin was damaged. The damage occurred after the bundle had been chemically cleaned. Previously, the bundle had been in operation for years without any problems. Presumably, boiling point retardation was prevented in the past by dirt accumulation on the pipe.
REMEDY	Renovation of bundle. An inert material was added to the vessel contents to prevent boiling point retardation.

CORROSION ATLAS

CASE HISTORY

06.11.34.01

MATERIAL	Aluminum brass.
SYSTEM	Product condenser.
PART	Pipe.
PHENOMENON	Erosion corrosion.



APPEARANCE	Severe attack, with flow pattern.
TIME IN SERVICE	6 years.
ENVIRONMENT	Hydrocarbon vapors contaminated with ammonia and cyanides.
CAUSE	High inflow velocity of the corrosive vapors (see also Case History 06.01.34.01).
REMEDY	Use of divider plates to break the flow.

CORROSION ATLAS

CASE HISTORY

06.11.34.02

MATERIAL	Copper.
SYSTEM	Fatly acid manufacture.
PART	Spray plate of the sulfuric acid distributor from a fatty acid vessel (saponification).
PHENOMENON	Erosion corrosion.

APPEARANCE	Uniform attack over the entire surface (original thickness: 3 mm, remaining thickness <1 mm).
TIME IN SERVICE	Several years.
ENVIRONMENT	96% sulfuric acid at 15–20 °C hitting the spray plate. Temperature in the vessel raised to 90–100 °C by the steam injection.
CAUSE	At elevated temperature, copper is attacked by 96% sulfuric acid. In this case, the attack was of course accelerated by the continuous erosion caused by the sulfuric acid stream colliding against the surface of the spray plate.
REMEDY	• Regular replacement, or • Make the spray plate of polyvinylidene fluoride.

CORROSION ATLAS

CASE HISTORY

06.11.34.03

MATERIAL	Bronze (cast CuSn10).
SYSTEM	Chemicals transport system.
PART	Impeller of centrifugal pump.
PHENOMENON	Erosion corrosion.

APPEARANCE	The entire surface of the impeller is attacked with a distinct flow pattern.
TIME IN SERVICE	21 days continuous.
ENVIRONMENT	A mixture of 23.5% H_2SO_4, 165 g/l TiO_2, and 5 g/l $FeSO_4$. Temperature 95–100 °C.
CAUSE	At this temperature, sulfuric acid causes slight corrosion (< 0.5 mm/year) to the present bronze quality. The presence of solids contamination and the high velocity of the medium along the impeller, however, also cause erosion. The combination of erosion and corrosion leads to accelerated attack.
REMEDY	The pump was replaced by a polypropylene pump equipped with a double mechanical seal (back-to-back).

CORROSION ATLAS

CASE HISTORY

06.11.34.04

MATERIAL	Tin bronze.
SYSTEM	Process installation.
PART	Circulating pump impeller.
PHENOMENON	Erosion corrosion.

APPEARANCE	Severe local attack.
TIME IN SERVICE	2 years.
ENVIRONMENT	1–2% cyanide containing solution at 40–50 °C. Depoisoning by a batchwise reaction with sodium hypochlorite.
CAUSE	Bronze is not resistant to cyanide.
REMEDY	Use of stainless steel AISI 316.

CORROSION ATLAS

CASE HISTORY

06.13.10.01

MATERIAL	Copper.
SYSTEM	Vacuum pump.
PART	Rejection water pipe.
PHENOMENON	Ammonia corrosion.

APPEARANCE	External uniform attack, with blue-colored corrosion products.
TIME IN SERVICE	3 years.
ENVIRONMENT	Humid atmosphere.
CAUSE	Owing to a nearby ammonia leak and condensation on the copper pipe, the latter was attacked by ammonia (the blue color is due to the formation of a copper–ammonia complex) (see also Case History 06.05.10.01).
REMEDY	Coat the pipe or construct it of plastic.

CORROSION ATLAS

CASE HISTORY

06.14.14.01

MATERIAL	Copper.
SYSTEM	Gas supply system.
PART	Underground pipeline.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Local attack (mechanically deformed by digging up).
TIME IN SERVICE	16 years.
ENVIRONMENT	Soil with low soil resistance (<10 Ohm · m); the pipeline lay in the groundwater.
CAUSE	Galvanic connection with concrete steel which, owing to the presence of an oxide skin, is more noble than copper at the prevailing high pH of the concrete.
REMEDY	Do not use an unprotected copper pipe in the soil, but protect it with a plastic jacket or polyethylene lining.

CORROSION ATLAS

CASE HISTORY

06.14.18.01

MATERIAL	Copper (Cu-DHP).
SYSTEM	Gas supply system.
PART	Underground pipeline.
PHENOMENON	Stress-corrosion cracking.

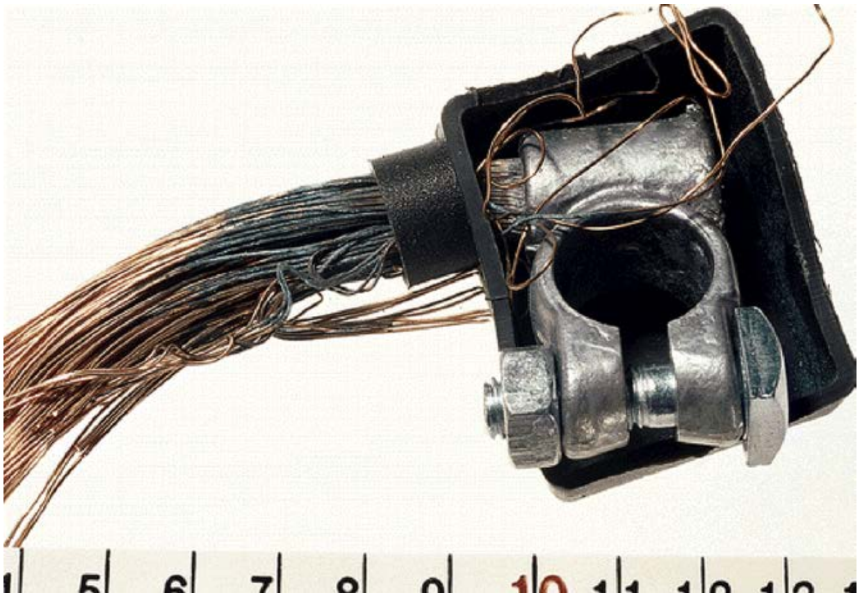
APPEARANCE	Fracture with blue corrosion products (pipe slightly distorted).
TIME IN SERVICE	6 years.
ENVIRONMENT	Peaty soil, contaminated with ammonia; the pipe lay above the groundwater level.
CAUSE	Mechanical stress due to subsiding soil and ammonia from the soil. This type of copper is sensitive to stress-corrosion cracking.
REMEDY	• Protection of the copper line (see Case History 06.14.14.01); or • Use of a flexible plastic (polyethylene) service line construction

CORROSION ATLAS

CASE HISTORY

06.15.11.01

MATERIAL	Copper.
SYSTEM	Electric installation of automative system.
PART	Battery cable.
PHENOMENON	Corrosion caused by soldering process.



APPEARANCE	Blue copper corrosion products on copper threads near soldered cable end.
TIME IN SERVICE	Immediately after manufacture.
ENVIRONMENT	Normal indoor climate.
CAUSE	Insufficient cleaning after soldering. Corrosion caused by zinc chloride–based flux residues used for soldering (see also Case History 06.06.11.01).
REMEDY	Thorough rinsing after soldering, followed by drying.

CORROSION ATLAS

CASE HISTORY

06.15.18.01

MATERIAL	Brass.
SYSTEM	House lighting system.
PART	Porch lamp cap, from a house beside a canal in Amsterdam.
PHENOMENON	Stress corrosion cracking (season cracking).

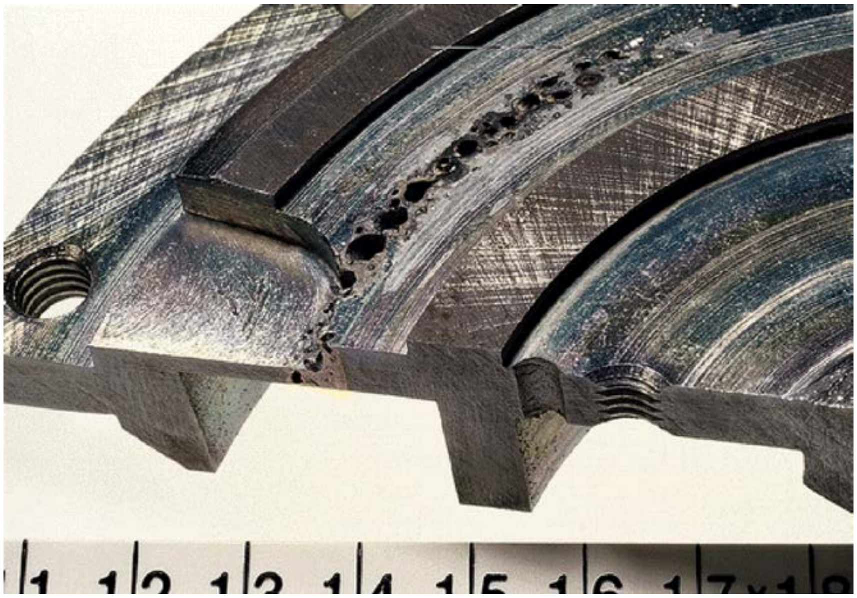
APPEARANCE	Cracking.
TIME IN SERVICE	Probably several decades.
ENVIRONMENT	Ammonia-containing atmosphere (ammonia originating from putrefaction process in the canal).
CAUSE	In combination with stresses present in the brass cap, ammonia attack causes this stress corrosion (see also Case Histories 06.02.18.01, 06.06.18.01, and 06.25.18.01).
REMEDY	Copper alloys should not be used for the present purpose.

CORROSION ATLAS

CASE HISTORY

06.20.04.01

MATERIAL	Brass segment in zinc-electroplated steel.
SYSTEM	Automotive system.
PART	Electromagnetic induction wheel.
PHENOMENON	Acid corrosion.



APPEARANCE	Severe pitting and penetration of the (yellow-colored) brass segment.
TIME IN SERVICE	Less than 1 hour (during the zinc plating process).
ENVIRONMENT	Water with process chemicals.
CAUSE	Brass is not resistant to the acidic chemicals used during pretreatment or during the plating process.
REMEDY	Use different construction or other surface treatment.

CORROSION ATLAS

CASE HISTORY

06.20.16.01

MATERIAL	Brass.
SYSTEM	Automotive system.
PART	Hose pillar of radiator.
PHENOMENON	Selective leaching (layer-type dezincification).

APPEARANCE	Deposits and corrosion products, with the brass color fading from yellow to red.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Use of bad-quality water with high salt and chloride content caused layer-type dezincification. The remaining copper colored the hose pillar red.
REMEDY	Use an appropriate water quality in combination with inhibitors and antifreeze.

CORROSION ATLAS

CASE HISTORY

06.21.14.01

MATERIAL	Protector cover: brass; securing bolts: Nimonic 80A (chromium–nickel alloy).
SYSTEM	Naval sonar system.
PART	Protector cover of transmitter/receiver.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Material worn away locally.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Seawater at 4–20 °C, flowing and standing.
CAUSE	The potential difference between the Nimonic bolts and the brass cover caused the less noble metal (the brass) to dissolve. This allowed the protective cover to detach. In spite of the favorable area ratio (large anode, small cathode), the brass cover was attacked due to the large potential difference and the high conductivity of the seawater.
REMEDY	Construct the protecting cover and the bolts of titanium.

CORROSION ATLAS

CASE HISTORY

06.24.18.01

MATERIAL	Aluminum brass.
SYSTEM	Test rig (stress-relief annealing test according to SIS 117101).
PART	Condenser pipe.
PHENOMENON	Stress-corrosion cracking.

APPEARANCE	Numerous parallel longitudinal cracks.
TIME IN SERVICE	1 hour (duration of test).
ENVIRONMENT	Mercury nitrate 1%; nitric acid 1%, temperature 21 °C.
CAUSE	High stresses in the brass exposed in the above medium.
REMEDY	Stress relief annealing.

CORROSION ATLAS

CASE HISTORY

06.25.18.01

MATERIAL	Free-cutting brass (alpha and beta brass, Zn >37%).
SYSTEM	Materials store.
PART	Rod.
PHENOMENON	Stress corrosion cracking (season cracking).

APPEARANCE	Fracturing.
TIME IN SERVICE	6 months.
ENVIRONMENT	Moist atmosphere contaminated with ammonia originating from the storage of fertilizers (including ammonium salts) at a previous stage.
CAUSE	Internal stresses and ammonia caused the occurrence of stress corrosion (see also Case Histories 06.02.18.01, 06.06.18.01, and 06.15.18.01).
REMEDY	Prevention by stress-relief annealing (tempering).

CORROSION ATLAS

CASE HISTORY

07.01.03.01

MATERIAL	Aluminum (99%).
SYSTEM	Steam consumer (granule press for preparing polystyrene blocks).
PART	Steam distributor plate.
PHENOMENON	Alkalinity corrosion.

APPEARANCE	Severe corrosion in the form of roughening over the entire surface, with perforation at various points.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Saturated steam at 1 MPa, regularly contaminated with alkaline boiler water.
CAUSE	Switching on the presses at intervals caused sharp peaks in steam consumption, exceeding the boiler's capacity. As a result, pressure reduced and hence enlargement of the volume of steam occurred, allowing the boiler to prime. The steam regularly contained 40% of boiler water. The aluminum plate was attacked by the alkalinity of this boiler water (see also Case Histories 07.09.03.01 and 07.11.03.02).
REMEDY	• Construct the distributor plate of carbon steel, and • Install a back-up steam accumulator to supply peak consumption.

CORROSION ATLAS

CASE HISTORY

07.04.04.01

MATERIAL	Aluminum (99%).
SYSTEM	High-efficiency gas-fired central heating boiler.
PART	Flue gas discharge pipe.
PHENOMENON	Acid corrosion.

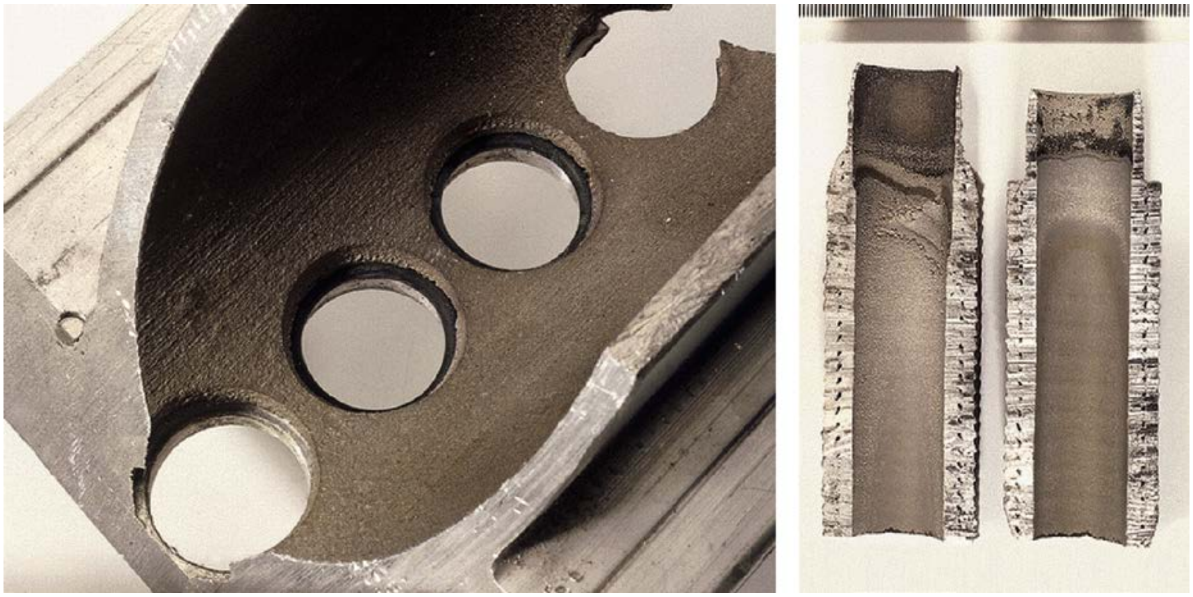
APPEARANCE	General attack with rough surface.
TIME IN SERVICE	About 12 months ($1\frac{1}{2}$ heating seasons).
ENVIRONMENT	Flue gases, contaminated with hydrochloric acid (HCl).
CAUSE	The combustion air of the central heating boiler, which was installed in a hairdressing salon, was contaminated with chlorine-containing organic solvents. When these were combusted, HCl was formed which attacked the aluminum discharge flue when it condensed in the high-efficiency boiler (see also Case Histories 01.04.04.01 and 02.01.04.01).
REMEDY	Application of a closed central heating boiler, the combustion air being drawn from outside.

CORROSION ATLAS

CASE HISTORY

07.04.04.02

MATERIAL	Aluminum (AIMgSi 0.5).
SYSTEM	Central heating system.
PART	Header and finned pipes from heat exchanger.
PHENOMENON	Acid corrosion.



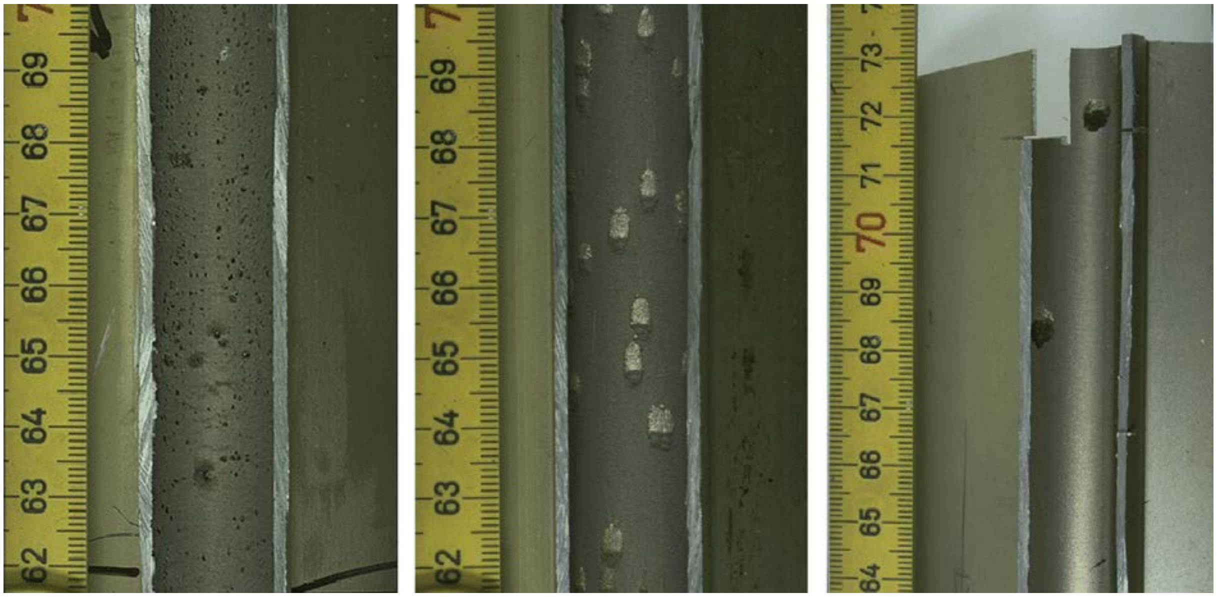
APPEARANCE	Uniform attack with pickled surface. Erosion corrosion caused by turbulence at the tube ends. The tube wall thickness is reduced from 2 to 0.1 mm.
TIME IN SERVICE	Total life span 2 months. Leakage took place 1 month after cleaning.
ENVIRONMENT	In service: heating water: temperature 70°C –90°C; pH 8.9–9.2; conductivity 88.6 mS/m; total hardness 2.3 ppm $CaCO_3$; chloride 15 ppm; phosphate 45 ppm PO_4^{3-}; Fe 0.3 ppm; Al 25 ppm. During cleaning: uninhibited 3% HCl at room temperature.
CAUSE	The most important cause is acid corrosion during cleaning with uninhibited 3% HCl instead of inhibited citric acid. This illustrates poor workmanship by the cleaning firm. The high aluminum content in the heating water indicates corrosion also during service, probably caused by the high pH.
REMEDY	• Filling the system with demineralized water; • Cleaning with inhibited citric acid if necessary.

CORROSION ATLAS

CASE HISTORY

07.04.12.01

MATERIAL	Aluminum (AA 6063; AlMgSi 0.5).
SYSTEM	Glasshouse central heating system (add-on to an old system constructed of steel).
PART	Radiant pipes.
PHENOMENON	Chloride attack.



APPEARANCE	Pitting attack.
TIME IN SERVICE	3 months.
ENVIRONMENT	Heating water consisting of mains water, with water treatment based on sodium molybdate and a dispersant. Temperature 40°C–70°C, pH 9.5–11; O_2 present (due to regular water make-up and replenishment when the system was constructed).
CAUSE	Pitting by chloride in the presence of oxygen, initiated by deposition of iron oxide (dispersed out of the old system) and promoted by the high pH (due to the dosing of sodium molybdate). The heating water contains 75 ppm. of Fe and 70 ppm of Al. Application of incorrect water treatment caused a loss of $110,000 (poor workmanship by the water treatment firm).
REMEDY	• All the aluminum radiant pipes were replaced and incorporated in a secondary heating system which was heated by the old system by means of a stainless steel heat exchanger. • The secondary system was filled with demineralized water without dosing of chemicals.

CORROSION ATLAS

CASE HISTORY

07.04.14.01

MATERIAL	Aluminum valve on bronze seat.
SYSTEM	Central heating system.
PART	Check valve.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Severe general corrosion.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Hot (70°C–90°C) mains water in closed circulation system; pH about 9.
CAUSE	The corrosion took place because of the potential difference between aluminum and bronze in the presence of oxygen originating from the open expansion tank. Besides, aluminum is not resistant to alkaline water (pH > 8.5).
REMEDY	Replacement of the open expansion tank by sealed expansion vessel(s) and construction of the valve from bronze.

CORROSION ATLAS

CASE HISTORY

07.04.14.02

MATERIAL Aluminum.

SYSTEM Closed hot water recirculation system for the heating of product tanks.

PART Aluminum tubes with cadmium-coated steel connecting piece.

PHENOMENON Galvanic corrosion.

APPEARANCE Severe uniform attack to aluminum, as a result of which wall thickness has reduced from 3 mm to <1 mm.

TIME IN SERVICE About 1 year.

ENVIRONMENT Mains water, aerated due to regular replenishment because of system modifications and open expansion vessels. Average temperature 50°C, with excursions to 90°C. pH 7.3.

CAUSE The aerated heated water caused galvanic corrosion at the steel/aluminum connection. (Upon examination, the black grains were found to consist of calcium carbonate covered with iron oxide and therefore have nothing to do with the corrosion.)

REMEDY

- Construct the entire system of stainless steel and use softened make-up water to prevent chalk deposition, or
- If the present system is retained, fill the system and use low-salt make-up water (demineralized water, condensate or reversed osmosis water).

CORROSION ATLAS

CASE HISTORY

07.05.14.01

MATERIAL	Aluminum.
SYSTEM	Water transport pipeline.
PART	Push-on flange.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Very severe attack over the entire surface.
TIME IN SERVICE	3 years.
ENVIRONMENT	Very wet environment in a paper mill production hall. The pipeline carried screenings at 50°C.
CAUSE	The couple between the stainless steel pipeline and the aluminum push-on flange; also between the steel bolts and the flange (see also next case). Poor workmanship by the installation firm.
REMEDY	Use of stainless steel push-on flanges and bolts as well.

CORROSION ATLAS

CASE HISTORY

07.05.14.02

MATERIAL	Aluminum.
SYSTEM	Whistling kettle for heating water.
PART	Base.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Severe pitting corrosion on the base.
TIME IN SERVICE	3 months.
ENVIRONMENT	Mains water.
CAUSE	Cell formation by the stainless steel jacket combined with the aluminum base, as a result of which galvanic corrosion occurred (see also former case).
REMEDY	Manufacture the kettle either entirely of aluminum or entirely of stainless steel.

CORROSION ATLAS

CASE HISTORY

07.05.16.01

MATERIAL	Aluminum-zinc alloy (5%–6% zinc).
SYSTEM	Glasshouse irrigation system.
PART	Water distributor pipes.
PHENOMENON	Selective leaching (dezincification).

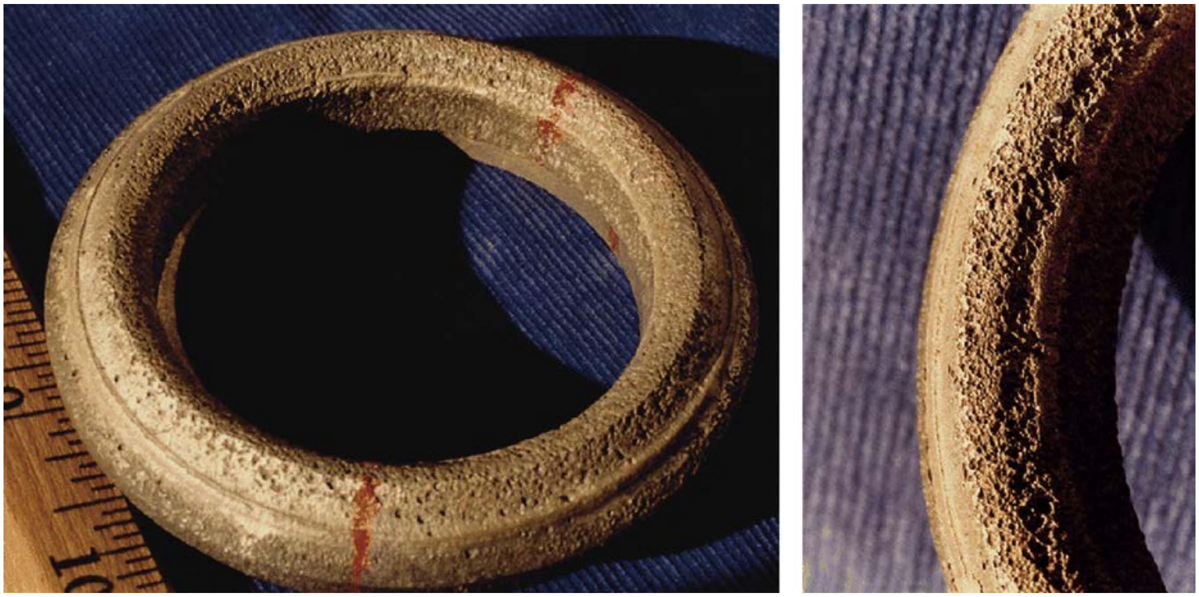
APPEARANCE	Severe uniform attack with pitting to the point of leakage.
TIME IN SERVICE	6 months.
ENVIRONMENT	Mains water containing plant nutrients (ammonium salts, nitrates, and organic matter) pH 7.5–8.
CAUSE	Leaching out of the zinc-rich phase of the inhomogeneous alloy.
REMEDY	Application of pure aluminum or an aluminum/magnesium/silicon alloy (e.g., AA 6063).

CORROSION ATLAS

CASE HISTORY

07.06.03.01

MATERIAL	Cast aluminum alloy (hypereutectic aluminum-silicon, similar to a 390 alloy).
SYSTEM	Closed cooling water system in a heavy-duty internal combustion engine.
PART	Valve seat.
PHENOMENON	Alkalinity corrosion.



APPEARANCE	Pitting (red marks were drawn on the surfaces to assist metallographic preparation).
TIME IN SERVICE	3 months.
ENVIRONMENT	Cooling water having a pH between 9 and 10. Proprietary coolant treatment with borate, silicate, phosphate, and other chemicals in ethylene glycol 50% solution.
CAUSE	Aluminum is attacked by certain waters having a pH > 8.5, in the absence of corrosion inhibitors such as silicate. The coolant was depleted of corrosion inhibitor by addition of water to the engine cooling system to replace last coolant (see also Case History 07.01.03.01).
REMEDY	The diluted coolant was drained and replaced with an ethylene glycol (50%) mixture containing the proprietary inhibitor at sufficiently high concentration to stop significant corrosion.

CORROSION ATLAS

CASE HISTORY

07.06.05.01

MATERIAL	Aluminum (5052; AlMg 2.5).
SYSTEM	Once-through cooling water system.
PART	Heat exchanger plate.
PHENOMENON	Sulfide corrosion.

APPEARANCE	Pitting.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	Sulfide-containing corrosive well water with iron oxide deposition. Sulfide (S^{2-}) 0.8 ppm.; iron (Fe^{2+}) 31 ppm.; pH 6.3; wall temperature approximately 100°C.
CAUSE	H_2S in the well water attacks the aluminum.
REMEDY	Change over to an indirect closed cooling system which is cooled with well water via a heat exchanger.

CORROSION ATLAS

CASE HISTORY

07.06.14.01

MATERIAL	Magnesium.
SYSTEM	Once-through cooling system.
PART	Sacrificial anode of the cathodic protection system of the carbon steel head of a cooler.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Left: used anode. Right: new anode.
TIME IN SERVICE	4 years.
ENVIRONMENT	Brackish water.
CAUSE	The anode is mounted on the head plate by means of a carbon steel threaded bolt. The part of the anode touching the steel surface dissolves more rapidly, causing the anode to detach from the steel surface.
REMEDY	Use of a rubber slab between the magnesium anode and the steel plate to prevent direct contact and hence detachment of the anode.

CORROSION ATLAS

CASE HISTORY

07.06.17.01

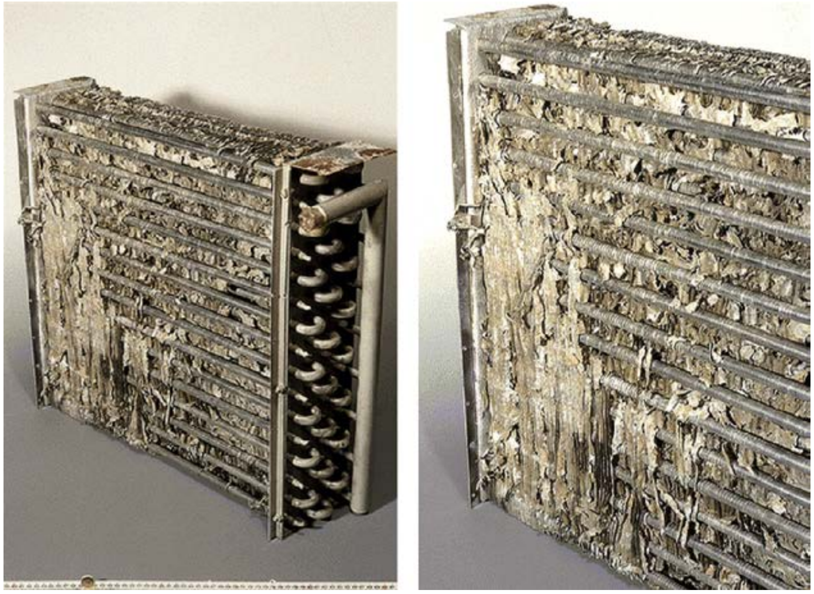
MATERIAL	Aluminum (commercially wrought alloy, similar to alloy 1100).
SYSTEM	Cooling side of a nitric acid condenser.
PART	Horizontal heat exchanger tube (OD 2.22 cm).
PHENOMENON	Microbiologically influenced corrosion.

APPEARANCE	Severe pitting.
TIME IN SERVICE	2 years.
ENVIRONMENT	Cooling water on shell-side; temperature: inlet 22°C, outlet 29°C; pH 7.8–8.2.
CAUSE	Pits were caused by sulfate-reducing bacteria beneath a slime layer. No chemical treatment of this system was applied. The exchanger was plagued by low flow (0.6 m/sec). Total aerobic bacteria counts exceeded 10^7 in the bulk water, and anaerobic counts were as high as 100 (see also Case History 01.06.17.03).
REMEDY	Biocide treatment involving maintenance of free chlorine residual level between 0.3 and 0.5 ppm. Before treatment, the exchanger was so severely damaged that it was replaced. No further failures were reported after treatment program was initiated.

CORROSION ATLAS

CASE HISTORY

07.07.04.01

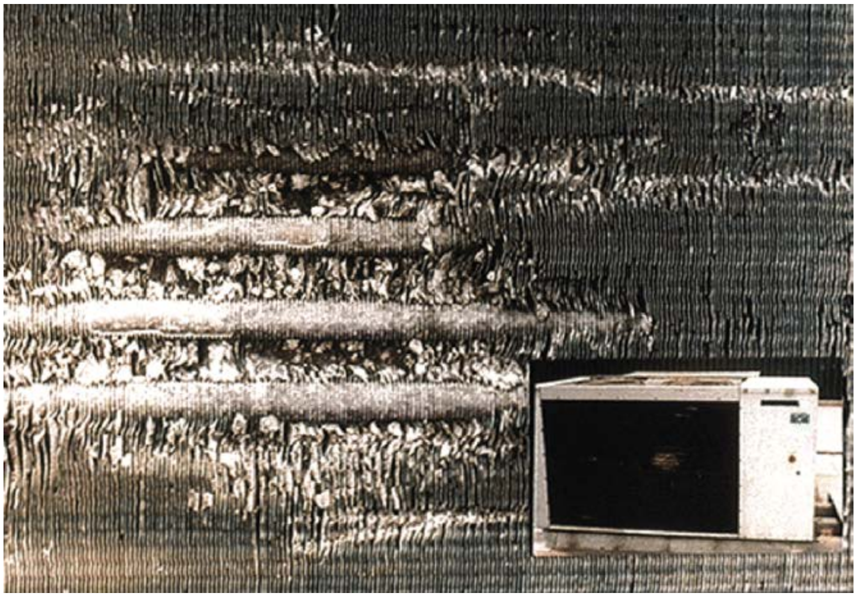
MATERIAL	Aluminum (8000) and stainless steel (AISI 316).
SYSTEM	Drying room for wood, mainly oak.
PART	Freon evaporator.
PHENOMENON	Acid corrosion.
	
APPEARANCE	Severe deterioration of the aluminum lamellae.
TIME IN SERVICE	Less than 2 years.
ENVIRONMENT	Humid air at approximately 50°C with traces of volatile organic acids.
CAUSE	The condensing water and traces of acetic acid dissolved the aluminum. The collected condensate had a pH of 4.5–3.5 and contained 500–800 ppm of organic acids (mainly acetic acid). The corrosion was accelerated by the potential difference between aluminum and stainless steel.
REMEDY	Use a more corrosion-resistant material (e.g., stainless steel, AISI 304 or 316).

CORROSION ATLAS

CASE HISTORY

07.07.24.01

MATERIAL	Aluminum.
SYSTEM	Computer cooling unit.
PART	Freon condenser.
PHENOMENON	Atmospheric corrosion.



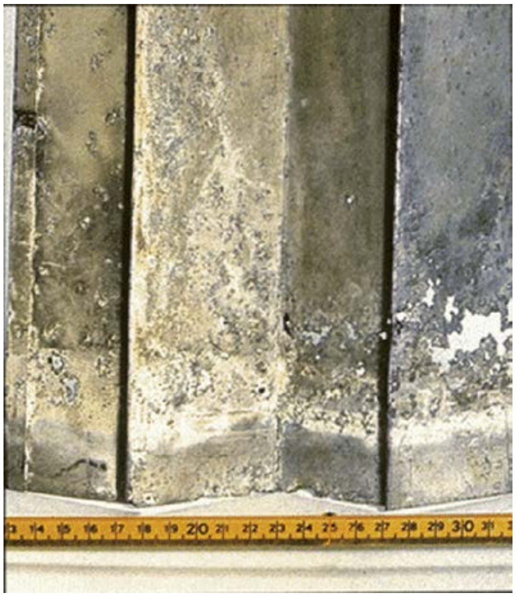
APPEARANCE	Cooling fins totally corroded away.
TIME IN SERVICE	4 years.
ENVIRONMENT	Atmosphere contaminated with salt particles from sea.
CAUSE	Aluminum is corroded by salt deposition. Vehicle exhaust fumes from a nearby motorway as well as aircraft exhaust fumes may also have played a contributory role. There is no explanation for the fact that the attack was so local. Probably, the fan did not function correctly.
REMEDY	Use of chromium-plated condenser pipes.

CORROSION ATLAS

CASE HISTORY

07.09.03.01

MATERIAL	Aluminum.
SYSTEM	Air conditioning plant.
PART	Drop catch of humidifier.
PHENOMENON	Alkalinity corrosion.



APPEARANCE	Uniform attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Softened circulating water, pH 9.5.
CAUSE	Atomization causes the formation of alkaline circulation water, and insufficient blowdown causes deposition of soda and sodium bicarbonate. This results in attack to the aluminum (see also Case History 07.06.03.01).
REMEDY	• Prevention of the circulation water becoming alkaline by making up with dealkalized water instead of softened water and blowing down sufficiently to prevent deposition (dealkalizing unit was present elsewhere in the plant). • Alternatives: make-up with completely desalted water (for example demineralized water) or construct the drop catch of plastic or coated steel.

CORROSION ATLAS

CASE HISTORY

07.09.09.01

MATERIAL	Aluminum.
SYSTEM	Air conditioning plant.
PART	Part of an aluminum air duct.
PHENOMENON	Salt corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Evaporated mains water.
CAUSE	Water drops entrained with the air stream from the humidifier; after evaporation of these drops deposited in the ducts, alkalized salt deposits were formed which caused the attack to the aluminum.
REMEDY	Because installation of drop catchers was not possible, it was advised • to make-up with low salt content water (demineralized water or condensate); • or to construct the ducts of plastic or coated steel.

CORROSION ATLAS

CASE HISTORY

07.09.09.02

MATERIAL	Aluminum.
SYSTEM	Air conditioning plant.
PART	Floor of the plenum.
PHENOMENON	Salt corrosion.

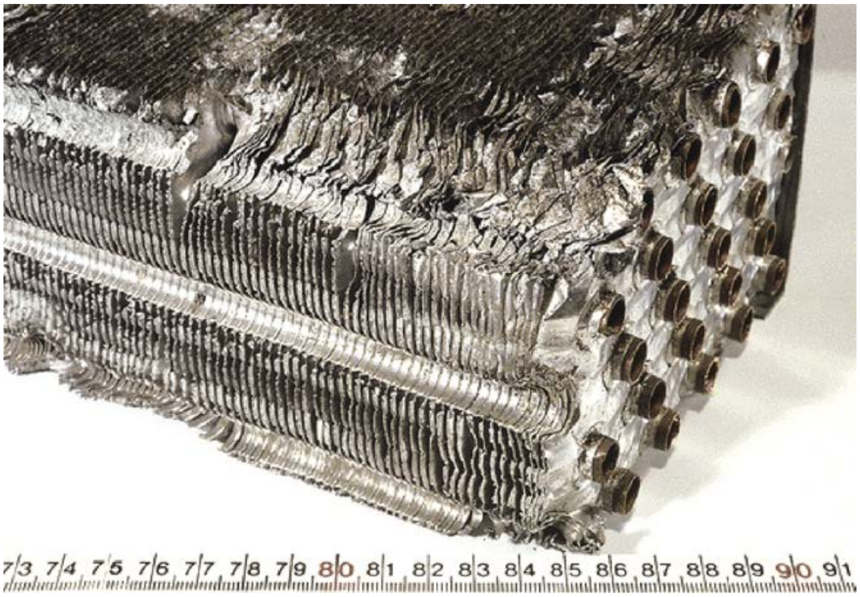
APPEARANCE	Uniform attack.
TIME IN SERVICE	About 4 years.
ENVIRONMENT	Air with relative humidity reduced in the air conditioning system from 87% to 78%; the floor was dry. The air circulates from the plenum to a cheese store and back to the air conditioning plant.
CAUSE	The white deposit consists of $Al(OH)_3$ in addition to some NaCl. In the past, the air was humidified with steam originating from a steam generator with poor separation of water. Accordingly, deposition of alkaline boiler water salts is the presumable cause.
REMEDY	The attack took place in the past (the new plena—without steam humidification—exhibit no attack). As long as the floor remains dry, no further attack will take place. For added certainty, the deposits should be removed by brushing and vacuum cleaning, optionally followed by washing with demineralized water.

CORROSION ATLAS

CASE HISTORY

07.09.14.01

MATERIAL	Aluminum (8000).
SYSTEM	Air conditioning system.
PART	Heat exchanger.
PHENOMENON	Galvanic corrosion.



APPEARANCE	Severe deterioration of aluminum fins of copper tubes.
TIME IN SERVICE	Less than 2 years.
ENVIRONMENT	Atmosphere (coastal area).
CAUSE	Saline condensate enhanced galvanic corrosion of aluminum sheets, by the potential difference between copper and aluminum (see also Case History 07.16.14.01).
REMEDY	Apply an additional surface treatment or eliminate the galvanic couple.

CORROSION ATLAS

CASE HISTORY

07.11.03.01

MATERIAL	Aluminum.
SYSTEM	Steel transport system for caustic soda.
PART	Push-on flange.
PHENOMENON	Caustic corrosion.

APPEARANCE	Uniform attack over the entire surface.
TIME IN SERVICE	Short.
ENVIRONMENT	Atmosphere.
CAUSE	Due to a leaking seal, the aluminum push-on flange came into contact with the caustic soda to which aluminum is not resistant.
REMEDY	In this case, use steel push-on flanges.

CORROSION ATLAS

CASE HISTORY

07.11.03.02

MATERIAL	Aluminum.
SYSTEM	Pasteurizer in brewery.
PART	Beer can.
PHENOMENON	Alkalinity attack.

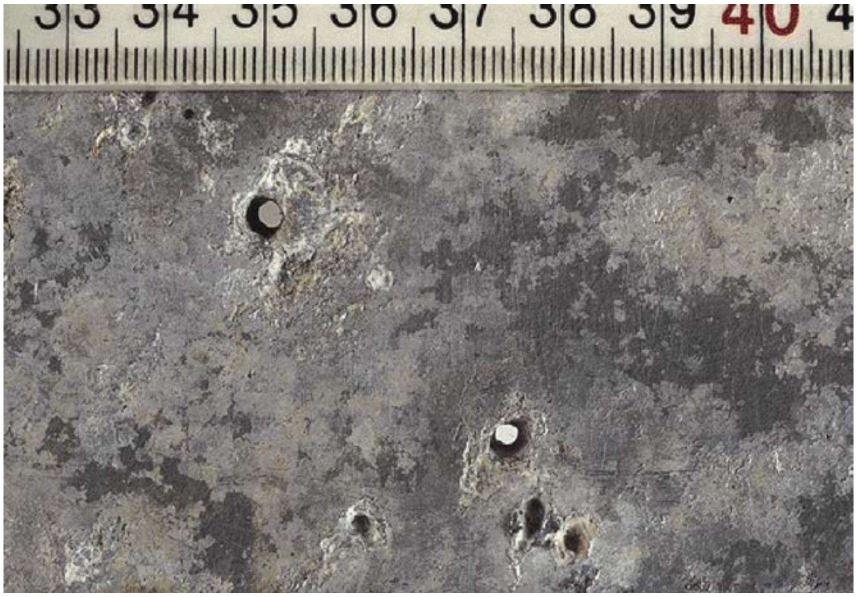
APPEARANCE	One half of the can is completely corroded away.
TIME IN SERVICE	2 months.
ENVIRONMENT	Softened water with sodium hypochlorite (0.1%–1.0%), pH 8–9; temperature 60°C.
CAUSE	The can had remained in a comer of the pasteurizer in contact with the medium. Aluminum is not resistant to the alkaline sodium hypochlorite (see also Case History 07.06.03.01).
REMEDY	• Lower the dosing of sodium hypochlorite. • Use another bactericide for elimination of beer slime.

CORROSION ATLAS

CASE HISTORY

07.11.15.01

MATERIAL	Aluminum (AlMg3).
SYSTEM	Storage tank.
PART	Bottom (6 mm thick).
PHENOMENON	Under-deposit corrosion.



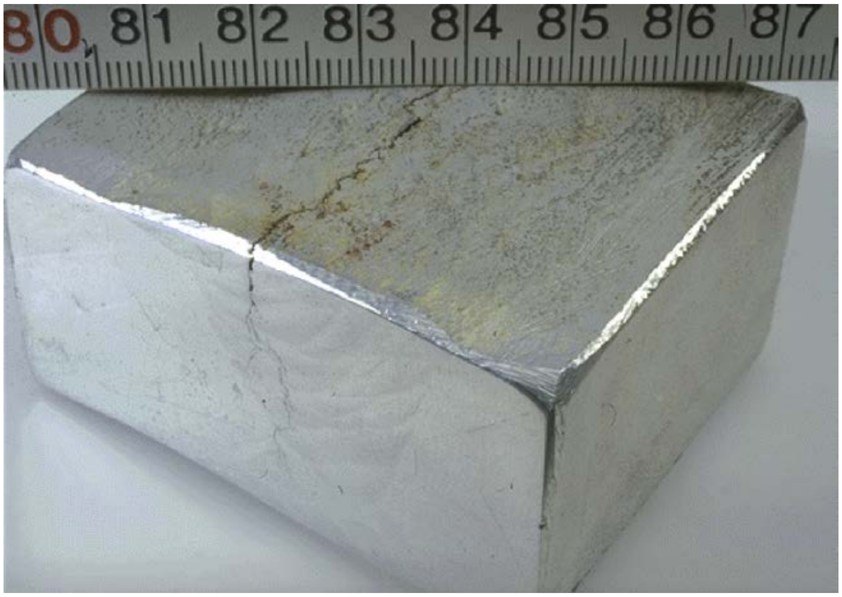
APPEARANCE	Pits and holes and white corrosion products at the underside of the bottom.
TIME IN SERVICE	8 years.
ENVIRONMENT	External: C12–C14 alcohols. Internal: inhomogeneous bedding consisting of clean sand with lumps of earth containing 3600 ppm Cl^-.
CAUSE	The presence of inhomogeneous soil allows the formation of aeration cells. The oxygen lean parts of the bedding (above the lumps of earth) are attacked by the presence of moisture and chlorides. In this situation, aluminum exhibits the same sensitivity as stainless steel (see Case History 04.10.15.01) and galvanized steel (see Case History 02.08.15.01).
REMEDY	• Jack up the tank and grit-blast the bottom, repair any sites attacked deeper than 2 mm with new aluminum plate sections. Then coat the tank bottom (three coats of two-component epoxy coating). • Replace the tank bedding with homogeneous clean sand.

CORROSION ATLAS

CASE HISTORY

07.11.18.01

MATERIAL	Aluminum 99%.
SYSTEM	Acetic acid storage vessel.
PART	Base plate.
PHENOMENON	Stress corrosion cracking (transgranular).



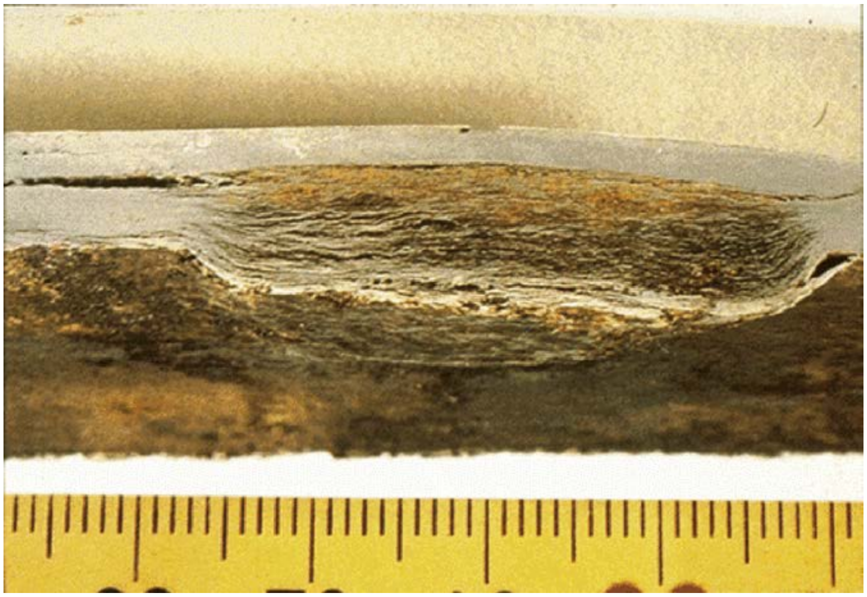
APPEARANCE	Fracture at the center of the weld, in the longitudinal direction of the weld.
TIME IN SERVICE	6–7 years.
ENVIRONMENT	Concentrated acetic acid, ambient temperature.
CAUSE	During welding of the thick aluminum plates, shrinkage cracks were formed due to excessive cooling rate. As a result of the presence of residual stresses in the vicinity of the crack tip, that area is exposed to attack by acetic acid and thereby to crack propagation resulting from the combination of stress and corrosion.
REMEDY	Shrinkage cracks during welding of thick wall plates can be prevented by prewarming of the plates and gradual cooling after welding. Shrinkage cracks present can be removed by remelting Gas Tungsten Arc Welding (GTAW).

CORROSION ATLAS

CASE HISTORY

07.11.19.01

MATERIAL	Aluminum (AlMg 3).
SYSTEM	Product storage tank.
PART	Bottom plate.
PHENOMENON	Integranular corrosion (exfoliation).



APPEARANCE	Local layered swelling of the material.
TIME IN SERVICE	25 years.
ENVIRONMENT	External: moist soil; internal: 100% lactam; temperature 80°C.
CAUSE	Moisture between the tank bottom and pad led to slight corrosion, which in the long term led to this form of intergranular stress corrosion parallel to the surface. The lamellar build-up of relatively noncorroded material is caused by the expansive force of the corrosion products (see also Case Histories 07.19.19.01/02/03/04 and 07.20.19.01/02).
REMEDY	Installation of a new tank, under which a covering layer of bitumen and tar sand was applied.

CORROSION ATLAS

CASE HISTORY

07.11.38.01

MATERIAL	Aluminum ($AlMg_3$).
SYSTEM	Transport piping system.
PART	Welds in 6″ pipe.
PHENOMENON	Weld defects.

APPEARANCE	Intergranular cracking in weld Heat Affected Zone (HAZ) (melt cracks).
TIME IN SERVICE	30 years.
ENVIRONMENT	Inside: air with Polyvinyl chloride (PVC) granules. Outside: industrial atmosphere.
CAUSE	Poor workmanship. Hot cracks in weld HAZ are generated by excessive heat input and excess welding consumable. Mechanical overload caused pipe break in weld HAZ after 30 years in service.
REMEDY	Improve welding performance.

CORROSION ATLAS

CASE HISTORY

07.16.12.01

MATERIAL	Anodized aluminum.
SYSTEM	Swimming pool.
PART	Section of movable intermediate floor.
PHENOMENON	Chloride pitting.

APPEARANCE	Pitting.
TIME IN SERVICE	During laboratory investigation of the material to establish the cause of damage in practice.
ENVIRONMENT	Swimming water with addition of sodium hypochlorite for disinfection. pH 8.
CAUSE	Presence of pores in the oxide layer due to insufficient sealing. The sealing failed as a result of the profile inserted in the flat sheet material, which had angles having too small a curvature radius.
REMEDY	Make the profile angles with a larger curvature radius.

CORROSION ATLAS

CASE HISTORY

07.16.13.01

MATERIAL	Aluminum alloy.
SYSTEM	Civil engineering structure.
PART	Facade element of a window frame.
PHENOMENON	Crevice corrosion.

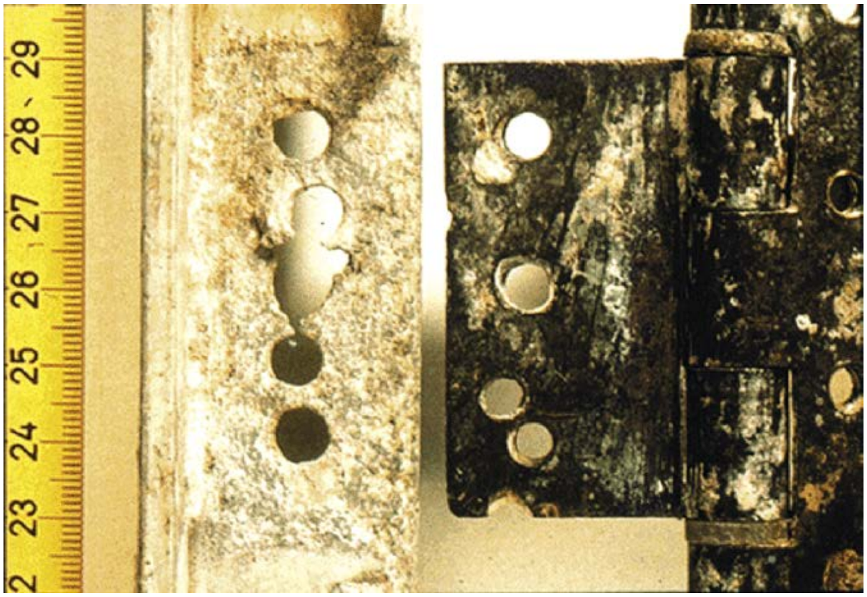
APPEARANCE	Slight pitting underneath whitish/beige-colored corrosion products immediately below the rubber strip seal.
TIME IN SERVICE	1.5 years.
ENVIRONMENT	Urban atmosphere.
CAUSE	Failure of the rubber strip seal, allowing rainwater to enter underneath the rubber strips. Differential aeration underneath and beside the strips allows corrosion to occur at the least aerated site. Aluminum exhibits the same sensitivity to crevice corrosion as stainless steel (see also Case Histories 07.19.13.01 and 07.25.13.01).
REMEDY	- Regular cleaning. - Modify window construction to improve the seal.

CORROSION ATLAS

CASE HISTORY

07.16.14.01

MATERIAL	Aluminum.
SYSTEM	Building.
PART	Factory door frame with hinge.
PHENOMENON	Galvanic corrosion.



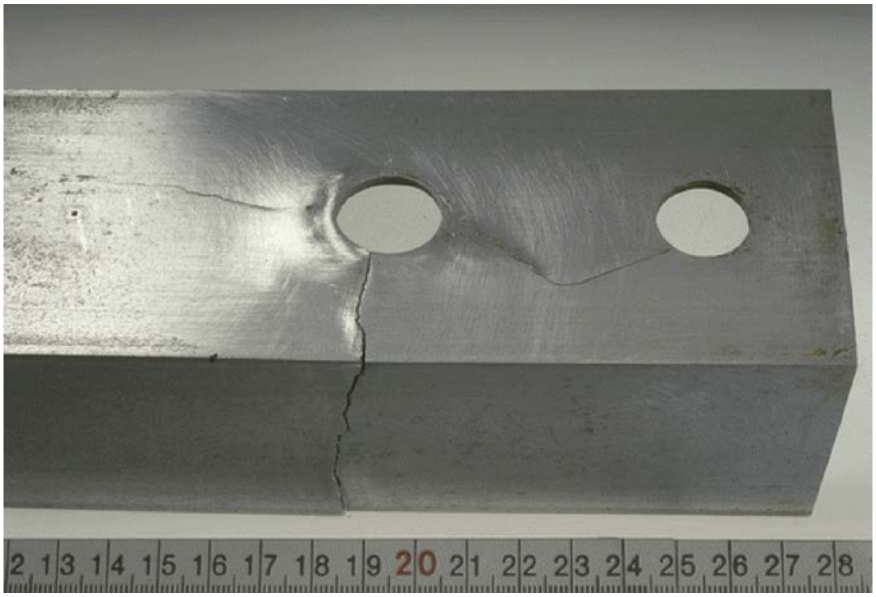
APPEARANCE	Uniform attack of the frame on contact surface with hinge.
TIME IN SERVICE	10 years.
ENVIRONMENT	Industrial atmosphere.
CAUSE	Cell formation due to contact between the aluminum frame and the bronze hinge.
REMEDY	Construct both the hinge and the frame from aluminum or hot-dip galvanize steel.

CORROSION ATLAS

CASE HISTORY

07.16.18.01

MATERIAL	Aluminum zinc alloy (5%–6% zinc).
SYSTEM	Roof structure of factory hall.
PART	Roof truss.
PHENOMENON	Stress corrosion cracking (intergranular).



APPEARANCE	Fracturing.
TIME IN SERVICE	2 years.
ENVIRONMENT	Indoor air of factory hall, normal temperature, and humidity, without chemical contamination.
CAUSE	Inhomogeneous alloy with too high a zinc content.
REMEDY	Use a homogeneous alloy without zinc, which is more resistant to stress corrosion, e.g., AA 5086 (AlMg3).

CORROSION ATLAS

CASE HISTORY

07.16.23.01

MATERIAL	Anodized aluminum (99%).
SYSTEM	Building.
PART	Windowsill.
PHENOMENON	Blooming.

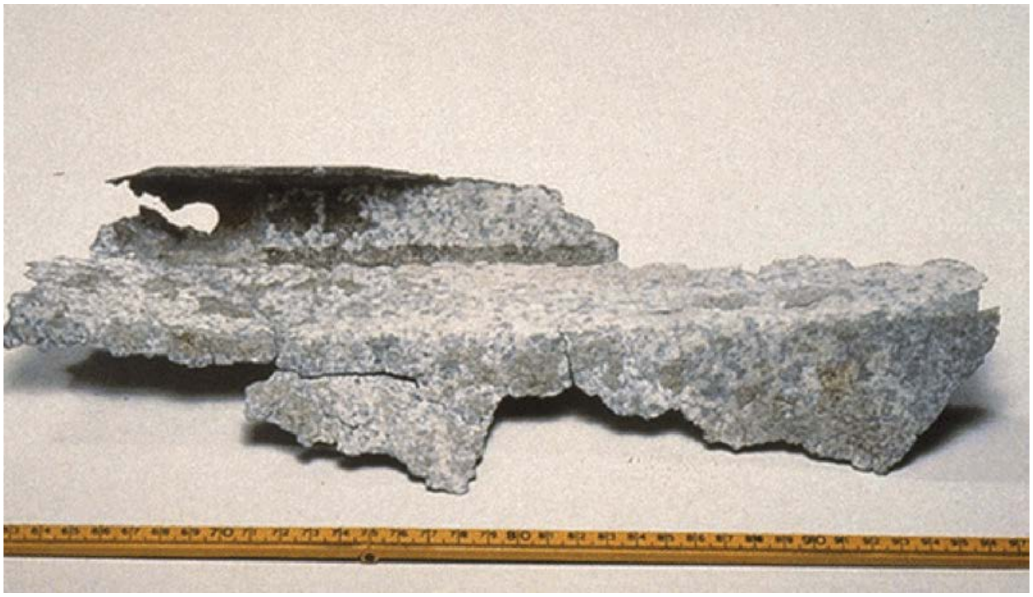
APPEARANCE	White bloom on the surface.
TIME IN SERVICE	Less than 1 year.
ENVIRONMENT	Atmosphere.
CAUSE	Due to insufficient rinsing after the aluminum was anodized, acid residues remain behind in the oxide layer and are enclosed upon sealing, and later on lead to corrosion. This phenomenon is known as blooming.
REMEDY	Improve the rinsing process and subsequently ensure a perfect seal, the seal bath composition requiring to be carefully monitored in order to prevent contamination.

CORROSION ATLAS

CASE HISTORY

07.16.24.01

MATERIAL	Aluminum.
SYSTEM	Aluminum factory building.
PART	Roofing.
PHENOMENON	Atmospheric corrosion.



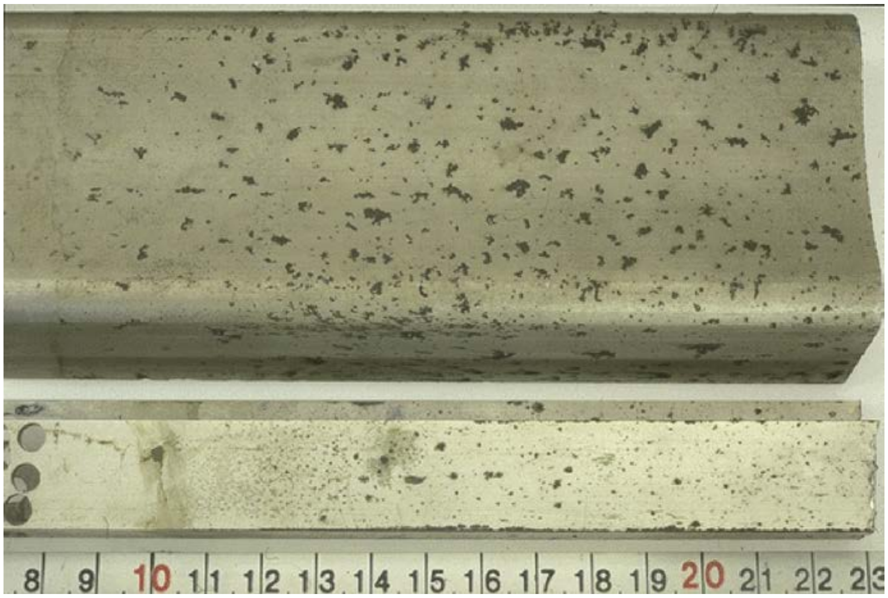
APPEARANCE	Uniform attack.
TIME IN SERVICE	3 years.
ENVIRONMENT	Atmosphere contaminated with flux salts (alkaline chloride–containing salts) used in the manufacture of aluminum.
CAUSE	Attack by flux salts carried to the roof by emissions.
REMEDY	The roofing was constructed of glass–fiber–reinforced polyester, and after 6 years, there are still no problems. Disadvantages: lower mechanical strength and aging by sunlight. The emission of flux salts should also be prevented for environmental reasons.

CORROSION ATLAS

CASE HISTORY

07.16.24.02

MATERIAL	Anodized aluminum (AA 6063).
SYSTEM	Building.
PART	Part of outer wall.
PHENOMENON	Atmospheric corrosion.



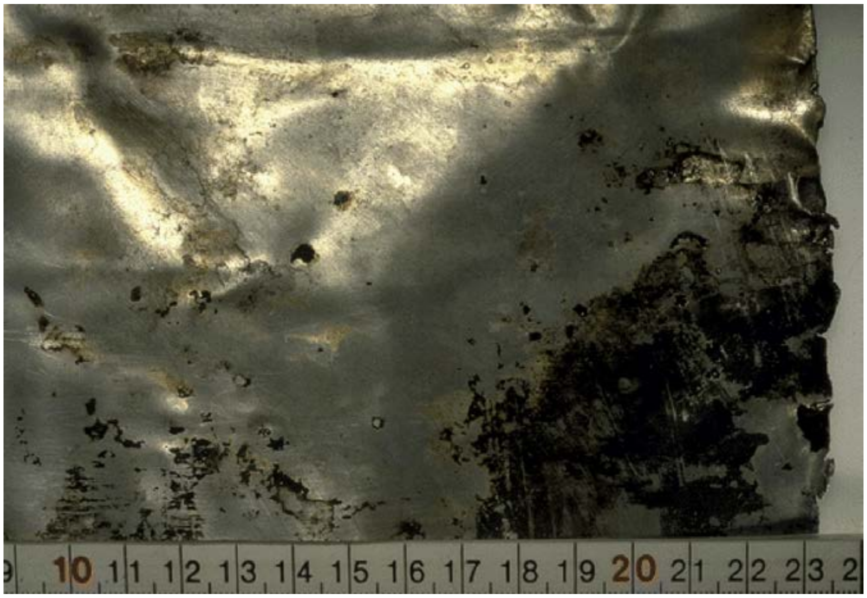
APPEARANCE	Pitting.
TIME IN SERVICE	About 5 years.
ENVIRONMENT	Marine atmosphere. The large piece comes from a demonstration: immersion of new material in a $CuSO_4$ solution.
CAUSE	Heterogeneity of the alloy and an unsealed anodizing layer, combined with the presence of chlorides in this atmosphere.
REMEDY	Provide a good anodizing layer on the aluminum without pores by means of proper sealing.

CORROSION ATLAS

CASE HISTORY

07.16.26.01

MATERIAL	Aluminum 99%.
SYSTEM	Building.
PART	Roof cover.
PHENOMENON	Stray current corrosion.



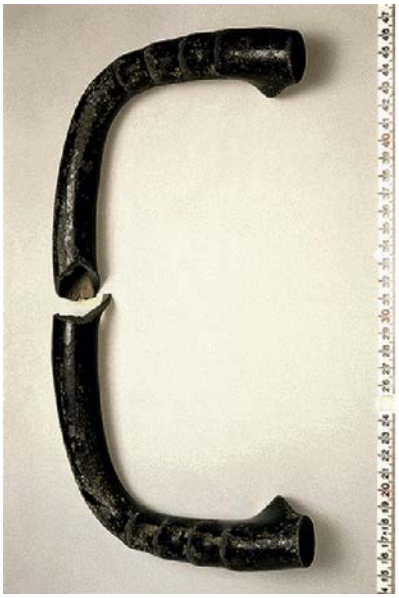
APPEARANCE	Pits and perforations around the antenna cable attachment sites.
TIME IN SERVICE	2–3 years.
ENVIRONMENT	Atmosphere.
CAUSE	Stray current corrosion of the roof covering occurred as a result of defective earthing of the antenna motor.
REMEDY	Ensure proper earthing of the motor.

CORROSION ATLAS

CASE HISTORY

07.19.09.01

MATERIAL	Magnesium (casting A 354).
SYSTEM	Aircraft.
PART	Steering wheel.
PHENOMENON	Salt corrosion.



APPEARANCE	General attack.
TIME IN SERVICE	10 years.
ENVIRONMENT	Acid/salt environment resulting from hand contact.
CAUSE	Deterioration of the corrosion protective system consisting of a CrO_3 anodic film, Araldite surface sealing resin plus decorative paint scheme and attack to the magnesium by prolonged exposure to perspiration moisture.
REMEDY	Material changed to plastic.

CORROSION ATLAS

CASE HISTORY

07.19.13.01

MATERIAL	Aluminum alloy (7075-T651).
SYSTEM	Maritime patrol aircraft.
PART	Elevator panel.
PHENOMENON	Crevice corrosion.

APPEARANCE	Sheet material in lap joint is severely attacked.
TIME IN SERVICE	Rejected during scheduled inspection after 11 years' service.
ENVIRONMENT	Marine atmosphere.
CAUSE	The spot-welded lap joint of two sheets remained unsealed. Hence, (salt) water was able to penetrate into the joint (see also Case Histories 07.16.13.01 and 07.25.13.01).
REMEDY	Application of sealant.

CORROSION ATLAS

CASE HISTORY

07.19.14.01

MATERIAL	High strength aluminum alloy (Al-Zn-Mg; AA7079-T6 forging).
SYSTEM	Aircraft.
PART	Side stay bracket.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Exfoliation of the side stay bracket surface around the bush hole.
TIME IN SERVICE	10 years.
ENVIRONMENT	The side stay bracket positioned in the main wheel bay is exposed to severe environmental conditions.
CAUSE	A damaged corrosion-protected system consisting of CrO_3 anodic film, Aerodur epoxy primer $S^{15}/_{60}$, and Aerodur finish $C^{21}/_{100}$ UVR paint layer allowed galvanic corrosion to occur between the cadmium plated Cr-Ni-Mo bush and the aluminum bracket, which finally resulted in exfoliation.
REMEDY	To exclude galvanic corrosion, the material of the bush was changed, and to reduce environmental influences, sealing was applied.

CORROSION ATLAS

CASE HISTORY

07.19.17.01

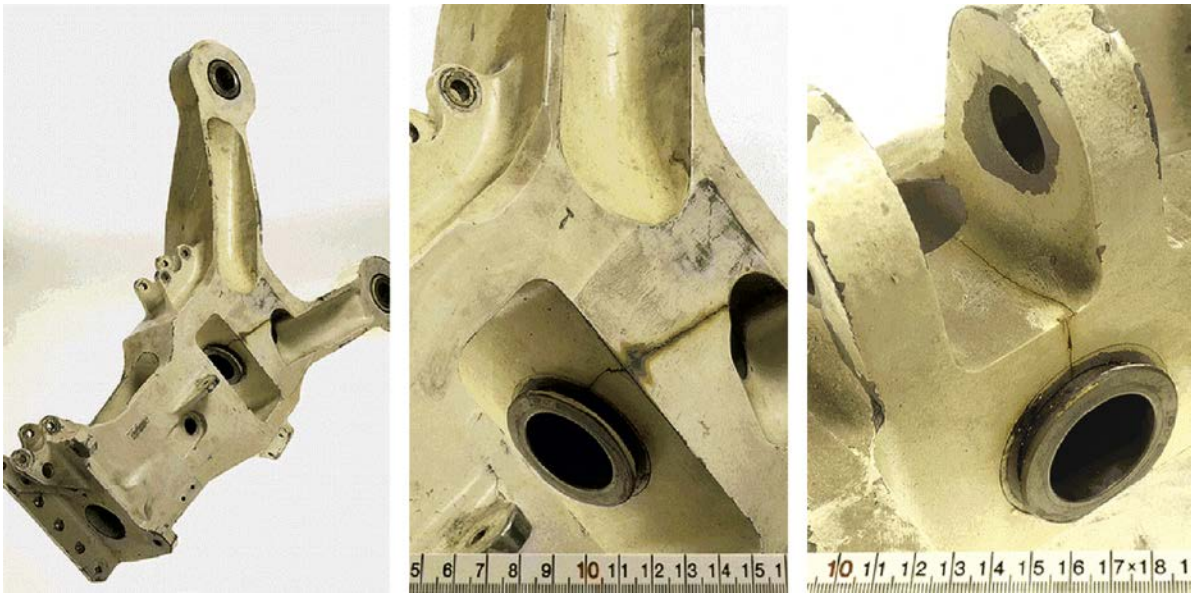
MATERIAL	Aluminum alloy (Al-Cu-Mg; AA 2024-T3).
SYSTEM	Aircraft fuel tank.
PART	Tank hatch.
PHENOMENON	Microbiologically influenced corrosion.

APPEARANCE	Pitting attack.
TIME IN SERVICE	6 months.
ENVIRONMENT	Tropical environment.
CAUSE	Microbiological activity of bacteria (*Pseudomonas fluoresces, micrococcus*), yeast (*Rhodoturula*), and fungi (*Cladosporium resinae, Penicillium chrysogenium, Aspergillus niger*) in fuel tanks resulted in the formation of sludge and metabolism products which induced severe pitting attack.
REMEDY	• Application of a fungus-resistant polyurethane tank coating, PR1560MC, Desoto 823-707, or Bostik 454-4-1; • Regular tank cleaning, and • Application of soluble fuel biocidal additives such as ethylene glycol or Biobor JF. A chemical treat of water using strontium chromate prevents growth, but spores remain vital.

CORROSION ATLAS

CASE HISTORY

07.19.18.01

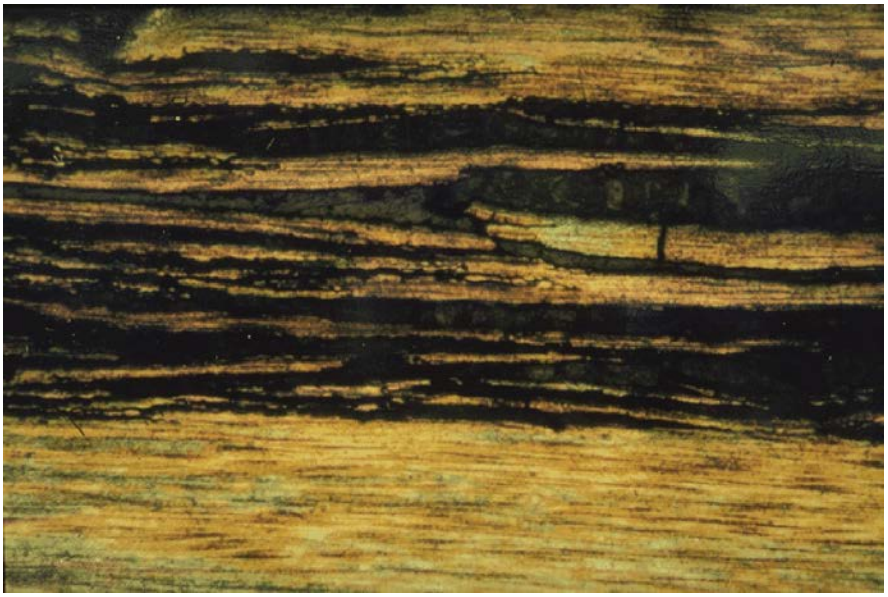
MATERIAL	High-strength aluminum alloy (Al-Zn-Mg; AA7079-T6 forging).
SYSTEM	Aircraft.
PART	Side stay bracket.
PHENOMENON	Stress corrosion cracking.
	
APPEARANCE	Through crack.
TIME IN SERVICE	6 years.
ENVIRONMENT	The side stay bracket, positioned in the main wheel bay, is exposed to severe environmental conditions.
CAUSE	Residual stresses in the forging as a result of the forging process, intermediate annealing temperature, quenching, and the built-in stresses of the interference fit of the bush leading to residual stresses. Improper mounting of the supporting beam and retaining bolt resulted in local damage in the bore for the cable pulley. From the damage sites, a crack proceeded in an intergranular stress corrosion cracking mode.
REMEDY	Improvement of the installation procedures in order to avoid local damage.

CORROSION ATLAS

CASE HISTORY

07.19.19.01

MATERIAL	Aluminum alloy (AA 7075–T6; AlZnMgCu 1.5, extrusion).
SYSTEM	Aircraft (Starfighter).
PART	Sample from the horizontal tailplane.
PHENOMENON	Intergranular corrosion (exfoliation).



APPEARANCE	Micro photo of layered corrosion, invariably initiating from a rivet hole.
TIME IN SERVICE	5 years.
ENVIRONMENT	Atmosphere.
CAUSE	Because of the highly pronounced, extended grain structure (typical of exclusions), which unfortunately intersects the surface, this material is sensitive to exfoliation corrosion (see also next three cases). Corrosive electrolytes have initiated the exfoliation by penetration in the space between rivet and hole.
REMEDY	The damage can cause the component to fail; therefore, measures must be taken. These could be: • An improved coating system, i.e., by using chromate-containing elastomers, or • Choice of different material, using a more exfoliation resistant aluminum alloy, or • Applying a heat treatment to get better precipitate distribution.

CORROSION ATLAS

CASE HISTORY

07.19.19.02

MATERIAL	High-strength aluminum alloy.
SYSTEM	Helicopter.
PART	Attached fitting.
PHENOMENON	Intergranular corrosion (exfoliation).

APPEARANCE	Selective corrosion along subsurface paths parallel to the surface. The voluminous corrosion products force the uncorroded metal layers away, giving rise to a layered appearance.
TIME IN SERVICE	Approximately 20 years.
ENVIRONMENT	Marine atmosphere.
CAUSE	Insufficient protection.
REMEDY	Remove corrosion, check if remaining cross-section is sufficient and apply protective coating.

CORROSION ATLAS

CASE HISTORY

07.19.19.03

MATERIAL	Aluminum alloy (7075-T651).
SYSTEM	Maritime patrol aircraft.
PART	Longeron in fuselage.
PHENOMENON	Intergranular corrosion (exfoliation).

APPEARANCE	Partly corroded away.
TIME IN SERVICE	Rejected during scheduled inspection after 11 years' service.
ENVIRONMENT	Marine atmosphere.
CAUSE	Water accumulated at this site and was able to cause exfoliation corrosion, since alloy 7075 in the T6(51) (= peak-aged) condition is prone to exfoliation corrosion.
REMEDY	Use aluminum alloy 7075 in the over-aged (T7) heat treatment condition.

CORROSION ATLAS

CASE HISTORY

07.19.19.04

MATERIAL	Aluminum alloy (7075-T651).
SYSTEM	Maritime patrol aircraft.
PART	Fairing (wing fuselage).
PHENOMENON	Intergranular corrosion (exfoliation).

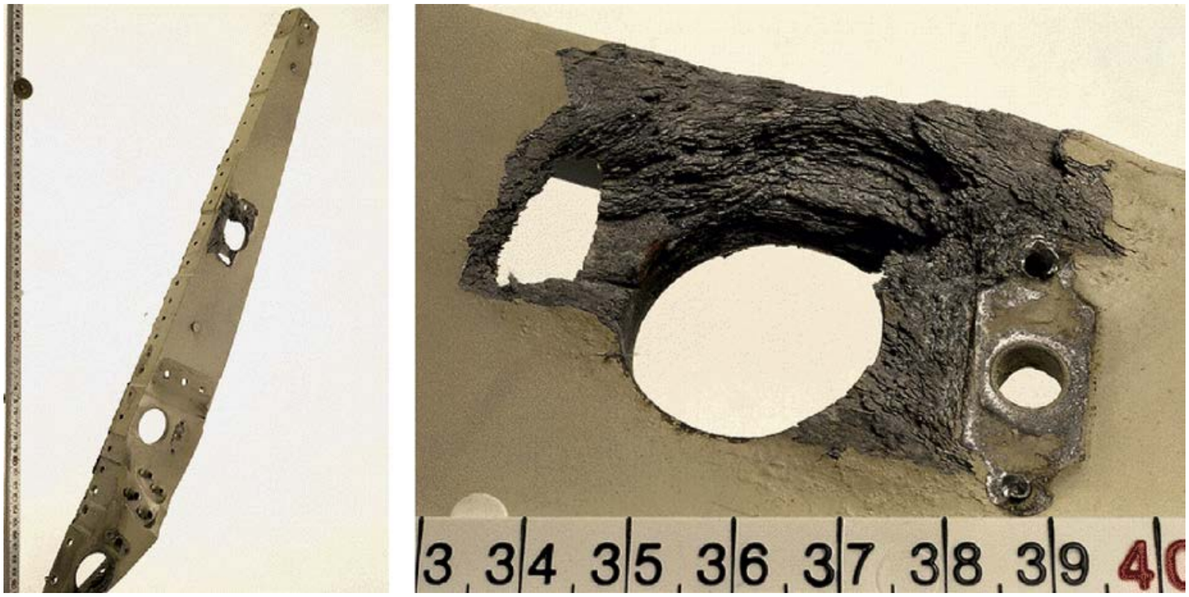
APPEARANCE	Partly corroded away.
TIME IN SERVICE	Rejected during scheduled inspection after 11 years' service.
ENVIRONMENT	Marine atmosphere.
CAUSE	Aluminum alloy 7075 in the T6(51) (= peak-aged) condition is prone to exfoliation corrosion (see also Case Histories 07.11.19.01 and 07.20.19.01).
REMEDY	Use of carbon fiber-reinforced plastic instead of aluminum alloy 7075-T651.

CORROSION ATLAS

CASE HISTORY

07.19.19.05

MATERIAL	High-strength aluminum alloy (Al-Zn-Mg; AA 7075–T6).
SYSTEM	Aircraft.
PART	Outboard rib left-hand flap.
PHENOMENON	Intergranular corrosion (exfoliation).



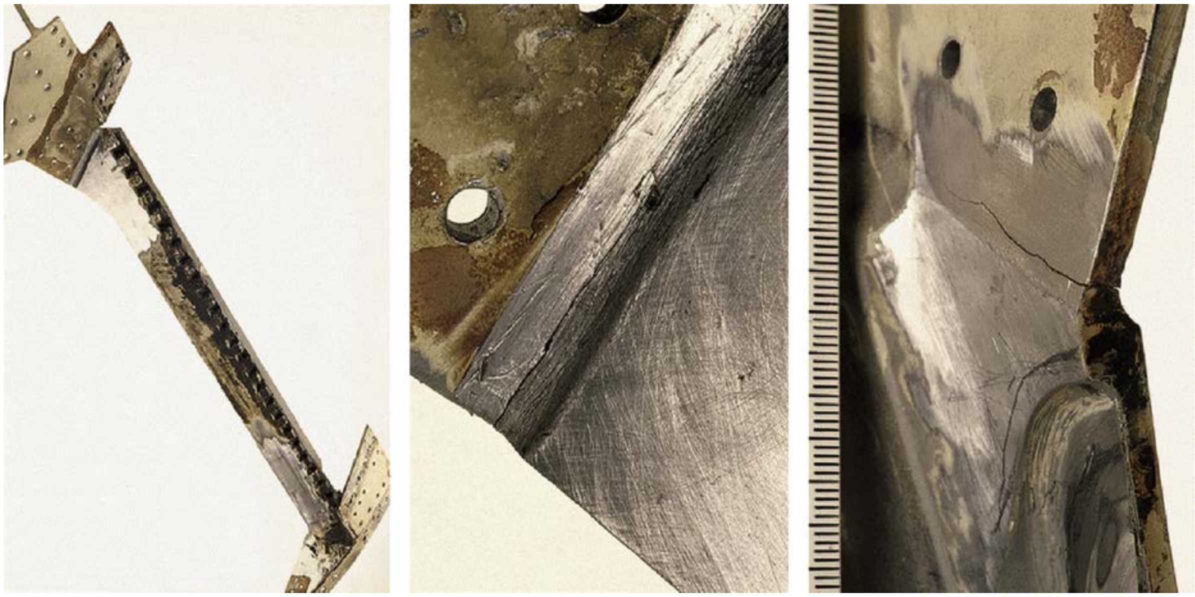
APPEARANCE	Layered corrosion around the bush hole.
TIME IN SERVICE	19 years.
ENVIRONMENT	Outdoor atmosphere.
CAUSE	The presence of a damaged corrosion protection system in the bush attachment hole in combination with pronounced elongated texture of the rib resulted in severe exfoliation corrosion (see also former Case Histories and Case History 07.20.19.02).
REMEDY	Replacement of the rib and improving the protection system.

CORROSION ATLAS

CASE HISTORY

07.19.28.01

MATERIAL	High-strength aluminum alloy (Al-Zn-Mg; AA7079-T6 forging).
SYSTEM	Aircraft.
PART	Window post.
PHENOMENON	Fatigue.



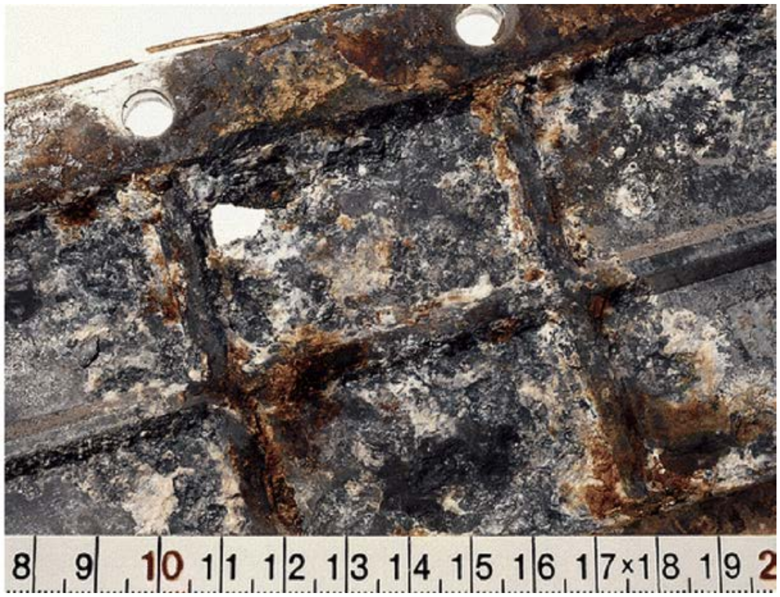
APPEARANCE	Surface flaw in radius of the window post.
TIME IN SERVICE	8 years.
ENVIRONMENT	Dry environmental conditions (ambient atmosphere) inside aircraft.
CAUSE	The cabin pressurization cycle generated fretting between skin edge and window post. Multiple fatigue sites, originating in the radius at the transition of the post-to-flange, form one primary crack front which proceeds through the cross-section.
REMEDY	Chamfering of the post-to-flange transition.

CORROSION ATLAS

CASE HISTORY

07.20.02.01

MATERIAL	Aluminum cast alloy (G-AlSi12(Cu)).
SYSTEM	Automotive system.
PART	Lid of engine cooling block.
PHENOMENON	Corrosion by aggressive water.



APPEARANCE	Pitting and overall corrosion with deposits.
TIME IN SERVICE	1 year.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Insufficiently inhibited aggressive water. Deposition of iron corrosion products from elsewhere in the cooling system has probably contributed to the corrosion. The vehicle was working under very severe field conditions.
REMEDY	Use good-quality water in combination with an inhibited antifreeze.

CORROSION ATLAS

CASE HISTORY

07.20.14.01

MATERIAL	Aluminum cast alloy (G-AlSi12(Cu)).
SYSTEM	Automotive system.
PART	Water heat exchanger lid.
PHENOMENON	Galvanic corrosion.

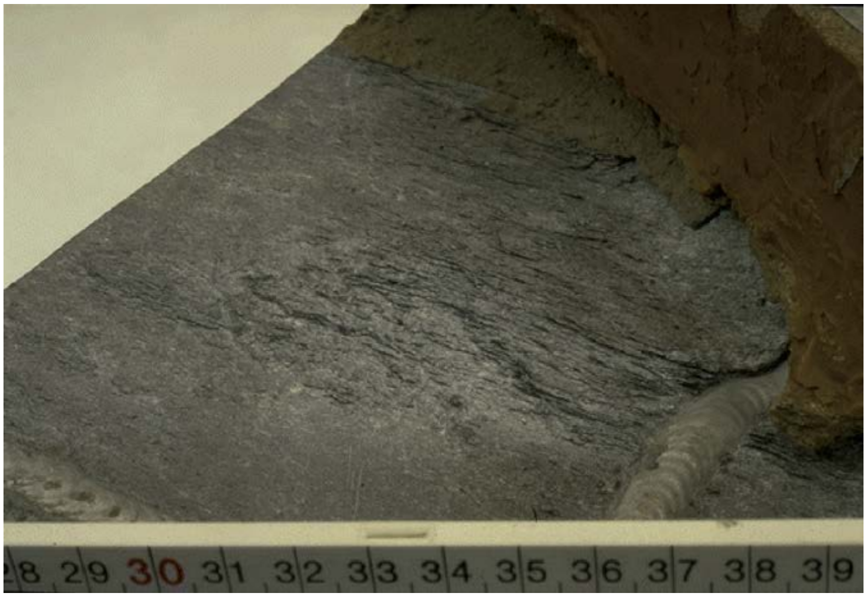
APPEARANCE	Severe corrosion near the connection with the brass tap. The lowest part of the lid (upside down on the left photo) shows very severe corrosion all around, with holes.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Direct metal contact between aluminum heat exchanger lid and brass tap in an electrolyte caused galvanic (bimetallic contact) corrosion.
REMEDY	Use an inhibited water–antifreeze mix and apply an effective isolation compound between aluminum and copper alloys.

CORROSION ATLAS

CASE HISTORY

07.20.19.01

MATERIAL	Aluminum 99%.
SYSTEM	Army tank.
PART	Part of the outside of the asbestos-insulated oil reservoir.
PHENOMENON	Intergranular corrosion (exfoliation).



APPEARANCE	Layered corrosion.
TIME IN SERVICE	Several years.
ENVIRONMENT	Atmosphere.
CAUSE	As a result of the regular wetting of the insulation and the direct contact with the asbestos, the aluminum is subject to layered attack so that more and more new aluminum oxide layers are formed (see also Case Histories 07.11.19.01 and 07.19.19.01/02/03/04).
REMEDY	It was possible to prevent the corrosion by applying a plastic film between the aluminum and the asbestos (nowadays the use of asbestos as insulation material is prohibited because of its carcinogenic effect).

CORROSION ATLAS

CASE HISTORY

07.20.19.02

MATERIAL	Aluminum alloy (AlZnMg1)
SYSTEM	Automotive system.
PART	Fuel tank.
PHENOMENON	Intergranular corrosion (exfoliation).

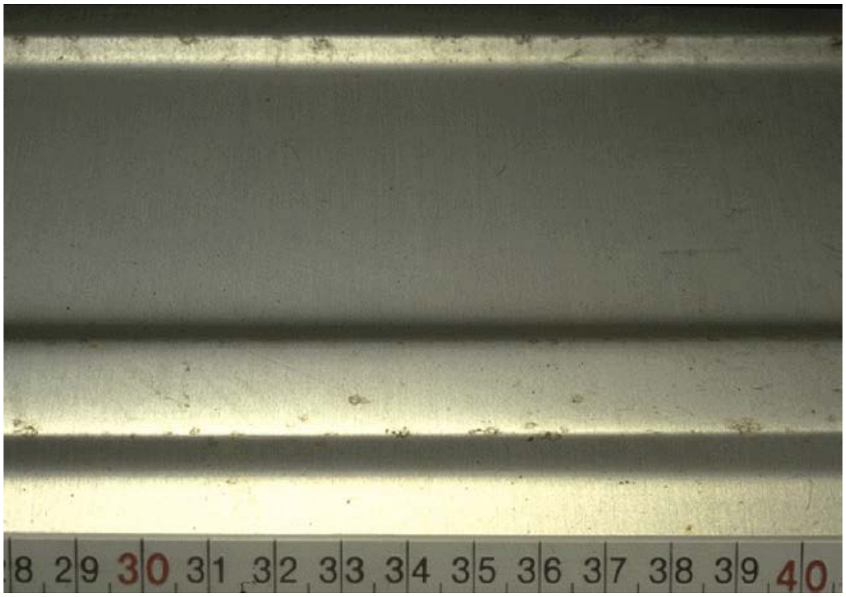
APPEARANCE	Loss of material by layered attack resulting in flaking-off.
TIME IN SERVICE	0.5 years.
ENVIRONMENT	Thermal insulation with organic coating, based on polycondensation. The insulation had a high chloride ion content.
CAUSE	During the polycondensation, water was formed and liberated. Wetting of the insulation caused a humid chloride-containing atmosphere to form on the surface of the aluminum fuel tank, resulting in exfoliation corrosion of the aluminum alloy (see also former case).
REMEDY	Provide the fuel tank with a dry and chloride-free insulation.

CORROSION ATLAS

CASE HISTORY

07.20.24.01

MATERIAL	Anodized aluminum.
SYSTEM	Railway wagon.
PART	Exterior wall.
PHENOMENON	Atmospheric corrosion.



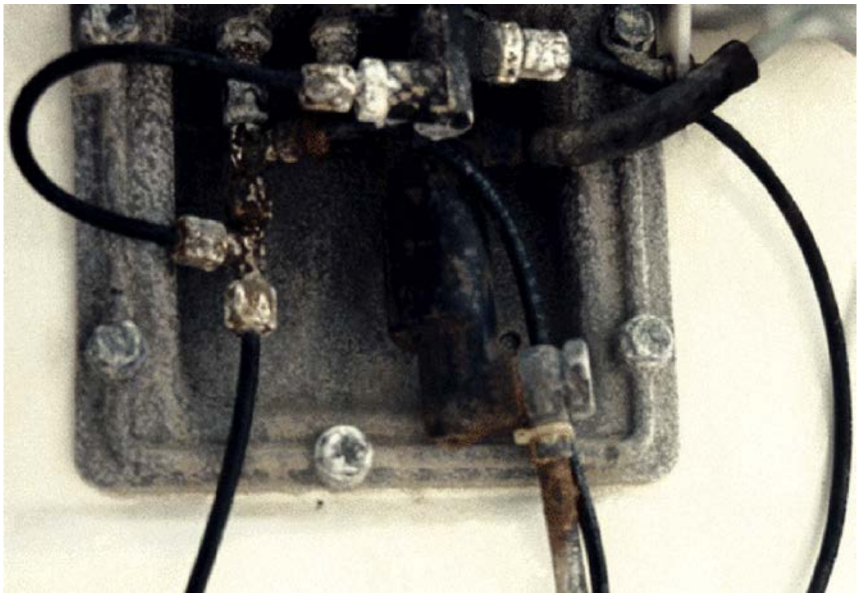
APPEARANCE	Pitting of the profiled edges.
TIME IN SERVICE	6–8 months.
ENVIRONMENT	Atmosphere.
CAUSE	Damage to the anodizing layer due to shaping of the aluminum plates after anodizing.
REMEDY	Perform the plate anodizing process after shaping.

CORROSION ATLAS

CASE HISTORY

07.20.24.02

MATERIAL	–Aluminum G-AlSi12(Cu). –Zinc-plated steel.
SYSTEM	Automotive system.
PART	Aluminum-mounting panel with various zinc-plated parts.
PHENOMENON’	Atmospheric corrosion.



APPEARANCE	Various white corrosion products and some red rust.
TIME IN SERVICE	Estimated: about 2 years under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test).
CAUSE	“Overall corrosion” caused by a combination of dirt, road salts, and humidity.
REMEDY	• Complementary protection by coating or shielding. • Electrocoating on aluminum parts.

CORROSION ATLAS

CASE HISTORY

07.20.24.03

MATERIAL	Aluminum coating on glass by vacuum deposition.
SYSTEM	Automotive system.
PART	Exterior vehicle mirror.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	A dull, nonreflecting mirror surface.
TIME IN SERVICE	Estimated: 1 year under normal road conditions.
ENVIRONMENT	Very severe road conditions (vehicle corrosion test): combination of dirt, road salts, and humidity.
CAUSE	• Insufficient sealing of the mirror housing. • Insufficient quality of the protective coating at the rear of the aluminum coating.
REMEDY	• Improved sealing of the mirror housing. • Improved protective paint system.

CORROSION ATLAS

CASE HISTORY

07.20.33.01

MATERIAL	Aluminum cast alloy (G-AlSi12(Cu)).
SYSTEM	Automotive system.
PART	Water-cooler lid.
PHENOMENON	Cavitation corrosion.
	
APPEARANCE	Inside: flow pattern with pitting. Outside: perforation of one of the hose pillars.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Excessive velocity and turbulence of the water flow in combination with corrosion. Strong vibration of hose near hose pillar (see also next case).
REMEDY	Use appropriate flow and vibration conditions and an inhibited water–antifreeze mix.

CORROSION ATLAS

CASE HISTORY

07.20.33.02

MATERIAL	Aluminum cast alloy (G-AlSi12(Cu)).
SYSTEM	Automotive system.
PART	Thermostat housing of cooling system.
PHENOMENON	Cavitation corrosion.

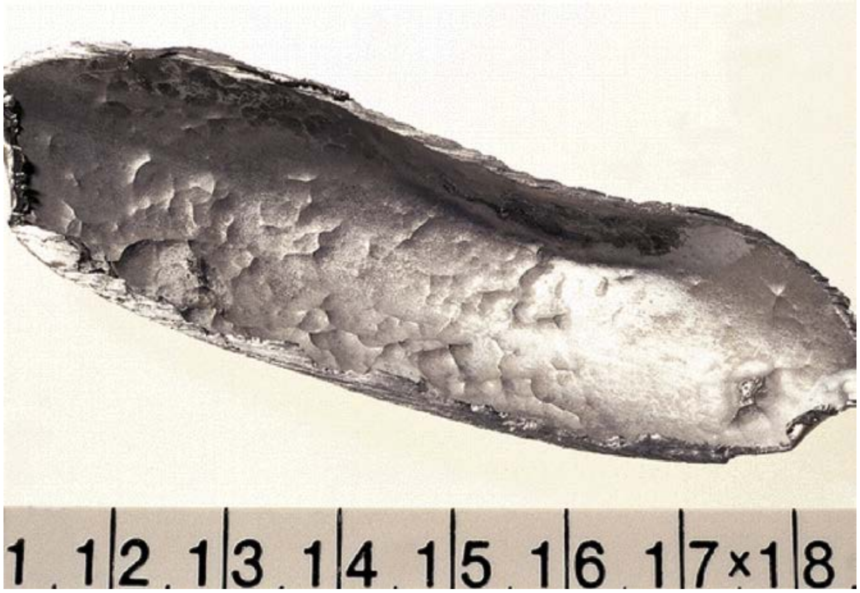
APPEARANCE	Material partly worn away; many sharp-edges pits and holes.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Part opening of the ineffective thermostat-caused cavitation of the aluminum housing by high velocity, turbulent, liquid flow (see also former case).
REMEDY	Replace by an effective thermostat.

CORROSION ATLAS

CASE HISTORY

07.20.34.01

MATERIAL	Extruded aluminum (AA 6063).
SYSTEM	Automotive system.
PART	Pipe from cooling system.
PHENOMENON	Erosion corrosion.



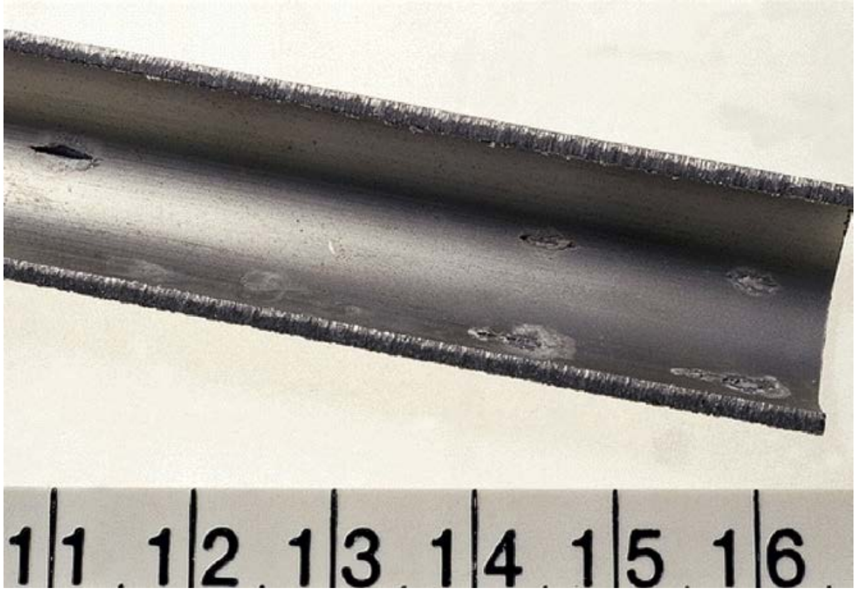
APPEARANCE	Thinning with horseshoe pattern.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Excessive velocity resulting in turbulent flow pattern.
REMEDY	• Create better, less turbulent, flow conditions. • Use inhibited antifreeze–water mixes.

CORROSION ATLAS

CASE HISTORY

07.20.38.01

MATERIAL	Extruded aluminum (AA 6063).
SYSTEM	Automotive system.
PART	Pipe from cooling system.
PHENOMENON	Material defects.



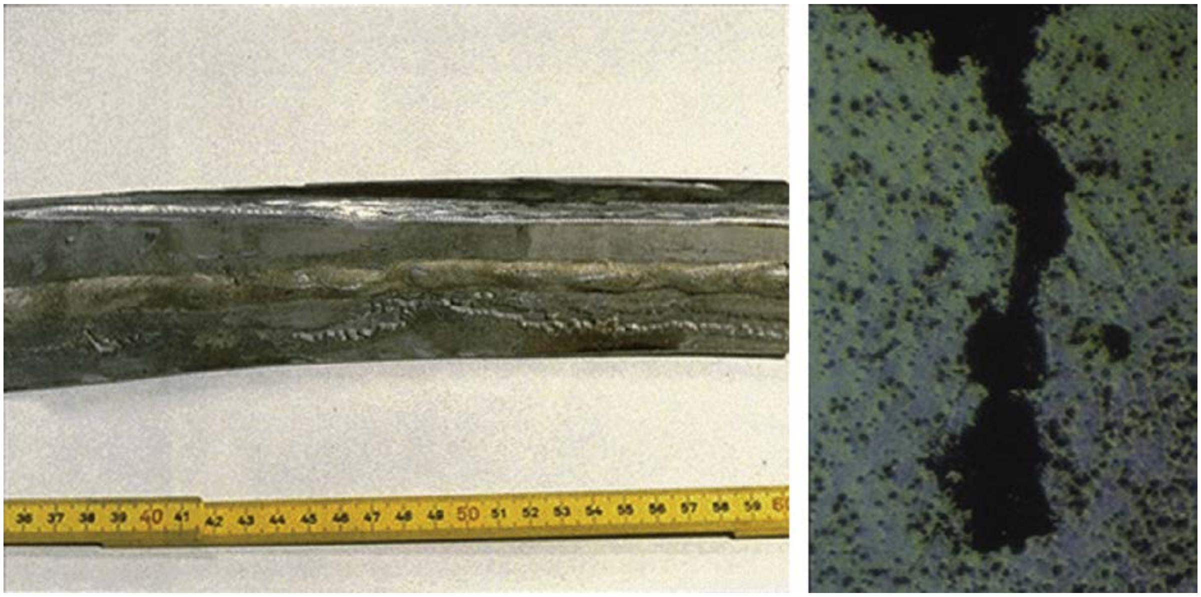
APPEARANCE	Line pitting attack to inner pipe surface.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Water-based engine coolant.
CAUSE	Defects in pipe surface caused by extrusion process: material overlaps (“doublings”) as shown by metallographic examination.
REMEDY	Use better-quality pipe, without defects.

CORROSION ATLAS

CASE HISTORY

07.23.19.01

MATERIAL	Aluminum (5052 quality: Al Mg 2.5)
SYSTEM	Gas scrubber.
PART	Air discharge pipeline.
PHENOMENON	Intergranular corrosion (weld decay).



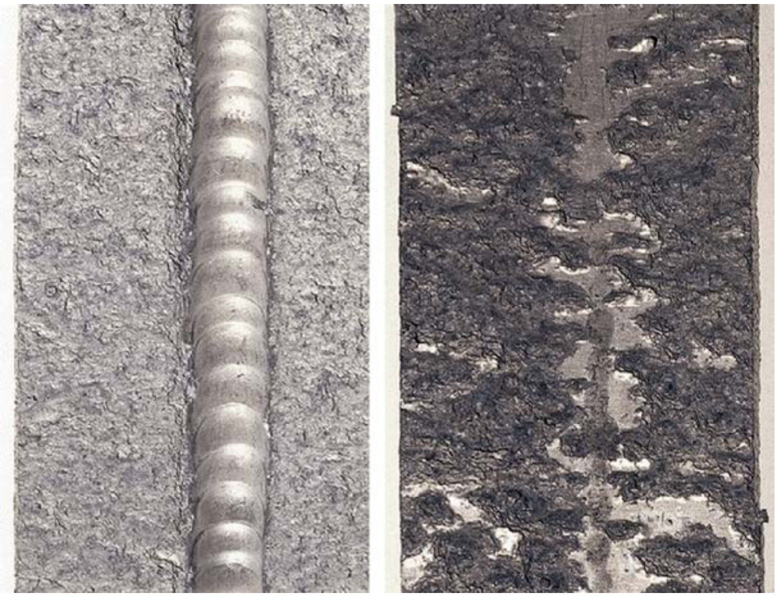
APPEARANCE	Severe attack beside the weld.
TIME IN SERVICE	3 years.
ENVIRONMENT	Air with a relative humidity of 100%, temperature 25°C, contaminated with traces of H_2S and CS_2, sometimes with NaOH. pH of condensate normally 7.5, occasionally rising to 10.
CAUSE	Excessive heat application on welding: not properly cooled. This has led to demonstrable structural changes, as disclosed by the microscopic examination, as a result of which the material has become locally sensitive to corrosion. At each side (at 2 cm) of the weld, the hardness of the material has decreased by 25%.
REMEDY	Weld decay can be restricted by sufficient cooling during the welding process. In the present case, the discharge pipeline is constructed as a glass–fiber–reinforced polyester pipe with PVC liner.

CORROSION ATLAS

CASE HISTORY

07.24.12.01

MATERIAL	Aluminum (S 57).
SYSTEM	Test rig.
PART	Welded aluminum test plate (weld: AlMn).
PHENOMENON	Chloride attack.



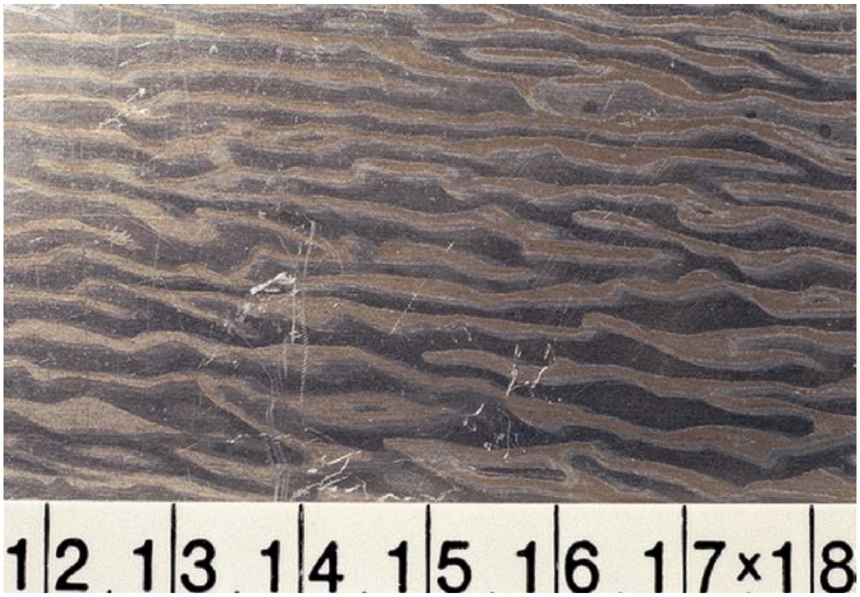
APPEARANCE	General corrosion of the sheet material, the weld itself was not corroded.
TIME IN SERVICE	5 months.
ENVIRONMENT	North Sea water, depth about 5 m below the surface.
CAUSE	The aluminum sheet is not resistant to seawater, in contrast to the weld with a different composition and structure.
REMEDY	Not relevant.

CORROSION ATLAS

CASE HISTORY

07.25.13.01

MATERIAL	Aluminum 99.
SYSTEM	Materials store.
PART	Aluminum sheet material.
PHENOMENON	Crevice corrosion.



APPEARANCE	Stripe-like discolorations (with scratches caused by mechanical damage).
TIME IN SERVICE	1–2 months.
ENVIRONMENT	Wet corrugated cardboard between aluminum sheets.
CAUSE	Forming of differential aeration cells by the aluminum being in close contact with the wet corrugated cardboard. The photo shows the very beginning of crevice corrosion.
REMEDY	Storage under dry conditions.

CORROSION ATLAS

CASE HISTORY

08.05.32.01

MATERIAL	Lead.
SYSTEM	Mains water system.
PART	Underground pipe.
PHENOMENON	Erosion (deformation by water hammer).

APPEARANCE	Pipe fractured.
TIME IN SERVICE	8–10 years.
ENVIRONMENT	Internal: mains water. External: soil.
CAUSE	The yield stress of the material was exceeded due to pressure peaks (water hammer) caused by the sudden closing of a valve (see also Case History 06.02.32.01).
REMEDY	Replace the valve by a slow-closing valve or provide the system with an expansion vessel to absorb the pressure peaks.

CORROSION ATLAS

CASE HISTORY

08.11.04.01

MATERIAL	Lead membrane between carbon steel and porcelain liner.
SYSTEM	Secondary butyl alcohol stripping section.
PART	Stripping column.
PHENOMENON	Acid corrosion.

APPEARANCE	Spalling porcelain, mechanical damage/corrosion lead, uniform corrosion carbon steel. For the purpose of the photograph, part of the porcelain liner is placed loose on the lead membrane.
TIME IN SERVICE	3–27 years.
ENVIRONMENT	50% sulfuric acid. Temperature: 110–130°C.
CAUSE	Porcelain spalled due to temperature changes, 50% H_2SO_4 touches the lead and above 90°C lead corrodes, after which carbon steel corrodes severely. Lead was also locally damaged by the mechanical force needed to remove the porcelain. As a result, the corroded lead surface is no longer visible.
REMEDY	Local replacement of the carbon steel wall with a new carbon steel plate with lead membrane and replace the porcelain liner with graphite bricks.

CORROSION ATLAS

CASE HISTORY

08.11.30.01

MATERIAL	Lead.
SYSTEM	Acid concentrator.
PART	Heating pipe.
PHENOMENON	Creep.

APPEARANCE	Pipe locally swollen and burst open.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Flue gases at approximately 80°C through the pipe; sulfuric acid around the pipe.
CAUSE	The temperature of the flue gases caused accelerated creep of the material (see also Case History 01.01.30.02).
REMEDY	• Change material by taking a copper pipe and sheathing it in lead, or • Construct the heating pipe from Hastelloy C.

CORROSION ATLAS

CASE HISTORY

08.15.26.01

MATERIAL	Lead.
SYSTEM	Energy transmission system.
PART	The jacket of an underground 10 kV cable.
PHENOMENON	Stray-current corrosion.

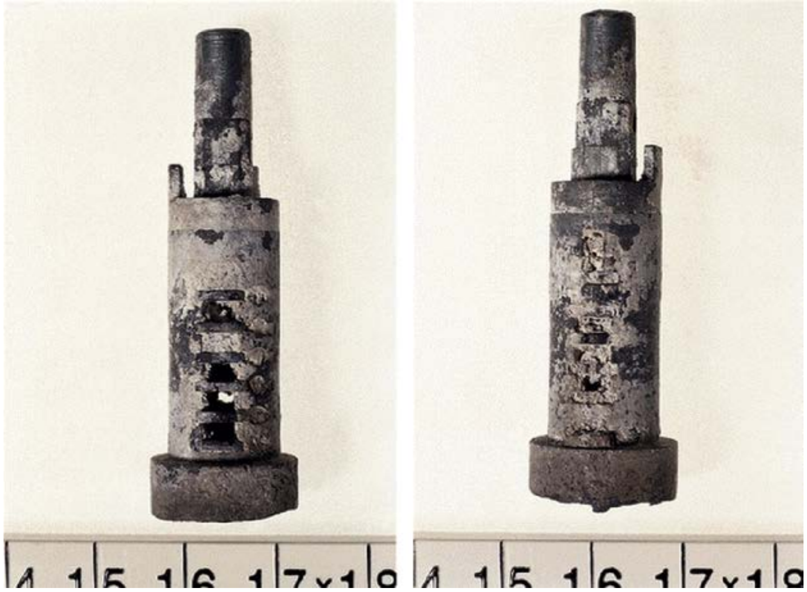
APPEARANCE	Pitting attack, characteristic of this phenomenon in lead.
TIME IN SERVICE	19 years.
ENVIRONMENT	Soil (no sulfide present); pH 8.3; not corrosive to lead; corrosion products: PbO_2, $PbSO_4$, $PbCl_2$.
CAUSE	Stray currents leaving the cable locally owing to its siting at a railway station. The pitting attack is typical of stray-current corrosion in lead.
REMEDY	The cable should be moved to a more favorable location, and for added certainty, the lead jacket should be replaced by a plastic jacket.

CORROSION ATLAS

CASE HISTORY

08.20.24.01

MATERIAL	ZAMAK [die-cast zinc alloy (GD-Zn Al 4 Cu 1) bousing with brass slides].
SYSTEM	Automotive system.
PART	Door lock.
PHENOMENON	Atmospheric corrosion.



APPEARANCE	Blocking of slides by zinc-corrosion products.
TIME IN SERVICE	1–2 years.
ENVIRONMENT	Moist from atmosphere with road-salts and road dirt.
CAUSE	Lock poorly greased or removal of grease by lock antifreeze. The combination of brass with zinc has probably contributed to the corrosion galvanically.
REMEDY	Regular greasing or oiling of lock especially after use of lock antifreeze.

CORROSION ATLAS

CASE HISTORY

08.25.24.01

MATERIAL	Tin.
SYSTEM	Church organ.
PART	Pipes.
PHENOMENON	Atmospheric corrosion (“tin plague”).

APPEARANCE	At the right-hand extremities, the pipes exhibit spots of grey tin, formation of white powder, and an uneven surface and have fractured locally.
TIME IN SERVICE	Over 300 years.
ENVIRONMENT	Cold damp atmosphere. Temperature <13°C.
CAUSE	The allotropic transformation from β- to α-tin below the temperature of 18°C: recrystallization of the tin. Lumps occur as a result of the larger volume of α-tin. The tin becomes brittle and disintegrates into powder, a phenomenon known as “tin plague”. According to the priest, however, it was the work of the devil, because the light of the Lord was prevented from shining upon the pipes.
REMEDY	Keep the temperature ≥20°C.

CORROSION ATLAS

CASE HISTORY

09.01.07.01

MATERIAL	Zircalloy.
SYSTEM	Boiling water reactor (pressure: 5.4 MPa).
PART	Fuel element filled with uranium oxide pellets.
PHENOMENON	Heat-flux corrosion (nodular corrosion).

APPEARANCE	On the interfaces of the pellets, small rings of pitting corrosion were present at the cooling side of the element. The corrosion product is still present as hard pustules.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Pure water.
CAUSE	The water–steam mixture runs along the outside of the Zircalloy cannings. The heat flux varies over the length of the element. On the interface of the tablets, the heat flux is critical for local boiling of the water, a process known as nucleate boiling or columnar boiling. This boiling process on nucleates causes pitting corrosion (see also Case Histories 01.01.07.03/04). In nuclear technology, this type of corrosion is called nodular corrosion.
REMEDY	Removal of the fuel elements before leakages occur. There is no remedy for nodular corrosion.

CORROSION ATLAS

CASE HISTORY

09.08.33.01

MATERIAL	Titanium.
SYSTEM	Effluent tank.
PART	Heating coil.
PHENOMENON	Cavitation corrosion.

APPEARANCE	Pitting corrosion in the form of numerous small cavities, the pipe being perforated at various places.
TIME IN Service	8 months.
ENVIRONMENT	Effluent with an organic phase consisting of laurinic acid in the upper part of the tank and an aqueous phase with 0.5% H_2SO_4, 1% NaCl, 1% Na_2SO_4, pH 1.5, in the lower part of the tank. Traces of H_2O_2 also present. For the purpose of emptying the tank, the contents were heated to 90°C by passing steam through the coil at 140°C
CAUSE	Originally, the coil was constructed of stainless steel. After 3 months, it was leaking at all the windings. The titanium coil only exhibited attack on the lowest (hottest) winding. Laboratory tests on titanium in the laboratory were positive. Presumably, the oxide skin on the bottom winding is exposed to continuous damage by collapsing steam bubbles, which cause pitting in the present environment.
REMEDY	The coil was constructed of Polyvinylidene difluoride (PVDF) (in view of the ample time for heating, the poorer heat transfer of this material was not a drawback). This has worked well for 5 years.

CORROSION ATLAS

CASE HISTORY

09.11.08.01

MATERIAL	Silver.
SYSTEM	Reactor.
PART	Gas inlet pipe.
PHENOMENON	Chlorine corrosion.

APPEARANCE	Uniform attack, with brittle silver chloride layer being formed.
TIME IN SERVICE	About 3 years.
ENVIRONMENT	Chlorine gas; temperature >100°C.
CAUSE	The inlet pipe was unsufficiently fixed. Because of the vibration, it was not possible for a tight silver chloride skin to form. The chlorine diffused further and further, thereby converting more and more silver into silver chloride (the silver-coated reactor covers were not attacked).
REMEDY	Use an enamelled inlet pipe.

CORROSION ATLAS

CASE HISTORY

09.11.08.02

MATERIAL	Zirconium.
SYSTEM	Heat exchanger in chlorine manufacturing plant (chlorine through and cooling water around the pipes).
PART	Pipe in pipe bundle. Above: constructed of titanium; below: constructed of zirconium.
PHENOMENON	Chlorine corrosion.

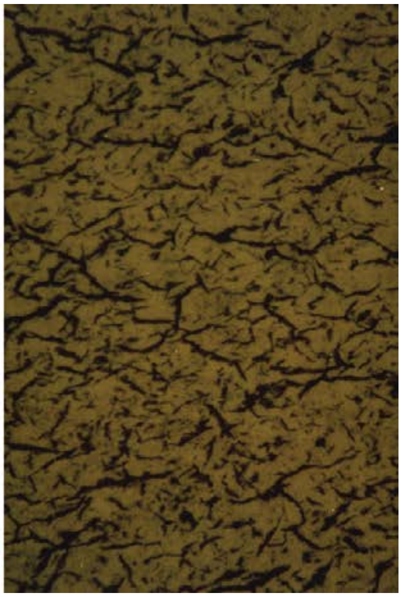
APPEARANCE	Uniform attack with white oxides and annealing colors.
TIME IN SERVICE	1 week.
ENVIRONMENT	Chlorine-containing condensate; temperature approximately 25°C.
CAUSE	Error in choice of material: one of the pipes was of zirconium instead of titanium. Zirconium is not resistant to this medium; on disassembly, spontaneous chlorine combustion occurred.
REMEDY	Improved checks on the material selection.

CORROSION ATLAS

CASE HISTORY

09.11.20.01

MATERIAL	Titanium.
SYSTEM	Ammonium carbamate condenser.
PART	Pipe of pipe bundle.
PHENOMENON	Hydrogen damage (hydride embrittlement).



APPEARANCE	Cracking and uniform corrosion, the wall thickness being reduced from 3 to 1 mm.
TIME IN SERVICE	5 years.
ENVIRONMENT	Cooling water around the pipes. Through the pipes, condensation of oxygen-free ammonium carbamate, temperature 120–130°C, pressure 6 bar, pH about 12.
CAUSE	Uniform corrosion of titanium by ammonium carbamate with reduction of hydrogen ions as cathodic half-reaction of the corrosion process. The forming hydrogen penetrates the titanium and forms needle-shaped titanium hydride secretions, leading to embrittlement.
REMEDY	• Extend lifetime by reducing the temperature by recycling the condensed ammonium carbamate. • Alternative: use duplex stainless steel.

CORROSION ATLAS

CASE HISTORY

09.11.34.01

MATERIAL	Titanium.
SYSTEM	Chlorine manufacturing plant (trapping surplus chlorine gas).
PART	Impeller.
PHENOMENON	Erosion corrosion and cavitation.

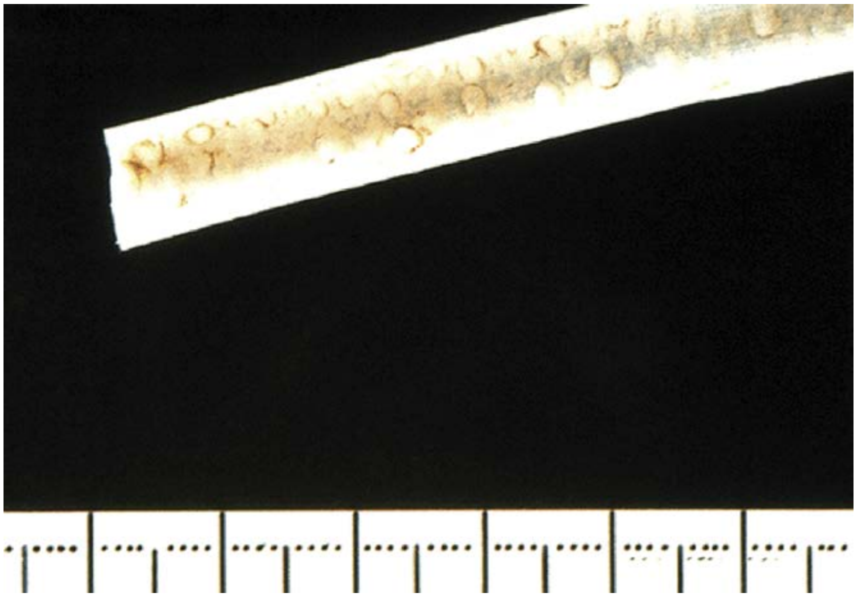
APPEARANCE	Attack to impeller, with a distinct flow pattern.
TIME IN SERVICE	About 1 year.
ENVIRONMENT	A mixture of caustic soda (concentrated), caustic bleach, soda (solid particles). Temperature normally 20°C, with occasional peaks of 70–80°C.
CAUSE	The solid soda particles caused erosion; the heat formed during the reaction of chlorine with caustic soda caused occasional high temperatures, as a result of which cavitation occurred; in addition, the titanium was corroded by the hot concentrated caustic solution.
REMEDY	Use of impeller constructed of Teflon perfluoroalkoxy.

CORROSION ATLAS

CASE HISTORY

10.02.37.01

MATERIAL	Polytetrafluoroethylene.
SYSTEM	Extruder.
PART	Cooling pipe.
PHENOMENON	Diffusion.



APPEARANCE	Blistering.
TIME IN SERVICE	1 year.
ENVIRONMENT	Steam condensate at 90°C as cooling medium through the hose (hose was sheathed in metal fabric).
CAUSE	Water-filled blisters arise by diffusion at the atmospheric dew point.
REMEDY	Use of a flexible metal pipe.

CORROSION ATLAS

CASE HISTORY

10.02.37.02

MATERIAL	Glass–fiber-reinforced epoxy.
SYSTEM	Steam condensate transport pipe.
PART	Pipe section.
PHENOMENON	Diffusion.

APPEARANCE	Flaking-off of the gel coat.
TIME IN SERVICE	5 years.
ENVIRONMENT	Condensate; temperature 95°C.
CAUSE	The diffusion velocity through the gel coat is higher than that through the glass–fiber-reinforced sheeting. As a result, liquid collects at the boundary plane, causing the gel coat to flake off.
REMEDY	Use of carbon steel.

CORROSION ATLAS

CASE HISTORY

10.06.36.01

MATERIAL	Acrylonitrile butadiene styrene.
SYSTEM	Cooling water system.
PART	Outdoor pipe.
PHENOMENON	Stress cracking (embrittlement).

APPEARANCE	Longitudinal cracking, with a piece broken out.
TIME IN SERVICE	4–5 years.
ENVIRONMENT	Internal: cooling water at 20°C–60°C. External: atmosphere.
CAUSE	Line was externally contaminated with organic solvents from the paint residues originating from painting work in the direct vicinity. Formation of stress embrittlement by the solvents in combination with stresses originating from poor assembly.
REMEDY	Plastic pipes should be covered during painting work.

CORROSION ATLAS

CASE HISTORY

10.08.36.01

MATERIAL	Polyvinyl chloride (PVC).
SYSTEM	Sewage treatment plant.
PART	Sewer.
PHENOMENON	Stress cracking (embrittlement).

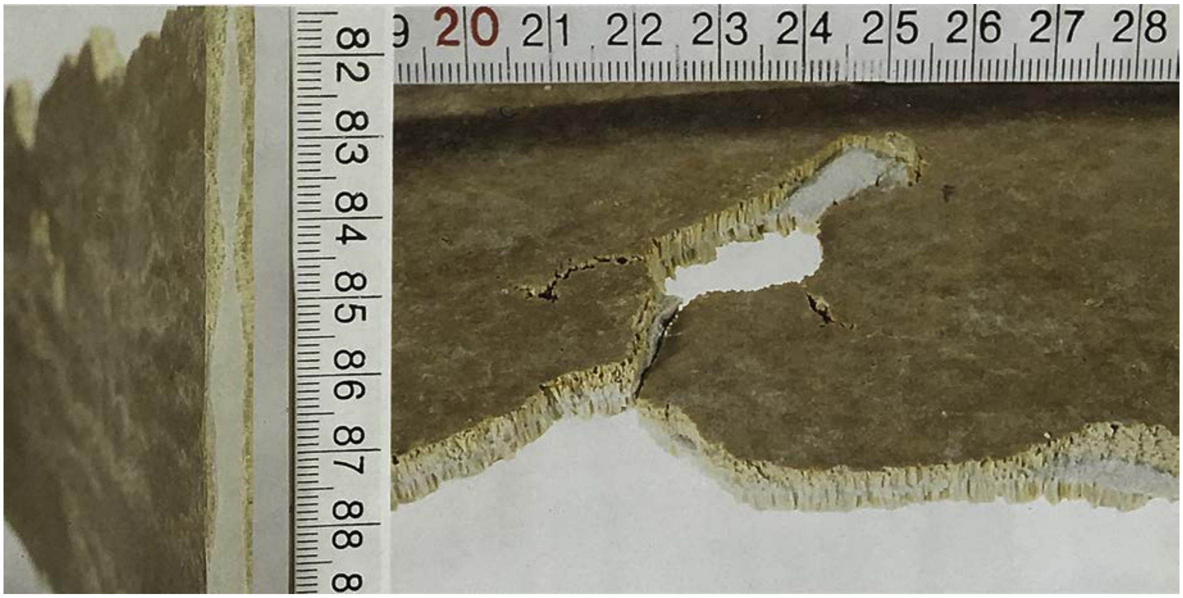
APPEARANCE	Parallel cracking.
TIME IN SERVICE	Several weeks.
ENVIRONMENT	Sewage contaminated with epoxidized soya oil which had deposited in the pipe in the form of a greasy sludge. Temperature about 20°C.
CAUSE	Epoxidized soya oil from the production process entered the sewer and acted as a softening agent on the PVC, as a result of which the pipe cracked in combination with stresses.
REMEDY	Sewer was constructed of polyethylene.

CORROSION ATLAS

CASE HISTORY

10.09.29.01

MATERIAL	Polypropylene.
SYSTEM	Extraction system.
PART	Upper part of cap.
PHENOMENON	Aging.



APPEARANCE	Material exhibits two-sided discoloration from gray to yellow, with needle structure.
TIME IN SERVICE	6 years
ENVIRONMENT	Water vapor with ammonia residues. Temperature rising to 90°C.
CAUSE	In the present atmosphere, thermal oxidation causes aging of the polypropylene, which embrittles as a result.
REMEDY	Cap partly made of polyvinylidene fluoride (PVDF).

CORROSION ATLAS

CASE HISTORY

10.11.03.01

MATERIAL	Glass–fiber-reinforced vinyl ester (Fibercast, type F 1222).
SYSTEM	Caustic transport pipeline.
PART	Pipe section (provided with thermal insulation with electric tracing).
PHENOMENON	Caustic attack.

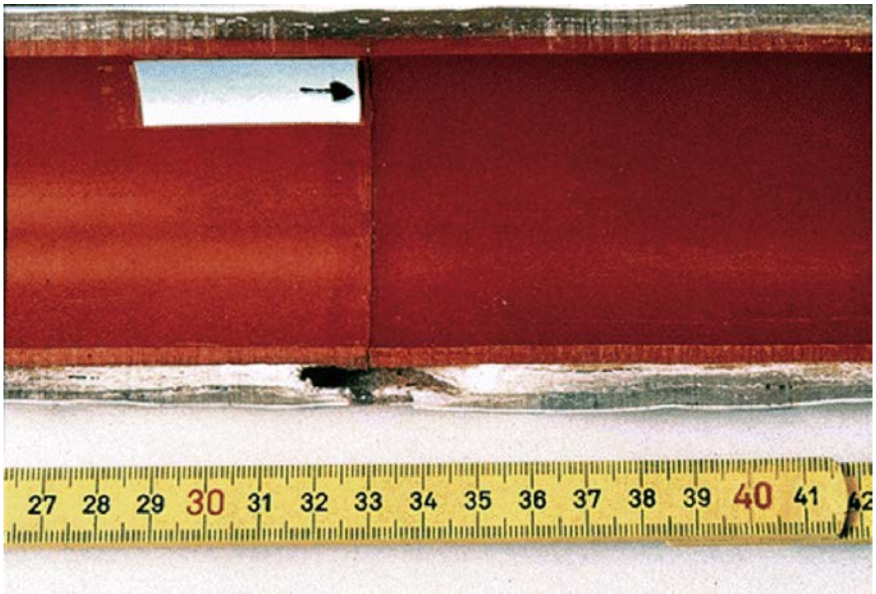
APPEARANCE	Resin layer partly disappeared, glass fibers frayed.
TIME IN SERVICE	$2\frac{1}{2}$ years.
ENVIRONMENT	50% NaOH; temperature 50°C–60°C; flowing and standing.
CAUSE	Diffusion of caustic through the resinous inner layer to the glass-fiber reinforcement, which was attacked. According to the supplier, the material was resistant to 50% caustic soda at 65°C.
REMEDY	Construction of the pipeline from epoxy or AISI 316 Ti stainless steel (W.-Nr. 1.4571).

CORROSION ATLAS

CASE HISTORY

10.11.03.02

MATERIAL	Glass–fiber-reinforced polyester with PVC coating.
SYSTEM	Electrolysis plant.
PART	Pipe section.
PHENOMENON	Caustic attack.



APPEARANCE	Attack to the polyester at the weld.
TIME IN SERVICE	A few weeks.
ENVIRONMENT	20% caustic soda (NaOH); temperature approximately 20°C.
CAUSE	Owing to poor welding workmanship, cracking occurred in the weld of the PVC coating, and the polyester was attacked by caustic solution.
REMEDY	Better weld quality by improving the inspection and approval procedure.

CORROSION ATLAS

CASE HISTORY

10.11.04.01

MATERIAL	Glass–fiber-reinforced epoxy.
SYSTEM	Formic acid transport system.
PART	Pipe with bonded connection flange.
PHENOMENON	Acid attack.

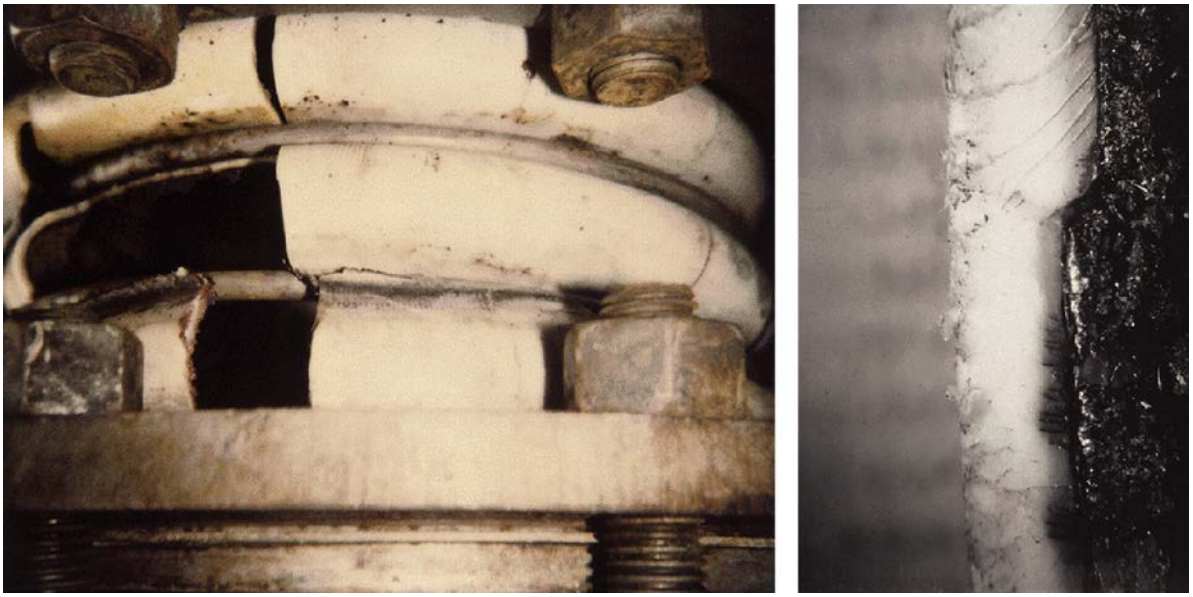
APPEARANCE	Total disintegration of the reinforcement.
TIME IN SERVICE	Approximately 1 year.
ENVIRONMENT	Concentrated formic acid.
CAUSE	The epoxy resin is not resistant to the medium. Consequently, the glass-fibers became detached and blocked the pipe.
REMEDY	Use stainless steel (AISI 316) pipe.

CORROSION ATLAS

CASE HISTORY

10.11.04.02

MATERIAL	Polytetrafluoroethylene (PTFE).
SYSTEM	Chemical circulating system.
PART	Bellows.
PHENOMENON	Acid corrosion.



APPEARANCE	Black brittle layer of corrosion products.
TIME IN SERVICE	1 year.
ENVIRONMENT	Initially 15% HCl, later on in the process a reaction mixture with *inter alia* aniline hydrochloride. Temperature: 30°C–90°C.
CAUSE	Chemical attack of PTFE by HCl and aniline (see also Case History 10.11.28.01).
REMEDY	System redesign eliminating the bellows.

CORROSION ATLAS

CASE HISTORY

10.11.28.01

MATERIAL	PTFE-lined steel.
SYSTEM	Circulation system.
PART	Pipe.
PHENOMENON	Corrosion fatigue.

APPEARANCE	Cracked lining.
TIME IN SERVICE	2 years.
ENVIRONMENT	Initially 15% HCl, later on in the process, a reaction mixture with *inter alia* aniline hydrochloride. Temperature fluctuations from 30°C to 90°C.
CAUSE	Corrosion fatigue due to temperature fluctuations and aniline in the medium (see also Case History 10.11.04.02).
REMEDY	Select Hastelloy C276 with corrosion allowance instead of PTFE-lined steel.

CORROSION ATLAS

CASE HISTORY

10.11.29.01

MATERIAL	Melamine.
SYSTEM	Pipeline system.
PART	Hold-down plate.
PHENOMENON	Aging (see also next two cases).

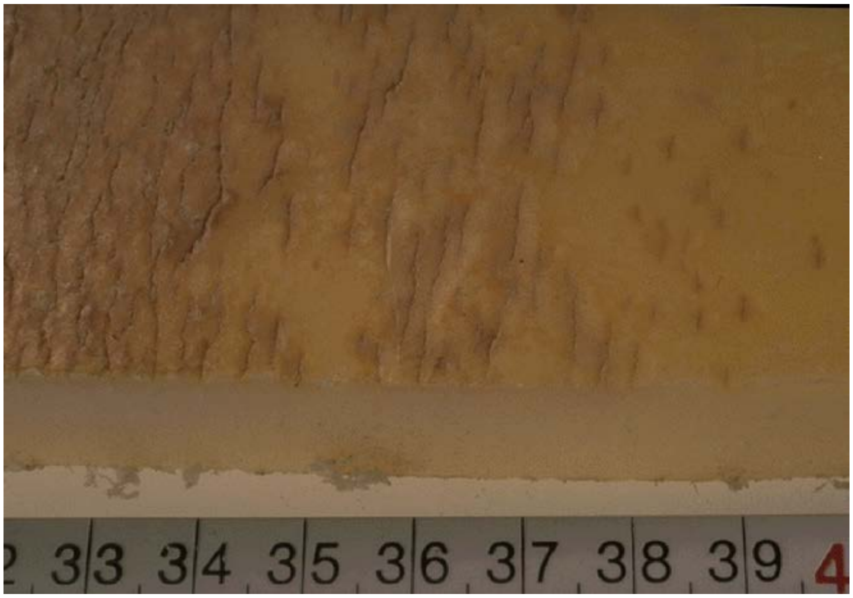
APPEARANCE	Network of cracks and brittle fracture.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Industrial atmosphere.
CAUSE	Insufficient hardening of the melamine resin and use of inappropriate fillers led to accelerated aging.
REMEDY	Use a better quality resin.

CORROSION ATLAS

CASE HISTORY

10.11.29.02

MATERIAL	Ultra-high-molecular-weight polyethylene.
SYSTEM	Artificial fertilizer transport system.
PART	Wearing plate.
PHENOMENON	Aging and erosion.



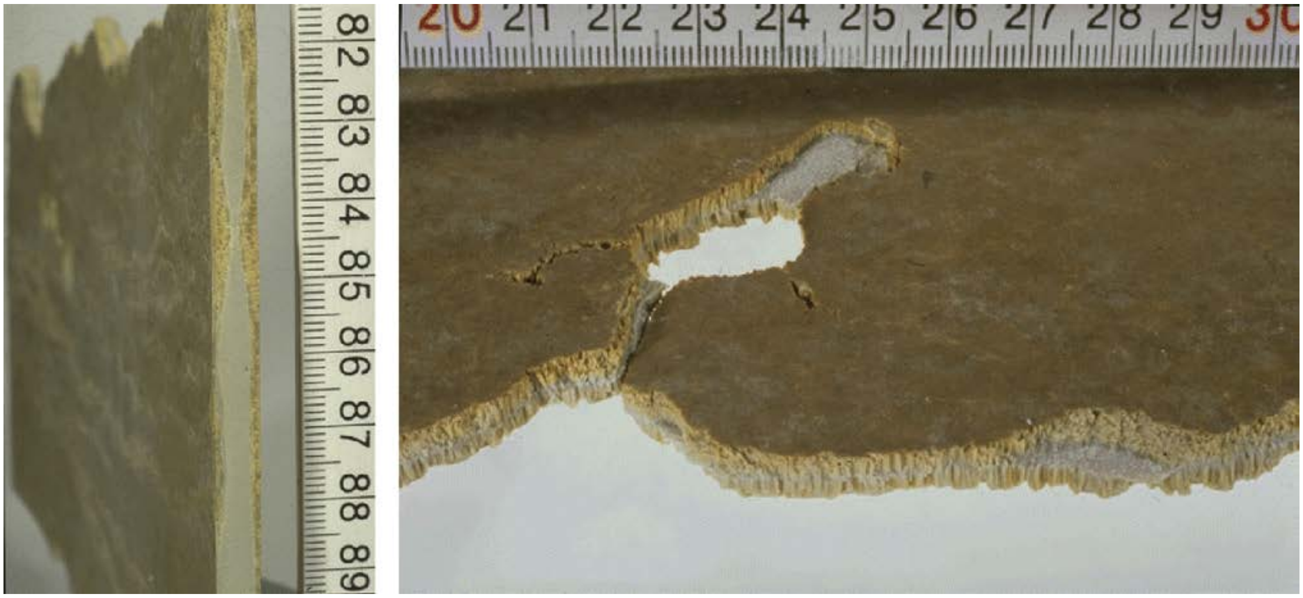
APPEARANCE	Discolouration with cracking.
TIME IN SERVICE	3 months.
ENVIRONMENT	Nonaggressive artificial fertilizer crystals. Temperature about 110°C.
CAUSE	Abnormal operating conditions. The design temperature was 90°C. Above 100°C, in the presence of oxygen, rapid aging takes place due to oxidation of the polyethylene.
REMEDY	Use wearing plates made of ceramic tiles.

CORROSION ATLAS

CASE HISTORY

10.11.29.03

MATERIAL	Polypropylene.
SYSTEM	Extraction system.
PART	Upper part of cap.
PHENOMENON	Aging.



APPEARANCE	Fractured. Material exhibits two-sided discoloration from gray to yellow, with needle structure.
TIME IN SERVICE	6 years.
ENVIRONMENT	Water vapor with ammonia residues. Temperature rising to 90°C.
CAUSE	In the present atmosphere, thermal oxidation causes aging of the polypropylene, which embrittles as a result.
REMEDY	Cap partly made of Polyvinylidene fluoride (PVDF).

CORROSION ATLAS

CASE HISTORY

10.11.34.01

MATERIAL	Glass–fiber-reinforced epoxy.
SYSTEM	Transport system.
PART	Pump impeller.
PHENOMENON	Erosion corrosion.

APPEARANCE	Impeller exhibits severe attack at various places, and pieces have broken off. Locally, the impeller shows fracturing.
TIME IN SERVICE	2 months.
ENVIRONMENT	Highly acid (HCl-containing) liquid. Maximum temperature 120°C.
CAUSE	Insufficient resistance of the material to the present medium.
REMEDY	Construct the impeller of carbon–fiber-reinforced polyether ether ketone (PEEK).

CORROSION ATLAS

CASE HISTORY

10.11.36.01

MATERIAL	PVDF.
SYSTEM	Gas scrubber.
PART	Welded discharge pipe.
PHENOMENON	Stress cracking (embrittlement).

APPEARANCE	Cracking in and beside the welds.
TIME IN SERVICE	9 months.
ENVIRONMENT	10% NaOH solution and products neutralized in gas scrubber, temperature 80°C.
CAUSE	At this temperature, the alkaline solution attacks the PVDF with cracking (see also next case).
REMEDY	Use of carbon steel, coated internally with PTFE.

CORROSION ATLAS

CASE HISTORY

10.11.36.02

MATERIAL	PVDF.W.
SYSTEM	Reactor circuit.
PART	Pipe section.
PHENOMENON	Stress cracking (embrittlement).

APPEARANCE	Cracking.
TIME IN SERVICE	1 month.
ENVIRONMENT	20%–30% NaOH with sodium hypochlorite and sodium chlorate; temperature maximum of 80°C.
CAUSE	Cracking due to excessively high alkalinity and temperature.
REMEDY	It was possible to reduce the temperature and the alkalinity by improved process control.

CORROSION ATLAS

CASE HISTORY

10.11.36.03

MATERIAL	Polypropylene.
SYSTEM	Filter unit.
PART	Components of a filter holder. Unused component on top, used components below.
PHENOMENON	Stress cracking and uniform attack, respectively.

APPEARANCE	Cracking and uniform thickness reduction, respectively.
TIME IN SERVICE	About 4 months.
ENVIRONMENT	Chlorine-containing brine (NaCl); temperature 50°C–60°C.
CAUSE	The chlorine oxidizes the polypropylene; that part subject to stress begins to crack.
REMEDY	Use of PVDF filter.

CASE HISTORY

10.11.36.04

MATERIAL	Polysulphone (PSU).
SYSTEM	Biological filter.
PART	Filter holder.
PHENOMENON	Stress cracking (embrittlement).

APPEARANCE	Cracking.
TIME IN SERVICE	3 weeks.
ENVIRONMENT	Acid liquid containing 1% methyl isobutyl ketone (MIBK). Temperature 40°C.
CAUSE	PSU is sensitive to the formation of stress cracking by combination of stresses with MIBK (but also by contact with acetone, benzene, butanol, ether, carbon tetrachloride, isopropanol, ethylbenzene, ethyl benzoate, methyl ethyl ketone, cyclohexanone, carbon disulfide, and nitromethane).
REMEDY	Filter holder made of polyamine.

CORROSION ATLAS

CASE HISTORY

10.11.37.01

MATERIAL	PTFE coating on steel.
SYSTEM	Hydrochloric acid absorption unit.
PART	Pipe section.
PHENOMENON	Diffusion.

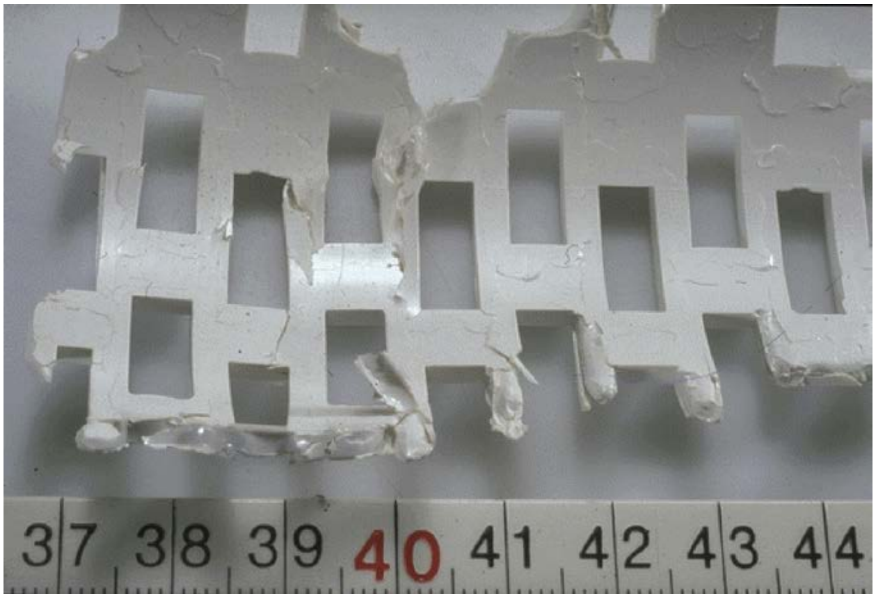
APPEARANCE	Blistering.
TIME IN SERVICE	6 months.
ENVIRONMENT	30% HCl with traces of carbon tetrachloride; temperature 105°C.
CAUSE	Internal condensation and pressure build-up due to diffusion of water and HCl.
REMEDY	Application of better treated PTFE (better sealing and sintering).

CORROSION ATLAS

CASE HISTORY

10.11.37.02

MATERIAL	PTFE lining.
SYSTEM	Reactor.
PART	Pipe section.
PHENOMENON	Diffusion.



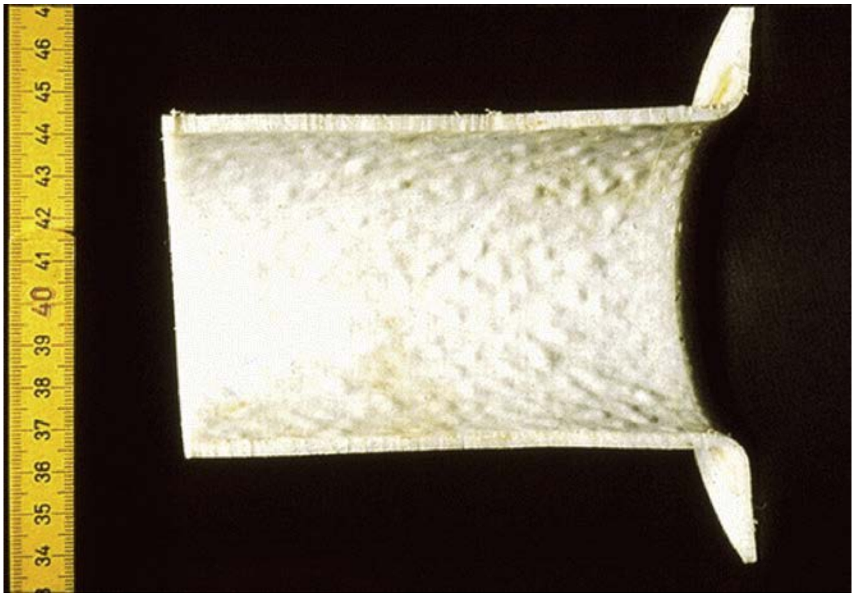
APPEARANCE	Blistering.
TIME IN SERVICE	2 years.
ENVIRONMENT	Benzaldehyde-containing medium.
CAUSE	Diffusion and condensation of benzaldehyde in the lining (see also preceding case).
REMEDY	Prevent diffusion by insulating and tracing the pipe.

CORROSION ATLAS

CASE HISTORY

10.11.38.01

MATERIAL	Steel core with perfluoroalkoxy (PFA) lining.
SYSTEM	Hydrochloric acid transport system.
PART	Ball-cock ball.
PHENOMENON	Material defect.



APPEARANCE	Coating fractured, underneath which the steel has corroded.
TIME IN SERVICE	A few weeks.
ENVIRONMENT	18% HCl; temperature 40°C–50°C.
CAUSE	Manufacturing error: after applying the PFA lining to the ball, it was cooled too rapidly so that large contraction stresses occurred in the lining, as a result of which it fractured.
REMEDY	Better checks on the production method.

CORROSION ATLAS

CASE HISTORY

10.11.38.02

MATERIAL	Steel core with fluorided ethylene propene coating.
SYSTEM	Product transport system.
PART	Plug-cock plug.
PHENOMENON	Material defect.

APPEARANCE	Local damage.
TIME IN SERVICE	A few months.
ENVIRONMENT	Chlorinated hydrocarbons.
CAUSE	Manufacturing error: because of the porosity in the coating, the liquid was able to penetrate to the steel core, and owing to formation of corrosion products, the coating was pushed up locally. This caused the plug to seize.
REMEDY	Improved production method and extended inspection procedure by inspecting each valve completely stripped down (spark-testing).

CORROSION ATLAS

CASE HISTORY

10.11.38.03

MATERIAL	PTFE lining on steel.
SYSTEM	Chlorination unit.
PART	Off-gas pipe.
PHENOMENON	Material defect.

APPEARANCE	Cracking (brittle fracture).
TIME IN SERVICE	About 1 month.
ENVIRONMENT	Inert gases, contaminated with hydrochloric acid, chlorine, and solvents; temperature 150°C, with abrupt drops to 40°C.
CAUSE	Poorly sintered PTFE. Cracking occurred owing to temperature fluctuations.
REMEDY	Application of better sintered PTFE.

CORROSION ATLAS

CASE HISTORY

10.11.38.04

MATERIAL	Polypropylene.
SYSTEM	Process line.
PART	Flange.
PHENOMENON	Material defect.

APPEARANCE	Granular fracture face.
TIME IN SERVICE	1 year.
ENVIRONMENT	Not applicable.
CAUSE	Insufficient fusing of the grains due to incorrect extruder setting.
REMEDY	Improved final inspection by manufacturer.

CORROSION ATLAS

CASE HISTORY

10.11.39.01

MATERIAL	Ethylene-propylene dimer rubber.
SYSTEM	Hydrochloric acid absorption unit.
PART	Flange seal.
PHENOMENON	Physical–mechanical degradation.

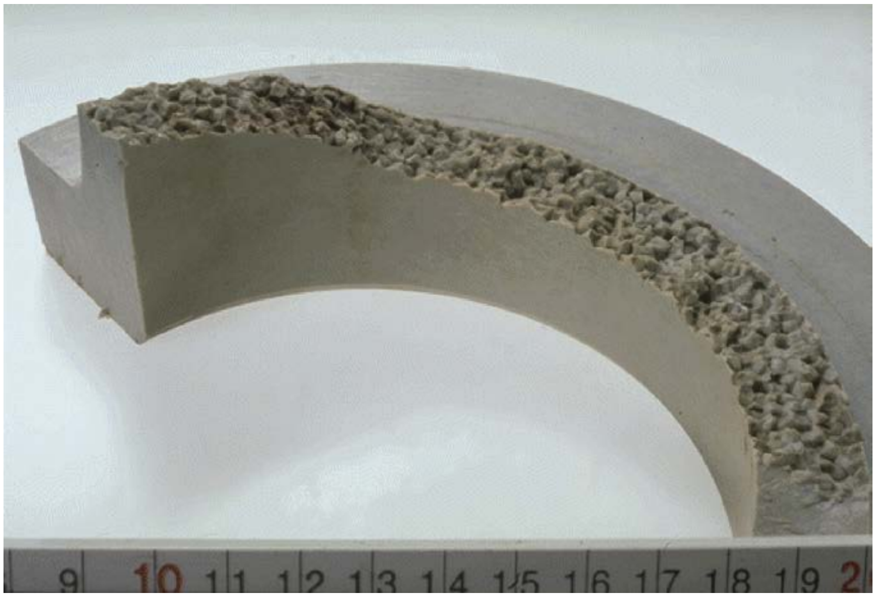
APPEARANCE	Rubber is swollen and exhibits cracks.
TIME IN SERVICE	A few years.
ENVIRONMENT	30% HCl with traces of chloroform and carbon tetrachloride; temperature approximately 50°C.
CAUSE	The solvents present caused strong swelling of the rubber, and finally notches and cracks occur.
REMEDY	Replacement by a fluorinated elastomer seal.

CORROSION ATLAS

CASE HISTORY

10.11.39.02

MATERIAL	PTFE.
SYSTEM	Polymerization reactor.
PART	Agitator shaft guide block.
PHENOMENON	Degradation (swelling).



APPEARANCE	The formation of globules in the PTFE caused severe swelling of the heat of the support.
TIME IN SERVICE	3 months.
ENVIRONMENT	Styrene-containing reaction medium. Temperature: 180°C. Pressure 20 MPa.
CAUSE	Polymerization of styrene in the microcavities of the PTFE.
REMEDY	Make guide blocks from glass–fiber-reinforced Polyether ether ketone (PEEK).

CORROSION ATLAS

CASE HISTORY

10.11.39.03

MATERIAL	PVC.
SYSTEM	Process installation.
PART	Stamper for preparing ion exchange columns.
PHENOMENON	Degradation.

APPEARANCE	Extensive swelling and softening.
TIME IN SERVICE	1 day.
ENVIRONMENT	Chlorinated organic solvents in ion exchange column.
CAUSE	In certain pilot-scale experiments, a PVC stamper is used to prepare glassy columns after filling them with ion exchange resin. The stamper was accidentally not removed after preparatory activities. PVC is very susceptible to many solvents.
REMEDY	Use polypropylene (PP) or Polyester (PE) (not stainless steel to prevent damage to the glass equipment).

CORROSION ATLAS

CASE HISTORY

10.23.36.01

MATERIAL	PP.
SYSTEM	Gas scrubber.
PART	Supporting grid.
PHENOMENON	Stress cracking (embrittlement).

APPEARANCE	Cracking at sites subject to highest loads.
TIME IN SERVICE	2 years.
ENVIRONMENT	Chlorine-containing aqueous solution, chlorine content approximately 1%; temperature 80°C.
CAUSE	The chlorine in the liquid attacks polypropylene, with cracking at sites subject to the highest stress.
REMEDY	Use of supporting grid made from glass–fiber-reinforced vinyl ester.

CORROSION ATLAS

CASE HISTORY

11.08.17.01

MATERIAL	Plain concrete.
SYSTEM	Sewer system.
PART	Prefabricated pipe of a gravity sewer.
PHENOMENON	Microbiologically induced corrosion (biogenic sulfuric acid attack).

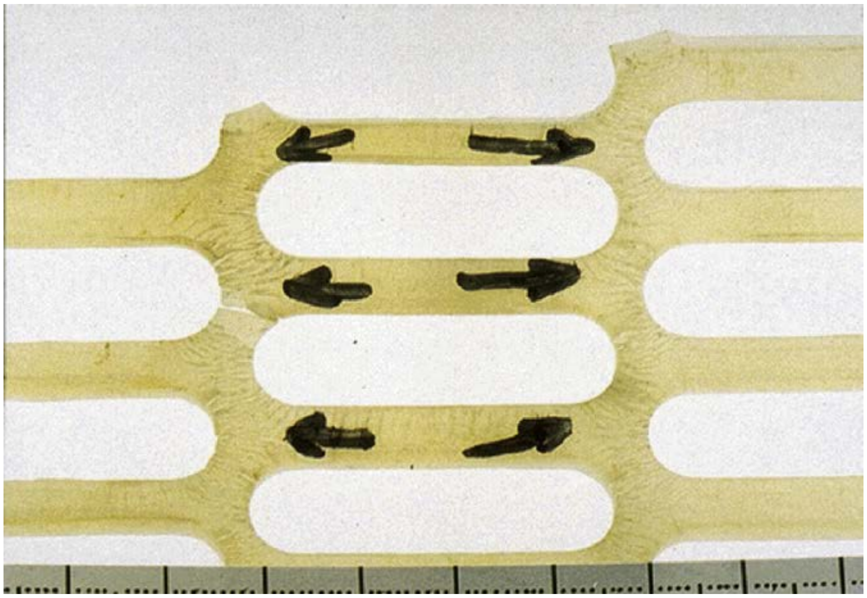
APPEARANCE	The gravel is exposed in the collapsed pipe.
TIME IN SERVICE	About 20 years.
ENVIRONMENT	Domestic sewage, stagnant due to uneven settlement of the pipes.
CAUSE	H_2S is formed from the stagnant sewage by anaerobic bacterial action and is subsequently converted into sulfuric acid by aerobic bacteria in the space above the liquid surface, thereby causing the cement of the upper pipe wall to dissolve (see also Case History 11.16.17.01).
REMEDY	• Prevent long residence times of the sewage in the pipe. • Ensure fresh air ventilation. • Protect the concrete with acid-resistant coating (e.g., a plastic).

CORROSION ATLAS

CASE HISTORY

10.11.30.01

MATERIAL	High-density polyethylene.
SYSTEM	Dibutyl chloride transport system.
PART	Pipe.
PHENOMENON	Creep.



APPEARANCE	Material began to yield and then cracked.
TIME IN SERVICE	5 years.
ENVIRONMENT	Dibutyl chloride; steam at 0.3 MPa and 130°C.
CAUSE	Overloading due to excessively high pressure and temperature while blowing down the pipe. The blisters were caused by the effect of the dibutyl chloride.
REMEDY	When installing a new pipeline, its service life should be determined in advance and replaced in good time, or. Better material should be selected.

CORROSION ATLAS

CASE HISTORY

10.11.30.02

MATERIAL	Silicon rubber.
SYSTEM	Mixing vessel.
PART	Sealing O-ring.
PHENOMENON	Cracking caused by overheating.

APPEARANCE	Cracks.
TIME IN SERVICE	Unknown.
ENVIRONMENT	Mixture of methanol, acetone, and ketones at 170°C.
CAUSE	In this environment, silicon rubber resists temperatures of up to 140°C. Cracking took place due to temperature overshoot. In air, silicon rubber can be used up to 260°C.
REMEDY	Silicon sealing rings sheathed with Polytetrafluoroethylene (PTFE) (Teflon), which is resistant to this environment.

CORROSION ATLAS

CASE HISTORY

11.16.12.01

MATERIAL	Reinforced concrete.
SYSTEM	Traffic tunnel under a canal.
PART	Tunnel wall with piece of reinforcing steel.
PHENOMENON	Chloride attack.

APPEARANCE	Locally very severe pitting corrosion to the reinforcement.
TIME IN SERVICE	11 years.
ENVIRONMENT	Damp concrete with 1% chloride (based on dry matter). Brackish water at the outside of the tunnel.
CAUSE	Chloride penetration into the concrete from the ambient water. Galvanic corrosion occurs owing to local differences in chloride content, while certain rods act as a cathode and are therefore not attacked due to formation of a so-called concentration cell (center of left photo).
Remedy	Remove concrete, grit-blast, and coat the corroded rods, then apply fresh concrete.

CORROSION ATLAS

CASE HISTORY

11.16.12.02

MATERIAL	Reinforced concrete.
SYSTEM	Ground floor construction.
PART	Precast concrete floor element rib.
PHENOMENON	Chloride-induced rebar corrosion.

APPEARANCE	Cracking of the concrete cover reveals severe rebar corrosion.
TIME IN SERVICE	About 12 years.
ENVIRONMENT	Crawl space above wet soil.
CAUSE	Chloride ions mixed in as setting accelerator (about 1% Cl^- to cement mass). In the case of damp concrete, the conditions are then ideal for corrosion and the corrosion products of the rebars force off the covering layer.
REMEDY	• Renovate the rebars and the covering layer. • Apply cathodic protection to the rebar steel. • Improve the bearing capacity by applying external strands under the floor, with a block between the strands and the floor, after which these strands are tensioned, and the floor is subjected to an upward pressure (the method chosen in this case). Preventive: no chloride addition.

CORROSION ATLAS

CASE HISTORY

11.16.17.01

MATERIAL	Reinforced concrete.
SYSTEM	Poultry manure storage pit.
PART	Ceiling.
PHENOMENON	Microbiologically induced corrosion (biogenic sulfuric acid attack).
	
APPEARANCE	Concrete cover dissolved; reinforcement severely attacked.
TIME IN SERVICE	18 years.
ENVIRONMENT	Closed manure environment.
CAUSE	Sulfur compounds in the manure are converted anaerobically by sulfate-reducing bacteria into H_2S which escapes in the gaseous form from the liquid slurry and subsequently dissolves in the condensation layer on the walls and the ceiling above the manure surface. There, H_2S is then aerobically converted by sulfur bacteria into sulfuric acid, which attacks the concrete and subsequently the reinforcement (see also Case History 11.08.17.01).
REMEDY	Preventive: use high-density concrete and apply an extra cover (sacrificial layer). Repair: chip away the attacked concrete, blast the corroded rods, if necessary lay extra reinforcement, and then apply new high-density concrete (with extra cover). Alternative to extra cover: use epoxy resin-based two-component coating.

CORROSION ATLAS

CASE HISTORY

11.16.24.01

MATERIAL	Reinforced concrete.
SYSTEM	Apartment building.
PART	Gallery slab.
PHENOMENON	Atmospheric corrosion (carbonation).

APPEARANCE	Uniform rust layer on exterior of structure.
TIME IN SERVICE	Approximately 15 years.
ENVIRONMENT	Urban atmosphere.
CAUSE	Reaction of carbon dioxide (CO_2) penetrated from the air together with the calcium hydroxide ($CA(OH)_2$) present in the concrete. The reinforcement steel is attacked in the consequently acidifying environment. The exterior of the core is carbonated, while behind the reinforcement, the concrete is still sufficiently alkaline (red indicator color; see also Case History 11.16.24.03).
REMEDY	In this case, it was sufficient to seal the concrete by means of an air-tight coating; in more serious cases of carbonation, the old top layer has to be removed and a new top layer applied.

CORROSION ATLAS

CASE HISTORY

11.16.24.02

MATERIAL	Reinforced concrete.
SYSTEM	Footbridge across motorway.
PART	Steps.
PHENOMENON	Atmospheric corrosion (“frost-thaw” salt attack).

APPEARANCE	Flaked-off cement coating, gravel visible.
TIME IN SERVICE	2 years.
ENVIRONMENT	Rural atmosphere.
CAUSE	Road salt caused a diminishing reduction in freezing point in an inward direction, as a result of which a frozen layer first occurs inside the concrete after which the surface freezes as the temperature falls further. Subsequently, the water in an as yet unfrozen intermediate layer will not be able to expand as the temperature falls further, and thereby (at sufficient degree of hydratation) will be able to force off the top layer.
Remedy	• Prevention by means of low water dosing (water–cement factor lower than 0.4) or for higher water–cement factors, use an aerator (the finely dispersed air bubbles give expanding water room to expand). • In this case, the step concrete was provided with a new top layer.

CORROSION ATLAS

CASE HISTORY

11.16.24.03

MATERIAL	Reinforced concrete.
SYSTEM	Building.
PART	Facade panels.
PHENOMENON	Atmospheric corrosion (concrete decay).

APPEARANCE	Pieces detached along the edges of the panels.
TIME IN SERVICE	10 years.
ENVIRONMENT	Marine-industrial atmosphere.
CAUSE	Corrosion of the reinforcement caused by penetration of moisture, CO_2, and SO_2. As a result of this diffusion, the pH of the concrete is reduced to below 7 and causes corrosion of the steel surface. The large volume of the corrosion products locally forces off the concrete cover (see also Case History 11.16.24.01). This phenomenon is also known as rebar corrosion.
REMEDY	• Use of hot-dip galvanized or coated (epoxy powder coating) reinforcement, or • Use of a higher concrete cover.

CORROSION ATLAS

CASE HISTORY

11.16.24.04

MATERIAL	Reinforced concrete.
SYSTEM	Coastal road.
PART	Concrete post.
PHENOMENON	Atmospheric corrosion.
	
APPEARANCE	Local wearing away of the concrete, with uniform corrosion of the reinforcement.
TIME IN SERVICE	15 years.
ENVIRONMENT	Highly saline atmosphere.
CAUSE	Diffusion of salt water through the insufficiently thick concrete cover caused a high chloride concentration and a low pH at the steel surface, as a result of which rebar corrosion took place, after which the concrete cover was forced off (see also Case History 11.16.12.01). In order to prevent accidents, a galvanized steel profile had been secured to the post by means of stainless-steel strips (see also Case History 02.17.24.03).
REMEDY	Use of galvanized or coated reinforcement bars or application of a thicker concrete cover.

CORROSION ATLAS

CASE HISTORY

11.16.24.05

MATERIAL	Reinforced concrete.
SYSTEM	Boulevard (St. Raphael).
PART	Concrete separation.
PHENOMENON	Atmospheric corrosion (concrete decay).

APPEARANCE	Totally or partly decayed concrete structure, with uniform corrosion of the reinforcement.
TIME IN SERVICE	About 15 years.
ENVIRONMENT	Marine atmosphere with regular wetting by overspilling sea water.
CAUSE	Corrosion of the reinforcement by very strong salt attack, after which the concrete cover was forced off (see also Case History 11.16.24.04).
REMEDY	General renovation with reinforced concrete provided with a coated reinforcement (hot-dip galvanized or with an epoxy powder coating 100–150 μm thick).

CORROSION ATLAS

CASE HISTORY

12.11.14.01

MATERIAL	Stainless steel (martensitic) provided with a tin coating provided by the Physical Vapor Deposition (PVD) process.
SYSTEM	Cutter.
PART	Knife.
PHENOMENON	Galvanic corrosion.

APPEARANCE	Rusty.
TIME IN SERVICE	1 month.
ENVIRONMENT	Moist air.
CAUSE	Galvanic corrosion of martensitic stainless steel in contact with tin PVD coating in moist air.
REMEDY	Use uncoated martensitic stainless steel.

CORROSION ATLAS

CASE HISTORY

12.15.24.01

MATERIAL	Brass, silver-plated, with silver contact.
SYSTEM	Electric installation in automotive system.
PART	Electrical switch (24 V DC system).
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Heavily corroded anode with blue copper corrosion products leaking out of the switch.
TIME IN SERVICE	1–2 years.
ENVIRONMENT	Normal road conditions.
CAUSE	Leakage of water and road salts into the switch along the connectors by capillary activity. The potential difference of 24 V between the poles created an electrochemical cell. This resulted in corrosion of the anode. Removal of the silver coating took place, followed by dezincification of the brass. As a result, the switch failed.
REMEDY	• Prevention of wetting by encapsulation. • Mounting on a dry place. • Replacing by a water-tight switch.

CORROSION ATLAS

CASE HISTORY

12.15.24.02

MATERIAL	Contact: brass, nickel-plated. Thread: thin aluminium in plastic foil.
SYSTEM	Electric installation in automotive system.
PART	Mirror heating element (24 V DC system).
PHENOMENON	Atmospheric corrosion.

APPEARANCE	Anodic contact (left) heavily corroded with blue copper corrosion products. Aluminium thread partly broken.
TIME IN SERVICE	1–2 years.
ENVIRONMENT	Humid atmosphere around contacts in combination with road salts.
CAUSE	Wetting of the contacts by capillary activity caused corrosion of the anodic contact, resulting in heating element failure.
REMEDY	• Improved contact between mirror rear and heating foil. • Improved positioning of contacts; more to the inward side of the mirror. • Coat the contact area for protection.

CORROSION ATLAS

CASE HISTORY

12.19.41.01

MATERIAL	Aluminium alloy (AA 7075-T6; Al–Zn–Mg–Cu 1.5) clad provided with coating system.
SYSTEM	Aircraft (Starfighter).
PART	Plating of wheel-housing.
PHENOMENON	Filiform corrosion.

APPEARANCE	Randomly distributed thread-like filaments under the coating.
TIME IN SERVICE	5 years (number of flying hours not of importance).
ENVIRONMENT	Atmosphere.
CAUSE	The discontinuity of the coating system at the rivets, allowing moisture to diffuse underneath coating, resulting in a filiform, fanning-out corrosion picture (see also Case Histories 03.20.41.01 and 03.24.21.01).
REMEDY	Improvement of the coating system by applying a corrosion inhibitor at the holes (incidentally, the filiform corrosion in itself is not critical; the dangerous thing is that the coating system has been attacked so that other forms of corrosion can occur).

CORROSION ATLAS

CASE HISTORY

12.20.24.01

MATERIAL	Copper–nickel–chromium coating over ZAMAK (die-cast zinc alloy, GD-Zn Al 4 Cu 1).
SYSTEM	Automotive system.
PART	Air horn and door handle.
PHENOMENON	Atmospheric corrosion.

APPEARANCE	The coating is blistered; the base metal is corroded. The red line is not important.
TIME IN SERVICE	Air horn 1 year. Door handle 1–2 years.
ENVIRONMENT	Atmospheric road conditions in the presence of dirt and road salts.
CAUSE	Pores in the coating caused base metal corrosion followed by blistering of the coating system.
REMEDY	• Minimizing porosity by less grinding and greater coating thickness. • Using lower current density during chromium plating. • Using duplex nickel and microcracked or microporous chromium.

CORROSION ATLAS

CASE HISTORY

12.22.35.01

MATERIAL	12% Cr steel with Babbit metal.
SYSTEM	Compressor lubricating system.
PART	Bearing ring.
PHENOMENON	Fretting.

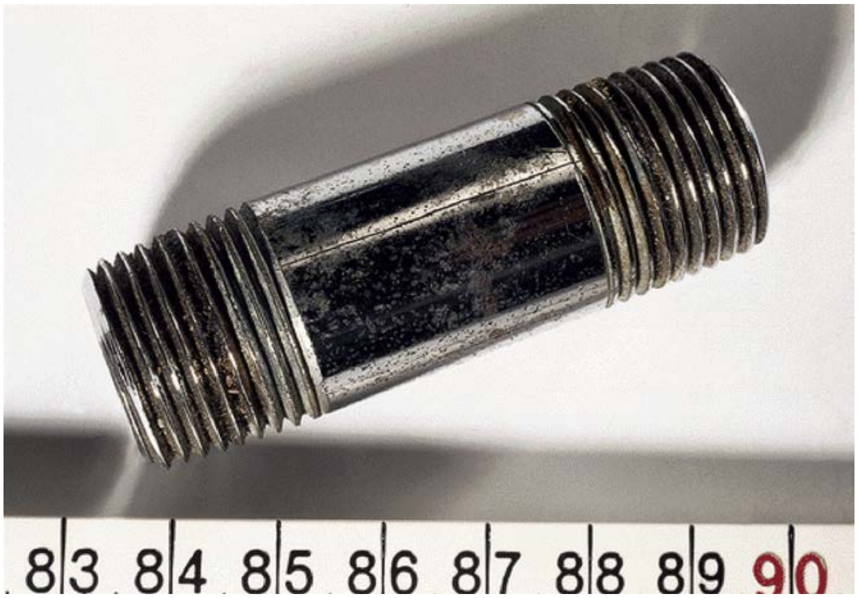
APPEARANCE	Babbit metal crumbled out.
TIME IN SERVICE	3 weeks.
ENVIRONMENT	Lubricating oil and air.
CAUSE	Due to improper segregation of the antimony and tin in the matrix because of incorrect casting procedure, the compression ring was insufficiently resistant to fretting.
REMEDY	Use proper procedure during casting of Babbit metal to ensure a better distribution of antimony and tin particles in the matrix.

CORROSION ATLAS

CASE HISTORY

12.25.18.01

MATERIAL	Chromium-plated brass.
SYSTEM	Emergency shower system.
PART	Threaded end.
PHENOMENON	Stress corrosion cracking (transgranular).



APPEARANCE	Pitting attack of this chromium layer with cracking of the brass.
TIME IN SERVICE	1 year.
ENVIRONMENT	NH_3 atmosphere; ambient temperature.
CAUSE	Copper–zinc alloys under tension are sensitive to stress corrosion cracking in an NH_3-containing atmosphere. The ammonia made contact with the brass through the pores in the chromium layer.
REMEDY	Construction of the threaded end (and more) of stainless steel.

CORROSION ATLAS

CASE HISTORY

13.01.03.01

MATERIAL	Glass.
SYSTEM	Water tube boiler (4.1 MPa).
PART	Gauge glass.
PHENOMENON	Alkalinity corrosion.

APPEARANCE	Uniform attack at the lower part (left side).
TIME IN SERVICE	Unknown.
ENVIRONMENT	Alkaline boiler water; pH 11.
CAUSE	The glass is not resistant to alkaline boiler water.
REMEDY	Use alkaline-resistant gauges or provide the gauge with a mica shield.

CORROSION ATLAS

CASE HISTORY

13.02.02.01

MATERIAL	Glass.
SYSTEM	Steam condensate system.
PART	Steam trap inspection glass.
PHENOMENON	Carbonic acid corrosion.

APPEARANCE	Uniform etching.
TIME IN SERVICE	6 months to 1 year.
ENVIRONMENT	Corrosive condensate; temperature 90–100°C.
CAUSE	The glass used is not resistant to the corrosive condensate.
REMEDY	Fitting a mica shield over the glass, thereby avoiding direct contact with the condensate.

CORROSION ATLAS

CASE HISTORY

13.11.12.01

MATERIAL	Glass.
SYSTEM	Distillation unit.
PART	Pipe.
PHENOMENON	Halide corrosion (fluoride attack).

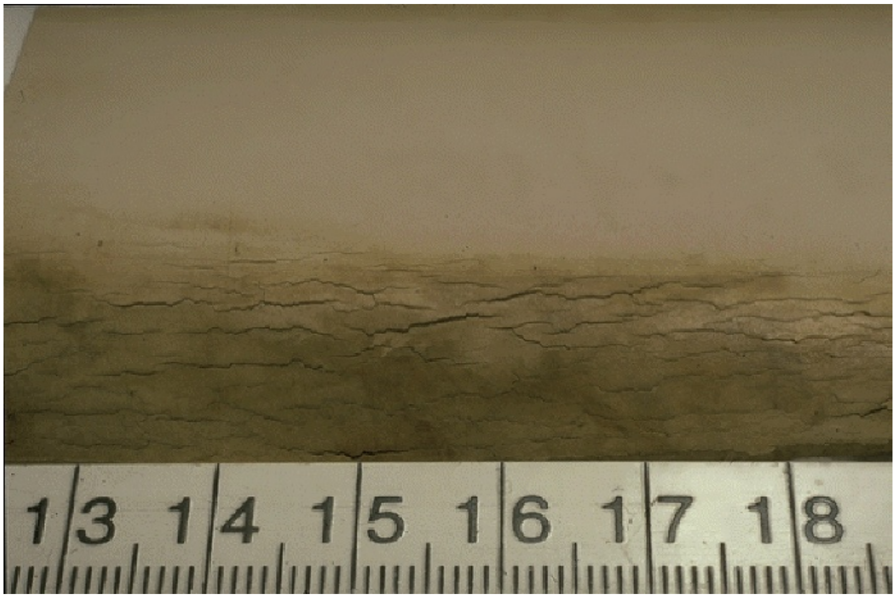
APPEARANCE	Severe overall attack of the system parts (both in the liquid and vapor phases). The surface roughness has increased strongly.
TIME IN SERVICE	5 months.
ENVIRONMENT	Solution of organic solvents and hydrochloride acid with 10–20 ppm fluoride; temperature: 80°C.
CAUSE	Glass is not resistant to environments containing F^- at elevated temperatures. Even at room temperature, glassy materials are attacked in a diluted HF^- solution.
REMEDY	Use any chemical or physical techniques to ensure a minimum fluoride level. The presence of SiO_2 dissolved in the solution inhibits the attack.

CORROSION ATLAS

CASE HISTORY

13.11.29.01

MATERIAL	Natural rubber (latex).
SYSTEM	Flexible connection of vibrating gutter with filling hole.
PART	Sealing sleeve.
PHENOMENON	Aging.



APPEARANCE	Parallel cracks.
TIME IN SERVICE	$\frac{1}{2}$ year.
ENVIRONMENT	Industrial atmosphere. Temperature of the product in the vibrating gutter about 40°C.
CAUSE	Natural rubber is readily degraded by light, in particular, ultraviolet light. In the presence of oxygen, rubber is also degraded by visible light (photo-oxidation), which causes cracking.
REMEDY	Sealing sleeve made of silicon rubber, which has much better atmospheric resistance.

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