CORROSION IN HEAT EXCHANGERS, THE VALUE OF MATERIAL SPECIFICATION

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ABSTRACT

An often observed cause for in service corrosion failures is erosion-corrosion. Despite the high failure risk carbon-steels are not yet specified on erosion-corrosion resistance. Based on published data a simple computer model is made with which the effects of various parameters on the erosion-corrosion rate can be calculated.
The erosion-corrosion resistances of 70 heats of carbon steel have been determined in a water-steam jet rig. Small amounts of "alloying" elements appeared to be very beneficial for erosion-corrosion resistance (Cu, Cr, Mo and C).
Modified carbon-steel should be applied in water-steam systems, to prevent erosioncorrosion. Return On Investment calculations show that the introduction of a modified steel can result in large money savings.

1. INTRODUCTION

An inventory of corrosion failures in the dutch electricity power industry in the period 1973 up to 1995 was made. It appeared that erosion-corrosion still is an important failure cause in water-steam systems. The costs for forced unavailability of a power plant due to corrosion failures are high. Mainly in the period 1981 up to 1985 many papers were published about the influence of the elements Cr, Cu, Mo and C on erosion-corrosion [2, 4, 5, 6].

2. CALCULATION-MODEL FOR EROSION CORROSION

Corrosion failures are a result of a combination of water conditioning, design parameters and material. Kastner published mathematical correlations, based on laboratory research and practical experience, with which the erosion-corrosion rate can be calculated [5]. KEMA used these correlations for creating a simple computer model, called KASEC (KEMA Advice System for Erosion Corrosion).

In this paper the data for the conditions mentioned below are used as the base case values for our calculations of the erosion-corrosion rate after an operation time of 16,000 hours.

Water conditioning	pH (8.5), oxygen (10 ppb)
Design	internal diameter (30 mm), mass flow (1000 kg/hr), temperature (175 °C), steam quality (0.05), geometry factor (0.3)
Material	Cr and Mo content in carbon-steel (Cr+Mo=016 w%

For a low erosion-corrosion rate the solubility of the oxide (magnetite or hematite) should be minimal. This solubility can be influenced by alloying elements in the steel but is determined mainly by the pH value and oxygen content of the water. In Figure 1 the corrosion rate for the mentioned base case values have been given in dependence of temperature for three different oxygen contents and pH values.

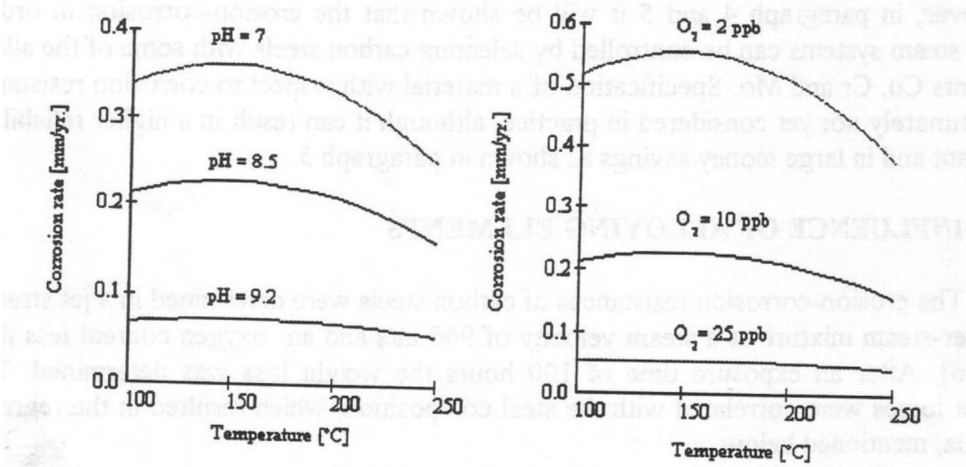

Figure 1: Erosion-corrosion rate in dependence of temperatwe.

The solubility of the oxide layer is in equilibrium with the iron content in the water and is diffusion controlled at high mass flow velocities. As a measure for the turbulence in various design situations (straight tubes and bends) geometry factors have been introduced [1]. The erosion-corrosion rate is very dependent on temperature. At about 150 ℃ a maximum in the corrosion rate is noticed, because of the maximum solubility of the magnetite at this temperature.

The influence of the variation of each parameter is visualised in a tornado diagram (Figure 2). In this diagram the separate influence of each parameter on the erosioncorrosion rate can be seen. When more than one parameter changes, the attribution in the corrosion rate from each parameter can be added to the base case value. The base case, low and high value of each parameter are mentioned in this diagram. In most cases countermeasures against corrosion are taken in the field of water treatment and design, influencing oxygen content, pH value and geometry factor.

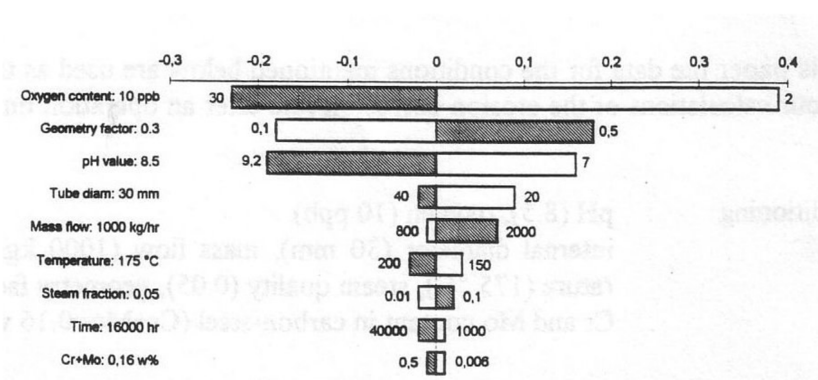

Figure 2: Variations in erosion-corrosion rate, base case corrosion rate: 0,27 mm/yr.

In the mathematical correlations of Kastner the Cr and Mo content of the steel is input. It can be concluded from the diagram that according to these correlations small amounts of alloying elements do not influence the erosion-corrosion rate very much. However, in paragraph 4 and 5 it will be shown that the erosion-corrosion in ordinary water steam systems can be controlled by selecting carbon steels with some of the alloying elements Cu, Cr and Mo. Specification of a material with respect to corrosion resistance is unfortunately not yet considered in practice, although it can result in a higher reliability of the plant and in large money savings as shown in paragraph 5.

3. INFLUENCE OF ALLOYING ELEMENTS

The erosion-corrosion resistances of carbon steels were determined in a jet stream of a water-steam mixture at a steam velocity of 960 m/s and an oxygen content less than 2 ppb [6]. After an exposure time of 100 hours the weight loss was determined. These weight losses were correlated with the steel composition, which resulted in the regression formula, mentioned below.

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

The calculated G_{KEMA} values were in the range of 40 up to 100 (Figure 3).

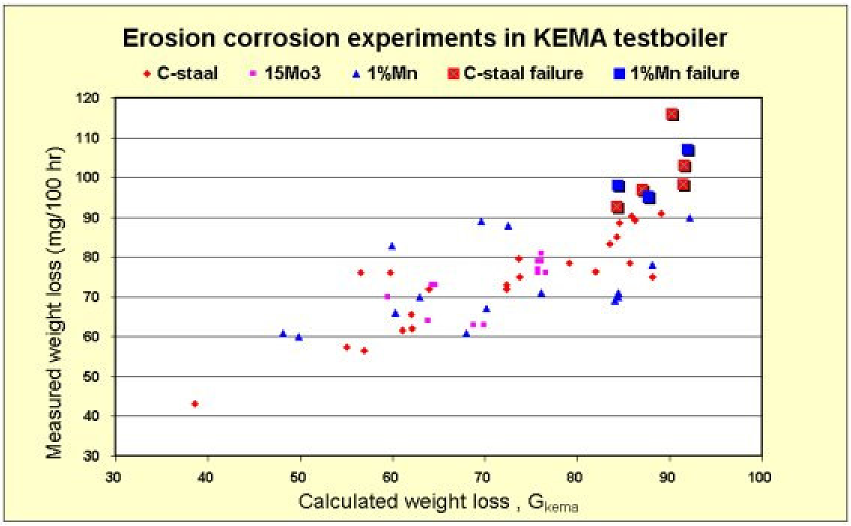

Figure 3: Measured and calculated weight loss of carbon steels from the KEMA erosion-corrosion tests.

4. EROSION-CORROSION AT SERVICE FAILURES

Erosion-corrosion failures occur in various components in the water-steam system such as appendages, wet steam lines and water separators, low and high pressure preheaters, economizers and evaporators. These cases have been discussed already in earlier papers [2, 6] and are given in a separate chapter in the appendix.

One of the most obvious cases is the erosion-corrosion of a plate in a water separator (Figure 4). Two plates were welded together. Only one plate was corroded, whereas on the other non-conoded plate the corrosion products had deposited. The horseshoe pattern of erosion-corrosion is very obvious. The corroded plate and the noncorroded plate had G_{KEMA} values of respectively 87 and 53.

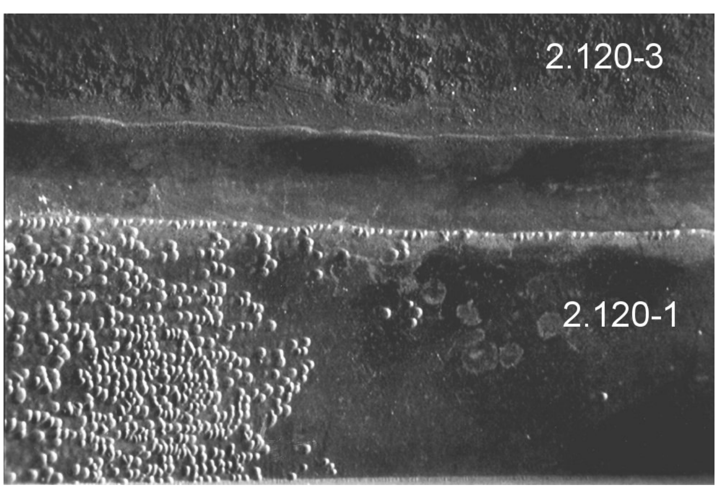

Figure 4: In service erosion-corrosion of carbon steel. Only the steel with high G_{KEMA}, value shows horse shoe pattern of erosion-corrosion.

Our experience is that in all observed erosion-corrosion failures in water-steam systems up to now the corroded steels had a G_{KEMA} value more than 80. In Figure 3 these cases have been plotted. Because small amounts of Cu, Cr and Mo improve the resistance to erosioncorrosion very much, a large variation in erosion-corrosion resistance of carbon-steel exists. Accidentally one heat can possess a much higher resistance compared to other heats from the same steel specification. Thus, erosion-corrosion resistance of the material is nowadays still a matter of "Russian roulette".

A steel specification on erosion-corrosion resistance of G_{KEMA} a less than 80 does not mean that expensive materials should be used in the future! The use of carbon-steel with some small additions of Cu, Cr or Mo results already in high erosion-corrosion resistance.

5. MONEY SAVING BY SELECTING BETTER MATERIALS

Money saving is the best argument for introducing a specification for carbon-steels to be used in water-steam systems. Thus, Return On Investment (ROI) calculations for the erosion-corrosion sensitive components power plant were made.

From the database of failures and forced outages of production units in the Netherlands the total forced unavailability and the percentage of production losses because of erosion-corrosion was estimated for evaporators, low pressure and high pressure preheaters and economisers. In these calculations the lowest and highest price for the modified steel was assumed to be 5 and 20% more expensive with 10% of the Base Case value. It can be concluded that for a 200 MWe plant the total Return On Investment over 15 years for the base case situation amounts about 9 million NLG. Most of the value is in the evaporator (4 million NLG) and in the HP preheater (3.8 million NLG). The variables that count are large power, base load and high power replacement costs. For small power plants with only a limited number of operating hours, the additional investment does not pay. It is worthwhile to choose better steels for erosion-corrosion sensitive components. The results of the calculations for Return On Investment for the various parameters have been given in the tornado diagram in Figure 5.

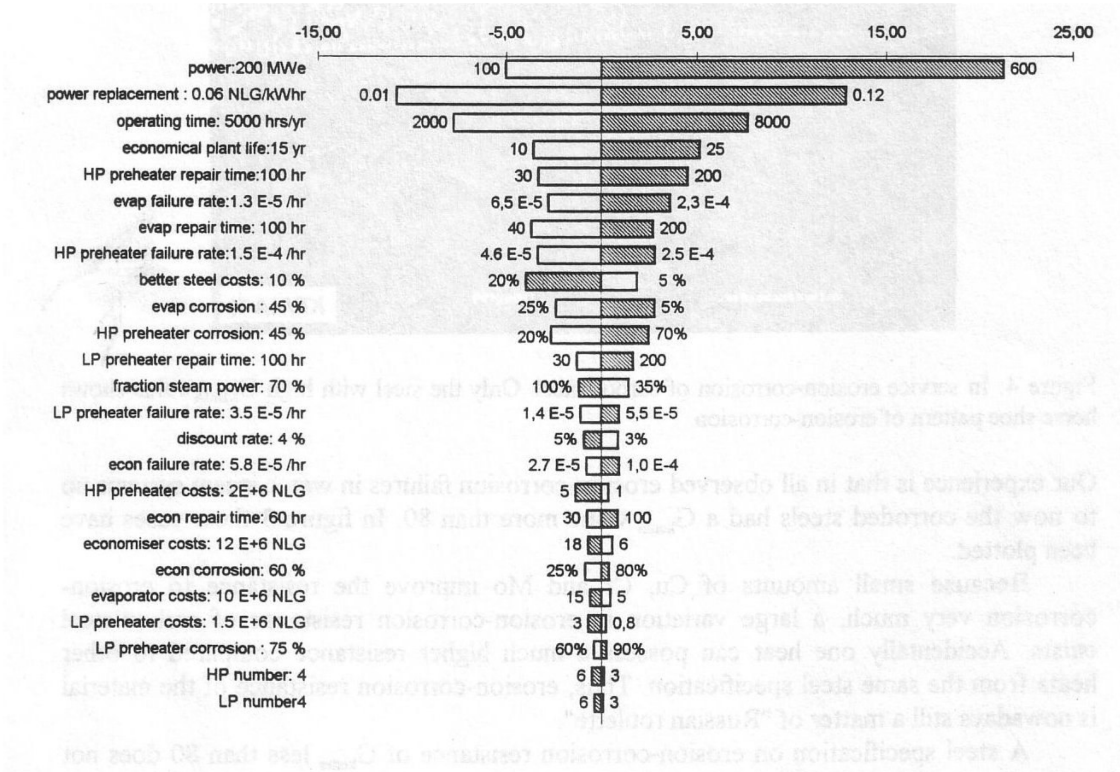

Figure 5. Variation in Return On Investment for all components- base case value 9.1 million NLG.

6. CONCLUSIONS

Specify the carbon steel (tube and welding material) for erosion-corrosion sensitive components in the water-steam system on erosion-corrosion resistance. The G_{KEMA} value should be lower than 80.

In case of very severe erosion-corrosion conditions modifications in water treatment and/or design should be made. The expected effects of the modifications can be calculated (pa by means of the KASEC program).

By making estimations of the minimal and maximal values of the parameters the effects on erosion-corrosion rate can be visualised in a tornado diagram.

Return On Investment calculations show that introduction of a modified steel can result in large money savings if applied under the conditions that count (large power, basic load, and high replacement costs).

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Appendix: In service failures

Erosion corrosion in Heat Exchangers, the Value of Material Specification.

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1. In Service failures

Erosion-corrosion failures occur in various components in the water-steam system such as appendages, wet steam lines and water separators, low and high-pressure preheaters, economisers and evaporators. Some of these cases have been discussed already in earlier papers (Huijbregts et all 1982, 1984). After finishing the experiments in 1982, several erosion- corrosion cases were offered for further research. Because good fitting correlation equations had been established, the new samples were not tested in the erosion-corrosion loop. They were only analysed chemically as to Cr, Cu, and Mo content, and the erosion-corrosion resistances were calculated.

The failures occurred in the steam-water circuit of power stations under various conditions. Hydraulic conditions and chemical water treatment can differ very much for these components. However, our experience is that in all observed erosion-corrosion failures in water-steam systems up to now the corroded steels had a G_{KEMA} value of more than 80. With this specification a minimum G_{KEMA} has been introduced.

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

To obtain an erosion-corrosion resistant carbon steel (under not too excessive erosion-corrosion conditions) the G_{KEMA} should be less than 80.

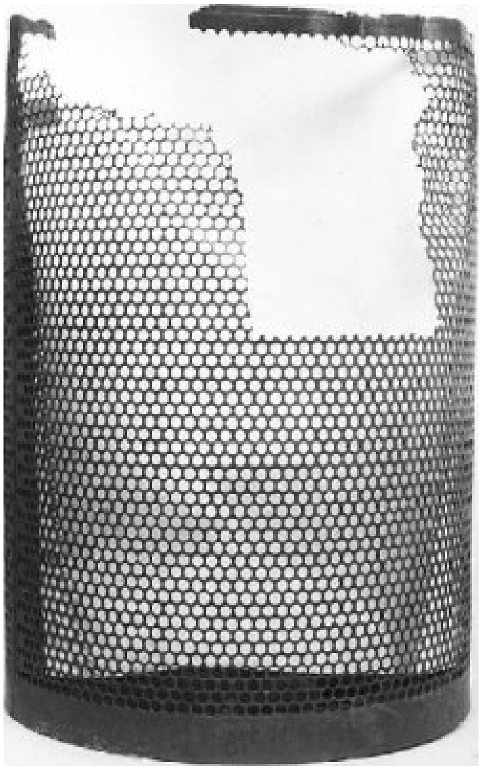
Because small amounts of Cu, Cr and Mo improve the resistance to erosion- corrosion very much, a large variation in erosion-corrosion resistance of carbon-steel exists. From one melt of steel various products (tubes of different diameter, plates etc) with possible various heat treatments are made. Such a melt of steel is called a heat. Different heats will accord to a specification of a steel type, pa 15Mo3. Accidentally one heat can possess a much higher resistance compared to other heats from the same steel specification.

Thus, erosion-corrosion resistance of the material is nowadays still a matter of "Russian roulette".

Erosion-corrosion was observed on steels having a high $G_{KEMA.}$ Special attention was paid to the cases in which certain parts of the component were corroded but other parts were not damaged, even though they had been operated under the same conditions.

2. Various appendages

Case 1

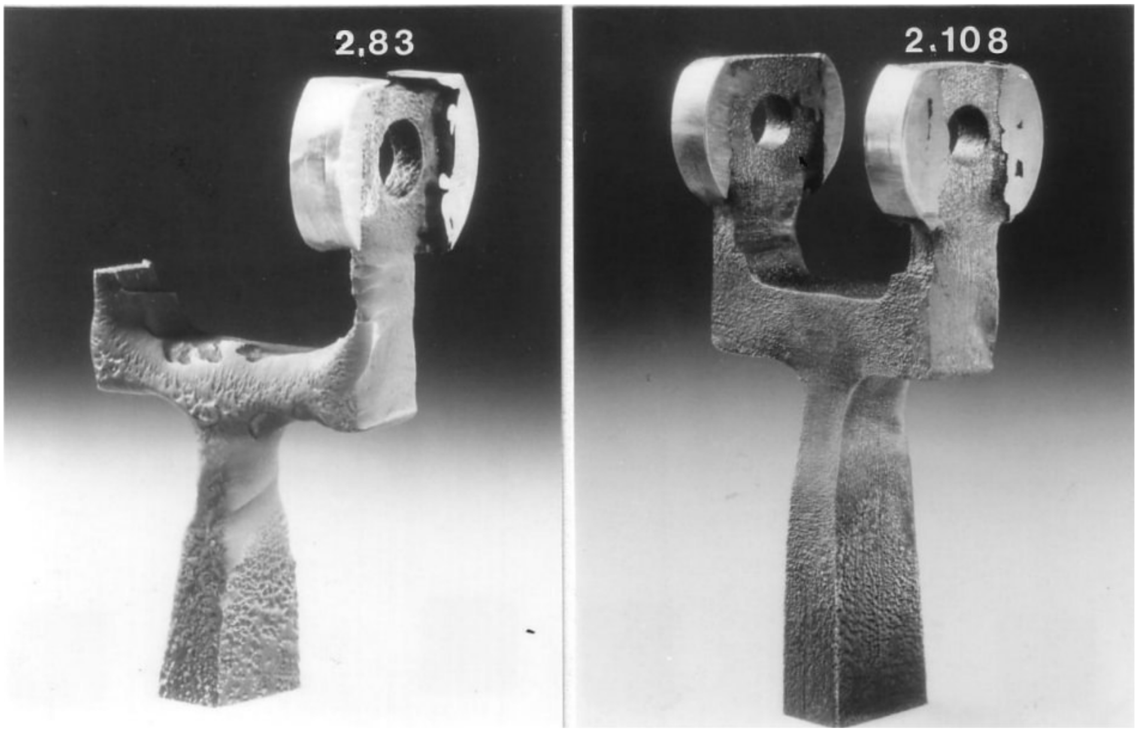


A number of steam sieves suffered erosion- corrosion. Chemical analyses showed that three different steel heats were applied. The calculated G_{KEMA} were 81.1 , 80.8 and 88.3. The last heat was corroded the most.

Case 2

A spindle from a condensate effluent valve of a low pressure preheater was coated only partly with a chromium steel (9% Cr). see Figure 4. It might be considered that on the top of the spindle the coating was not necessary because in general there are no corrosion failures. But because of the too low Cr-equivalent the carbon steel was corroded. The G_{KEMA} was 83.1.

Case 3

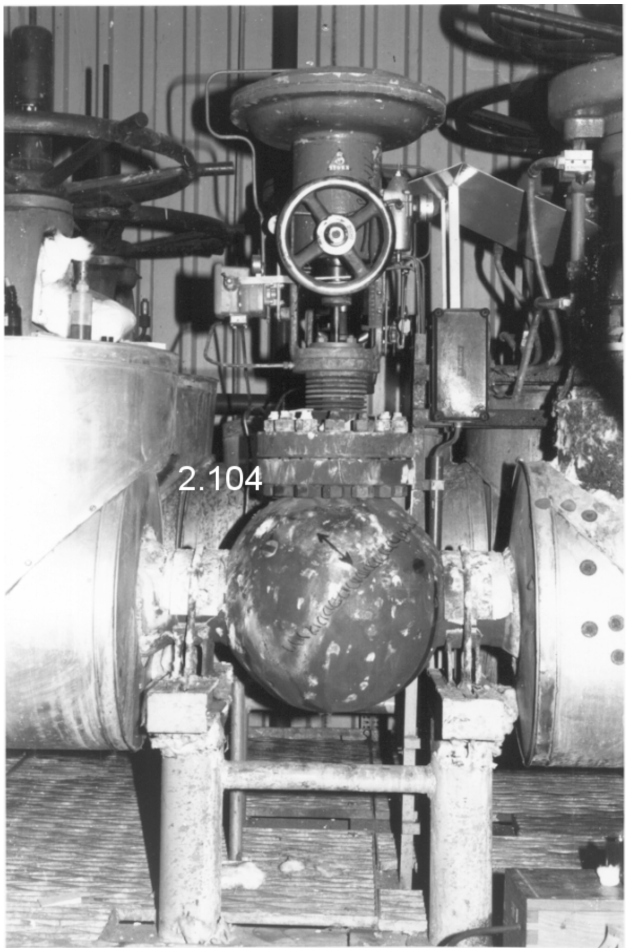


The switch lever of a supply water pump had been attacked severely by erosion-corrosion.

Left photo: The G_{KEMA} was 90.2. The operation time of this lever was 10,000 hours.

Right photo: Another lever from an identical pump at the same station showed less corrosion after 40,000 hours. The Cr, Cu, and Mo contents of this steel are slightly higher, resulting in a G_{KEMA} of 83.6.

Case 4



There was severe erosion-corrosion in a control valve housing, resulting in a leakage. This steel had a high weight loss in the erosion-corrosion test, 107 mg. The G_{KEMA} was 91.8.

Case 5

In the KEMA experimental boiler, erosion-corrosion occurred in a steam pressure drop vessel in which steam expanded and where the water steam jet hitted a buffle plate in the vessel. See Figure 6. After 10 years of operation, there was a leakage in the buffle plate and the vessel wall. The steel plate (10 mm thick) and the vessel wall (5 mm thick) were corroded and a leakage occurred. The G_{KEMA} of the steel plate was 74.1. For such situations (a buffle plate for protecting the vessel to the wet steam flow) steel with a lower G_{KEMA} is required.

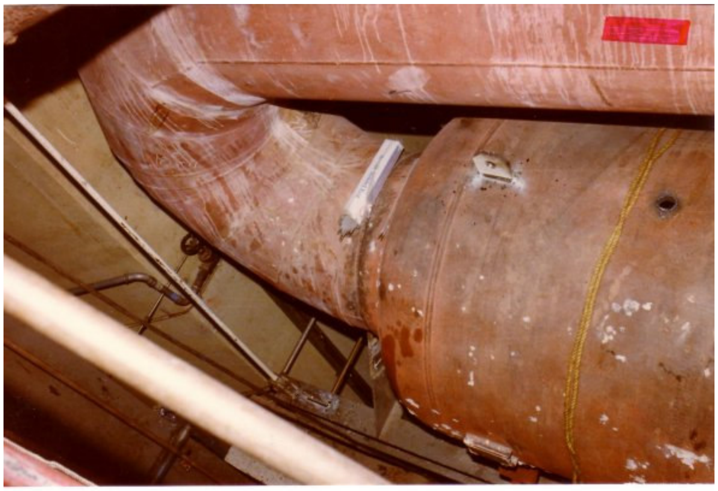
3. Wet steam pipes and water separators

Erosion-corrosion had occurred in wet steam pipes and in the low and high-pressure water separators of a BWR. These components were made of a simple carbon steel. See Figures 7 and 8.

Cases 6, 7, and 8

The low and high pressure water separators, the pre-waterseparator and the wet steam tubes in the BWR were replaced by stainless steel components in the last few years, before the erosion-corrosion tests were finished.

Case 6

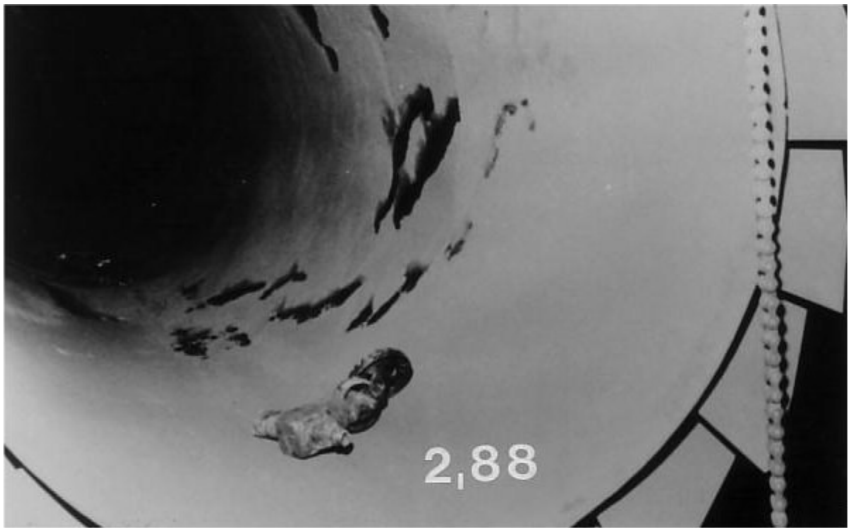


A pipe behind the BWR water separator was constructed by welding bent steel plates. One of those plates had been attacked severely. The other plates, both upstream and downstream, had not been attacked. The corroded plate showed a different chemical composition. The G_{KEMA} of the corroded steel was 91.5, whereas the values of the uncorroded plates were much lower 72.1

Case 7

Other, smaller diameter wet steam tubes also showed erosion-corrosion, and the G_{KEMA} of the two different heats amounted to 88.0 and 89.7.

Case 8

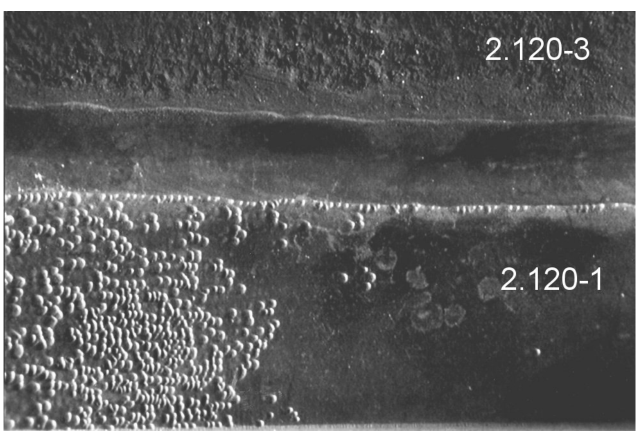


The high-pressure water separator of the BWR also had severe erosion-corrosion. see Figure 8. Low Cr, Cu, and Mo contents were measured in the steel, resulting in a G_{KEMA} of 87.6. Besides, there is a remarkable phenomenon in this failure. The so called "tiger skin" pattern of erosion-corrosion on the inside of the pipe was also present on the outside. This phenomenon can be explained in terms of electrochemical polarisation of the corrosion reaction by diffusion of hydrogen through the steel wall. There where the millscale on the outside of the wall was not present anymore erosion-corrosion was started on the inside.

Case 9

The low pressure water separator of a BWR showed erosion corrosion. Two different steel heats were used, both with high G_{KEMA}: 90 and 93.2.

Case 10



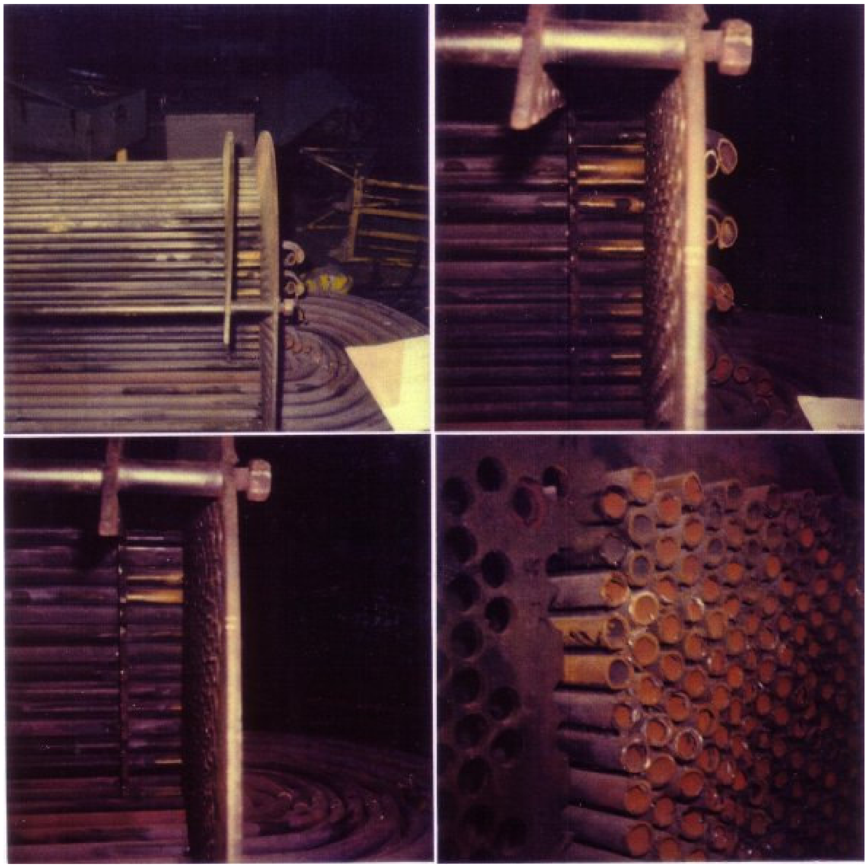
One of the most obvious cases is the erosion-corrosion of a plate in a water separator of a PWR. See Figure 9. Two plates were welded together. Only one plate was corroded, whereas on the other non-corroded plate the corrosion products had deposited. The horse- shoe pattern of erosion-corrosion is very obvious. The corroded plate and the non- corroded plate had G_{KEMA} of respectively 91.4 and 58.4.

4. Preheaters

Case 11

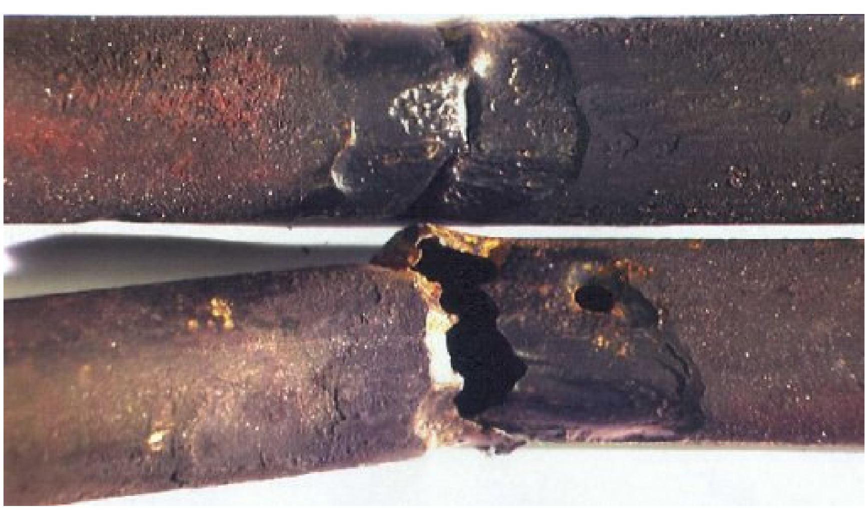
Two tubes of a backpressure unit were received; one showed severe erosion-corrosion, and the other had only some corrosion spots. The erosion-corrosion G_{KEMA} for the uncorroded tube 2.121 was much lower than that of the corroded tube (60.9 and 85.7).

Case 12



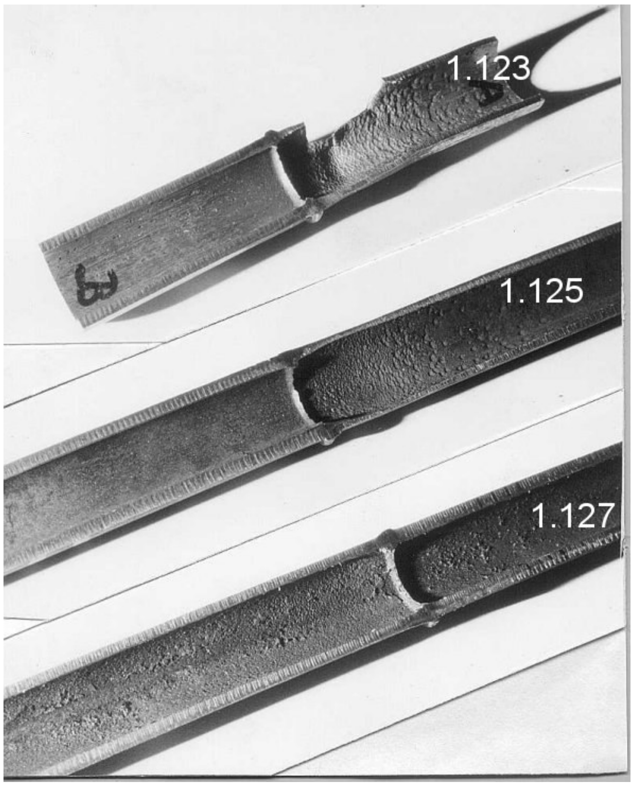
The preheater of a PWR had to be renewed because of severe erosion-corrosion. The preheater was dismantled row by row and 24 tubes were analysed The 24 tubes had been made from 2 different heats (G_{KEMA} of 85.5 and 79.0). It could be seen that in one row some tubes were corroded more severely than other tubes adjacent to them. The most severely attacked tubes were found to have the higher G_{KEMA} .

Case 13



The preheater of a power station suffered local corrosion near the support plates where the flow velocity is high. The G_{KEMA} was 90.6. Coarse magnetite crystals were found adjacent to the corroded area. Precipitation of such coarse iron oxide crystals is often observed in case of erosion-corrosion. A second tube with a higher G_{KEMA} (71.4) did not show any corrosion.

Case 14



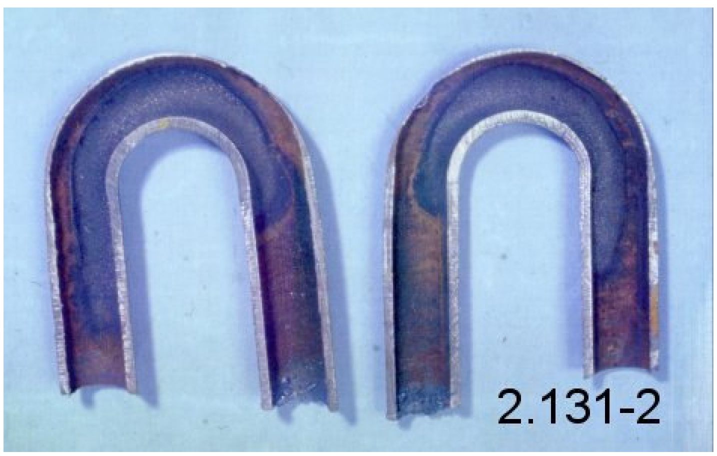
In a high pressure preheater, erosion-corrosion was found downstream several butt welds. See Figure 12. The inner diameter of the 15Mo3 steels was 20 mm, and the weld heights for the three tubes were 1.8, 1.6, 1.7 and 2.0 mm. Two tubes 1.123 and 1.125, both downstream and with the highest G_{KEMA} (75.7 and 74.1), were corroded severely, one having a leakage. Two tubes (1.127) downstream with low G_{KEMA} (59.2 and 54.4) had no erosion-corrosion under these severe conditions. The conditions downstream such high butt welds are very unfavourable, so even the 1.123 and 1/125 with rather low G_{KEMA} were not resistant enough.

5. Economisers

Case 15

Slight erosion-corrosion was observed on thin tubes in an economiser of a waste heat boiler. The G_{KEMA} was very high, 90.6.

Case 16



There was severe erosion-corrosion in the economiser tube bends of a waste-heat boiler. Steaming occurred in the economiser. This could also be concluded from some failed tubes where erosion-corrosion occurred on the outer radius and steam blanketing on the inner radius. The water film had come loose from the inner radius surface where coarse magnetite crystals had formed. Analysis of the steel shows the erosion-corrosion resistance of this steel to be low, because of the high G_{KEMA} (90.2).