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PROBLEMS IN COOLING WATER SYSTEMS CAUSED BY POOR DESIGN, OPERATION AND WATER TREATMENT – SOME CASE HISTORIES

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ABSTRACT

In general, the operation of a cooling water system focuses on water treatment. However in addition, corrosion equipment failures can be caused by other factors such as fatigue or freezing (mechanical overload). The presentation includes some case histories of equipment failures caused by the aforementioned reasons. Furthermore, the case histories demonstrate the importance of undertaking a thorough failure investigation in order to establish the cause of failure and thereby select the correct remedy.

Keywords: Cooling Water, Water Treatment, Corrosion, Fatigue, Freezing, Failure Investigation

INTRODUCTION

In many industries the cooling water system is a nuisance. The reason is that contrary to the process equipment that generates profit, the cooling water system is an annoying expense that only generates problems. Consequently, the cooling water system becomes a "low" status area that – as long as it works satisfactorily – does not receive the same attention as the more "valuable" process equipment. This lack of attention is often followed up by allocation of a corresponding moderate budget, i.e. a tendency to buy cheap when designing and ordering a new cooling water system, and a tendency to allocate insufficient funds to water treatment and systematic maintenance when operating the cooling water system. Contrary to the aforementioned "laid back attitude" that prevails when the cooling water systems works satisfactorily, the neglected cooling water system receives a lot of attention when it suffers a serious failure. Unfortunately, in such circumstances it is not unusual that the owner of the cooling water system, the supplier of the cooling water system as well as the supplier of the water treatment chemicals have an infuriated exchange of views before initiating a thorough failure investigation in order to establish the cause of failure and thereby select the correct remedy. The case histories in the presentation demonstrate the advantages of undertaking a thorough failure investigation instead of "jumping" to the wrong conclusions.

CASE HISTORIES

Case # 1 Failure Investigation of a Brazed Plate Heat Exchanger

The heat exchanger was part of an air conditioning (AC) system installed in a ship during the summer of 1998. However, the AC plant had only been in operation for about a month when the heat exchanger in the summer of 1999 was dismantled because of leakage. Since the heat exchanger in question was only one of several identical heat exchangers, all used in AC plants on ships, it was decided that the heat exchanger should be subjected to a failure investigation.

The plates in the copper brazed heat exchanger were made from 0.4 mm stainless steel plates, type AISI 316. The nominal operating conditions were as follows:

- The primary refrigerant was 6.1 tons type R507 per hour, evaporation at about 3°C.
- The secondary refrigerant was approximately 38.5 tons of treated cooling water per hour. During the process, the temperature drops from about 12°C at the inlet to about 6°C at the outlet.

The failure investigation was undertaken by use of the following procedures and techniques:

1. Search for leakage and cutting out sample containing the leakage
2. Visual inspection and stereo microscopy
3. Light optical microscopy (LOM)
4. Scanning electron microscopy (SEM)

By use of the procedure described in Table 1, an internal leakage in the brazed plate heat exchanger was detected near porthole T4, i.e. near the pressure plate outlet of superheated vaporized refrigerant. This position corresponded to the observation of a bulge on the outside of the heat exchanger, see Figures 1-2.

A rectangular sample containing the leakage was cut out, see Figures 2-3. A significant local volume expansion in the area adjacent to the leakage area showed that the heat exchanger at this position had suffered mechanical overload. By a process of elimination, freezing damage seemed to be the likely cause of failure.

In order to get a close view of the leakage, the rectangular sample was further cross-sectioned, see Figures 4-6. A fissure with a "bloated" appearance typical of freezing damage was observed. This cause of failure was further supported by the fact that stereo microscopy showed no cracks or corrosion products. Judging by the penetration depth of the copper, the brazing was of a good quality, see also Figure 7.

A microsection was taken across the aforementioned fissure, see Figure 6. From Figures 7-12 showing selected areas of the microsection, it is seen that the rupture was caused by mechanical overload, see the ductile necking. Furthermore, it is important to note that no cracks were observed. Both these observations substantiated that freezing was the cause of failure.

The surface of the fracture was examined by use of a scanning electron microscope (SEM), see Figures 6 and 13-15. The SEM investigation left no doubt that the rupture was caused by mechanical overload, see the lip in Figure 13 and the many dimples in Figures 14-15. Consequently, the results of the SEM investigation also point to freezing as the cause of failure.

The clear result of the failure investigation helped the damage investigation by eliminating other damage hypotheses, e.g. poor water treatment, poor brazing etc. Thus, many unprofitable discussions were avoided and the effort was focused on the operation conditions in order to find the background for the reported freezing.

The refrigerant R507 enters the bottom of the heat exchanger as a mixture of fluid and gas. When the refrigerant reaches the outlet at the top of the heat exchanger, the refrigerant is superheated approximately 5-10°C. The refrigerant temperature in the heat exchanger depends on the refrigerant pressure. In this case where water is utilized as secondary refrigerant, the primary refrigerant R507 has a critical minimum pressure of 6.3 bar (corresponding to 0°C). The failure investigation proved that the pressure during operation of the heat exchanger at least once had been below 6.3 bar.

Case # 2 Failure Investigation of Cracks in Cooling Jackets in Yeast Storage Tanks

Six yeast storage tanks (YSTs) were put into operation immediately after they were delivered ten years ago. The cooling jackets were made from stainless steel type AISI 304. The YSTs, insulated with polyurethane foam, are placed outside in a humid climate where temperatures are up to 40°C. The cooling medium in the cooling jackets is propylene glycol.

Originally, the cooling system was not planned to operate with positive pressure, but in recent years the pressure in the cooling jackets has been 2-3 bar. The inlet and outlet temperatures are approximately –2°C and +10°C respectively.

It was reported that the cooling jackets in two of the six YSTs were leaking due to the presence of cracks in the knuckled areas of the dimples. Unfortunately, the leaks had been repair welded just prior to the on-site inspection of tanks, see Figure 16. However, a sample had been "spared" for metallurgical examinations, see the cut out-procedure described in Table 2.

The failure investigation was undertaken by use of the following procedures and techniques:

1. Visual inspection and stereo microscopy
2. Scanning electron microscopy (SEM)
3. Light optical microscopy (LOM)

The received parts of the dimple plates (see Figure 17), which were colored with remaining residues from a dye penetrant test, were cleaned with a mild alkaline detergent in an ultrasonic bath. Neither the internal nor the external sides of the dimple plates suffered from corrosion attacks like pits or general corroding of surfaces. A test using a magnet revealed that the regions with the cracks, i.e. the knuckled areas of the dimples, were greatly strain hardened. The internal sides of the dimple plates were investigated using stereo microscopy and this revealed that there were some places, where two crack tips had not made contact with one another during their propagation.

A crack was opened so the surface of a fracture could be studied, see mark 3 on Figure 17. Of those cracks that did not penetrate through the plate, on a rough estimate 95% were initiated from the internal side and the remainder from the external side. In addition, many steps ("notches") were observed on the fractured surface. The many steps ("notches") on the fractured surface show that there have been many crack initiating sites.

Scanning electron microscopy was also utilized to study a fractured surface. In addition to the features seen in the stereo microscope, beach marks ("crack-arrest lines") that propagated from the internal side were also observed, see Figure 18. At about half of the plate thickness, the cracks have met each other. Thus a single crack has been created, so the crack finally broke through the plate over a long distance at the same time. At a greater magnification, these cracks were observed to be transcrystalline. At very high magnifications, striations showing fatigue were observed, see Figure 19. The curvature of the beach marks, the presence of striations on the fracture surface and the unbranched course of the cracks are all strong indications of fatigue initiated predominantly from the internal side.

The fracture surface of a crack tip was also investigated, see the circle marked at cut 1 on Figure 17. If a ductile fracture was present, it may have indicated that the stress hardening had lowered the ductility unacceptably with respect to fatigue resistance. However, no signs of ductile rupture were seen.

In order to investigate the structure of the steel as well as the propagation of cracks, a microsection was prepared, see cut 2 on Figure 17. All cracks were unbranched and localized to the knuckled area of the dimple, where strain hardening was highest. The large crack from the internal side indicates that the damage has mainly been initiated from this side. The absence of parallel cracks on the internal side is due to the stress relieving effect of the rapidly growing large crack. Electrolytical etching of the microsection in chromic acid showed that the steel was rolled and had a normal austenitic structure, see Figure 20. All these observations substantiated that fatigue initiated from the non-corrosive environment at the internal side was the cause of failure.

Based on the clear result of the failure investigation, the brewery made a further damage investigation with focus on pressure pulsations. It turned out that the regulating of cooling medium to the cooling jackets of the six YSTs was controlled by use of six valves on six parallel pipelines coupled to one pump. The pump had insufficient capacity when cooling requirements was highest thus causing fluctuating pressure.

Case # 3 Failure Investigation of Brass Motor Valves

The brass motor valves were part of a closed circuit cooling water system that supplies cooling for both electronic data processing equipment and air conditioning (offices). The operating temperature is 10-15°C. The system is equipped with an expansion vessel with preset gas cushion and butyl rubber bag, minimum pressure 1.5 bar.

From commissioning, the system was equipped with air release valves, a side stream filter unit and a micro bubble-eliminator. The cooling water was untreated tap water with a hardness of approximately 22 °dH and a conductivity of approximately 75 μS/cm. The consumption of make-up water was very low.

After about one year's operation, the cooling water system experienced minor problems with leaking air release valves. Only strictly necessary repair work was undertaken. Simultaneously the side stream filter unit was taken out of operation because of an annoying clogging with some dark brown corrosion products. However, after about two and a half years operation the number of leaks had reached an unacceptable magnitude and there was a general concern regarding the risk of serious damage to electronic equipment and building. Thus, a damage investigation was requested.

The first step in the investigation was to measure the oxygen content in the cooling water using a colorimetric test kit consisting of ampules, measuring range 0-1 ppm. The cooling water system was operated 24 hours non-stop whereupon the oxygen measurements were carried out on the return flow prior to the inlet of the micro bubble-eliminator. Five measurements were made, and in all cases the result was a powerful positive reaction showing that the oxygen content was more than 1 ppm. In agreement with the result of the oxygen measurements, the cooling water was dark rust colored.

A thorough inspection of the cooling water system was undertaken to find the source of the oxygen ingress, for example a local position with low pressure. No obvious oxygen source was observed however attention was focused on the pipe materials. The main pipes in the system are made from steel pipes but the majority of pipes are PEX pipes with a diffusion barrier of ethylene-vinyl acetate applied as a thin film directly to the external pipe surface. Information as to the film thickness cannot be obtained. As a rough estimate the total length of PEX pipes was about 1000 m. The majority of the PEX pipes have an external diameter of 20 mm.

The PEX pipes were delivered in conformity with the German standard DIN 4729 "Rohrleitungen aus Kunststoffen" that specifies the maximum amount of oxygen allowed to enter through polymer pipes intended for heating installations. The utilized diffusion barrier of ethylene-vinyl acetate has very good barrier properties under dry conditions and is widely used as an oxygen diffusion barrier on polymer pipes for heating systems. However at high relative humidity the barrier properties are reduced and if wet, the barrier properties of a thin ethylene-vinyl acetate film applied to a polyethylene pipe is in practice negligible. Table 3 shows some examples of barrier properties.

The installed PEX pipes were not insulated. Thus, if the temperature of the pipe surfaces is lower than the dew point of the surrounding air, a water film will be formed on the pipe surface. Consequently, the barrier properties of the ethylene-vinyl acetate film will be reduced significantly. At 20°C and 45% relative humidity, the dew point is close to 14°C. Since the cooling water temperature during operation is 10-15°C, the formation of a water film on the PEX pipe surfaces is possible. In order to check this damage hypothesis, brass motor valves were taking out for failure investigation. The valves were manufactured from dezincification resistant brass.

In accordance with the fact that circulating tap water is not particularly aggressive towards dezincification resistant brass, a visual and stereo microscopic inspection of the valves showed no signs of corrosion of the valves themselves. Corrosion products and particles originating from the steel pipes had precipitated at the valves mechanical parts and o-rings of rubber, see Figures 21-22. O-rings are very sensitive to abrasive wear, therefore it was no surprise that the precipitation of corrosion products and particles had caused the valves to leak.

To ensure that the steel pipes had not suffered severe corrosion, a "radiation on stream" investigation was carried out at ten positions. The investigation showed only uniform corrosion of insignificant depth.

To solve the problems with leaking valves, it was necessary to prevent corrosion of the steel pipes by preventing oxygen ingress or by water treatment with corrosion inhibitors.

As the need for cooling did not allow higher cooling water temperatures, it was not possible to ensure that the ethylene-vinyl acetate film was kept dry at all times. Thus oxygen ingress could not be prevented. Therefore it was decided to treat the water with corrosion inhibitors. The program for water treatment was chosen giving particular consideration to the need for minimal service and surveillance. An inhibitor system based on molybdates and carboxylates was selected.

Prior to adding corrosion inhibitors, the steel pipes were cleaned for precipitated corrosion products and particles. The side stream filter unit was put back into operation and a service plan for filter change was implemented. Within a few weeks, the circulating water was clear. The changed motor valves operated without problems, i.e. no leaks have been reported.

Instead of requesting a damage investigation, the property company was about to "solve" the problem by changing all valves. The consequences would at best have been a waste of money, and at worst have resulted in serious damage to electronic equipment and building. This scenario was avoided because the failure investigation showed that the problems with leaking valves were not related to the valve quality. The reason was oxygen ingress due to unsuitable pipe materials and operation at low temperatures. Although diffusion of oxygen through polyethylene is relatively slow, the large surface area due to very long pipe lengths allows plenty of oxygen to enter if the ethylene-vinyl acetate is wet.

SUMMARY

The three cases demonstrate the advantages of undertaking a thorough failure investigation of damaged equipment in order to establish the cause of failure and thereby select the correct remedy. In this way, many prospective problems can be avoided, e.g. unforeseen dowmtime due to operating trouble or even breakdown. In addition, many unprofitable discussions can be avoided.

ACKNOWLEDGEMENTS

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TABLE 1.
PROCEDURE FOR SEARCH FOR LEAKAGE IN A BRAZED PLATE HEAT EXCHANGER

1	Air compression is supplied to one side of the plate heat exchanger
2	With the portholes facing upwards, water is slowly supplied to the other side of the plate heat exchanger until a bubbling sound is detected. Bearing is taken on the water level and result is marked on the outside of heat exchanger. NB: Undertake visual control of the open portholes to check for leaky soldering in the cylindrical holes in the plate pack under the portholes.
3	Place the heat exchanger upright and supply the lowest porthole at the waterside with a water-gauge-glass. Fill heat exchanger slowly with water. When a bubbling sound is detected, the water level is marked on the outside of the heat exchanger. If no bubbling sound is detected, the heat exchanger is turned upside down and the process repeated (the leak is located higher than the top porthole).
4	Place heat exchanger on side. Proceed as under 3.
5	The leak is close to the cut between the three marked water levels. The heat exchanger is sawn through in three levels each distancing the expected leakage area by 15-20 mm. A cube appears that has a side length of 30-40 mm.
6	Thoroughly inspect cuts and cavities visually, e.g. by use of stereo microscope. If the damage/leakage is not detected, the cube of plates is opened by immersion in concentrated nitric acid. Hence copper is dissolved and the plates can be studied visually until leakage is detected.
Comments	A leakage caused by a leak soldering only occurs along the four outsides of the heat exchanger, in the cylindrical holes in the plate pack under the portholes or around the portholes. A leakage in other places is caused by holes in the plates, i.e. by corrosion (crack, pitting) or by overload (too high pressure, fatigue).

TABLE 2.
PROCEDURE FOR CUTTING OUT DIMPLE PLATE-SAMPLES FOR METALLURGICAL EXAMINATIONS

1	It is important that the cutting out of samples be made as cold and lenient as possible, e.g. by careful use of a small cutter or a hollow drill.
2	It is recommended to make a circular cut a good distance away from the dimple between the jacket and the tank bottom and subsequently – in one movement – break-off the sample.
3	Weld in a replacement dimple – preferably supplied by the tank manufacturer.

TABLE 3.
SOME EXAMPLES OF BARRIER PROPERTIES

Resin	$P(O_2)$, 25°C $cm^3/(mil\ day\ 100\ in^2\ atm)$
Ethylene-vinyl acetate (EVAL)	0.02 (dry only)
HDPE	150
LDPE	420

Polymer Permeability, J. Comyn, Ed., Elsevier, London 1985

FIGURE 1 – Overview of the brazed plate heat exchanger that was investigated for an internal leakage.

FIGURE 2 – An internal leakage in the heat exchanger was detected near porthole T4, i.e. near the pressure plate outlet of superheated vaporised refrigerant. This position corresponded to the observation of a bulge on the outside of the heat exchanger, see the white markings.

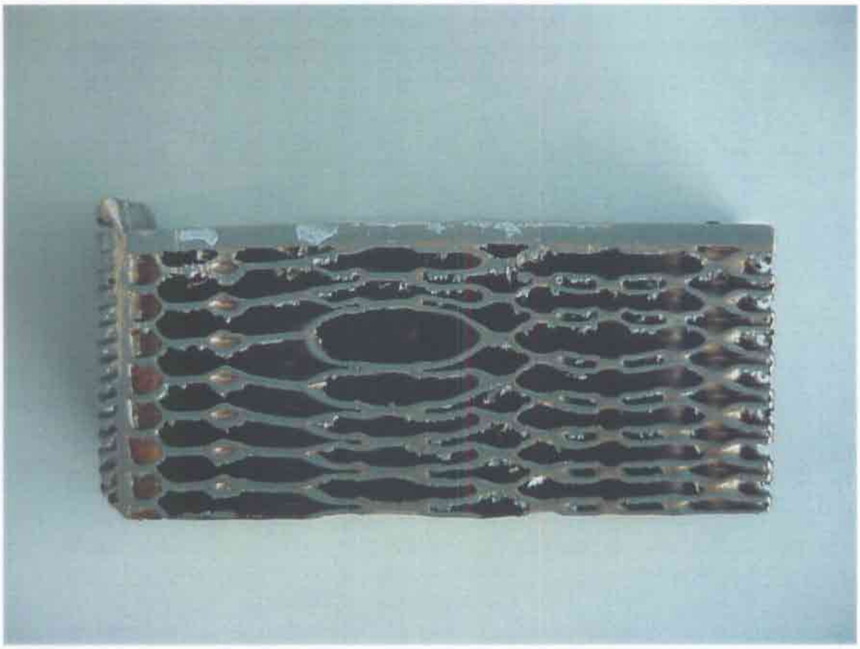

FIGURE 3 – A rectangular sample containing the leakage was cut out of the heat exchanger, see Figures 2-3.

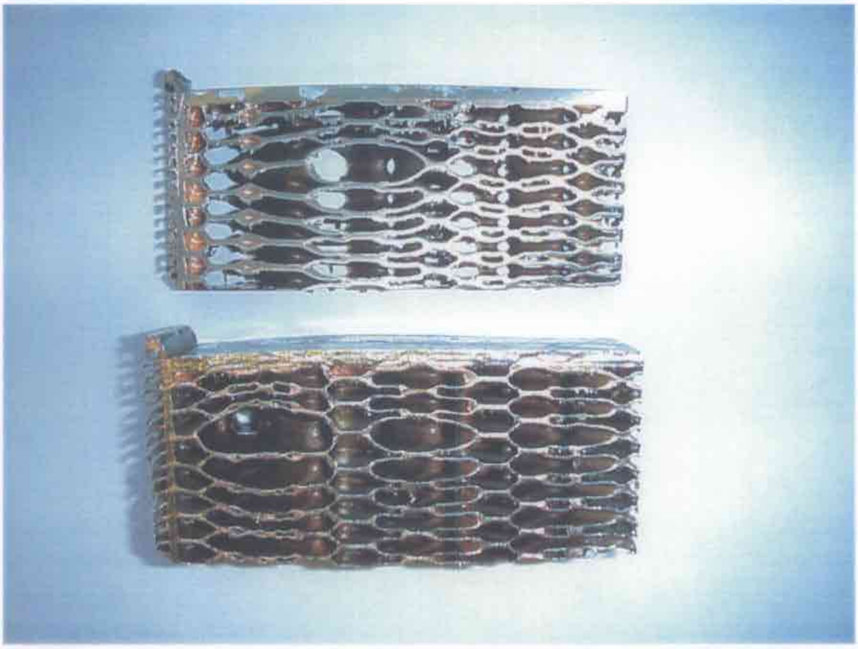

FIGURE 4 – In order to get a close view of the leakage, the rectangular sample shown in Figure 3 was further cross-sectioned.

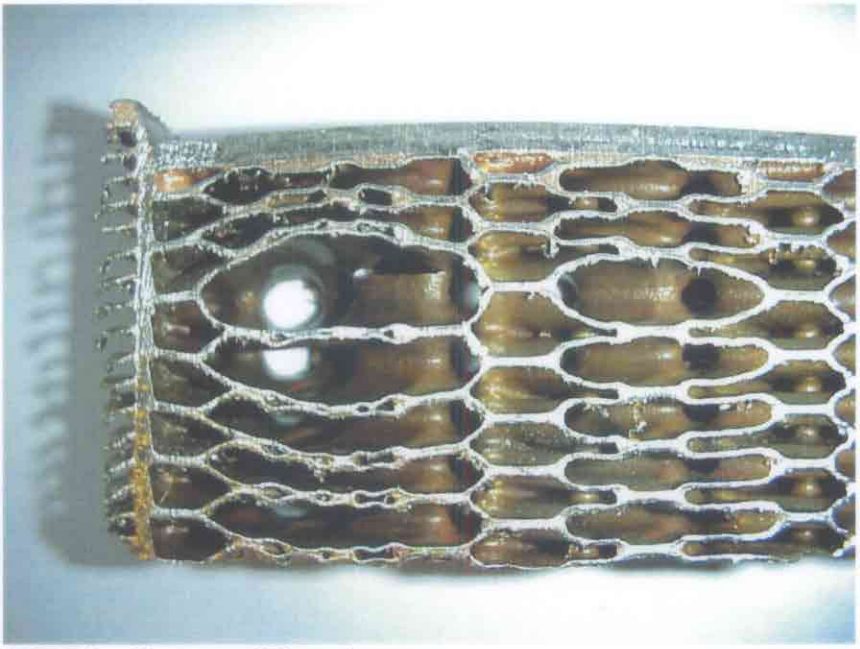

FIGURE 5 – Close-up of Photo 4.

FIGURE 6 – Close-up of Figure 5. The "bloated" appearance of the fissure is a strong indication of freezing damage. The right side of the dotted line shows where the microsection in Figure 7 was taken whereas the upper surface of fracture to the left of the dotted line was examined by use of scanning electron microscopy (SEM), see Figure 13.

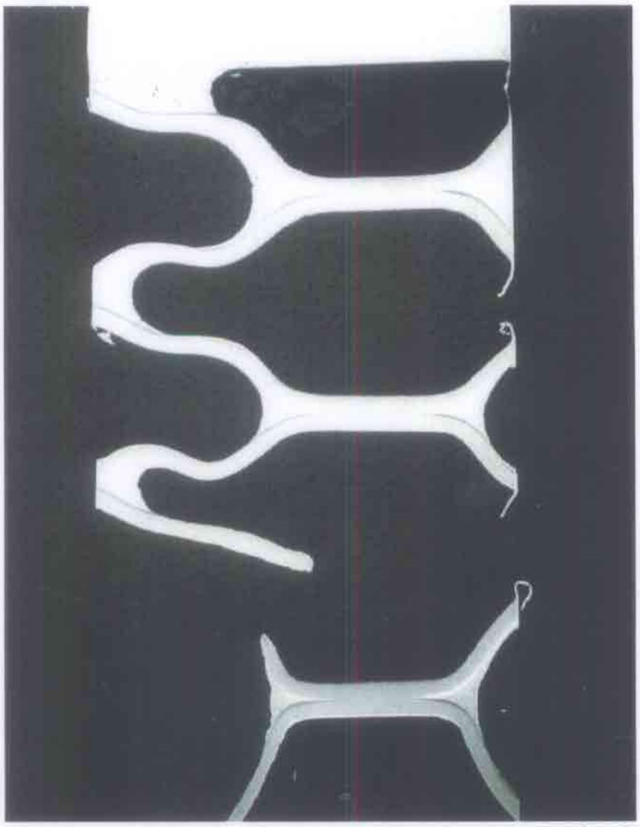

FIGURE 7 – LOM-micrograph of microsection taken across the fissure shown in Figure 6. Magnification 6.5x.

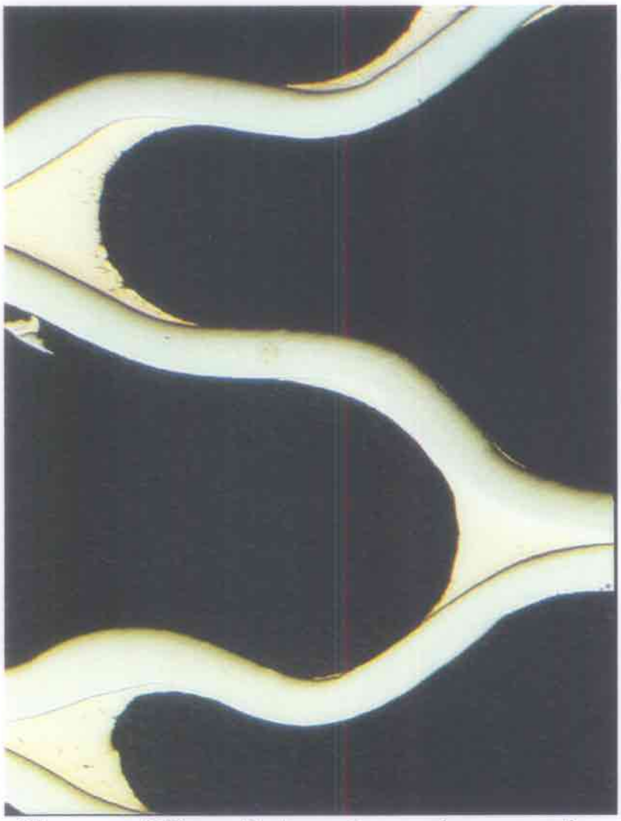

FIGURE 8 – Close-up of Figure 7. An undamaged cross-section of the brazed plate pack. Magnification 17x.

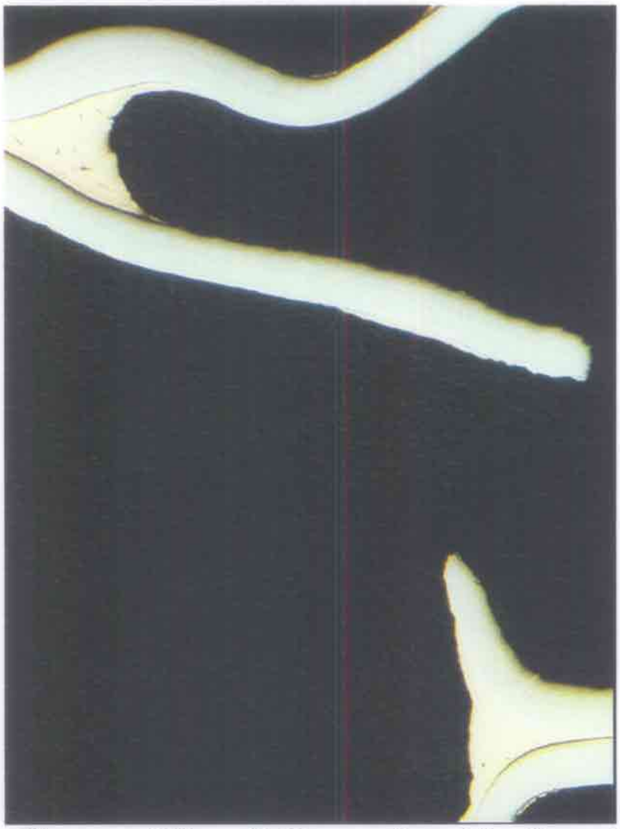

FIGURE 9 – Close-up of Figure 7. Cross-section of the fissure in the brazed plate pack. Magnification 17x.

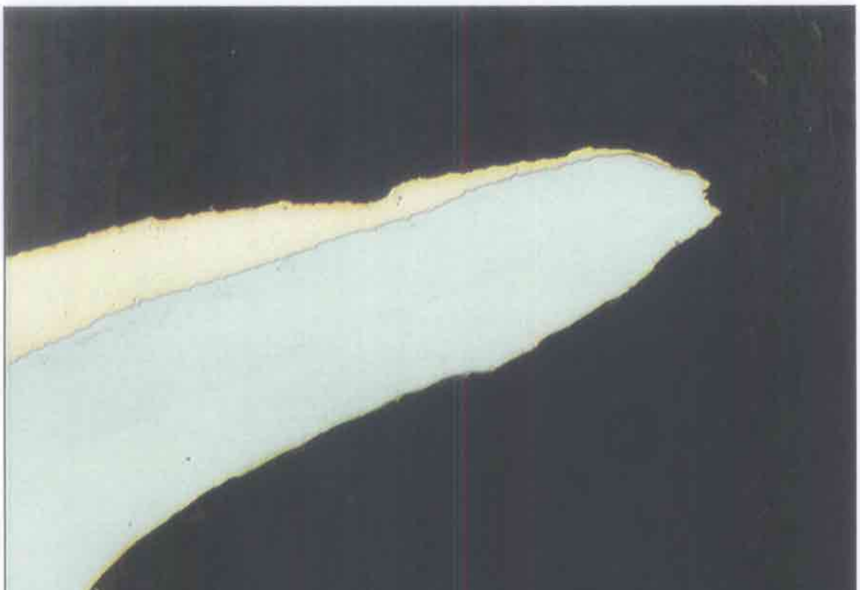

FIGURE 10 – Close-up of Figure 9. The ductile necking shows that the rupture was caused by mechanical overload. Magnification 90x.

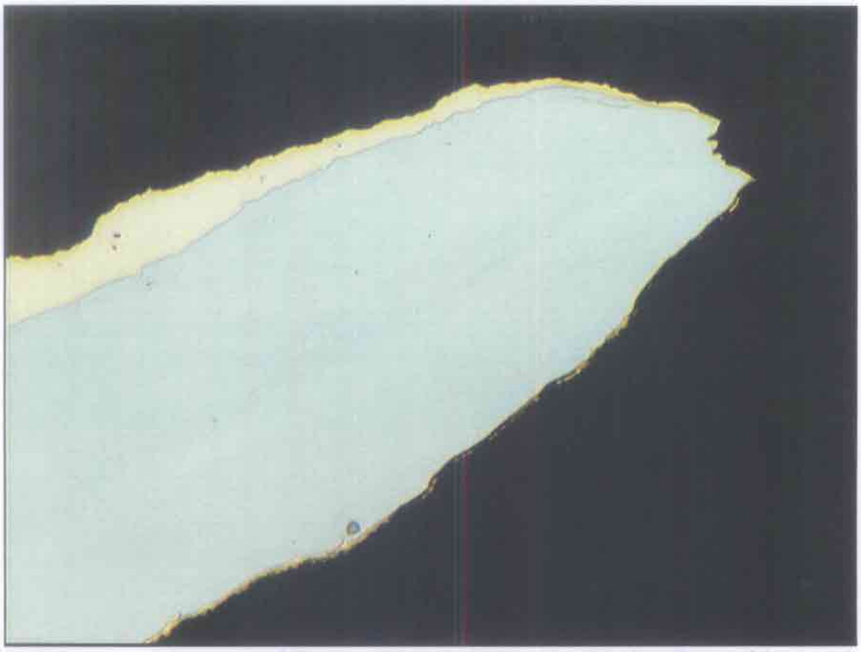

FIGURE 11 – Close-up of Figure 10. In addition to the ductile necking typical of a rupture caused by mechanical overload, it is important to note that no cracks are observed. Magnification 180x.

FIGURE 12 – Close-up of Figure 9. Same comments as for Figure 11. Magnification 180x.

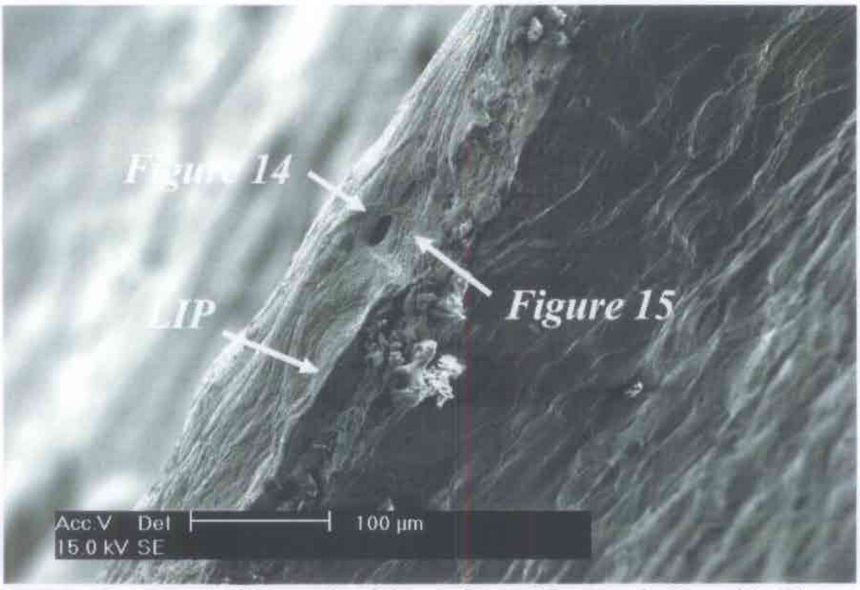

FIGURE 13 – SEM-micrograph of the surface of fracture indicated in Figure 6. The lip is typical of a ductile rupture caused by mechanical overload. The inserted text boxes refer to close-ups in Figures14-15.

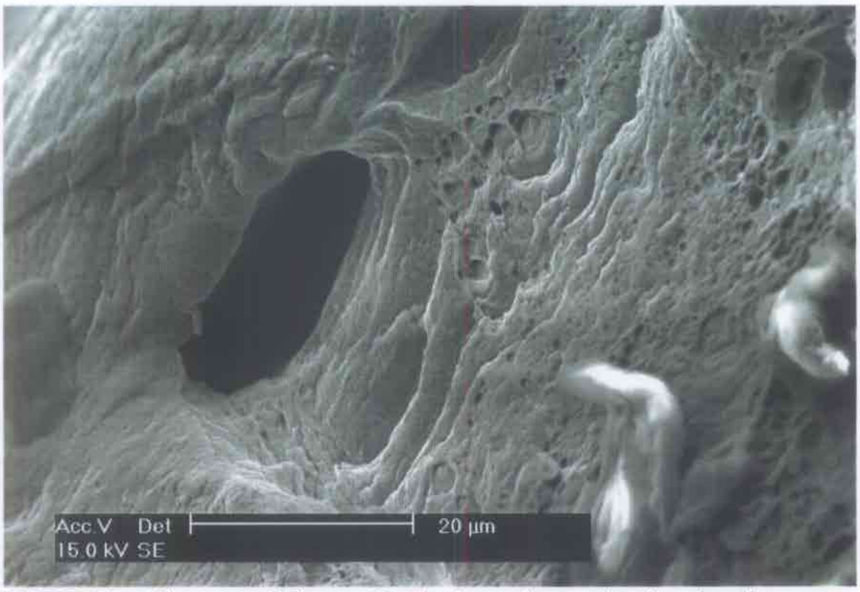

FIGURE 14 – Close-up of Figure 13. The large depression is a ductile rupture at the initiation stage. The many small cup-like depressions are dimples, i.e. a definite characteristic of a ductile rupture.

FIGURE 15 – Close-up of Figure 13. The many small cup-like depressions are dimples, i.e. a positive characteristic of a ductile rupture.

FIGURE 16 – Overview of the bottom of the yeast storage tank after removal of the insulating material. The great majority of the repair-welded dimples were observed in clusters. Unlike the original welds at the dimples between the jacket and the tank bottom, it seemed that the repair welding had been performed using filler material.

FIGURE 17 – Macrograph of damaged dimple plate with the internal side of cooling jacket uppermost. Crack was opened at position 3 so fractured surface could be studied. At cut 2, a microsection was taken. Magnification 2x.

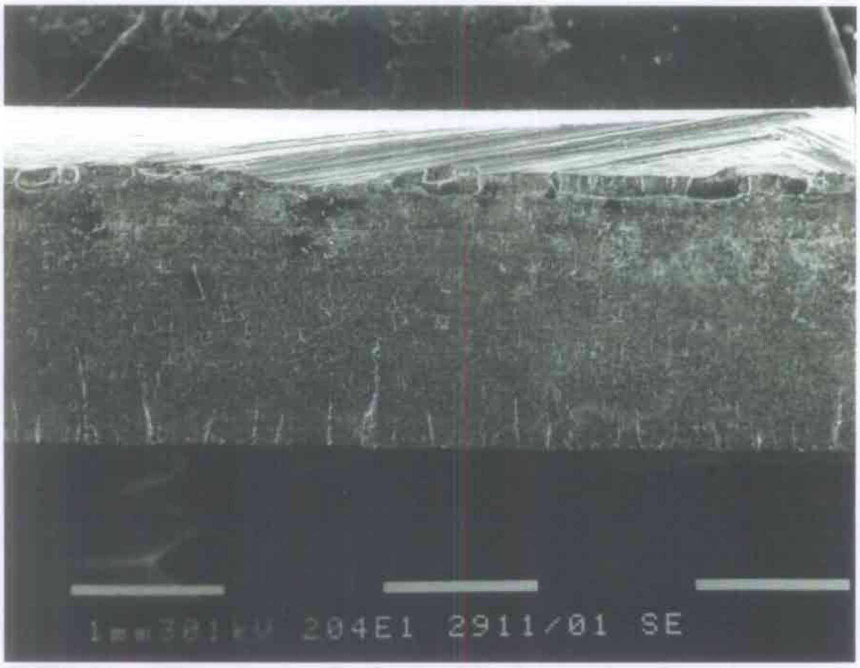

FIGURE 18 – SEM-micrograph of part of the fractured surface (see mark 3 on Figure 17) with internal side of the cooling jacket at the bottom of the micrograph. Note the presence of beach marks and steps ("notches"). Magnification 20.4x.

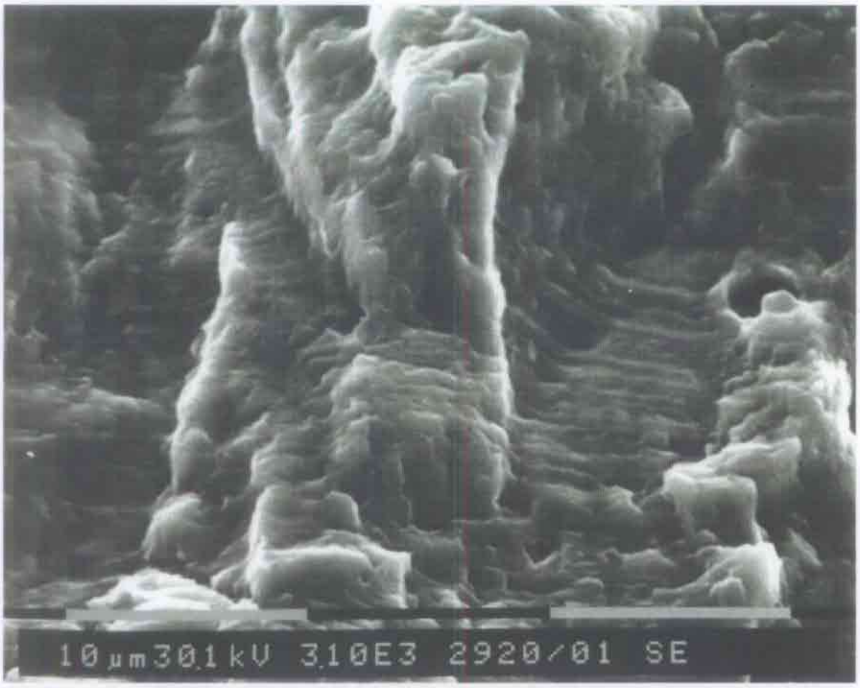

FIGURE 19 – SEM-micrograph at high magnification of fractured surface on Figure 18. Note the presence of striations. Magnification 3100x.

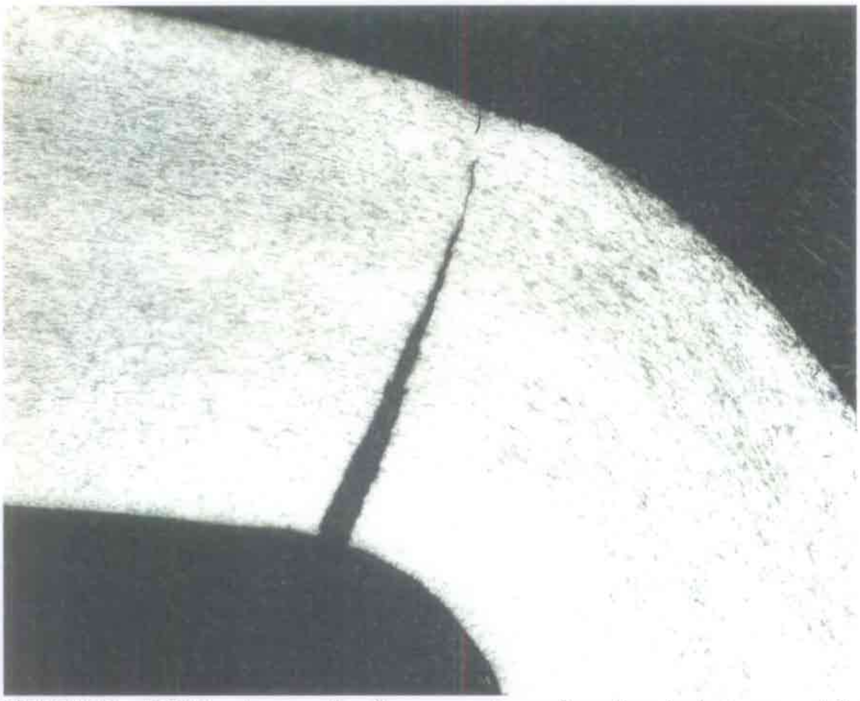

FIGURE 20 – LOM-micrograph of cross-section of cooling jacket, see cut 2 on Figure 17. The cracks are localized to the knuckle area of the dimple. The large crack enters from the internal side of cooling jacket. Magnification 3100x.

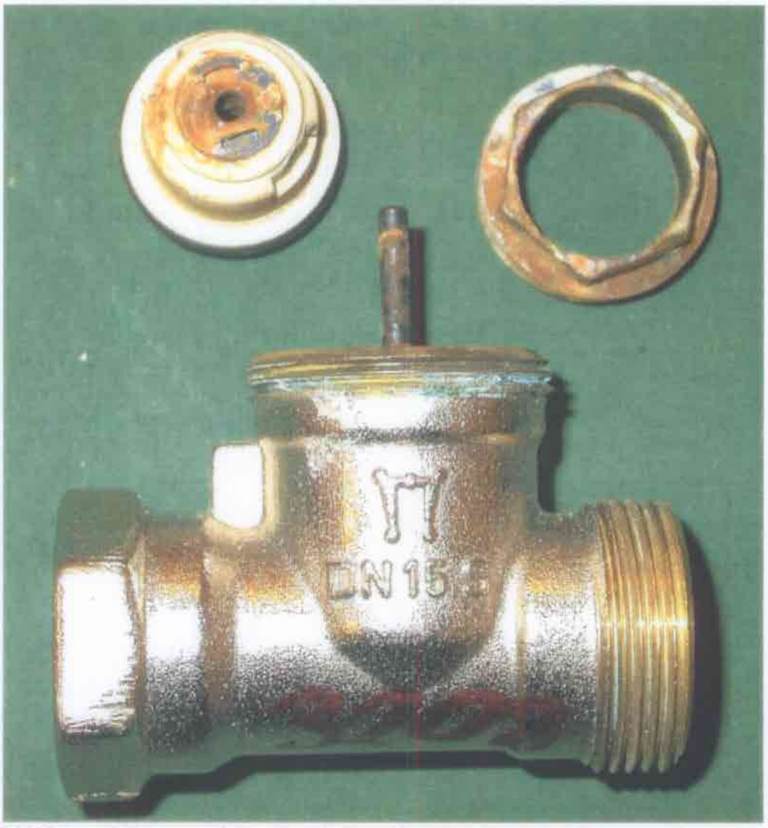

FIGURE 21 – Motor valve. Precipitated corrosion products and particles are seen at mechanical parts

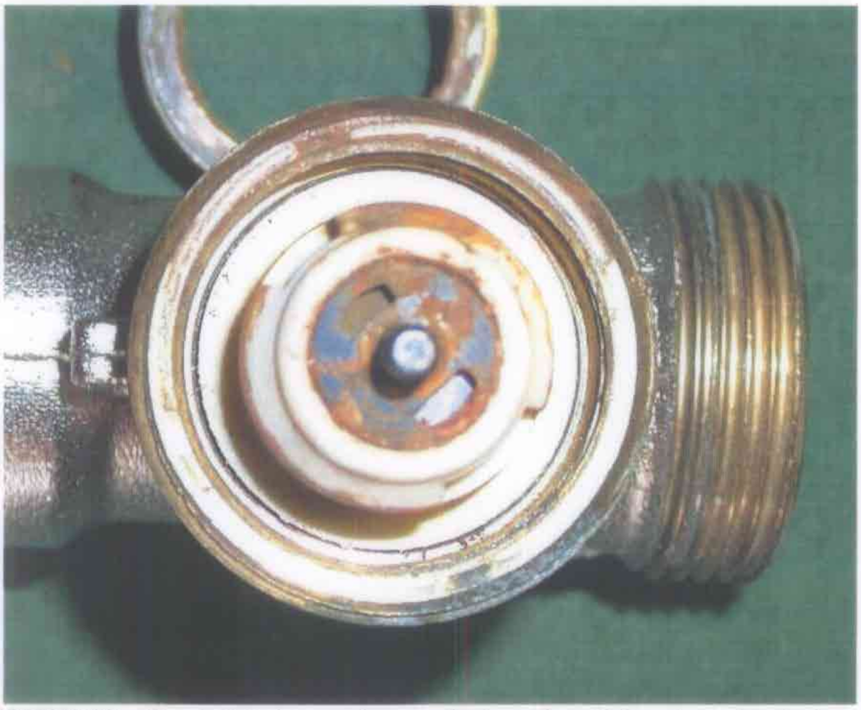

FIGURE 22 – Precipitated corrosion products and particles at mechanical parts in motor valve.