PWRs Operation and Maintenance

Feedwater Plant and Other Secondary Components – Mechanical Components

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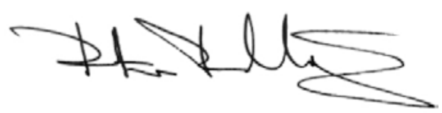

Mr. Peter Rudling, Chairman of the Board of ANT International

Content

1 Summary

This report compiles field operating experience and maintenance of some of the following PWRs components: heaters and reheaters, pumps, valves, piping and their supports, heat exchangers and bolted connections. Reactor coolant pumps, steam generators and primary system piping are excluded as presented in other reports.

The report is separated in two sections.

The first section is dedicated to the feedwater plant and other secondary system components, i.e.: feedwater plant reheaters, moisture separator re-heaters, feedwater plant pumps and steam generator turbine driven auxiliary feedwater pumps.

The second section is dedicated to mechanical components, i.e.: piping and supports, valves, pumps and bolted connections.

2 Secondary system overview

The figures (Figure 2-1 to Figure 2-3) show 3 examples of secondary systems layouts in operation at EdF units. The first one is related to 3 loop PWRs secondary systems supplied by Alsthom. The second one is related to 3 loop PWRs secondary systems supplied by CEM. The third one is related to 4 loop PWRs secondary systems supplied by Alsthom Atlantique.

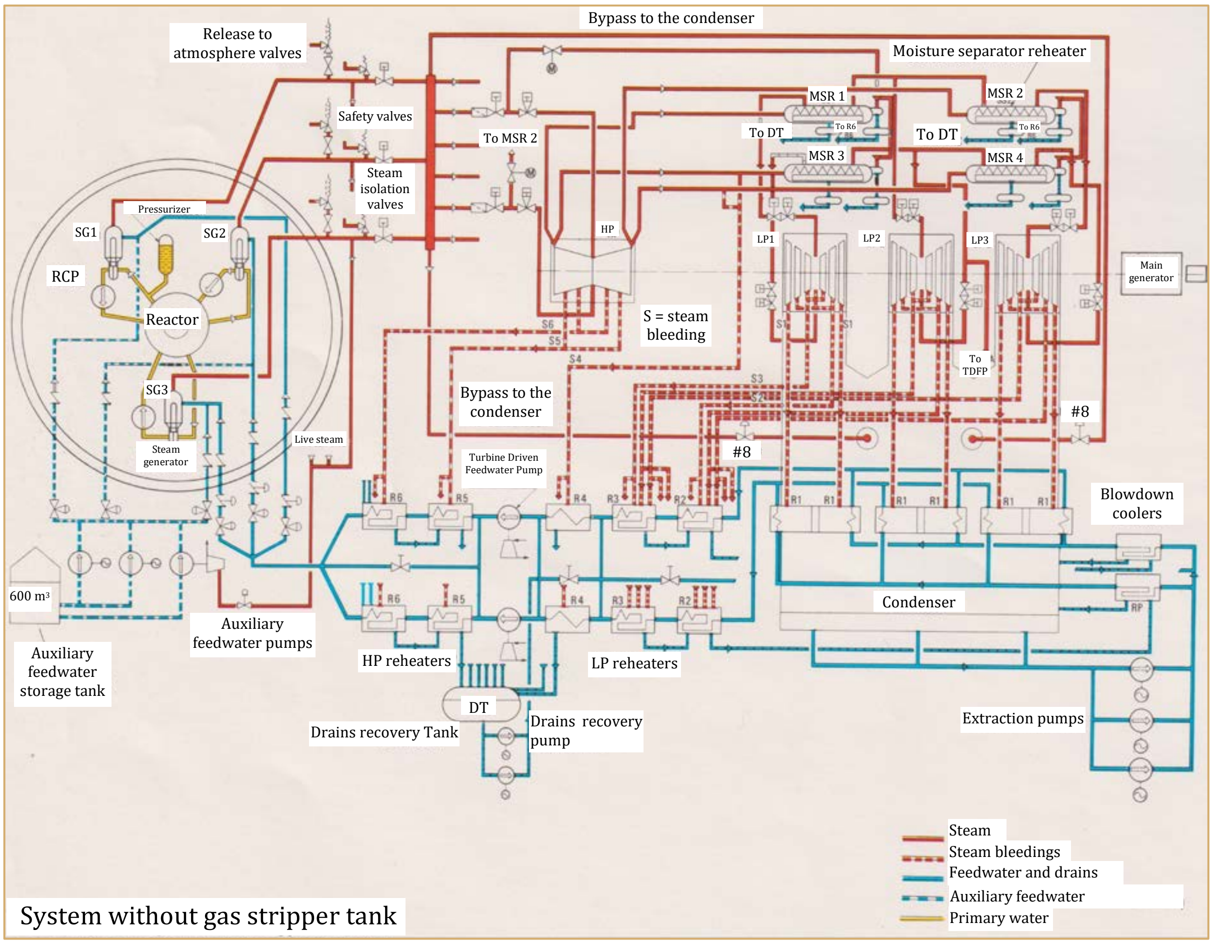

Figure 2-1: Layout of the secondary system of EdF 3 loop PWRs, vendor: Alsthom [Dürr, 1978].

3 Chemistry

The chemical conditioning of the secondary system has been extensively presented by Francis Nordmann at LCC16 and in the ANTI report [Nordmann, 2020]; therefore, only minimum information is reported her.

Feedwater conditioning.

Parameter	Unit	Expected number	Limit number	Analysis frequency	Remarks
pH at 25°C		8.8 to 9.3		On-line	In presence of copper alloys
		8.8 to 9.8			In absence of copper alloys
Oxygen	µg/kg	< 100		On-line	
Cationic conductivity at 25°C	µS/cm		≤ 2	Occasional	Limiting numbers are to be met before switching from auxiliary feedwater to normal feedwater.
Sodium	µg/kg		< 10		
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Steam generators normal feedwater, power operation or hot standby, amine (i.e., morpholine conditioning), presence of copper alloys.

Parameter	Unit	Expected number	Limit number	Analysis frequency	Remarks
pH at 25°C		9.1 to 9.3	9.0 to 9.4 8.8 to 9.6 for < 24h	On-line	
Total conductivity at 25°C	µS/cm	3 to 5		Occasional	To compare pH and chemical concentrations
Morpholine	mg/kg	4 to 6	4 to 8	Weekly	Lower limit: 2 mg/kg in presence of methylamine
Ammonia	mg/kg in NH_4	< 0.3	< 0.5	Weekly	Comes only from hydrazine and morpholine decomposition
Oxygen	µg/kg	< 1	< 3	On-line	The upper limit can be exceeded during start-up
Hydrazine	µg/kg	> 10	> 5	On-line	Depending on steam generators blowdown resins set-up
Suspended iron	µg/kg	< 5		Occasional	Obtained from suspended solids analyses
Suspended copper	µg/kg	< 2		Occasional	Obtained from suspended solids analyses
Soluble copper	µg/kg	< 2		Occasional	
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Steam generators normal feedwater, power operation or hot standby, amine (i.e., morpholine conditioning), absence of copper alloys.

Parameter	Unit	Expected number	Limit number	Analysis frequency	Remarks
pH at 25°C		9.5 to 9.6	9.2 to 9.8 9.0 to 10.0 for < 24h	On-line	
Total conductivity at 25°C	µS/cm	7 to 13		Occasional	To compare pH and chemical concentrations
Morpholine	mg/kg	6	4 to 8	Weekly	
Ammonia	mg/kg in NH_4	1 to 2	< 5	Weekly	Comes only from hydrazine and morpholine decomposition
Oxygen	µg/kg	< 1	< 3	On-line	The upper limit can be exceeded during start-up
Hydrazine	µg/kg	100 to 200	> 50	On-line	Depending on steam generators blowdown resins set-up
Suspended iron	µg/kg	< 2		Occasional	Obtained from suspended solids analyses

Steam generators normal feedwater, power operation or hot standby, ammonia conditioning, absence of copper alloys.

Parameter	Unit	Expected number	Limit number	Analysis frequency	Remarks
pH at 25°C		9.5 to 9.6	9.2 to 9.8 9.0 to 10.0 for < 24h	On-line	
Total conductivity at 25°C	µS/cm	7 to 13		Occasional	To compare pH and chemical concentrations
Ammonia	mg/kg in NH_4	2 to 5	Required content	Weekly	Can come only from hydrazine conditioning
Oxygen	µg/kg	< 1	< 3	On-line	The upper limit can be exceeded during start-up
Hydrazine	µg/kg	100 to 200	> 50	On-line	Depending on steam generators blowdown resins set-up
Suspended iron	µg/kg	< 2		Occasional	Obtained from suspended solids analyses

4 Feedwater plant and other secondary components

In this section, we are going to review some important secondary system components: reheaters, feedwater plant pumps, moisture separator reheaters and steam generator turbine driven auxiliary feedwater pumps. More "standard" components are reviewed in a generic way at section #3.

4.1 Feedwater plant general setup

The feedwater plant is composed of various equipments collecting the secondary water out of the condenser, reheating it and conditioning it before sending it back to the steam generators feedwater system (Figure 4-1).

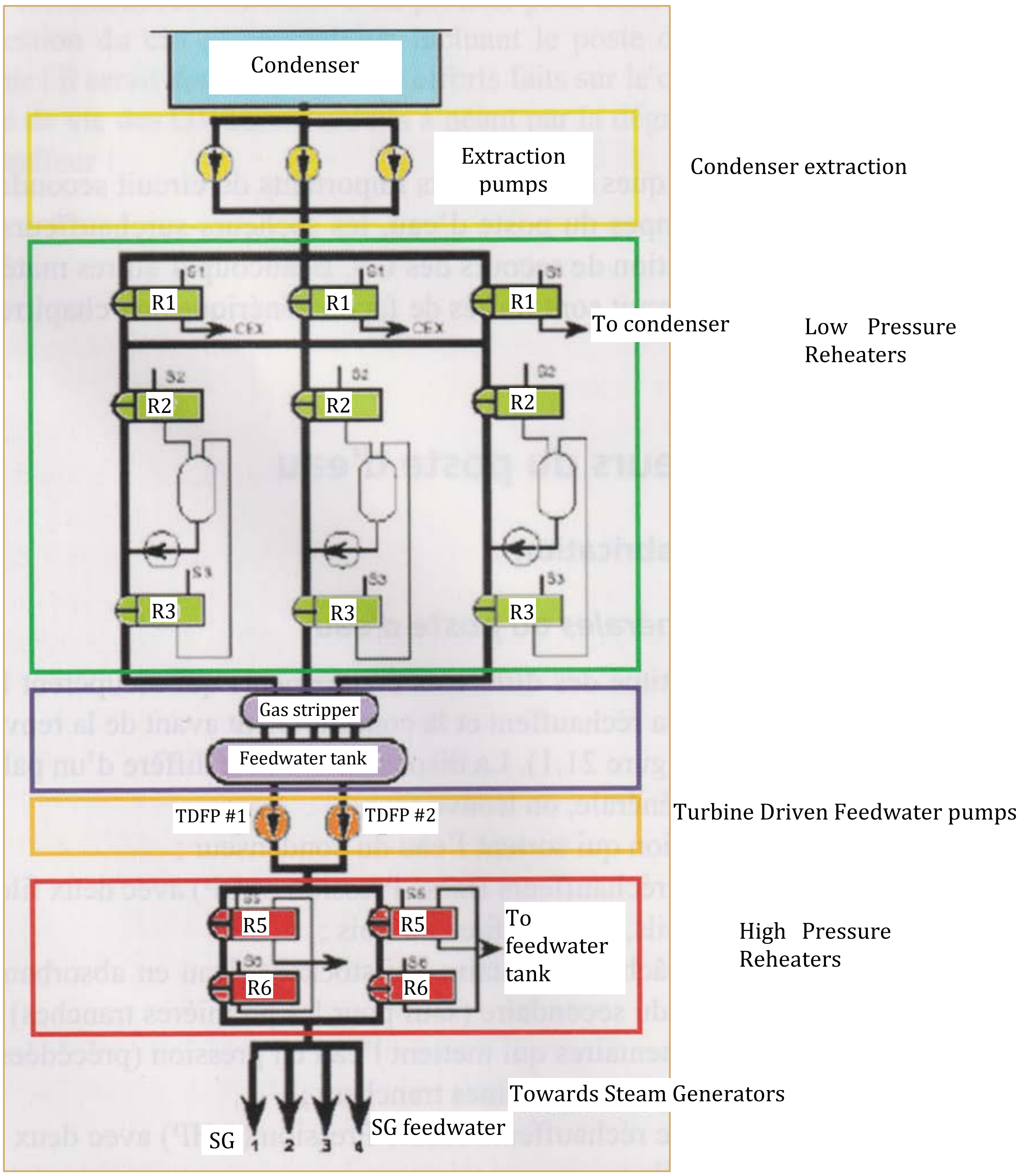

Figure 4-1: General sketch of a typical feedwater plant, from the condenser outlet up to steam generators water feeding [Hutin, 2016].

The layout varies from one design to another but basically, all feedwater plants contain the following equipment's:

- Extraction pumps extracting water out of the condenser;
- A first series of low pressure reheaters with typically two trains of three or four reheaters or three trains of three reheaters;
- A gas stripper tank along with a feedwater tank which stores the feedwater and buffers the secondary system water inventory variations (earlier units don't have these equipment's);
- Turbine driven feedwater pumps which raise the feedwater pressure, on some units' turbine driven feedwater pumps come downstream booster pumps;
- A second series of high pressure reheaters with two trains of one or two reheaters;
- The steam generators feedwater system composed of many valves and pipes;
- A set of auxiliary equipment's such as condensates coolers, condensates collecting tank, drain transfer pump, closure valves, etc.

Here, we are going to focus only on reheaters.

4.2 Feedwater plant reheaters

4.2.1 Reheaters design and fabrication

Reheaters are basic heat exchangers: a wrapper into which a U-tubes bundle is installed typically horizontally although some are sometimes installed vertically (Figure 4-2).

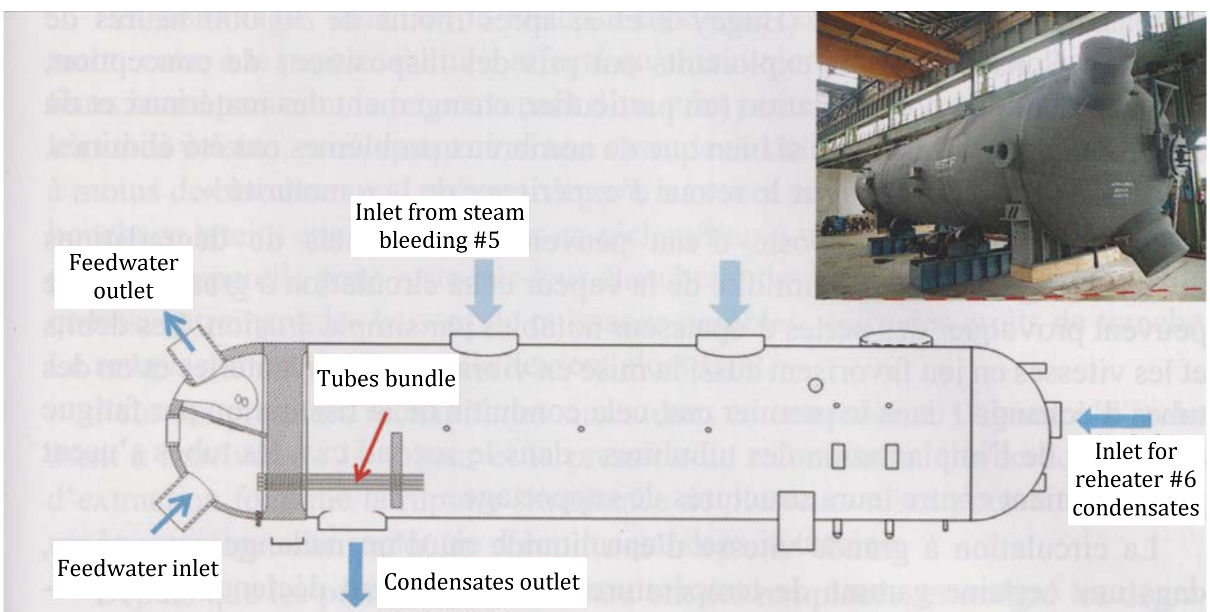

Figure 4-2: Simplified sketch of a high pressure reheater, partial section view [Hutin, 2016].

The tubes are installed in a tube sheet to which is welded a channel head for the inlet and outlet of the feedwater to be reheated. The water coming out of the condenser flows into the tubes and is heated by bleeding steam flowing at the tubes OD; once as condensate, it flows back to the condenser. The shells and tube sheets are typically made of carbon steel (although some shells are made of stainless steel). The tubes are either made of brass (for some low pressure reheaters), or of carbon steel or of austenitic or ferritic stainless steel. It is worth mentioning that if brass is a good choice for reheaters, it forbids the implementation of a high pH chemical conditioning that would be requested by some other secondary system components and therefore has been banished from feedwater plants when major refurbishing work was performed on low pressure reheaters.

In case of a low pressure reheater leak, it is possible to separate one train to fix it; as a consequence, the output power will decrease by 15 MWe for a 900 MWe unit (or more if the remaining operating reheater of the other train has many plugged tubes). Note that if a leak occurs on the first reheater of the train, this reheater cannot be isolated steam side because it is located inside, at the top, of the condenser (Figure 4-3). As a consequence, if a reheater #1 leaks, identifying and plugging the leaking tube(s) require a plant shutdown for one or two days.

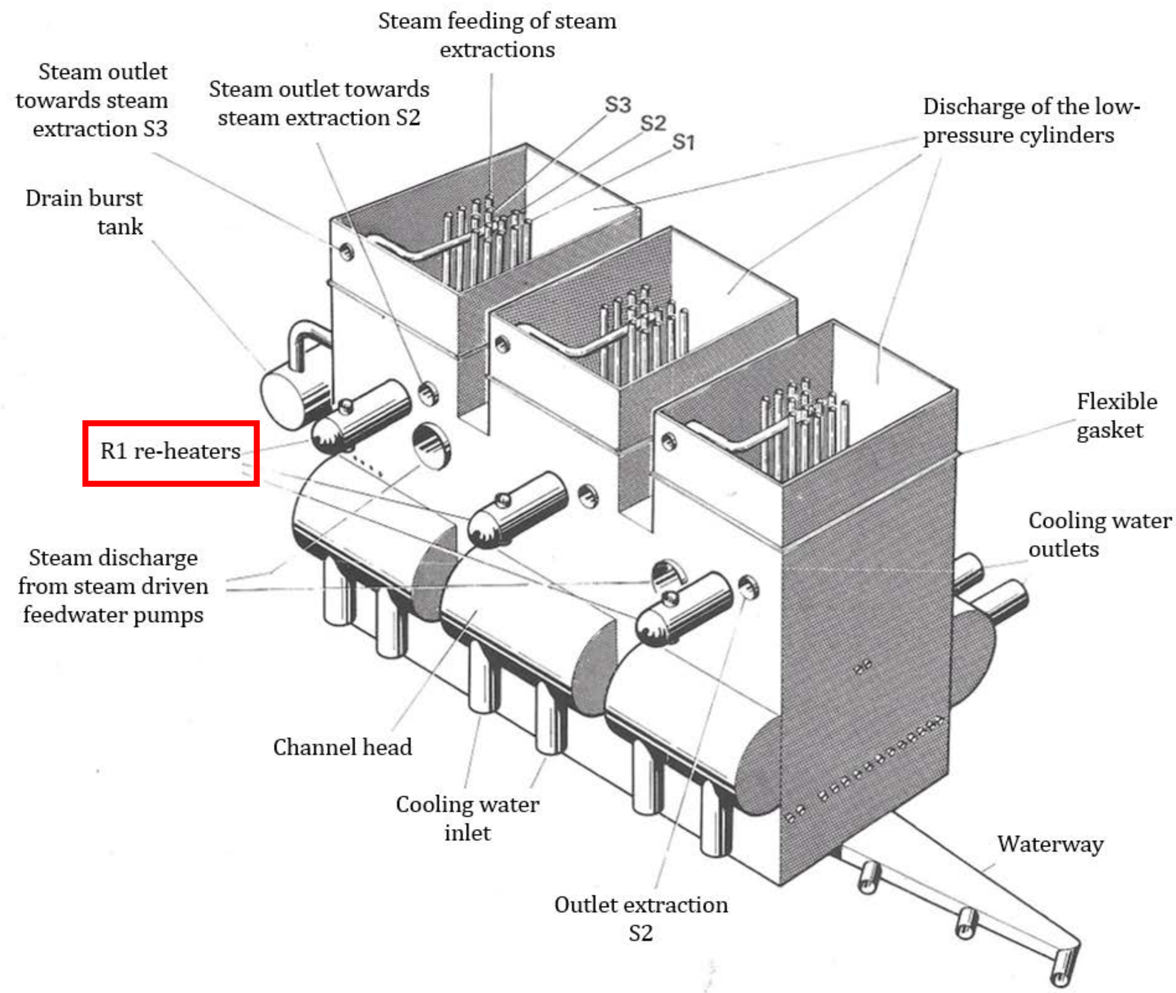

Figure 4-3: Condenser, view from the cooling water inlet side. Location of the R1 re-heaters [Cattant, 2021].

Regarding high pressure reheaters, isolating a train for leak detection and remediation is also possible, providing the unit output power is decreased by 5 to 30 MWe. However, when all reheaters are in poor condition, the operator prefers decreasing the output power by 30% during the fixing work (in average, four days) in order not to overload the train which is still in service.

According to the regulator, most of the reheaters are pressure equipment's; therefore, they are equipped with safety valves and are amenable to regulatory inspections.

4.2.2 EdF operational experience

We will focus here only on mature issues and not the "early illnesses" reheaters suffered from, of which some induced reheaters replacements after less than 30,000 hours of operation. Both vendors and Utility took the necessary actions in the field of design, construction (materials replacement) and operation (modification of the chemical conditioning), to solve most of these early issues.

5 Mechanical components

5.1 Foreword

In this chapter #5, we are going to review mechanical components flowing or containing liquids. Emphasis has been put on pipes and their supports, valves, pumps to end with bolted connections.

5.2 Pipes and supports

5.2.1 General description

In terms of pipes, almost all diameters are present. On the NSSS and associated systems, the vast majority of the pipes are made of austenitic stainless steel, especially those flowing borated water into the circuits connected to the RCS. They are fabricated from butt welded pipe segments and the connections to the various components such as valves and heat exchangers, are welded or bolted (bolted flanges and gaskets). For most of the systems, the flowing fluid is supposed to be single phase. In some systems where water is stagnant (as for example fire-fighting systems), we can find pipes made of composites. In the secondary systems, flowing either water or steam, pipes are typically made of carbon steel. In raw water systems, pipes are typically made of carbon steel either (with or without liner or coating), along with concrete pipes with metallic web.

Supports are designed to bear the pipes' weight including its inside fluid, pipes various accessories along with the stresses stemming from external loads such as earthquake. They allow limiting stresses put on connected equipment's along with allowing them some displacements induced by thermal expansion and restrain during thermal transients. Many types of supports exist, depending on their designed function: stationary support (named as: fix support), moving support at constant bearing (named as: constant support), moving support with variable bearing (named as: variable support), restraints, pads, guides, etc. In any case, a support is composed of 3 parts: the attachment to the pipe (collar, strap, clamp, clip, welded part, etc.), the support itself (bracket, arm, rod, spring with its box or its counterweight, hanger, frame, etc.) and the mounting to a building or to a beam (plate, bracket, bolt, studs and nuts, etc.).

One can note the difficulty for designing a pipe network with the associated supports when looking for a good compromise between having pipes flexible enough to accommodate the thermal expansion while limiting the stresses and stiff pipes to resist to earthquake loads.

5.2.2 Field experience

The field experience with pipes is in overall good. Often considered as idle equipment and therefore trouble free, pipes are that close to be ignored by maintenance engineers. It is true that commonly, pipes stay out of plant daily burden which can explain why they remain out of maintenance engineers' mind. However, should a failure occur, the EdF fleet standardization makes soon this even generic which can have a dramatic impact on plants availability and maintenance costs. Regarding safety, redundancy generally allows keeping pipes failures under control by switching from one train to another. Furthermore, the materials and operating conditions are such that most of the time the "leak before break" concept applies, allowing operators to be informed about the progress of a failure before it reaches the pipe rupture.

For each field event, we will indicate the pipes groups of concern, making generally the rough difference between NSSS stainless steel pipes and balance of plant carbon steel pipes.

5.2.2.1 Corrosion

Various corrosion mechanisms can develop in pipes.

NSSS side, the one coming first is boric acid corrosion. When boric acid is diluted (pH > 4), and if the oxygen residual content is low enough, low alloy steels corrosion rate is very low (less than 20 microns per year) and even lower for stainless steels (a few microns per year). On another hand, if boric acid is concentrated (pH < 4) and the environment is aerated, then all types of steels can more or less corrode. Boric acid corrosion is temperature dependent and also depends on the chromium content for stainless steels. In case of borated water leak, pipes accessories such as supports, flanges bolts, valves bodies, can also suffer from corrosion.

Corrosion below the water level line occurs into pipes where there is either a dual phase aerated environment or a stagnant liquid (situation for RCS auxiliary piping). Sometimes, we can also observe pitting corrosion either into low alloy steel or into stainless steel which can be passivated pipes. In this last situation, it is a concern rather for circuits which have been polluted by a deleterious specie. As regards stress corrosion cracking, it can be a concern for austenitic stainless-steel pipes wetted by primary water in areas where high residual stresses are present along with a highly cold worked material. However, stress corrosion cracking can rather occur in presence of high stresses along with an environment polluted with chlorides and/or sulphates. It has been observed into the RCS auxiliary piping, into dead legs between two valves, and into leak-off lines of valve packing and also on some welded base plates of pipes supports (observed into the reactor cavity and spent fuel pit cooling and treatment system at one unit and into the containment spray system at another unit (Figure 5-1)).

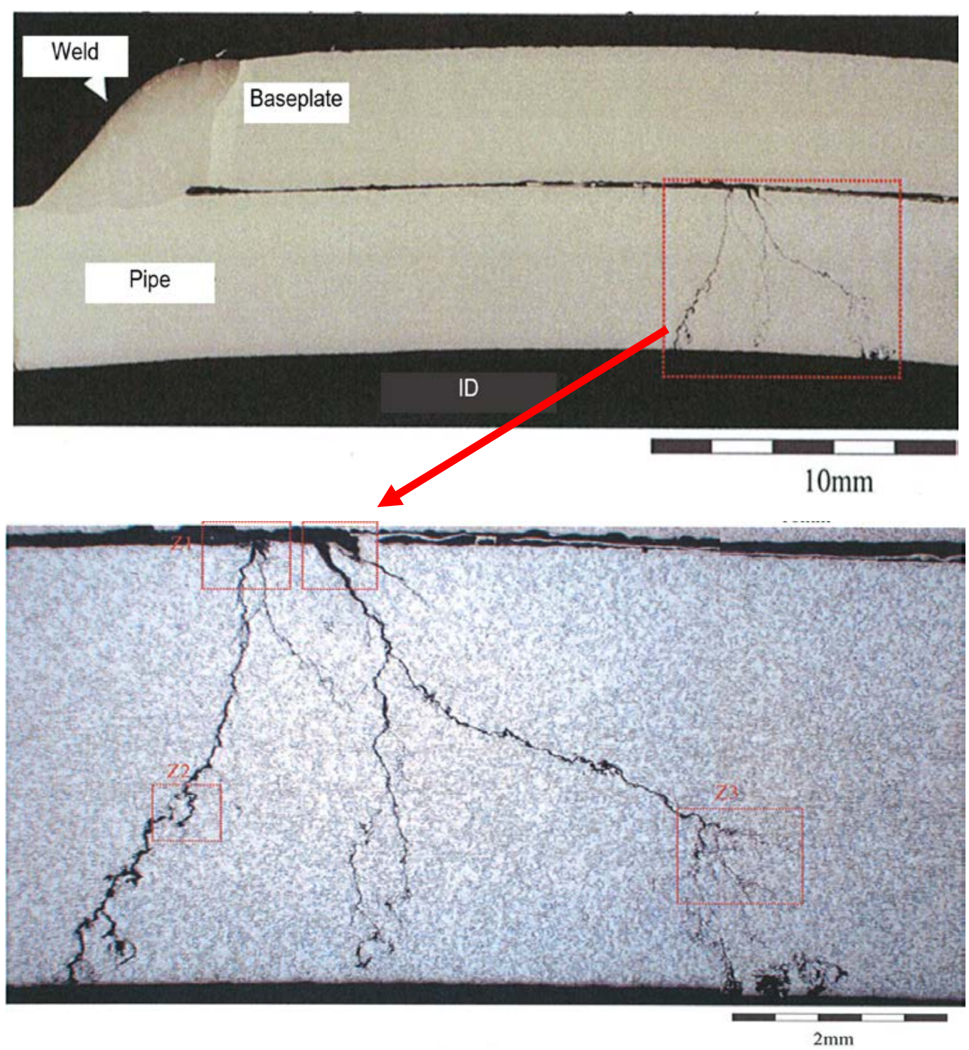

Figure 5-1: SCC observed into a containment spray pipe made of 304L: cracks have initiated at the pipe OD, from pits initiated into the gap between the welded base plate and the pipe (oxygenated environment polluted with chlorides) [Hutin, 2016].

Regarding accidental pollutions, it is worth to mention that materials have a "memory effect", in the sense that extremely low pollutants amounts can remain in place despite cleanings and further operation and initiate much later on severe degradations. As for example, a high-pressure safety system elbow suffered from a through wall crack in 1983 from a system pollution which occurred several years before.

However, the most worrying failure mechanism is the flow assisted corrosion of carbon steel pipes. Why is this so worrying? Because this failure mechanism translates in a general wall thinning over a large surface which can eventually end up in pipe burst, without any preceding leak that could warn the operator something wrong is going on. Furthermore, as this thinning can occur in pipe free span, non-destructive examination cannot be of a major help as generally targeting welds, fittings and other similar exceptions. Because of this at Surry, on a steam generator feedwater pipe (upstream the turbine driven feedwater pump), an eighteen inches diameter and half inch thick elbow has literally exploded, being torn over a meter long and killing four people (Figure 5-2). It is also flow assisted corrosion which is responsible for the burst of a 560 mm diameter straight pipe located downstream low pressure reheaters, after 21 years of operation at Mihama (Figure 5-2). The residual thickness of the relevant pipe was 1.4 mm for an initial thickness of 10 mm and nothing alerted the operator; more than 200 persons were working in the turbine hall at this time to prepare the coming outage, five of them were killed.

Figure 5-2: View of bursts of feedwater pipes at Surry (top left) and Mihama (top right) following flow assisted corrosion wall thinning mechanism. Bottom: typical aspect of flow assisted corrosion ID features [Hutin, 2016].

Operators should keep in mind the parameters governing flow assisted corrosion: the steel chromium content, the temperature, the water pH, the steam quality if dual phase and the fluid velocity.

6 Conclusion

It has been over half a century now that commercial nuclear reactors are in service. During all these years, considerable amount of information about operation and maintenance of these reactor has been acquired by nuclear utilities. This report compiles a comprehensive set of data about operation and maintenance of the feedwater plant and associated mechanical components.

Feedwater plant reheaters can suffer from various forms of degradation: flow accelerated corrosion, erosion, vibration fatigue, wear, Damages have been observed on tubes, on tube support plates, on internal structures and to the body itself. On the EdF fleet, most of the original reheaters equipped with brass or carbon steel tubes have been eliminated and replaced with austenitic stainless steel for the tubes and with chromium and molybdenum alloyed steel for the shells and for the tube support plates. These choices limit the release of deleterious species towards the steam generators.

The moisture separator reheaters not equipped with stainless steel tubes, experienced leaks and tubes ruptures, caused by either fatigue, or erosion and/or erosion-corrosion. As a consequence, they had to be replaced. However, despite all remedial actions taken against corrosion erosion initiation, this damage is nevertheless still active.

Rotating equipment's like pumps, exhibit more degradation modes than static components due to the presence of moving parts in pumps; for extraction pumps, the list of damages is long: cast iron erosion under the action of the running water, cracking due to the over torquing of the cast iron flanges, water guides cracking, at the outlet of the discharge bulbs, cracking of the external ribs of the bulbs, wear of the shaft bearings at the location of the guiding bushings, bearings' wear, erosion of the suction impellers due to cavitation, damage by impact of foreign objects travelling through the pump, bearings and thrust bearings wear, loss of lubrication. Aa a consequence, extraction pumps deserve a heavy program of inspections and maintenance.

Regarding turbine driven pumps, either main or auxiliary, the main issues encountered in the field are: erosion triggered by cavitation of the flow nozzles and less frequently, of the impellers, metal tearing on the shaft or on the turbine-pump coupling, erosion of the blades of the turbine final rows and blades damaged by foreign objects, rotor seizures, locking of the carbon rings, blistering of the chromium coating of the shaft… Regarding the shaft, poor support of the rotor by the bush bearings along with a decrease of the thrust bearing clearance, have been observed. Like for extraction pumps, these pumps have extended programs of inspection and maintenance.

Various corrosion modes can develop in pipes: boric acid corrosion, differential aeration/Evans effect corrosion, chemical corrosion by pollutants, MIC corrosion, cavitation erosion, etc. but the worse mode is flow accelerated corrosion because this degradation mechanism can kill people as it happened in Surry and Mihama. Pipes can also suffer from fatigue, either vibration fatigue or thermal fatigue, most often due to poor design.

As concerns supports, they have their own specific issues. For example, pipes vibrations can induce unscrewing of bolted connections, unbedding of expansion anchors, and fatigue cracking of welds. An abnormal displacement of a pipe can apply high loads on a support and break some of its parts. Same failure can occur following a dynamic overload generated by a water hammer event. Last, a support can deteriorate because of harsh environmental conditions (such as corrosion) and its moving parts can wear.

For valves, given the large variety of designs, it is no surprise that they can suffer from an extended list of various damage mechanisms. For example, the pressure boundary of a valve can suffer from several failure mechanisms such as various forms of corrosion (general corrosion, galvanic corrosion, pitting, stress corrosion cracking, erosion-corrosion), thermal fatigue and erosion generally from cavitation. Regarding internal parts, they can suffer from the same damage mechanisms as the body (all kinds of corrosion, erosion, fatigue) but also from wear and caulking which can induce seizing following the normal displacement of parts or because of a chatter phenomenon. Also, some springs material can suffer from hydrogen assisted stress corrosion cracking. Therefore, it is no surprise that valves' maintenance represents a significant ratio of all maintenance works at the plant, however, fortunately decreasing over time.

7 Industry perspective

This document reports the degradation modes that have been identified during several decades of PWRs feedwater plant and mechanical components' operation. Therefore, it is a help to identify any degradation mechanism that could be discovered on the components reviewed in this report.

For each degradation mechanism, tools are provided for remedial actions, including how to inspect, how to maintain, along with how to repair or replace, to solve the issue of concern.

Therefore, this document should be part of the tools box of any system engineer in charge of balance of plant operation, inspection, maintenance and repair.

This report is the second of a list of a new ANT line of 12 reports about PWRs operation and maintenance:

- Condenser (released LCC17);
- Feedwater plant and other secondary components – Mechanical components (released at LCC18);
- Raw water system and cooling towers (release planned at LCC19).

Planned, with no specific release order:

- Reactor cooling system piping and associated systems;
- Reactor cooling pumps;
- Pressure vessel (including penetrations);
- Steam generators (including blowdown and feedwater);
- Pressurizer (including heaters, valves, surge line, nozzles);
- Pressure vessel internals;
- Control rod drive mechanisms;
- Turbine;
- Main generator.

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Appendix A : Feedwater plant reheaters field experience and publications

Example #1: Low pressure reheater [Mousset, 1990].

Plant main characteristics: Framatome, PWR, 3-loop, 900 MWe.

Steam characteristics: 270°C, 55 bars.

Relevant component: Low-pressure reheater.

Specimen data: Carbon steel tubes, from A42 AFNOR designation. Support plates made of mild steel.

Service conditions: Inlet steam temperature: 184°C. Water inside the tubes: inlet: 134°C, outlet: 180°C.

Operation time: 27,000 hours.

Failure discovery: Severe damage was observed on both the tubes and the support plates during an inspection after the reheater wrapper has been removed.

Results: The tubes are covered with a dark-grey deposit, with a crystal-like aspect, containing magnetite (Fe_3O_4). Smooth and bright areas are visible here and there, sometimes extending on several dozens of centimetres which correspond to surfaces that have been damaged by erosion-corrosion (Figure A-1). This damage, when very severe, can be through-wall. The support plates located upstream side on the steam circuit, present many joined small cavities which look like a shot-peened surface (Figure A-2 and Figure A-3). These damages are also from corrosion-erosion.

Remedial actions: A morpholine conditioning instead of an ammonia conditioning would probably have postponed the degradations, however, carbon steel tubes in contact with a water-steam mixture at high temperature are doomed to fail by corrosion in the long term. Carbon steel tubes should be replaced with austenitic stainless-steel tubes like AISI 304L (AFNOR Z2 CN 18-10).

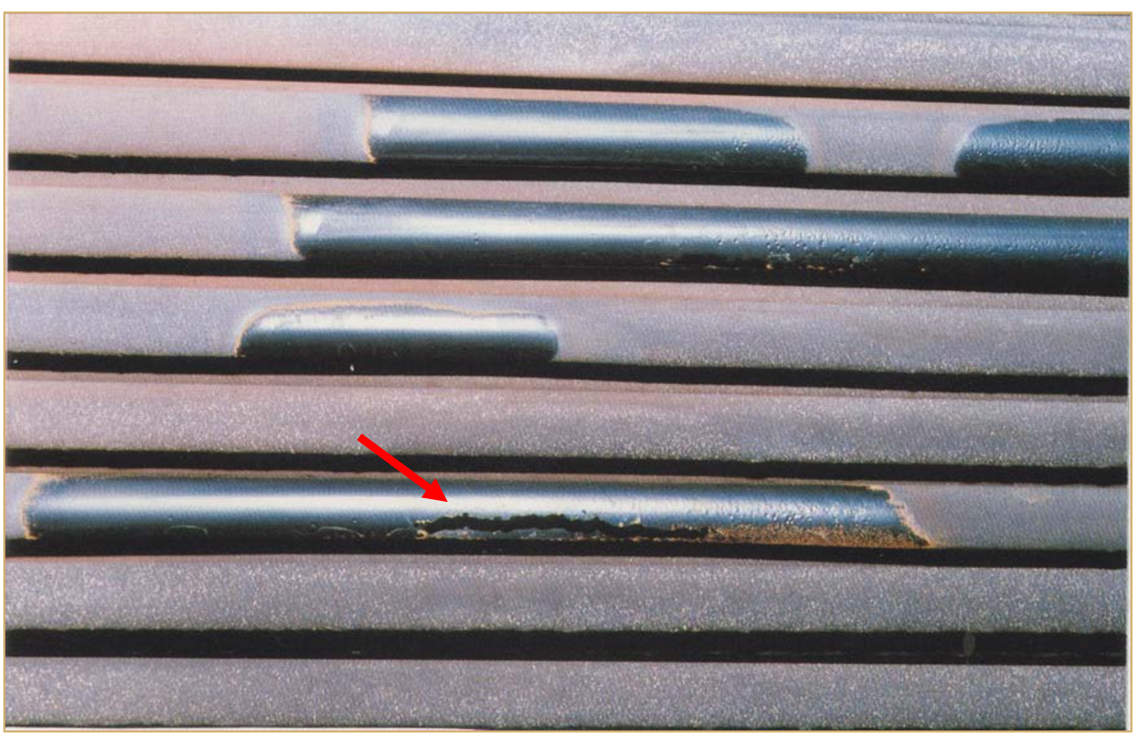

Figure A-1: The tube bundle exhibits here and there, smooth and oxide-free surfaces, made thinner by corrosion-erosion up to through-wall (red arrow) at some places [Mousset, 1990].

Figure A-2: View of damage to tube support plates and to tubes in the vicinity [Mousset, 1990].

Figure A-3: The shot-peened aspect of the surface of the tube support plates results from corrosion-erosion [Mousset, 1990].

Example #2: Flow-assisted corrosion of high-pressure feedwater heat exchangers low carbon steel tubes [Coste and Rousvoal, 2018].

Plants main characteristics: Framatome, PWR, 3-loop (900 MWe) and 4-loop (1300 MWe).

Relevant components: High pressure heat exchangers fleet and tube material.

EdF NPPs are sorted into 3 series:

- CP0/CP1 series (24 units): two trains with one R5 and one R6 high pressure feed water heat exchangers each (R5 and R6 are set vertically);
- CP2 and PALUEL series (14 units): two trains with one R5 and four trains with one RCS each. R5 and RCS are set horizontally. RCS heat exchangers cool the MSRs' condensates;
- 1300/N4 series (20 units): two trains with one R5 and one R6 each. R5 and R6 are set horizontally.

EdF fleet is then composed of 216 high pressure feed water heat exchangers.

Tubes are made of low carbon steel (ASTM A106 grade B) except the latest four 1300 family units and the four N4 family units, which tubes are made of ferritic stainless steel (AISI 444). So, in total only 32 high pressure feed water heat exchangers (out of a total of 216) are not sensitive to flow assisted corrosion.

The tubes were manufactured before year 2000 and they are seamless tubes. All tubes have a nominal thickness of 2 mm.

The new heat exchangers tubes are made of ferritic stainless steel (AISI444). Those tubes were manufactured after 2000 (year when the manufacturing process changed to rolled and weld tubes).

Surveillance of heat exchangers tubes: The condition of high-pressure feed water heat exchanger tubes is regularly monitored during operation cycles and outages:

- Efficiency monitoring: the heat transfer coefficient may decrease due to the presence of iron oxides (magnetite). In this case, tubes have to be cleaned mechanically (for example using high pressure water jet);
- Drain flow rate monitoring: the drain flow rate (measured on the shell outlet) increases in case of tube leak. When reaching a threshold between 5 to 10 kg/s according to the feed water heat exchanger type, the high-pressure train concerned by the leak is isolated, the leak identified and the leaking tube is plugged;
- A leakage test using helium is regularly performed during outages to check the integrity of the bundle;
- Remote field eddy current testing: an inspection strategy of the remaining tube thickness has been set since 2008. A first inspection on 20% of the heat exchanger tubes has to be performed. Depending on the bundle condition, a second inspection is planned within 5 years with a sampling rate up to 100% of the tubes;
- A hydraulic pressure test, specific to the French regulation on pressure equipment, has to be done every 10 to 12 years during outage.

The loss of power production from the moment a leak is detected to the moment when the leaking tube is plugged is between 0 to 4 production days, due to the constrain of slightly reducing the reactor power to isolate the heat exchanger train.

Moreover, when a leak is detected, it is necessary to plug the leaking tube as quick as possible (say less than one week) in order to avoid collateral damage on adjacent tubes by the steam jet from the leak.

Appendix B : Moisture separators reheaters field experience and publications

Example #1: MSR tubes failures [Mousset, 1990].

Plant main characteristics: Framatome PWR, 900 MWe, 3-loop.

Equipment/Component: Moisture Separator Reheaters.

The tubes are made of carbon steel (A 37) finned tubes. The tubes OD is 17.5 mm and their wall thickness is 5 mm.

Inside the MSRs, plates and barriers drive the steam through chicanes. Protections have been installed to prevent FAC of the walls.

Operating conditions: Of the steam to be reheated: inlet steam: 186°C, outlet steam: 252°C. Heating steam: 267/270°C, 52/55 bars.

Time of operation: 40,000 hours.

Failure discovery: Through wall holes and OD damages at tubes' end observed during maintenance of the equipment.

Specimen/sample: Finned tubes (Figure B-1).

Results: The end of the periphery lower tubes is covered with iron oxide deposits: Fe_3O_4 and αFe_2O_3; some are eroded, some are leaking (Figure B-1).

A leak at the 7th tube spacer plate induced major erosion damage. The destructive examination reveals these incidents are the result of OD corrosion-erosion.

The tubes' end damages are due to a lack of tightness of the last tube spacer plate, inducing some wet steam jet.

Conclusion and remedial action: In order to avoid the wet steam by-pass, the vendor has installed, between the last two tube spacer plates, an overlapping gasket and a drilled plate inducing an extra pressure drop limiting the steam jet velocity directed towards the bundle end.

Figure B-1: Top left: iron oxides deposits covering the tubes' end. Bottom left: end of the lower tubes at the periphery showing through wall erosion. Top right: area damaged by local corrosion-erosion, then by erosion close to a tube spacer plate. Bottom: axial cut of a zone damaged by corrosion-erosion [Mousset, 1990].

Example #2: MSR support plate failure [Mousset, 1990].

Plant main characteristics: Framatome PWR, 900 MWe, 3-loop.

Equipment/Component: Moisture Separator Reheaters.

The tubes of the first 3-loop PWR MSRs are made of carbon steel (A 37) finned tubes. The tubes OD is 17.5 mm and their wall thickness is 5 mm.

Inside the MSRs, plates and barriers drive the steam through chicanes. Protections have been installed to prevent FAC of the walls.

Operating conditions: Of the steam to be reheated: inlet steam: 186°C, outlet steam: 252°C. Heating steam: 267/270°C, 52/55 bars.

Time of operation: 40,000 hours.

Failure discovery: When repairing the tube bundle, the workers discovered cracks on the last tube spacer plate (Figure B-2).

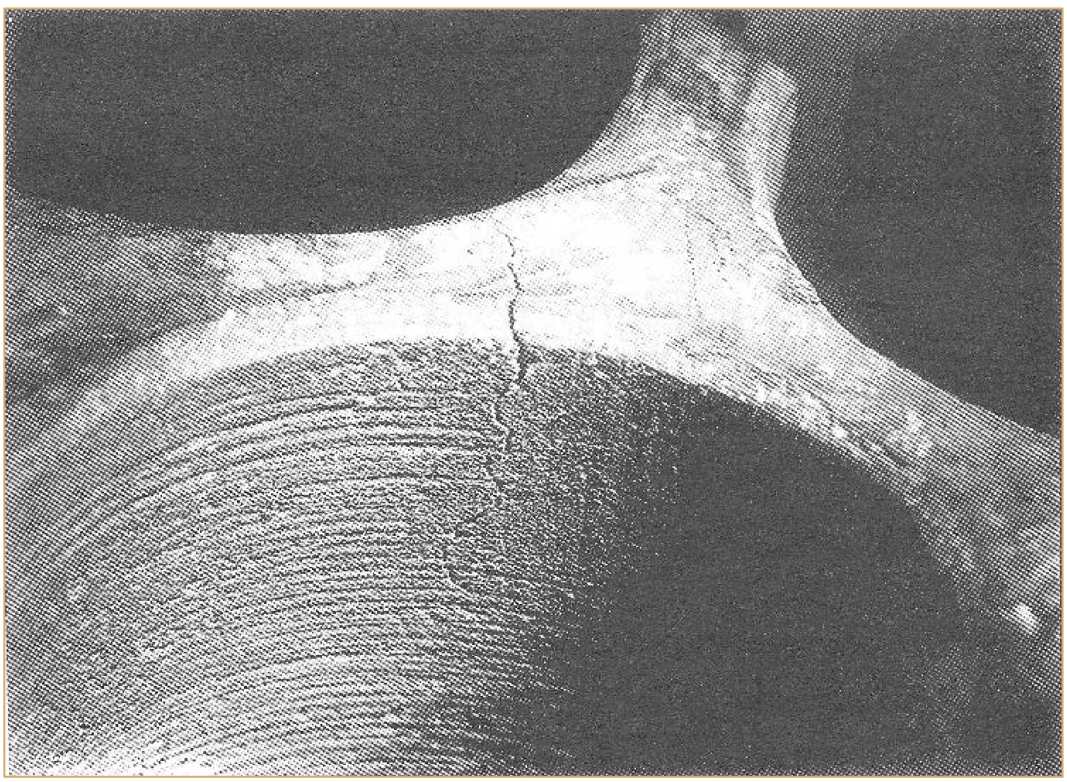

Figure B-2: View of tube spacer plate cracking [Mousset, 1990].

Specimen/sample: Last tube spacer plate made of carbon steel (A 42).

Results: Some cracks propagate through the entire ligament thickness. Some are visible at both, steam to be reheated side and U-bends side (Figure B-3). Micrography of cracked zones, steam to be reheated and U-bends sides shows similar results. These last are wide opened, branched and trans granular (Figure B-3 bottom).

SEM examination reveals the presence of a coarse and oxidized striation typical of fatigue cracking.

Appendix C : Extraction pumps field experience and publications

Example #1: Motor of an extraction pump [Mousset, 1990].

Plant type: Framatome, PWR, 3-loop, 900 MWe.

Steam characteristics: 270°C, 55 bars.

Relevant component: Extraction pump motor.

Specimen data: Ball bearing made of carbon steel (AFNOR 100 C 6), installed in the upper bearing of the pump's motor.

Service conditions: In normal operation, 2 pumps are running and one spare is idle.

Operation time: 3,500 to 5,200 hours.

Failure discovery: Ball bearings damages have been observed following a temperature increase of the upper bearings.

Results: The bearing tracks exhibit periodic figures (Figure C-1), with more or less significant grooves shape (Figure C-2). The balls exhibit melting traces.

The SEM examination of the surface reveals in the grooved area, the presence of craters resulting from micro-fusion as the consequence of current flow (Figure C-3). On a cross section perpendicular to the surface, structure modifications are visible over a depth of 10 to 15 microns, they correspond to the layer modified by the local fusion.

This type of damage due to electric current flow is likely the result, when the motor is running, of the generation of induction currents into the stator, the bearings and the shaft. Because of vibrations, very short disconnections of the current flow occur between the tracks and the balls, creating electric arcs. The grooves can appear because the vibration cycles are synchronized and as a consequence, make the electric arcs occur in the same periodic locations.

Remedial action: The remedial action consists in breaking the current flow by inserting an isolating ring into the bearings.

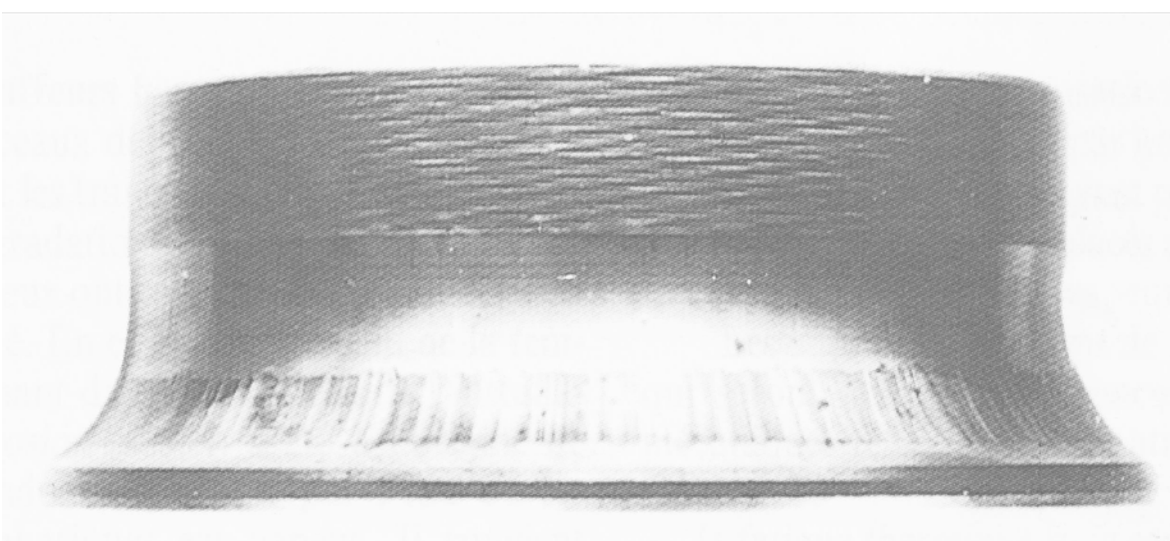

Figure C-1: View of the grooves on the lower track of a bearing [Mousset, 1990].

Appendix D : Turbine driven feedwater and auxiliary feedwater pumps field experience and publications

Example #1: Feedwater pump sleeves stress corrosion cracking [Mousset, 1990].

Plant main characteristics: Framatome PWR, 1300 MWe, 4-loop, France.

Equipment/Component: Feedwater pump.

Operating conditions: 180°C, 14 bars, 1330 rpm.

Time of operation: 150 hours.

Failure discovery: Following major leaks, the pump was dismantled allowing the discovery of the sleeves cracking.

Specimen/sample characteristics: Protective sleeves below thermal barrier, made of Z 30 C13 steel, with a thermal treatment targeting HB = 350/400.

Results: The sleeve, free side of the pump (opposite side to the control), exhibits a through wall axial crack, around 200 mm (7.87'') long at the sleeve OD. This crack is slightly longer at the ID (203 mm) (7.99'') (Figure D-1). The crack initiated at the ID bevel location, in the shrunk zone in contact with the pump shaft shoulder. In this area, the crack, once broken open, exhibits a lunula with a fine grain, around a corrosion pit (Figure D-2). The remaining crack surface presents a coarser aspect, with lines-like marks calling for a quick propagation. Other corrosion pits are visible on the bevel, where the crack initiated (Figure D-3). SEM examination of the initiation area reveals an intergranular surface, consistent with a stress corrosion cracking phenomenon. Beyond, a semi-brittle shearing with a mix of inter and trans granular surface is visible. The mechanical properties of the sleeve material, are very high (UTS = 1400 MPa/203 KSI). A microprobe analysis carried out into an intergranular cracks network located at the bottom of a pit reveals the presence of sulphur, chlorine and calcium (Figure D-4).

Figure D-1: View of the sleeve ID cracking [Mousset, 1990].

Figure D-2: Detail of the initiation zone where a dark lunula has been observed. Beyond, a first propagation zone is visible [Mousset, 1990]

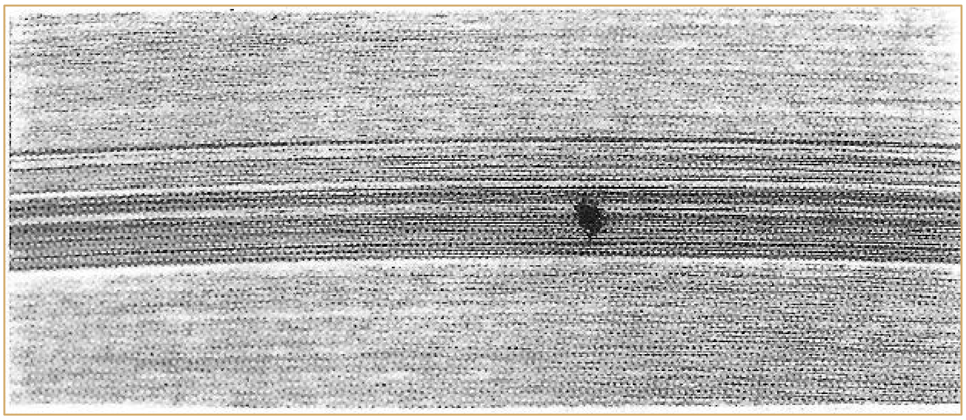

Figure D-3: View of the ID bevel where cracking initiated. Some coarse machining marks along with corrosion pits are visible [Mousset, 1990].

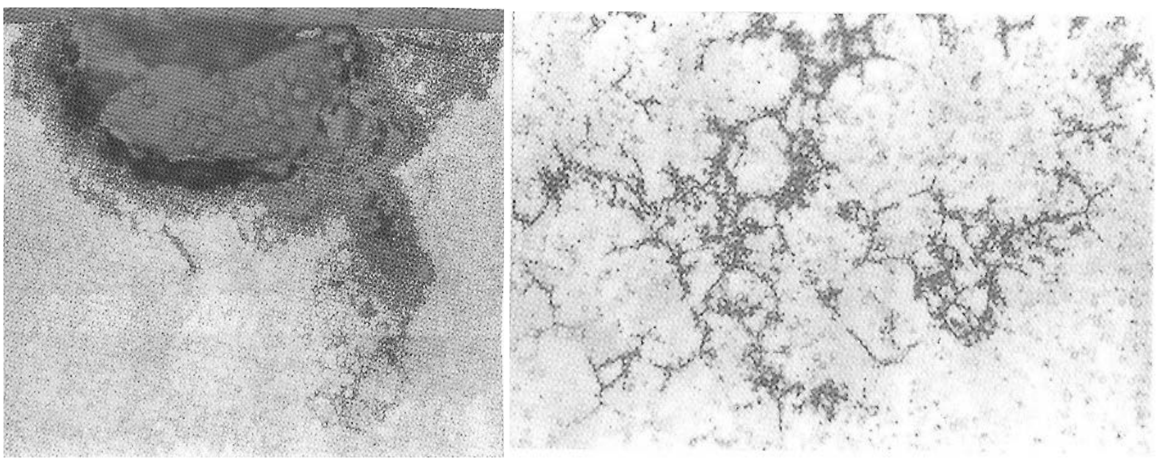

Figure D-4: Left: section micrograph of one pit. An intergranular crack network has initiated at the bottom. Right: crack network detail [Mousset, 1990].

Conclusion and remedial actions: The sleeve cracked from SCC because of its very high mechanical properties. Using a material with such high mechanical properties in contact with water is inappropriate.

Lowering the mechanical properties of the Z 30 C 13 steel would improve its resistance to SCC.

Example #2: Steam inlet valve of turbine driven auxiliary feedwater pump [Lai et al, 1990].

Plant type: PWR, 951 MWe, Taiwan.

Relevant component: Steam inlet valve of turbine driven auxiliary feedwater pump. The (Figure D-5) shows the schematics of the feedwater system.

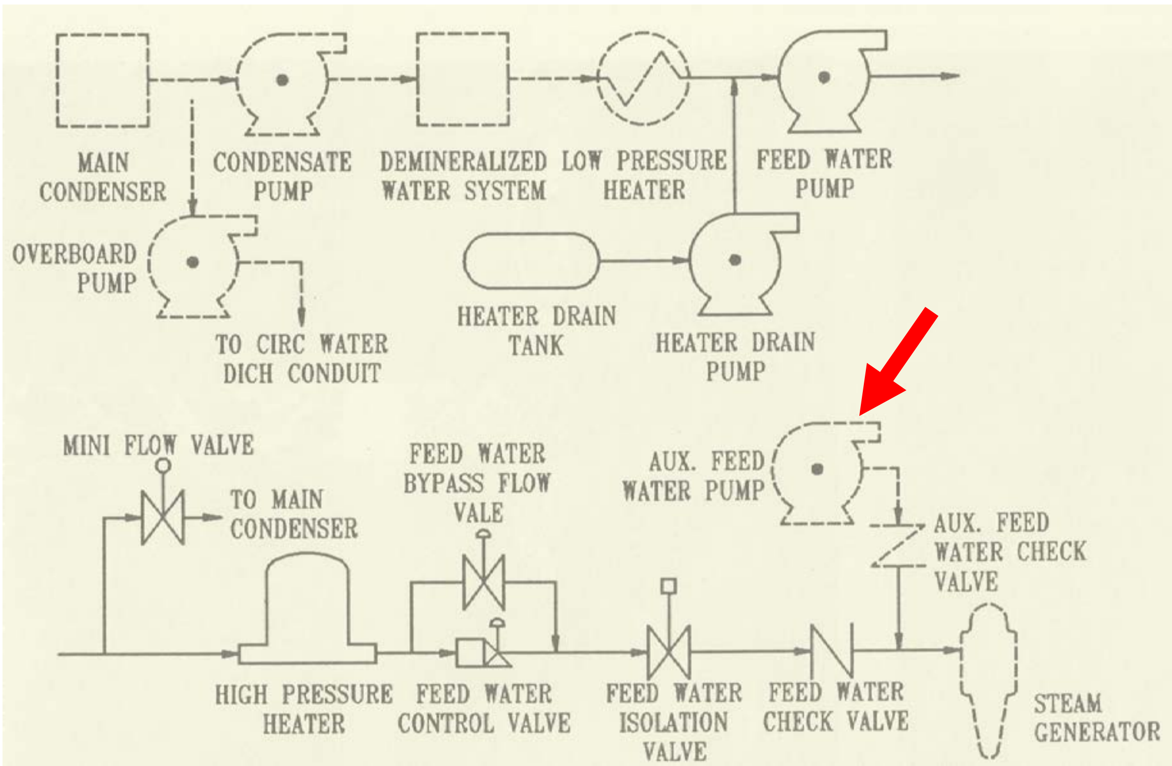

Figure D-5: Sketch of the feedwater system [Lai et al, 1990].

Specimen data: Spring of a valve of an auxiliary feedwater pump made of AISI 5160 steel (AFNOR 55Cr3). Carbon: 0.560% – 0.640%, Chromium: 0.7% – 0.9%, Manganese: 0.750% – 1%.

Operation time: About 3 years.

Failure discovery: This spring failure is part of a list of some feedwater systems components which have failed at this plant.

Results: The (Figure D-6) shows the failure appearance and the intergranular crack surface of a spring in cylinder assembly of the steam inlet valve after 3years of operation.

A non-homogeneous microstructure was observed by metallography, which showed the retained austenite in a martensitic matrix and the precipitated acicular ferrite along the prior austenite grain boundary. The average grain size was from 0.5 to 1 mm. The results of Charpy V-notch impact test revealed a very poor toughness (0.8 kg.m), and the fracture mode is intergranular.

Higher magnification of the fracture grain boundary showed a chromium carbide film covered along the grain boundary surface. The observation above suggested that there had been over-heating encountered during the material treatment process. Inclusions and high degree of roughness were also found on the spring surface. When a drastic load was imposed on the spring, cracks could initiate from the sites of surface imperfections and propagate intergranularly. A material qualification procedure is recommended when, material replacement is taken as a fix.

Appendix E : Pipes and supports field experience and publications

Example #1: RHR pipe cracked [Mousset, 1990].

Plant type: Framatome PWR, 900 MWe, 3-loop, France.

Steam characteristics: 270°C, 55 bars.

Relevant component: RHR.

Specimen data: Austenitic stainless-steel pipe made of AFNOR Z6 CN 18-09 (AISI 304). Wall thickness: 10 mm.

Service conditions: Borated water, maximum temperature: 180°C, pressure: 31 bars.

Operation time: 25,000 hours.

Failure discovery: In operation, a crack was observed on the pipe OD (Figure E-1).

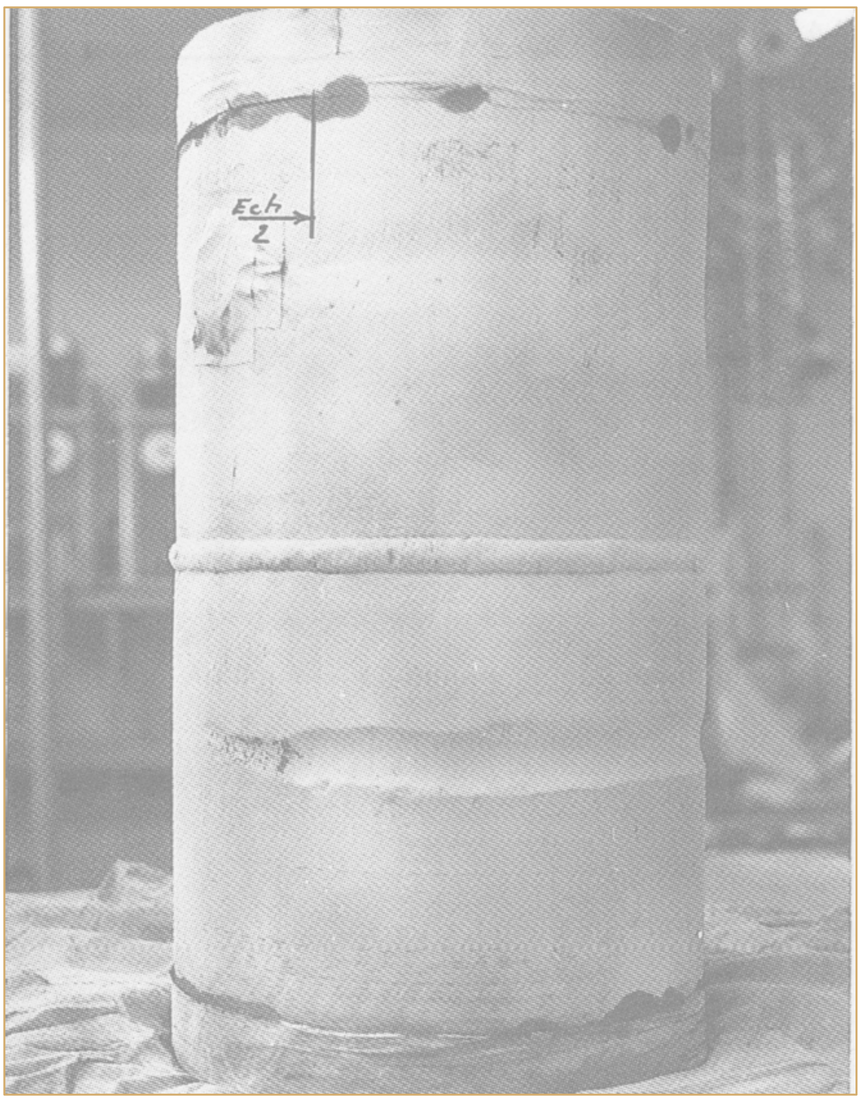

Figure E-1: Cracked pipe segment exhibiting a transverse ground area [Mousset, 1990].

Results: A network of SCC cracks has been observed at the OD of the RHR pipe (Figure E-2). This cracking takes place in a circumferential band, at the location of the tape used as datum during installation. The cracks are very branched and trans granular (Figure E-3 and Figure E-4).

Micro-analysis reveals the cracks oxides contain a high chlorine ratio. Some cracks are half through-wall. The chlorine polluted oxides found into the cracks likely stem from the thermal decomposition of PVC bands. The condensation of the room humidity allowed the generation of an electrolyte. The internal stresses result, depending on the location, of the forming or welding processes, and on the installation of the pipe.

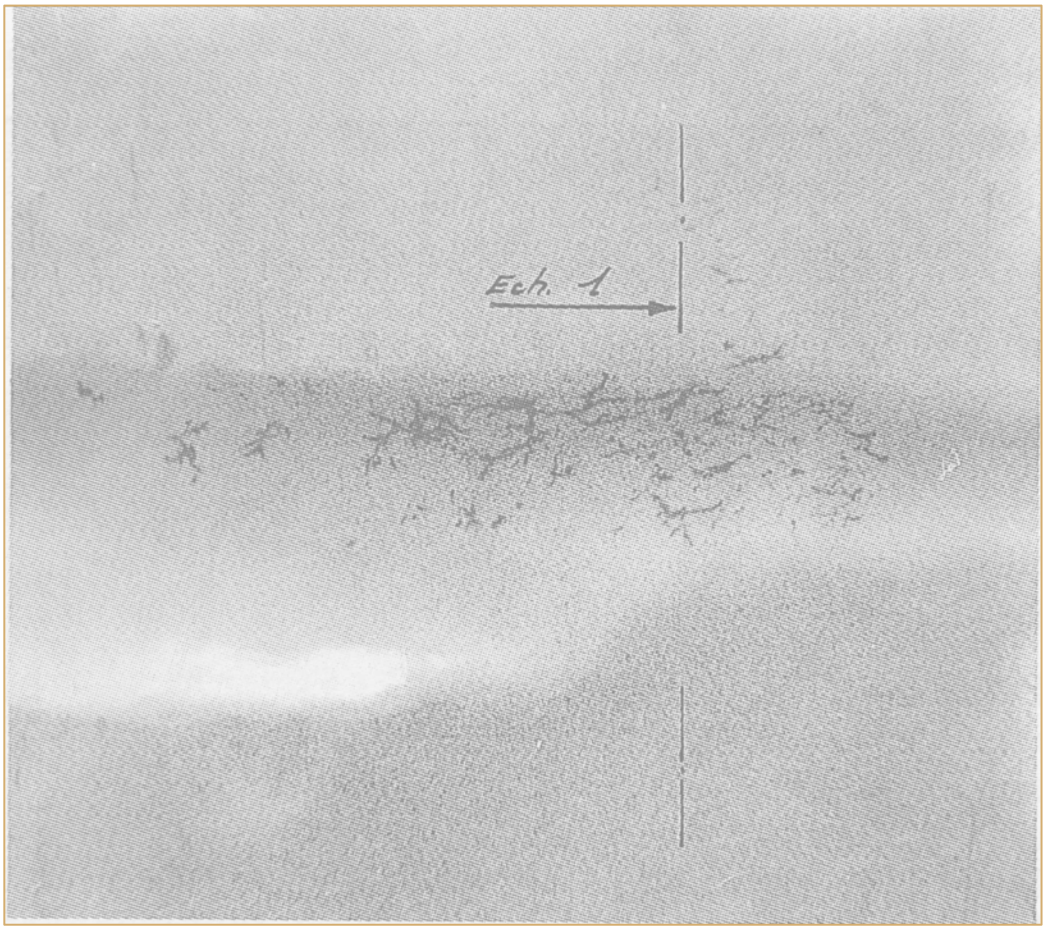

Figure E-2: Crack network observed after PT at the tip of the ground area [Mousset, 1990].

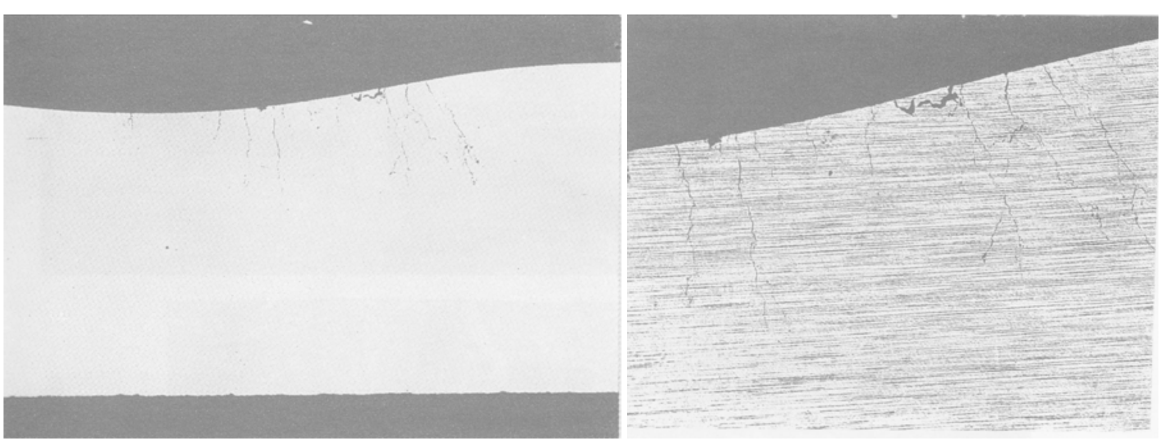

Figure E-3: Left: cross section showing the cracks ‘propagation in the bottom of the ground area (x5.9). Right: view at higher magnification (x12.2) [Mousset, 1990].

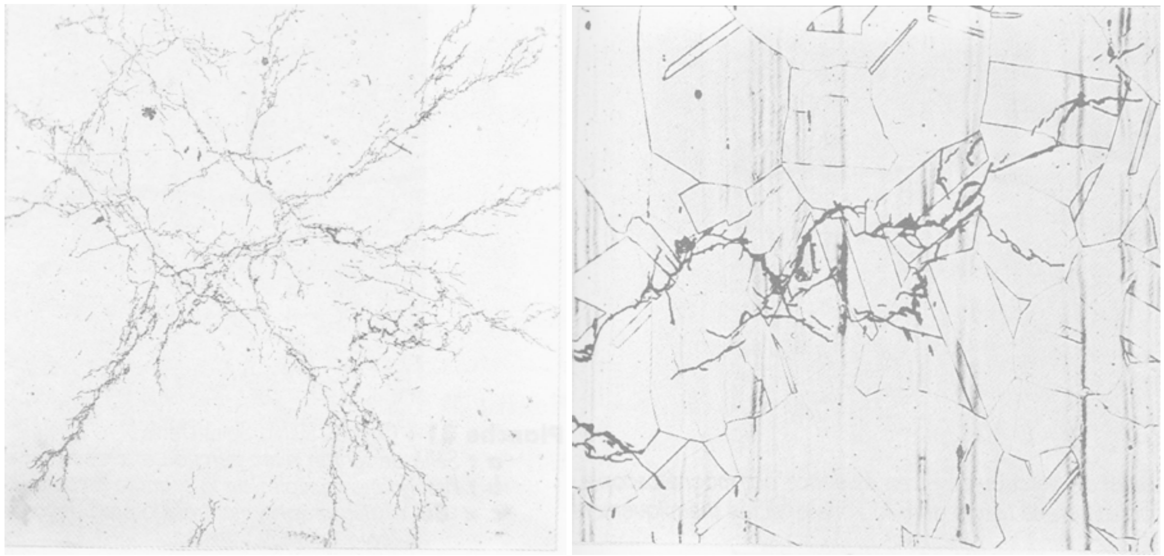

Figure E-4: Left: replica taken in a cracked area showing a dense network of all-directions cracks (x52). Right: after chemical etch, the cracks appear as branched and trans granular (x230) [Mousset, 1990].

Conclusion, remedial actions: The products containing chorine or sulphur should be strictly forbidden when in contact with austenitic stainless-stell.

In the present case, NDE (visual examination, penetrant test, surface state replicas) have been implemented in order to evidence the areas exhibiting stress corrosion cracking.

Appendix F : Valves field experience and publications

Example #1: Examination of a feedwater bypass flow valve [Lai et al, 1990].

Plant type: PWR, 951 MWe, Taiwan.

Relevant component: Feedwater bypass flow valve. The (Figure F-1) shows the schematics of the feedwater system.

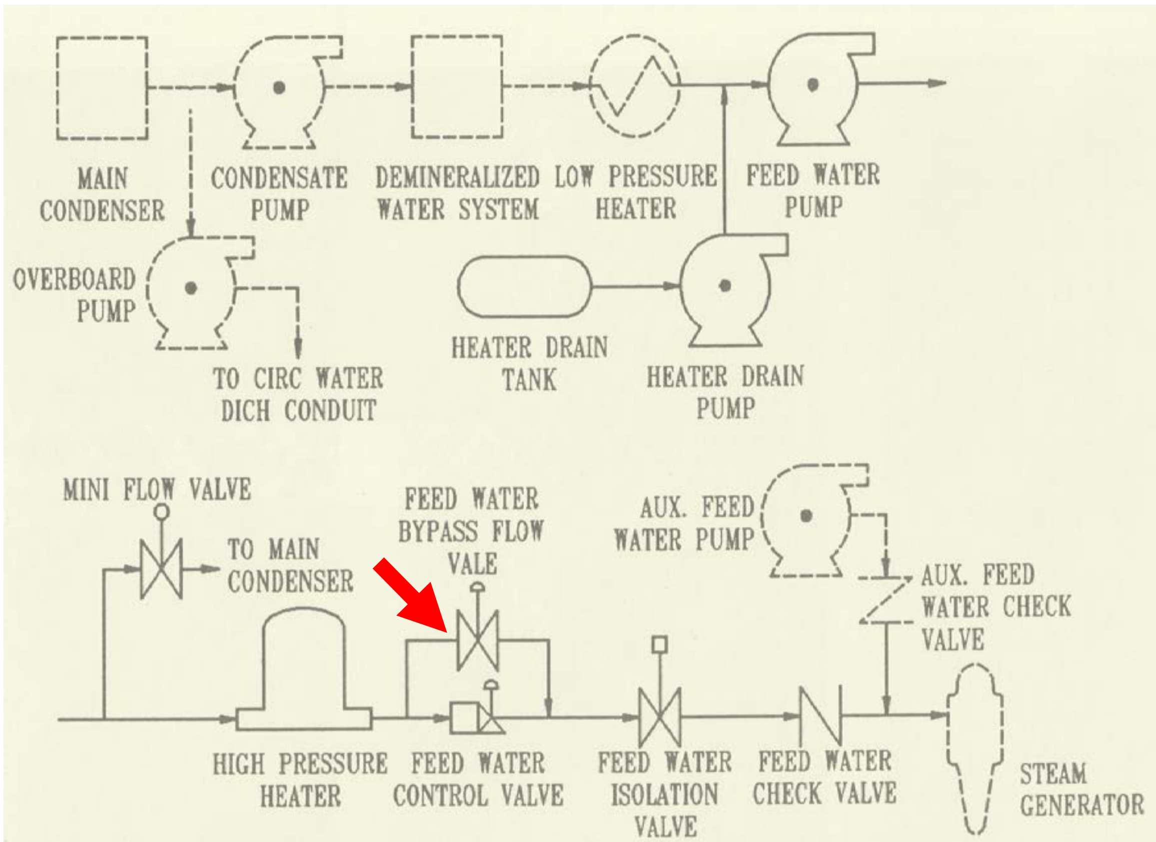

Figure F-1: Sketch of the feedwater system [Lai et al, 1990].

Specimen data: Plug, made of AISI 316 austenitic stainless-steel, of the feedwater bypass flow valve.

Operation time: About 1 year.

Failure discovery: Erosion-corrosion and water impingement phenomena were found on the plug surface of the feedwater bypass flow valve. The valve manufacturer recommended a stellite clad on the plug surface. After being cladded with stellite, the plug was used for one year and a lot of cracks were observed on the seal ring surface as shown on (Figure F-2).

Results: After the examination of a cross section of the plug, some stellite free area was found on the lower root in the seal ring area. (Figure F-2) also shows the cracks initiated at the stellite free surface, and propagated in TGSCC mode. The residual stresses, measured by the hole drilling method, on the surface of the seal ring, were superior to 700 MPa, which is well above the yield stress of AISI 316.

An EDS analysis revealed the presence of a chlorides pollution of the fracture surface. The corrosion potential of the stellite is 200 mV more noble than the one of 316L (active state) in 0.5 µS/cm demineralized water at room temperature.

Conclusion, remedial actions: The combination of high residual stresses, along with a chlorides contaminated environment (in the seal ring area), and the galvanic effect, is believed to be the root cause of TGSCC.

The careful inspection of the plug dimensions, of the cladding process and of the final machining during the manufacture process is proposed as remedial actions.

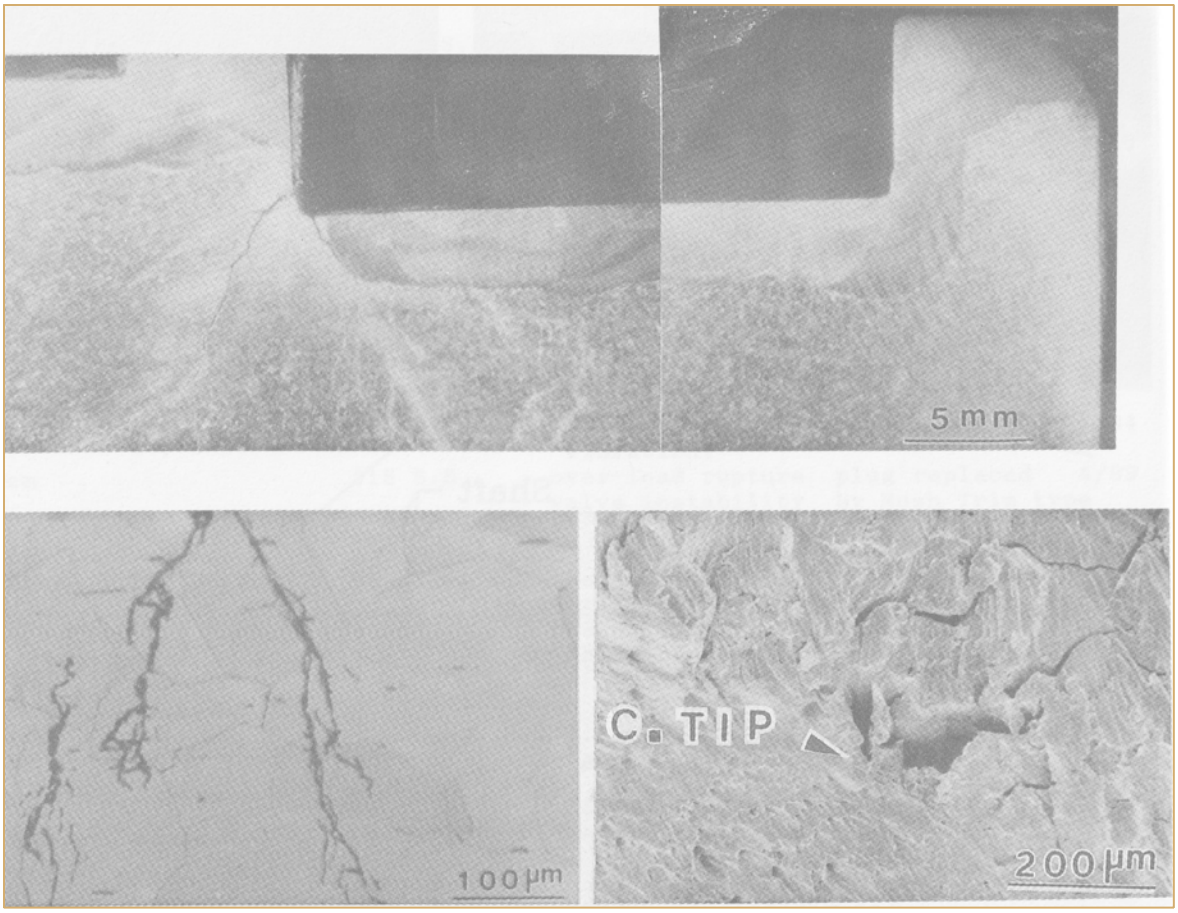

Figure F-2: TGSCC cracks initiated at the stellite free surface of the feedwater bypass flow valve plug [Lai et al, 1990].

Example #2: Examination of a feedwater mini flow valve [Lai et al, 1990].

Plant type: PWR, 951 MWe, Taiwan.

Relevant component: Mini flow valve of the feedwater plant. The (Figure F-3) shows the schematics of the feedwater system.

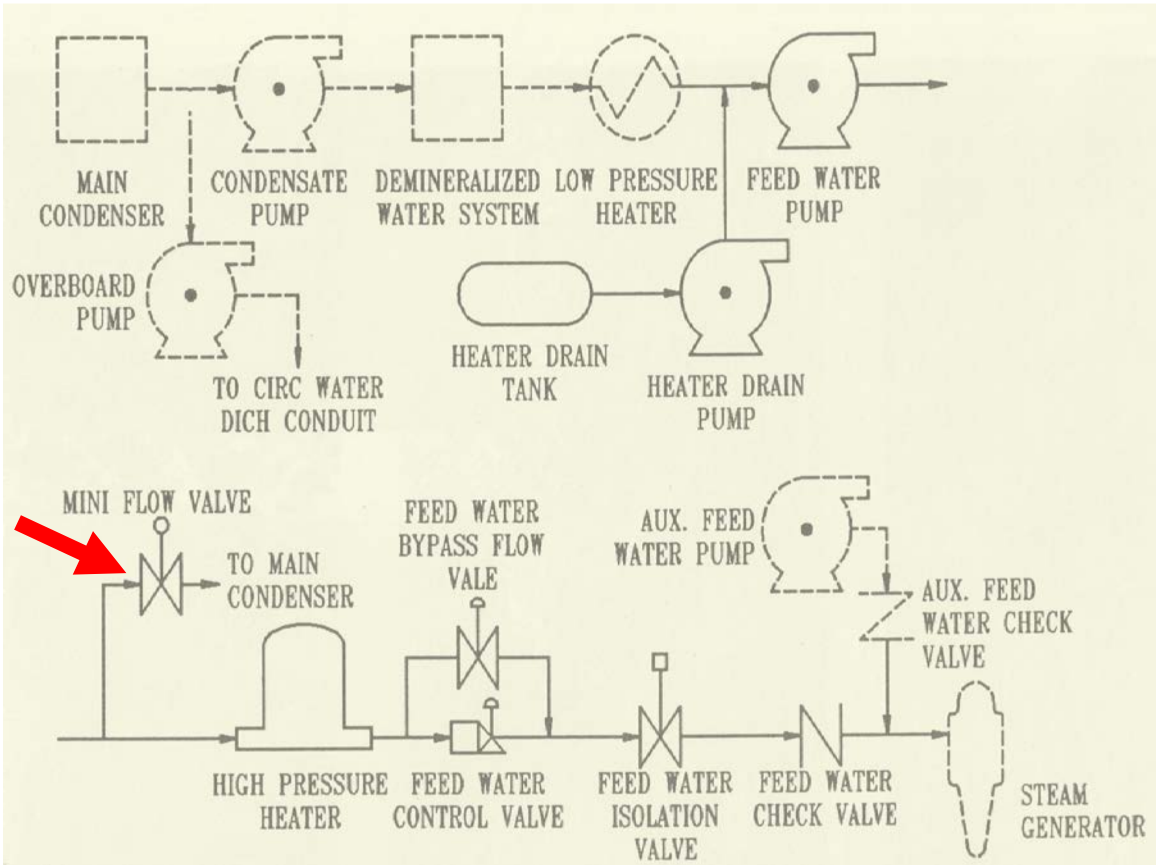

Figure F-3: Sketch of the feedwater system [Lai et al, 1990].

Specimen data: Casing bolts of the feedwater mini flow valve. These bolts are made of low chromium steel (0.15%).

Operation time: About 4 years.

Failure discovery: A few casing bolts of the feedwater mini flow valve were found broken. A low Cr content steel was used instead of the original specification which was Cr-Mo steel (ASTM A193 Gr.B).

Results: As shown in (Figure F-4), the fracture surface exhibits features typical of a fatigue failure. Non-homogeneous microstructure, such as decarburization of the surface layer, un-completely transformed martensite, ferrite, pearlite and bainite mixed structure, was found on the metallography of the broken bolts, as shown in (Figure F-5). The non-homogeneous microstructure may come from a normalizing heat treatment or hot forging and air-cooling treatment. Compared with the quenched and tempered martensitic Cr-Mo steel (ASTM A193 Gr.B), the mechanical properties and fatigue endurance of the low Cr steel were correct.

Conclusion, remedial action: The replacement of the original bolts with ASTM A193 Gr.B material and a qualification practice have been suggested a remedial actions.

Appendix G : Pumps field experience and publications

Example #1: Examination of a heated drain pump [Lai et al, 1990].

Plant type: PWR, 951 MWe, Taiwan.

Relevant component: Heater drain pump shaft made of AISI 410 stainless-steel. The (Figure G-1) shows the schematics of the feedwater system.

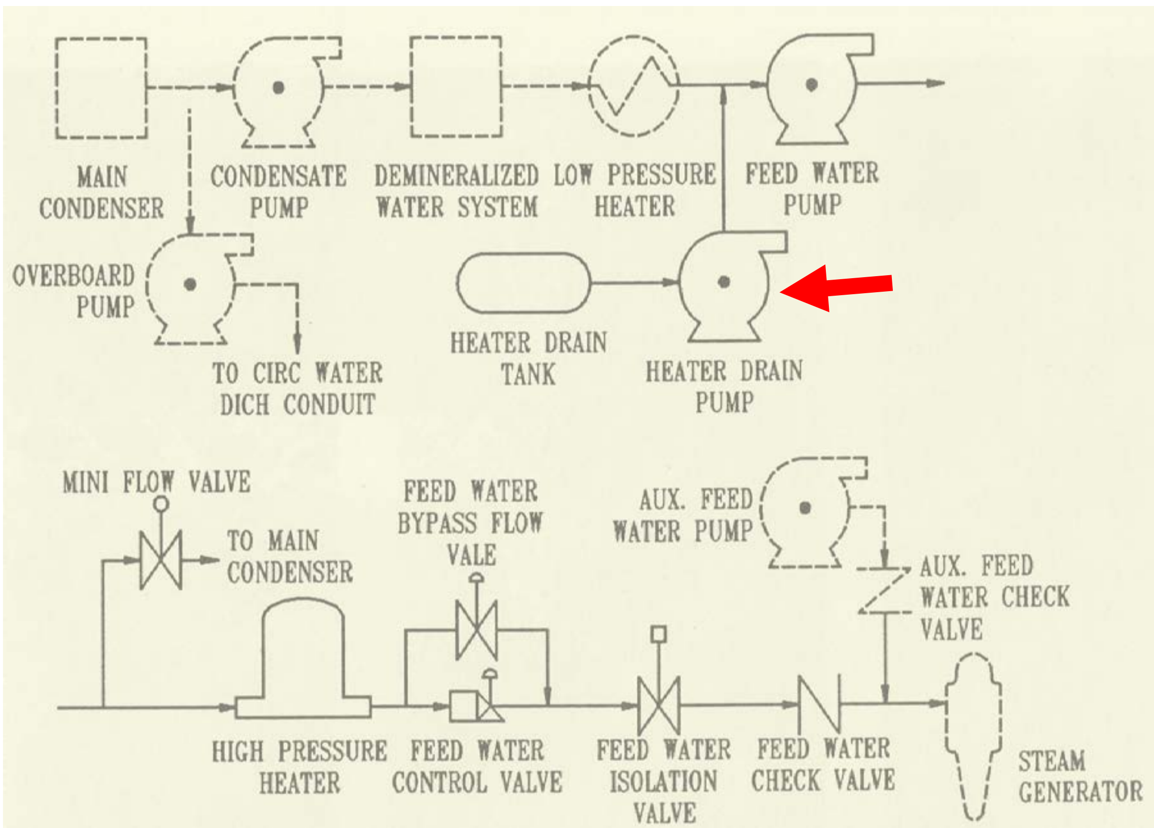

Figure G-1: Sketch of the feedwater system [Lai et al, 1990].

Specimen data: The heater drain pump type used in the units is a 8-stage vertical water pump, about 10 meters high and the vertical motor power is 1,250 horse power, its rotating speed being 1,780 rpm. The pumps flow rate is 3,914 gallon per minute (890 m^3/h). The water temperature is 196.6°C. The water pressure is 1.34 MPa in the suction line and 4.55 MPa in the discharge line in normal operation conditions.

Heater drain pumps are designed to start when the reactor power reaches 50%. When the reactor scrams, the condensate water will automatically be directed towards the heater drain pumps to compensate for the water drain reduction.

Failure discovery: There have been two heater drain pump shafts ruptures at the plant.

Results and remedial actions: Serious wear scratches and failure were found on the bearings, sleeves, impellers, wear rings, coupling bolts and supporting plate. The broken shaft is shown on (Figure G-2), which also shows the schematics of the shaft necking during abnormal wearing and the hypothetical failure process. The microstructure of the shaft observed on a cross section of the necking area reveals the shaft had experienced overheat conditions, since it exhibits a high temperature annealed martensitic microstructure in addition to the normal quench and tempered microstructure.

The root cause of one shaft failure was due to a lack of lubrication caused by the rupture of the lube pipe (schedule 80 carbon steel), and the other shaft rupture was due to long operation at low flow rate.

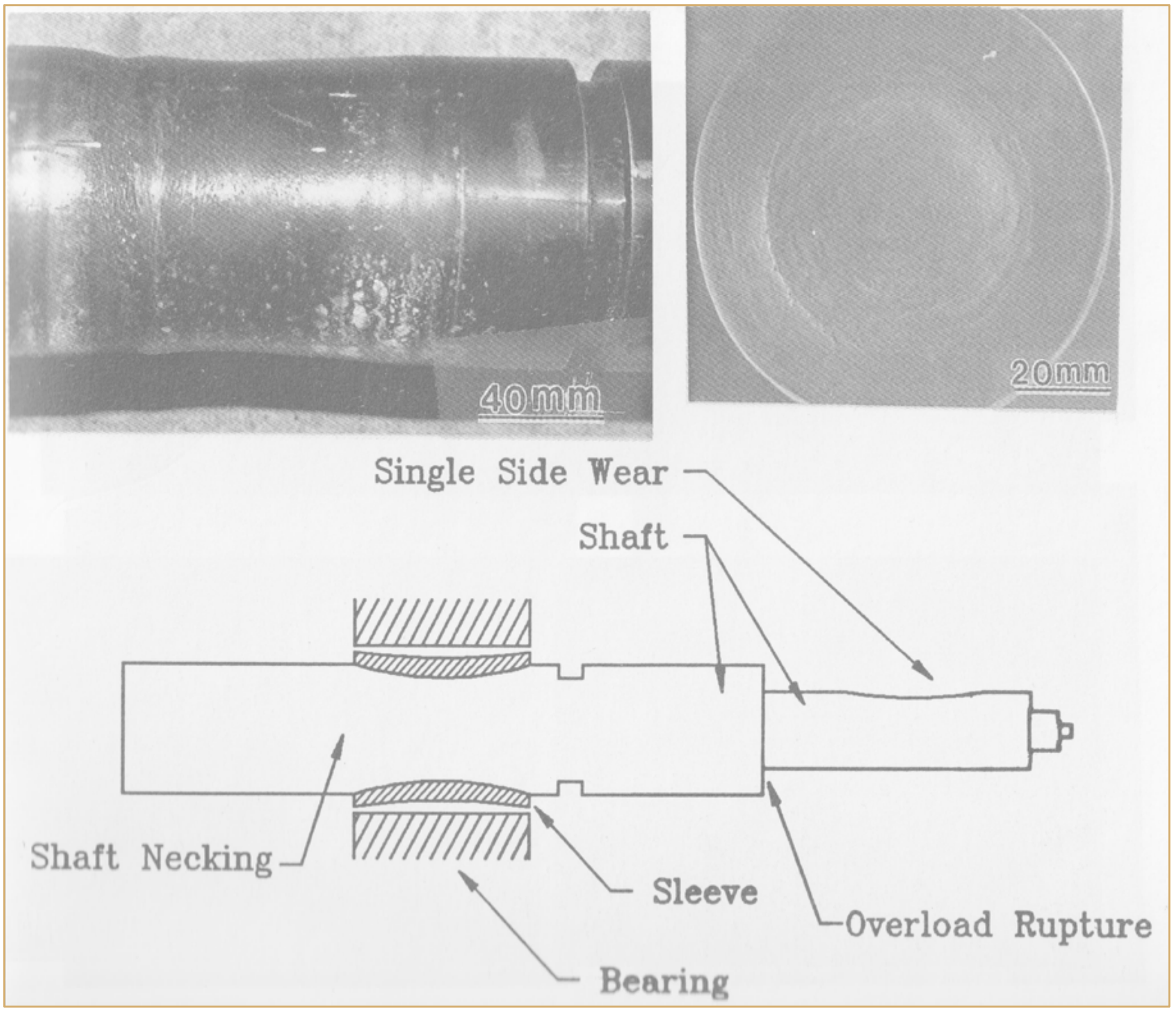

Figure G-2: View of the broken shaft and presentation of the hypothetical failure process with abnormal wear [Lai et al, 1990].

As remedial actions, it was suggested to replace the lube pipe with a schedule 160 carbon steel pipe coupled with a supporting plate, and to install a low flow rate time delay trip.

Some impeller fixing bolts (made of AISI 410 steel) were occasionally found broken during scheduled maintenance on the other heater drain pumps in the plant, and low cycle/high strain fatigue marks were observed on the fracture surface shown on (Figure G-3).

Dimple structure was observed between the fatigue marks, and the number of marks was found consistent with the frequency of plant shut-downs.

Since heater drain pumps start at 50% of the reactor power, when the temperature difference between the heater drain tank pipe and the heater drain pump is about 140°C, a thermal stress is therefore imposed by this temperature gradient. The root cause of the bolts' failure is therefore believed to be due to thermal fatigue.

To eliminate this thermal stress, a 1" pipe has been added to the heater drain mini flow valve in order to provide some hot heater drain water through the heater drain pump to the condenser in order to pre-warm the system and reduce the temperature gradient along the heater drain pump when it begins to operate.

The origin of the thermal and operation stresses found into the heater drain pumps need to be further investigated.

Appendix H : Bolted connections field experience and publications

Example #1: Examination of bolts from an isolation valve [Mousset, 1990].

Plant type: Framatome PWR, 900 MWe, France.

Steam characteristics: 270°C, 55 bars.

Relevant components: Valves isolating the steam generators.

Specimen data: Studs made of low alloyed steel, ASTM A193 B7 (C = 0.35/0.45%, Cr = 1.30/1.50%, Mo = 0.50/0.90%). Their thermal treatment is: oil quenched à 830°C, then tempered at 650°C in order to get: YS ≥ 616 MPa and UTS ⩾847 MPa.

Service condition: Steam at 270°C.

Time of operation: 10,000 hours.

Failure discovery: Four studs have been found broken during a routine inspection triggered by the replacement of the guides driving the closure members.

Results: The ruptures occurred at the bottom of the threads and are not tie to any deformation of the stud (Figure H-1).

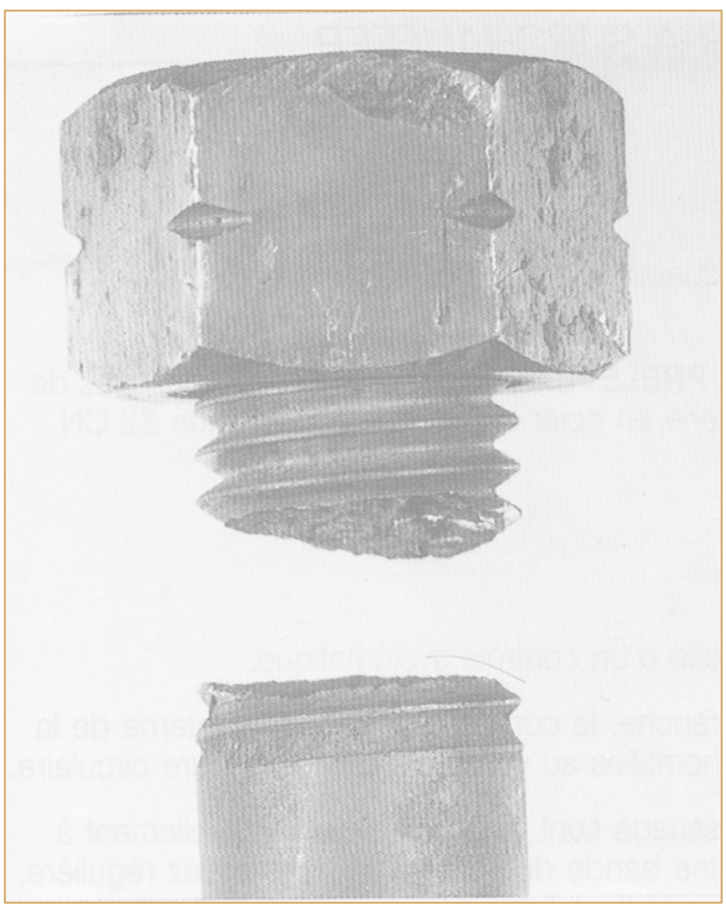

Figure H-1: View of a broken stud, no deformation is visible in the thread bottom [Mousset, 1990].

They exhibit a brittle aspect and radiate from peripheric initiation sites (Figure H-2). These initiation sites correspond to very small pits.

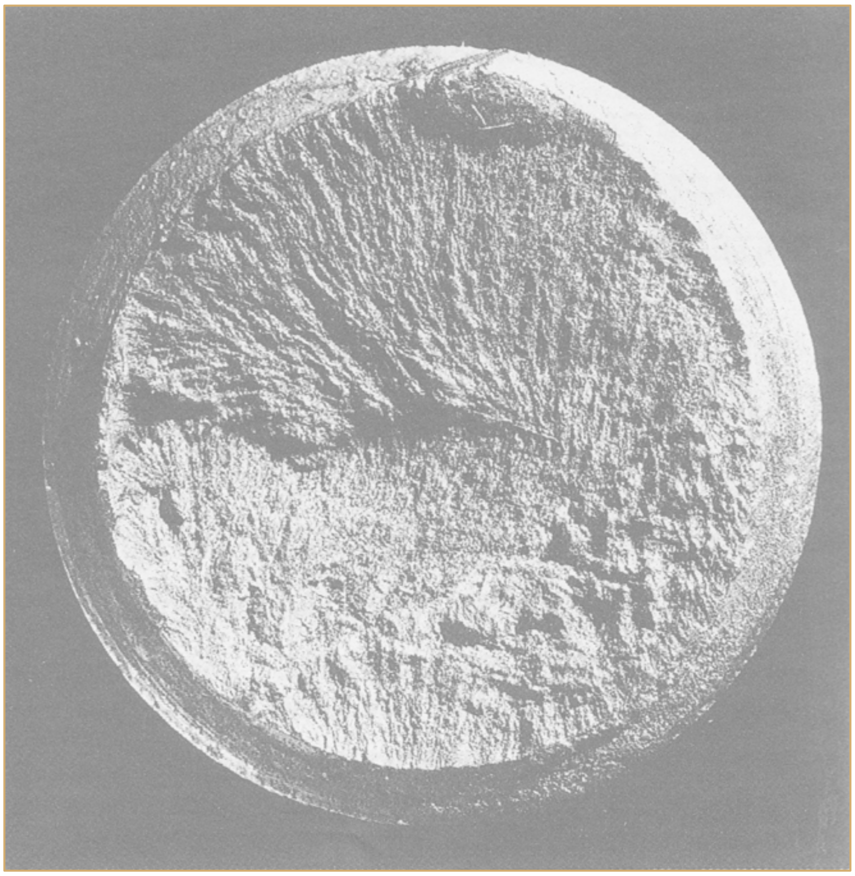

Figure H-2: Rupture by stress corrosion cracking propagating from peripheric initiation sites [Mousset, 1990].

Axial sections reveal the presence of other branched and trans granular cracks (Figure H-3), initiated in the bottom of the threads (Figure H-4).

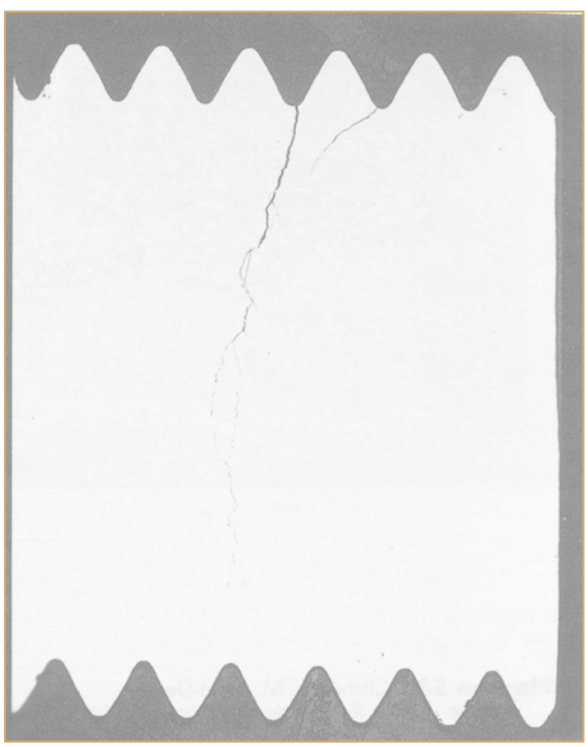

Figure H-3: Branched cracking observed on an axial section of a stud [Mousset, 1990].

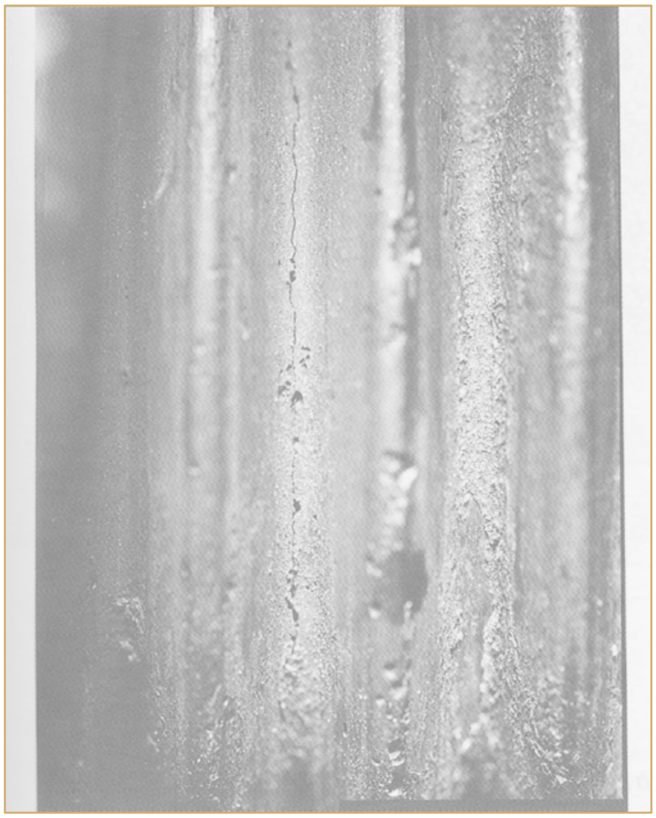

Figure H-4: Visual examination of a crack located in the bottom of a thread [Mousset, 1990].

Microanalysis conducted with a microprobe, allowed the detection of a sulphur pollution into the cracks. This element likely stems from the thermal decomposition of the grease containing molybdenum disulphide (MoS_2). This grease was often used during the installation of valves.

The mechanical properties of the broken studs are very high: the UTS exceeds 1,000 MPa.

The various cracks or ruptures observed on the studs are due to stress corrosion cracking coupled with an embrittlement of the material because of some hydrogen diffusion. The hydrogenated sulphur (H_2S) stemming from the decomposition of molybdenum disulphide, in contact with steam at 270°C, is responsible for the failures. The studs' steel was very prone to this type of cracking because of its very high mechanical properties.

Conclusion, remedial actions: Either studs made of the same material or studs made of a material less prone to stress corrosion cracking such as the 25 CD 4 low alloyed steel, were installed without any lubricant. The mechanical properties of the new studs have been limited with an UTS specified at ≤ 850 MPa.

The use of molybdenum disulphide was forbidden in all plants.

List of Abbreviations

AFNOR	Association Française de NORmalisation
AFS	Auxiliary Feedwater System
AISI	American Iron and Steel Institute
ANTI	ANT International
APA	motor driven feedwater system
ASTM	American Society for Testing Materials
AVT	All Volatile Treatment
BWR	Boiling Water Reactor
CCS	Component Cooling System
CP0	Contrat Programme n°0
CP1	Contrat Programme n°1
CP2	Contrat Programme n°2
CVCS	Chemical and Volume Control System
CWS	Circulating Water System
DE	Destructive Examination
EAC	Environmental Assisted Corrosion/Environmentally Assisted Cracking
ECT	Eddy Current Test
EdF	Electricité de France
EDS	Energy Dispersive Spectroscopy
EPR	European Pressurized water Reactor
EPRI	Electric Power Research Institute
FAC	Flow Assisted Corrosion
HAZ	Heat Affected Zone
HP	High Pressure
ID	Inside Diameter
ISI	In Service Inspection
LP	Low Pressure
LWR	Light Water Reactor
MPT	Magnetic Particle Test
MSR	Moisture Separator Reheater
MWe	Mega-Watt electrical
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NPSH	Net Pressure Suction Head
NSSS	Nuclear Steam Supply System
OD	Outside Diameter
ppm	parts per million
PT	Penetrant Test

PVC	PolyVinyl Chloride
PWR	Pressurized Water Reactor
RCCM	Règles de Construction et de Conception des matériels Mécaniques
RCP	Reactor Cooling Pump
RCS	Reactor Cooling System
RHR	Reactor Heat Removal
rpm	round per minute
RRI	Réacteur Réfrigération Intermédiaire (CCS)
RT	Radiography Test
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SG	Steam Generator
SHE	Standard Hydrogen Electrode
SICC	Strain Induced Corrosion Cracking
SIS	Safety Injection System
SNPI	Suzhou Nuclear Power research Institute
SS	Stainless Steel
SSRT	Slow Strain Rate Tensile test
TDFP	Turbine Driven Feedwater Pump
TGSCC	Trans Granular Stress Corrosion Cracking
US	United States
UT	Ultrasonic Test
UTS	Ultimate Tensile Strength
VT	Visual Test
YS	Yield Stress

Unit conversion

TEMPERATURE		
°C + 273.15 = K	°C × 1.8 + 32 = °F	
T(K)	T(°C)	T(°F)
273	0	32
289	16	61
298	25	77
373	100	212
473	200	392
573	300	572
633	360	680
673	400	752
773	500	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	600	1112
878	605	1121
893	620	1148
923	650	1202
973	700	1292
1023	750	1382
1053	780	1436
1073	800	1472
1136	863	1585
1143	870	1598
1173	900	1652
1273	1000	1832
1343	1070	1958
1478	1204	2200

Radioactivity	
1 Sv	= 100 Rem
1 Ci	= 3.7×10^{10} Bq = 37 GBq
1 Bq	= 1 s^{-1}

MASS	
kg	lbs
0.454	1
1	2.20

DISTANCE	
x (µm)	x (mils)
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	1.00
100	3.94

PRESSURE		
bar	MPa	psi
1	0.1	14
10	1	142
70	7	995
70.4	7.04	1000
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	10000
1000	100	14211

STRESS INTENSITY FACTOR	
MPa√m	**ksi√inch**
0.91	1
1	1.10