The condenser: a key player for a good feedwater chemistry

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Content

1 Summary

This report compiles the main degradations observed on condensers, either steam side or raw water side. The oldest ones were known before the nuclear era, the newest came to the light with the development of nuclear reactors. However, more attention was brought to nuclear plant condensers as if operating with a few leaks was allowed in fossil fired plants, this was strictly forbitten in pressurized water reactors, mainly because of the steam generators susceptibility to pollution.

1.1 Condenser tubes

1.1.1 Steam side degradations

- Erosion induced by the water droplets generated by the steam condensation has affected all tubes materials. However, titanium and 304L austenitic stainless-steel exhibit the best resistance to this type of degradation.

- Vibrations of the tubes can generate various failures: fatigue-induced circumferential cracking, contact wear between neighbouring tubes and wear of the tubes at intermediate support plate's locations.

- Corrosion is mainly limited to brass or copper alloy tubes. Corrosion appears as local brass dissolution in presence of ammonia and oxygen in the air-cooling areas. By design, air-cooling area's goal is to trap the none condensable gases, including ammonia stemming from the decomposition of the chemicals used for conditioning the secondary system in pressurized water reactors. Stress corrosion cracking has also been observed when the residual stresses from fabrication were high enough.

1.1.2 Raw water side degradations

Raw water side, the main mechanism of failure is corrosion:

- Corrosion under deposits. This type of corrosion occurs during outage periods, into heat exchangers not equipped with on-line tubes cleaning in operation.

- Erosion-corrosion, which is a dual mechanism, mixing corrosion and the mechanical impact of the flow. Abrasive material carried by the flow enhances this type of degradation.

- Pitting is a form of local corrosion. Pitting is mainly limited to stainless-steels, especially when their protective layer has been damaged during the fabrication or the installation of the equipment.

- Stress corrosion cracking occurs mainly on brass tubes, in areas where high residual stresses, from fabrication remain (from the tubing of the heat exchanger or from the rolling of the tubes into the tubesheets).

- Abrasion, or more accurately, erosion under abrasion, results from progressive tubes' wall wear by abrasive particles carried by the cooling water.

To all these degradations' types, one should also add the consequences of fabrication defects or of installation damages.

1.2 Condensers tubesheets and necks

Most of degradations affecting these condensers' components are relevant to corrosion.

- Corrosion under deposits of the carbon steel tubesheets of the river cooled units.

- Preferential corrosion of some particular phases or galvanic corrosion has been observed on sea side units, on tubesheets made of cooper-aluminum alloy containing 5% nickel.

2 Introduction: some basics

The condenser is a heat exchanger which role is to condensate the secondary steam at the exhaust of the low-pressure cylinders of the turbine below which it stands. This component is mainly composed of a casing and several tube bundles inside which flows cooling water from the ternary circuit or from the raw water system. In contact with tubes, the steam cools down and condensates to water which flows back to the steam generators (PWR) or to the pressure vessel (BWR) through low-pressure and high-pressure re-heaters.

The lower the condensation temperature, the higher the turbine performances. Thus, it is paramount to maintain an as low as possible pressure inside the condenser, much lower than the atmospheric pressure. The typical pressure target, also named “condenser void”, is around 50 mbar. Such a low pressure requires a careful fabrication and a good operation.

The cooling water flowing inside the tubes comes from a heat sink: either a river (sometimes with a cooling tower) or the sea. In a unit with an open cooling circuit, the water at the condenser exit, which is a few degrees hotter, flows back to the river or the sea. In a unit with a closed cooling circuit, the water is recycled, from the condenser outlet to a cooling tower where it cools down and then flows back to the condenser inlet and so on. Fabrication and operation of condensers can vary, depending on the cooling water characteristics (river, brackish, sea) along with the water circuit type (open or closed).

3 Design considerations

As all condensers' designs cannot be presented, in this chapter, the design description has been focussed on PWRs' condensers.

The first EdF 3-loop PWRs were equipped with condensers as sketched on Figure 3-1. On these condensers, the tubes bundles had an oval shaped as illustrated by Figure 3-1 and Figure 3-2.

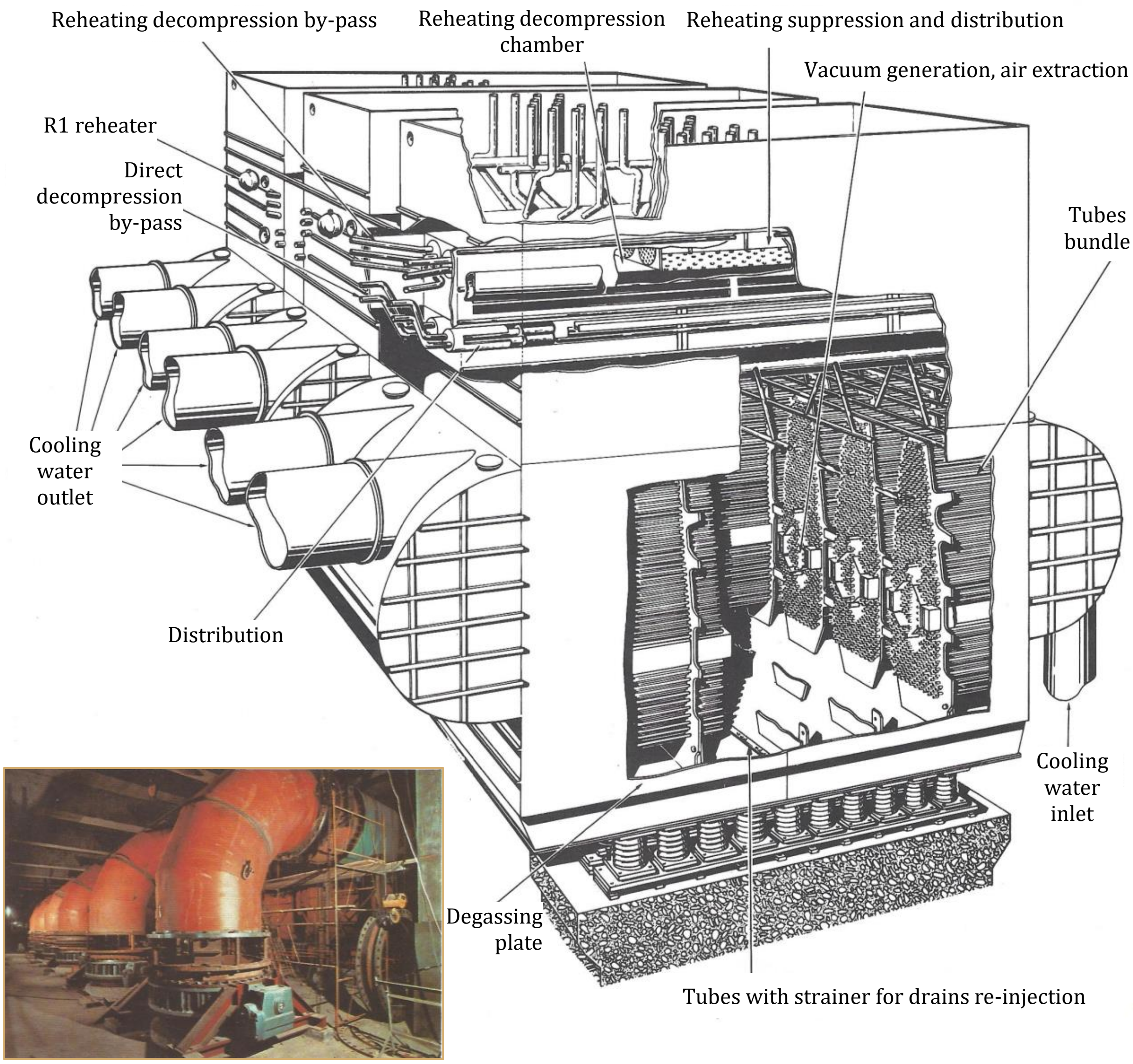
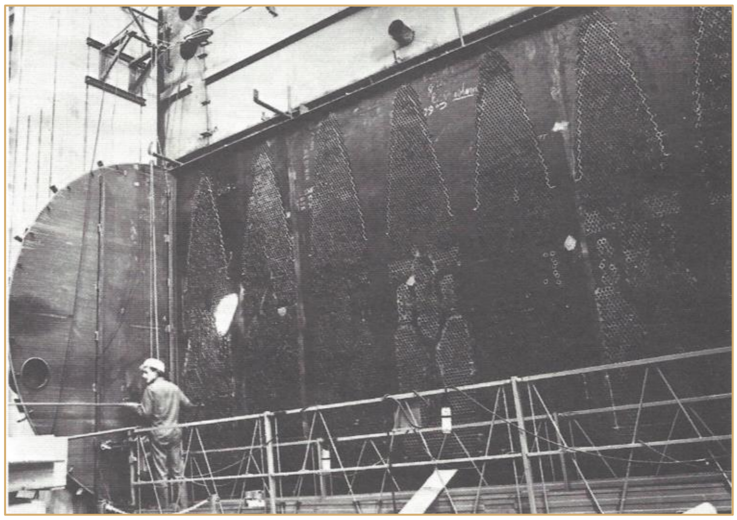


Figure 3-1 EDF 3-loop PWRs, early condensers design [Dürr, 1978].



Note at the centre of each tube bundle a zone surrounded by a tubes-free area. These tubes belong to the air cooler: around this zone, a guard plate protects the tubes from the steam jet.

Figure 3-2 View of the tubing of an early 3-loop PWR condenser [Dürr, 1978].

On the later 3-loop and on the 4-loop PWRs, the condenser tubes were assembled by modules (Figure 3-3). In each module, the tubes are distributed in lobes (Figure 3-4 and Figure 3-5).

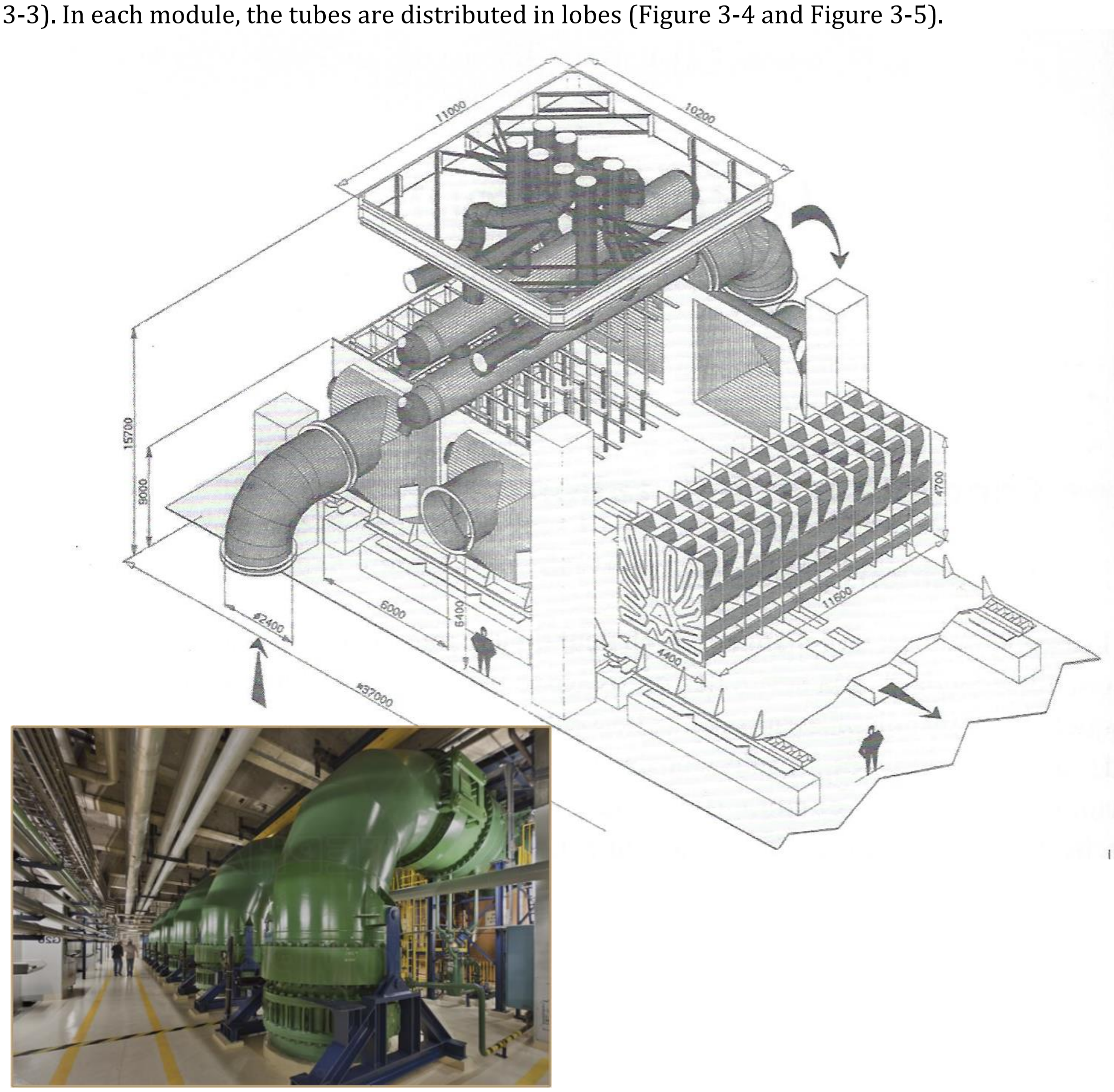


Figure 3-3 Sketch of a 4-loop PWR condenser with tubes arranged in modules. Dimensions in cm [Hutin, 2016].

4 The stakes of having a condenser in good condition

In PWRs, even if the condenser is typically not a major contributor to the unavailability factor, a condenser in poor condition, or not operated properly, can have a deleterious impact on other components which in the end can induce unavailability and major expenses. Hereafter are presented some examples of these collateral impacts.

- The selection of the tube's material governs the type of PWRs secondary side chemical conditioning, and thus, the physical-chemical conditions into the steam generators which can be very "susceptible" components. Brass tubes set, for example, a low pH morpholine conditioning, which is harmful regarding the fouling risk of the steam generators whereas stainless-steel and titanium tubes allow a high pH conditioning less detrimental for steam generator fouling (although high pH conditioning can induce other detrimental effects regarding other types of corrosion).

- In PWRs, depending on operational conditions, the condenser and feedwater plant materials will release corrosion products which will travel to the steam generators, generating deposits which will enhance the concentration of deleterious chemical species.

- A single tube failure has obviously no significant consequence on the condenser life time. If required, it is possible to plug hundreds of tubes without any major impact on the plant performances. However, a tube leak implies a raw water ingress into the condenser and this raw water will ultimately end up into the steam generators in PWRs. Raw water naturally contains various chemical species (especially regarding sea water) which can concentrate into the steam generators and trigger high growth rate corrosion.

- Seals and gaskets leak at pipes penetrations or around valves moving parts can result in condenser vacuum loss along with a decrease of plant performances (one mbar less corresponds to a loss of approximately one MWe). In the absence of quick leak mitigation, the turbine integrity could be impaired.

- An air ingress, even into the water phase and without impact on the condenser vacuum level, means dissolved oxygen brought into the condensed water. In the absence of condensate polishing, this oxygen will enhance oxides and deposits formation into the feedwater plant and in the end, will bring more deposits and oxides into the steam generators in PWRs.

- In BWRs, it is paramount to have a tight condenser in order not to release any radioactivity into the cooling water and to the environment.

In summary in PWRs, the condenser condition also governs the turbine and the steam generators conditions, in other words, the condition of the majority of the plant.

Note that some plants are equipped with condensate polishing, these plants are less susceptible to water and air ingresses.

5 The materials issue

Looking very carefully to each condenser, one can note that there are as many models as units. Two paramount parameters are taken into account when it comes to design and fabricate condensers:

- Does the unit operate in closed or open circuit?
- Is the water fresh, brackish or salted?

These two parameters govern the materials selection. The materials choice is extremely important regarding field experience along with the condenser integrity, thus for the whole plant, even if experience shows there is no miracle solution.

For the heat exchanging tubes, the original choice for EdF PWRs' condensers was titanium for sea-side plants and brass for river cooled plants, except for the four N4 plants which were equipped with stainless-steel tubes from the start. Brass tubes limitations soon appeared under the form of several degradation modes: flow assisted corrosion, stress corrosion cracking, pitting, ammonia corrosion, etc… Another limitation of brass as compared to titanium is the maximum allowable flow velocity: 1.8 m/s for brass as compared to 2.3 m/s for titanium. Last, a final drawback of brass is its copper release towards the steam generators where it has a very detrimental impact on nickel base alloys.

Thus, early decision was made to replace brass tubes with stainless-steel or titanium tubes, both alloys seeming performing well (even if not protected against erosion and friction wear). However, it is nowadays well known that given raw circuit operation conditions, bacteria can develop, some being pathogenic, but also that condenser tubed with brass tubes are naturally protected against bacteria development because of the anti-bacteria properties of copper. Raw water can be treated with biocides, such as monochloramine, however biocides are not environment friendly, so a compromise solution can consist in a hybrid combination of brass tubes along with stainless-steel tubes.

In conclusion, the condenser materials' selection is a true headache, such is the choice of the chemical conditioning of the secondary system in PWRs.

6 Condenser field experience

6.1 In general

6.1.1 Unavailability

During the first years of operation of the condensers at EdF, due to early illnesses and to the rapid degradation of the brass tubes, condensers had a significant contribution to plants unavailability. After repairs, refurbishments and replacements, this contribution dropped significantly down. For example, between 2008 and 2014, condensers have been responsible, in average, for 15 days per year of unavailability for the whole EdF fleet of 54 PWRs. Moreover, during this same period, the condensers did not account for any outage extension. These good results should not hide the fact that condensers can induce power losses, either because their thermal performances decrease (formation of deposits, fouling, air ingresses) or because a raw water ingress can lead to isolate part of the component. And this, without to mention indirect consequences on other plant components.

6.1.2 Raw water ingresses

One of the operator "black sheeps" is raw water ingresses, often as a consequence of a condenser tube failure. A raw water ingress generally reduces the condenser thermal performances and can induce other troubles in the secondary system.

For a 1,000 MWe PWR, roughly, a raw water ingress means one day of power loss for condensers not equipped with isolation valves, 1,000 to 3,000 MWh of power loss for a condenser for which it is possible to isolate the relevant leaking module and up to one week of unit shutdown for severe pollution of the secondary side.

On the 1990-2014 period, the 18 EdF PWRs on the sea shore have experienced between one and seven sea water ingresses per year whereas the fleet of 24 EdF 900 MWe river cooled PWRs has experienced an average of 25 raw water ingresses per year (with "black years", 2002 and 2003, with a hundred of ingresses). Regarding the fleet composed of 16 four-loop river-cooled PWRs, the average is about 20 raw water ingresses per year, with a peak close to one hundred in 2007. One could sumarize this field experience by stating that, on the EdF fleet, the river-cooled units experience one raw water ingress to the condenser per year and that the sea-cooled units experience one sea-water ingress every 3 or 4 years.

From a design and materials perspectives, a lesson learned from this average picture, is that there is a striking difference between river-cooled and sea-cooled units. However, this picture does not give a realistic view of the daily operation of these plants with an alternance of "relax" and "black" years. For example, the plant C2 (river-cooled 4 loop PWR), experienced one or two yearly raw water ingresses from 1988 to 2009 and suddelly, in 2009, this unit suffered from around 15 raw water ingresses. Same story for the plant SA2 (river cooled 4 loop PWR), which suffered from 15 raw water ingresses in 2008 and not a single one during the following years.

"Black" years usually occur when a condenser refurbishement, including tubes replacement, is planned then postponed (so, not a well-advised decision!). The decision of massive preventive plugging of the most susceptible tubes explains why, after several raw water ingresses, an ingress-free period is observed. Of course, when a condenser is fully refurbished with all its brass tubes replaced with either stainless-steel or titanium tubes, the field experience drastiscaly changes with several raw water ingress-free years to follow.

6.2 Tube's bundle

We will start this section by presenting some major tubes degradation modes, then we will switch to specific materials issues.

6.2.1 OD erosion

OD erosion is a concern mainly for the impact tubes (the first tubes to be hit by steam); they can leak in less than 15,000 hours of operation. Leaks on units equipped with cooling towers are delayed because the wetted steam pressure and velocity are more favourable. Usually, the worse located tubes are protected by screens, however, the operator may be forced to increase these protections if not efficient enough (installation of anti-erosion grids).

Tubing material can be sorted into 4 categories related to their steam impingement resistance:

- Excellent resistance (but not immunity!) for: AISI 304 SS and titanium;
- Good resistance for: 70/30 Cu/Ni, and cold worked 90/10 Cu/Ni;
- Fair resistance for: Aluminum brass and Admiralty brass and
- Poor resistance for: annealed 90/10 Cu/Ni, Arsenical copper and Aluminum alloys.

Appendix A presents some examples of condenser tubes having suffered from OD erosion.

6.2.2 Vibration, fatigue and wear

The internal structures and the tubes vibrate as a consequence of the steam flow. When the level of vibrations becomes too high, tubes can break by fatigue (Figure 6-1).

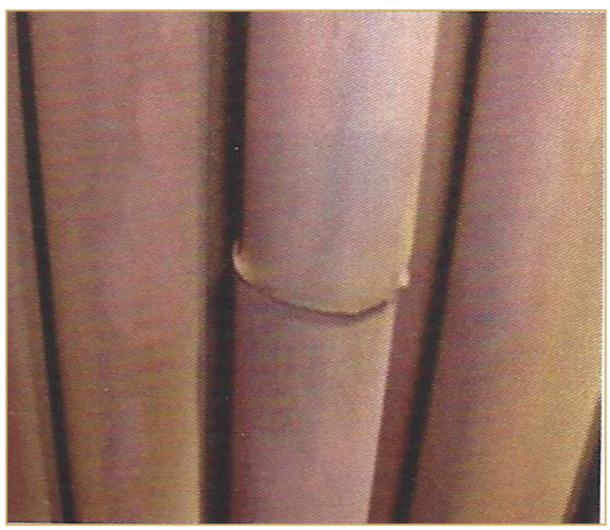


Figure 6-1 Condenser tube broken by mechanical fatigue [Hutin, 2016].

However, more commonly, adjacent tubes get into contact and wear each other until through wall wear. Installing backing bars is a good means to lock tubes in place, however, it is not the end of it as backing bars can themselves move, vibrate, be worn or break, therefore requiring inspections and/or repairs. Vibration of condenser internals such as plates or support structures can lead to their rupture and as a consequence, generate foreign objects which can wear or break tubes.

Appendix B presents some examples of condenser tubes having suffered from vibration, fatigue or wear.

6.2.3 Foreign objects

Any foreign object moving into the secondary circuit is a potential danger for the tubes and structures integrity. Foreign objects can stem from components or structures’ damage or from human errors during maintenance activities, like forgotten tools. Raw water side, channel heads and tubes ID can be damaged by foreign objects coming from the cooling water which had not been trapped by the rotating drums filters.

6.2.4 Scale deposits and fouling

Regarding the tubes ID, one of the main operational issues is scale deposits, especially for closed cooling systems. Scale forms by precipitation of mineral salts contained into the raw water at the ID, under the modification of physical (i.e., temperature) and chemical (i.e., concentration) conditions. Scale deposits are more or less hard and bonded to the surface and their thickness can reach one millimetre if nothing is done to prevent it (Figure 6-2).

Figure 6-2 View of condenser tubes ID. Left: clean tube. Middle: tube with scale deposits. Right: tube almost plugged by deposits [Hutin, 2016].

Generally, the main constituent of scale deposits is calcium carbonate, however, other elements, more or less deleterious, can also precipitate. The consequences of scale deposits are multiple: the heat exchange between secondary /steam water and cooling water is impaired, and therefore, the condenser thermal efficiency decreases which in turns, decreases also the plant output level. Moreover, the deposits favour the concentration of harmful chemical species, thus increasing the corrosion risk of condenser materials.

Another consequence of the presence of scale deposits in tubes is the reduction of the flow section to the point the cleaning balls cannot travel through the tubes anymore.

Last consequence, tubes inspection can become impossible when the tubes free section is less than the inspection probes diameter.

Fouling is another degradation mechanism which can also decrease condenser thermal efficiency. Depending on the kind of tubing material, micro living organisms can form a biological film which will significantly drop the thermal exchange coefficient.

Shells can also settle down, thus generating initiation sites for deposits or fouling.

Finally, various debris can also more or less plug condenser tubes.

Of course, deposition and fouling risks strongly depend on the cooling water composition, either river or sea water. The injection of conditioning additives in order to slow down or stop deposition and/or fouling mechanisms is always an option, however, of not easy implementation given the huge flow rates involved. In any case, one of the top priorities for thermal (fossil or nuclear) plant engineers is to clean condenser tubes ID, as often and as deeply as possible.

6.2.5 Specific materials issues

6.2.5.1 Brass tubes

Brass tubes early showed they were susceptible to several degradation mechanisms such as:

- ID abrasion (up to 0.2 mm at a 3 loop PWR after only 20,000 hours of operation);
- Local corrosion (craters);
- Erosion-corrosion;
- Ammonia corrosion when the secondary water is conditioned with ammonia;
- Pitting in stagnant conditions, especially occurring during outages;
- Stress corrosion cracking in areas with high residual stresses from fabrication (i.e., hard rolled areas).

Another side deleterious consequence of some of these degradation mechanisms is the release of copper to the steam generators and copper is harmful to nickel alloys.

Appendix C presents some examples of condenser brass tubes failures.

6.2.5.2 Titanium tubes

From the beginning, titanium has been selected for sea water cooled nuclear plants. Titanium is much more expensive than brass but is much more corrosion resistant and therefore more leak-tight in operation, preventing steam generator major pollution by chlorides and associated severe corrosion. However, given the high mechanical properties of titanium as compared to those of brass, titanium tubes wall is thinner, typically 0.5 mm instead of 1 mm for brass, making these titanium tubes more sensitive to vibration and wear-initiated failures.

Titanium tubes, as any other tubes, remain susceptible to water/steam impingement erosion. Another failure mechanisms specific to titanium condenser tubes is embrittlement under hydrides formation.

Appendix D presents some examples of condenser titanium tubes failures.

6.2.5.3 Stainless-steel tubes

Pitting has been observed on AISI 439 ferritic and AISI 304 austenitic stainless-steel tubes. Of course, stainless-steel tubes may suffer from the same failure modes that any other tubes in particular erosion, fatigue, wear, scale deposition…

Appendix E presents some examples of condenser stainless-steel tubes failures.

6.3 Support plates

On some four loop PWRs, some tubes support plates installed between two tubesheets, have been found deformed likely because of constrained differential expansions. Additional mechanical reinforcements have been added between these plates.

6.4 Channel heads and tubesheets

At EDF, sea-water cooled plants are equipped with twins Cu/Al tubesheets, the interspace being filled up with demineralized water. This protects the condenser against leaks at tubes' rolls. However, Cu/Al alloy has a poor performance on condensers equipped with titanium tubes instead of brass tubes. Corrosion can initiate at holes periphery if, during outages, the tubesheets are not flushed with soft water. Some tubesheets are equipped with cathodic protection, however, to be fully efficient, this system requires appropriate operation and maintenance.

Regarding river side units, tubesheets are made of carbon steel with some being protected by a titanium plate or by an epoxy resin. The behaviour of these plates varies depending on the unit, however, overall, it is rather fair.

No generic issue has been raised regarding tubesheet field experience, however, some local repairs have been required because, tubes rolling failures, wall thickness losses, coating degradation and tubesheet/shell welds cracking under SCC.

The ID of channel heads of sea side units is lined with neoprene or ebonite. The first one can suffer from bonding issues whereas the latter is more brittle. In any case, care should be taken during maintenance operations in order not deteriorating these protections.

Sea side channel heads can be overrun by shells, forcing operators to periodic cleanings or to implement relevant treatments.

Appendix F presents some examples of condenser channel heads and tubesheets failures.

6.5 Gaskets and metallic expansion joints

Flexible elastomer joints achieving the leak tightness of some component's junction such as turbine/condenser or channel head/raw water sleeve, are susceptible to ageing and, as a consequence, can lose their original properties. Some have been found damaged or even torn out. The consequence of theses failures is a leak leading to condenser vacuum lost which can in turn, lead to flanges failures. For these parts, EdF applies routine preventive maintenance/replacement.

Steam extraction lines are typically equipped with corrugated metallic expansion joints. Some have failed, sometimes with extended tearing, along with missing sections generating lose parts (Figure 6-3).

Figure 6-3 Steam extraction expansion joint, corrugated steel severely torn out [Hutin, 2016].

6.6 Internal structures

Condenser internal structures are composed of a complex mix of plates, pipes, boxes, sheets, braces, tie rods and other parts that can fail, mainly under erosion. All these components can also suffer from flow-induced vibrations, from flow-induced fatigue or from fretting wear. As a matter of facts, the decompression chambers of the turbine by-pass are particularly susceptible to these failures as they can receive a sudden high steam flow which is going to lose energy by turning pressure to heat via the generation of flow turbulences, which will in the end generate vibrations. Several EdF units have suffer from such failures and fatigue cracking.

7 Operation monitoring

7.1 Vacuum monitoring

Operating a plant requires a close monitoring of the condenser vacuum. Operating technical specifications contain procedures telling operators how to react when the pressure becomes too high. This monitoring is also a means to detect various failures, of tubes, gaskets, internal pipes and moving part of some components.

7.2 Chemistry monitoring

In PWRs, a condenser in good condition means an optimized chemical conditioning and the absence of leak. The close monitoring of the physical and chemical parameters of the secondary water supports these two objectives. The on-line analysers which monitor the conductivity of the condenser modules allow detecting any leaking area of the tubes bundle. This leaking area is then isolated and the operator can look for the leaking tube(s). Several techniques can be used, the most popular being the helium test. Should valves allowing isolating the leaking module exist, then the power loss in operation is limited to around 20 Mwe. In the absence of isolating valves, a larger area of the condenser needs to be isolated, requiring a power reduction down to 40% in order to avoid, into the remaining active zone of the condenser, a large increase of the steam flow velocity which could induce vibration levels harmful to the tubes.

Monitoring the air extraction flow and the dissolved oxygen content allow detecting air ingresses. Various techniques are then implemented (i.e.: gas tracer) to find the leaking tube(s) and fix the air ingress(es).

Regarding the oxygen content, the target is less than 5 µg/l at the steam generator inlet. In the absence of degassing tank, this limit should be met at the condenser outlet. When the unit is equipped with a degassing tank, the condenser must achieve an oxygen concentration in the 12 to 20 µg/l range.

7.3 Performance's monitoring

At EdF, a periodic thermal balance, i.e.: every week, of the secondary system is performed. Using the results of various sensors installed on the secondary system, different operating performance parameters can be computed, such as the thermal efficiency and compared to anterior or expected values. Any significant deviation requires remedial actions, such as tube bundle cleaning.

7.4 Cooling water conditioning

In order to avoid scale deposits and fouling at the tubes ID along with the whole cooling system, the industry offers various conditioning products to add to the raw water. These products typically contain chlorine, bromine, ferrous phosphates or various scale or corrosion fighting agents. However, great care should be taken given large quantities have to be injected because of the huge flows involved. Also, the efficiency can be disappointing, moreover, we have to make sure that no deleterious impact can occur on other areas of the plant or to the environment given these conditioning agents will end up into the nature. As an example, we can mention the Mexel® which, when injected in microquantities during several dozens of minutes a day forms a molecular film at the tubes ID, preventing scale and sludge deposits, corrosion, fouling and even the settle down of mussels. Despite being toxic free and biodegradable, this miraculous product efficiency is not always as good as expected when flows are high.

After many tests, EdF decided to install chemical treatment facilities implementing sulfuric acid injection at plants with cooling towers in order to minimize the scale deposit risk.

Selecting the best option is even harder if you take into account the fact we also have to fight against the development of pathogenic germs and sometimes also to protect cooling towers components.

8 Maintenance in outage

When a unit is shutdown, it is paramount to take all necessary actions to keep the condenser in good conditions during the shutdown period.

8.1 Routine inspections

At each outage, the operator inspects the following components:

- Mounting of the nozzles spaying de-superheating water into the decompression chambers;
- Channel heads, elbows and necks, raw water side: visual examination and thickness measurements (of parts coating free, if any significant corrosion);
- Tubes bundle, raw water side: visual examination of fouling and deposits, removal of sludge and debris trapped in channel heads or at tubes inlet (water jet cleaning);
- Raw water strainers: visual examination, checking of the meshes or filters good condition;
- Instrumentation nozzles: visual examination;
- Tubesheets, raw water side: visual examination of the whole surface, search for impact or corrosion traces, removal of outer deposits, recording of potential deformations;
- Nonstop cleaning system;
- Leak test of the space between the two tubesheets for seaside units.

Every other outage, this inspection programme is supplemented as follows:

- Tubes bundle, steam side: visual and manual examination of the upper tubes (the ones which are of easiest access to) for detection of erosion;
- Lower internal structures: visual examination of the decompression chambers, search for plates and walls welds cracking, search for chambers and piping corrosion or erosion, checking for the absence of foreign objects;
- Corrugated expansion joints: visual examination of the whole with special attention to corrugated areas;
- Turbine bypass chambers: internal inspection, search for cracks, deformations and erosion into the plates, stiffners and welds.

In addition, every fourth outage, the welds of the corrugated expansion joints of the bleeding circuits should be inspected by penetrant test.

8.2 Special inspections

Some inspections are planed according to intervals and sampling tuned to the condenser specific design along with its condition based on previous inspections and the results of operating on-line monitoring:

- Junction between channel heads and tubesheets: visual examination of bolting and welds, sometimes along with penetrant test;
- Corrugated expansion joints located on the steam extraction circuit: visual and manual examinations;

9 Refurbishing and replacement

Beyond typical repairs, major overhaul or modifications can be required to prevent re-occurrence of some major failures, as for example:

- Addition of grids to protect the tubes exposed to erosion by steam.
- Addition of backing strips for better support of the tubes exposed to vibrations.
- Addition of epoxy coating on the tubesheets and on the channel heads surfaces.
- Addition of epoxy coating on some tubes either limited to their ends or over their entire length.

Regarding epoxy coating application, this technique has been applied mainly in the US in fossil fired plants as well as in nuclear plants (i.e.: Plastocor® process). In France, EdF has applied a similar process into channel heads and on tubesheets which required a better protection. As concerns the tubes, on some condensers, an epoxy coating was applied at their inlet, over a few centimetres distance only, in order to limit the raw water ingresses induced by material loss under erosion-corrosion. However, coating the entire tube length results in a significant decrease of the thermal exchange coefficient and therefore this option has been abandoned by EdF.

On the units not equipped with from origin, valves allowing the isolation of individual modules, while the plant is still operating, can be added, thus allowing on-line maintenance with only limited power loss.

However, the ultimate maintenance operation consists in the total replacement of the tubes' bundle. As for example, in the mid-10s', EdF had already completely refurbished over 20 condensers originally equipped with brass tubes, and some more have to come. Most of the time, brass tubes have been replaced with stainless steels tubes, much less often with titanium or new brass tubes. Condenser tubes replacement can be conducted as a single operation or module by module. Remind that the replacement material selection depends not only on its resistance to the various degradation mechanisms, but also on the risk of pathogen bacteria's development into close-cooling systems, and so on the resistance to biocides treatments. Sometimes, not only the tubes' bundle is replaced but also the tubesheets.

Last, the total refurbishment of a condenser can open the door for a design modification, leading to better thermal performances and so, to increased plant power output. On a 1300 MWe unit, a few MWe can be saved.

Sometimes, replacing the tubes' bundle material can come along with a modification of the chemical conditioning of the secondary system. In this case, it is recommended to think globally and study a new global operational strategy for the whole secondary system, including not only the condenser but also the feedwater plant and the steam generators. It would be nonsense that the tremendous work done to refurbish a condenser with the objective of extending the steam generators life, results in an unanticipated failure of a reheater.

10 Conclusion

You cannot separate good feedwater chemistry from good condenser conditions, they do go together. It is extremely difficult to meet the feedwater chemical specifications when the condenser suffers from air or water ingresses.

Several different materials have been used for tubing power plants condensers. However, if some materials are better than others, there is no miracle material, each can suffer from at least one form of degradation mechanism as reported in Table 10-1.

Table 10-1: Main condensers' tubing materials and degradation mechanisms [Guiblin et al., 1994].

	Steam side	Cooling water side
Brass	- Ammonia corrosion (air cooling area) - Vibrations - Stress corrosion cracking - Erosion by steam impact	- Steady abrasion - Stress corrosion cracking - Erosion-corrosion
Stainless steel	- Erosion by steam impact - Vibrations	- Pitting corrosion (316L less susceptible)
Titanium	- Erosion by steam impact - Vibrations	- Hydriding

The prevalent degradation mechanism is corrosion, as shown by Table 10-2 and Table 10-3 . However, corrosion is less and less an issue given there is a growing trend to replace brass tubes with more corrosion resistant tubes such as stainless-steel or titanium.

11 Industry perspective

This document reports the degradation modes that have been identified during several decades of power plant condensers' operation. Therefore, it is a help to identify any degradation mechanism that could be discovered on a nuclear power plant condenser.

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

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

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Appendix A Some examples of condenser tubes having suffered from OD erosion

Example #1

Plant main characteristics: Framatome PWR, 900 MWe, 3 loops, France.

Steam characteristics: temperature 270°C and pressure 55 bars.

Equipment/Component: condenser, tubes bundle.

Operating conditions: steam to condense.

Time of operation: 36,000 hours.

Failure discovery: presence of OD erosion on the impact tubes.

Specimen/sample characteristics: brass tubes 70/30 with arsenic. Outside diameter = 26 mm (1.02'), wall thickness = 1.2 mm (0.047''). One tube has been harvested for destructive examination.

Results

On the OD, the eroded length is limited to a short distance. The surface has a sponge aspect over about one fifth of the tube circumference (Figure A-1).

A cross section through the most damaged zone reveals a very rough surface composed of joined erosion craters generated by the impact of the water droplets contained in the steam (Figure A-2). The remaining wall thickness at the bottom of some craters is around 0.6 mm (0.024'') which about half of the original wall thickness (Figure A-3).

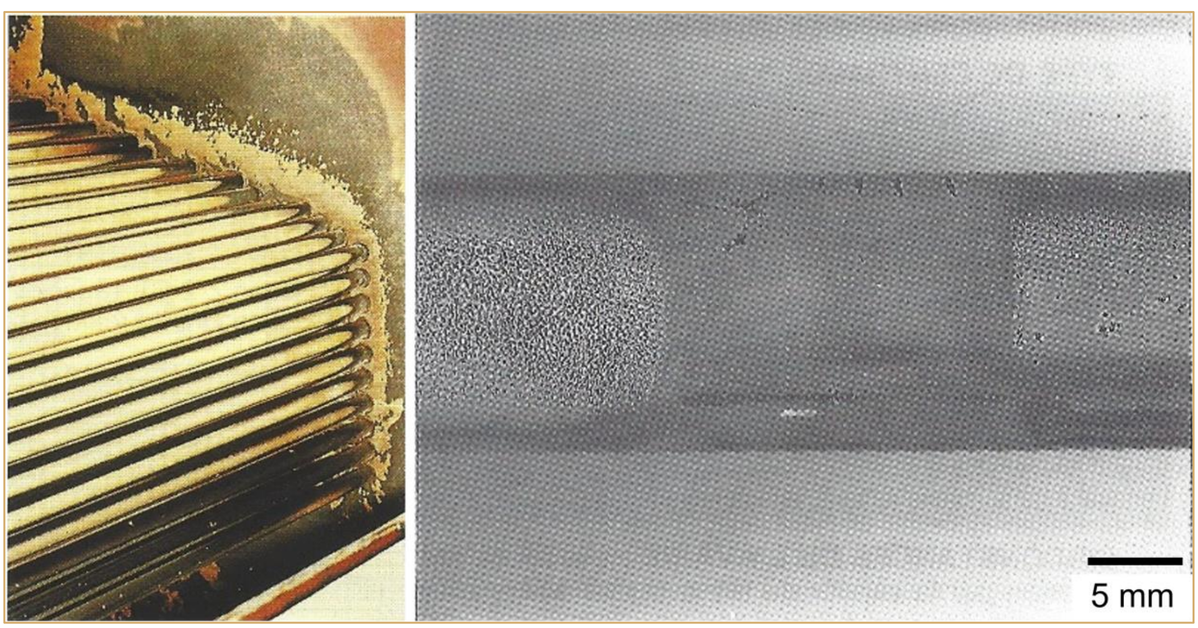

Figure A-1 Left: view of the eroded area. Right: OD surface eroded each side of a partition plate [Cattant, 2021].

Appendix B Some examples of condenser tubes having suffered from fatigue, vibration or wear

Example #1

Plant main characteristics: fossil fired plant, 250 MWe, France.

Steam characteristics: temperature 565°C and pressure 165 bars.

Equipment/Component: condenser, tubes bundle.

Operating conditions: steam to condense.

Time of operation: 6,500 hours.

Failure discovery: tube broken while the plant was operating.

Specimen/sample characteristics: tubes made of brass.

Results

The transverse tube rupture (Figure B-1) results from cyclic loading (fatigue, Figure B-2) which occurred over a long tube span. Traces of contact with adjacent tubes are visible each site of the rupture (Figure B-1). Similar traces have been observed on other tubes over similar long spans (Figure B-3).

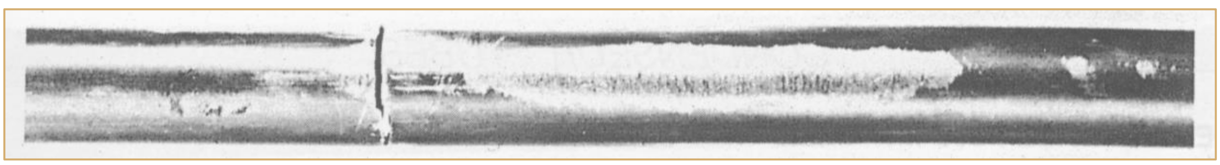

Figure B-1: The tube rupture is transverse and traces of fretting with the adjacent tubes are visible each side of the rupture [Mousset, 1990].

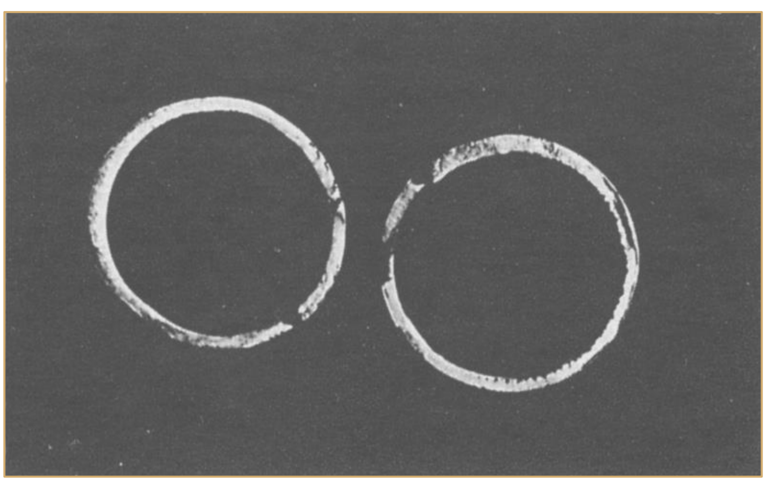

Figure B-2: The two rupture faces are damaged by impacts, which prevents any metallurgical examination. The macroscopical aspect of the rupture suggests a rupture under a fatigue mechanism [Mousset, 1990].

Appendix C Some examples of brass tubes failures

Example #1

Plant main characteristics: natural uranium graphite gas cooled reactor, 500 MWe, France.

Steam characteristics: temperature 390°C and pressure 34 bars.

Equipment/Component: condenser.

Operating conditions: steam to condense.

Time of operation: 120,000 hours.

Failure discovery: major wall thickness losses have been detected during an eddy current inspection of the condenser; therefore, several tubes have been pulled out in order to fine tune the correlation between eddy current signals and real defects types and dimensions.

Specimen/sample characteristics: tubes made of brass. Outside diameter = 22 mm, wall thickness = 1 mm.

Results

The inspections reveal a major ID abrasion of the tubes under the action of the abrasive balls used for the on-line cleaning. The low remaining wall thicknesses (0.17 to 0.59 mm) have modified the natural frequency of the tubes which new vibration regime resulted in damages to the tubes OD at the tube support plates locations (Figure C-1).

The jagged and cold worked surface in front of the tube support plates is likely the consequence of the uneven size of the drilled holes along with the presence of very hard particles (weld metal droplets and/or oxides debris) trapped between the tubes and their support plates (Figure C-2 and Figure C-3).

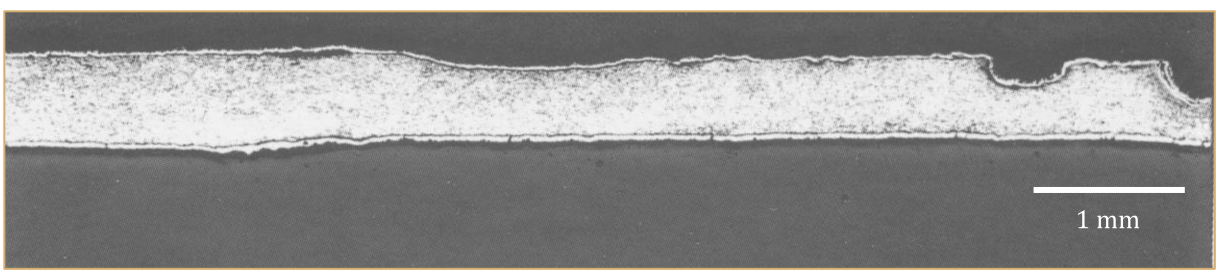

Figure C-1: Axial cut exhibiting the wall thickness decrease and the jagged OD surface at the location of a tube support plate [Mousset, 1990].

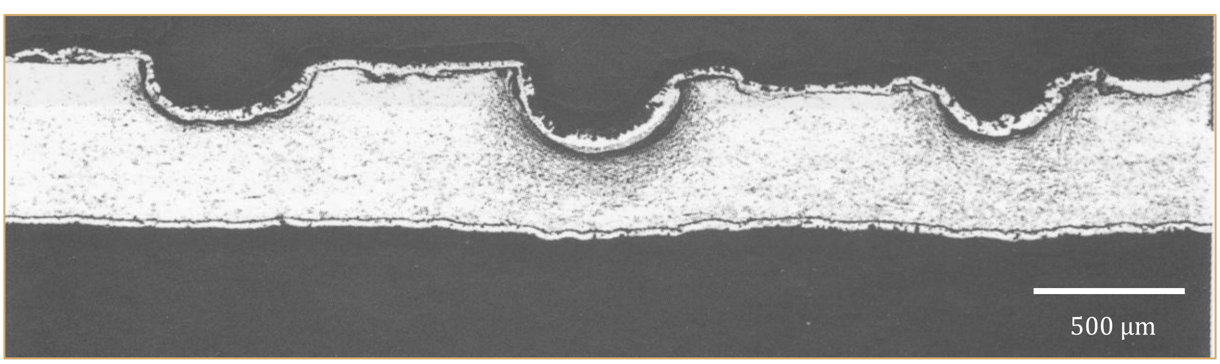

Figure C-2: View of the OD punching and cold work in front of a tube support plate at the location of very hard particles trapped between the tube OD and the tube support plate. The white layer is nickel coating used for metallography [Mousset, 1990].

Appendix D Some examples of titanium tubes failures

Example #1

Plant main characteristics: Framatome PWR, 1,300 MWe, 4 loops, France.

Steam characteristics: temperature: 285°C, pressure: 70 bars.

Equipment/Component: condenser.

Time of operation: 0 hour.

Failure discovery: during the hydrotest of the space between the two tubesheets, several tubes exhibited leaks into the hard roll, steel tubesheet side.

Specimen/sample characteristics: rolled and seamed titanium tubes. OD = 19 mm (3/4''). Wall thickness = 0.5 mm (0.02'').

Results

The examination of the ID reveals the presence of hard rolling tool traces showing that the tube was rolled twice (Figure D-59).

The first rolling was misplaced (half into the tubesheet, half out of it) whereas the second was implemented at the right location.

The weld bead is shifted as the consequence of the tube twisting because of the wrong position of the first hard rolling (Figure D-60). This area suffers from cracking along the weld bead groove.

A micrography shows this cracking is from low cycle fatigue (Figure D-61). This fatigue cracking was triggered by the wrong location of the hard roll into the steel tubesheet (Figure D-62). This phenomenon was duplicated in the laboratory.

Figure D-59: View of the tube ID showing the presence of a double hard roll, one being performed out of the tubesheet [Cattant, 2021]

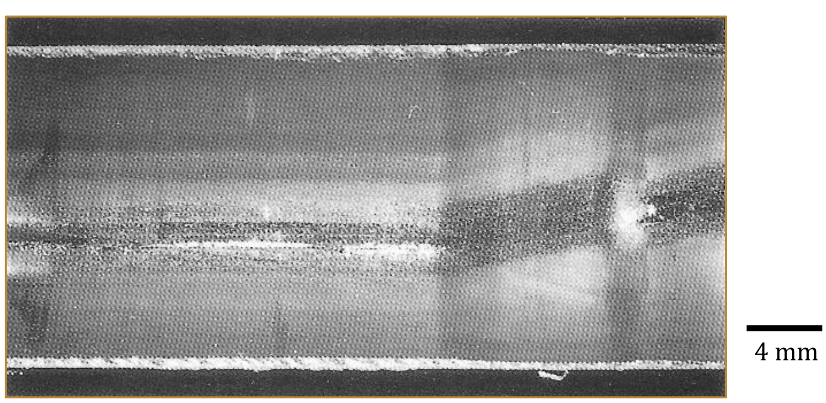

Figure D-60: View of the twisting generated by hard rolling the tube out of the tubesheet [Cattant, 2021].

Appendix E Some examples of stainless-steel tubes failures

Example #1

Plant main characteristics: Framatome PWR, 1,300 MWe, 4 loops, France.

Steam characteristics: temperature: 285°C, pressure: 70 bars.

Equipment/Component: condenser.

Operating conditions: cooling water = river water.

Time of operation: plant commissioning.

Failure discovery: an inspection of all the tubes of a channel head has been triggered by a chemistry deviation. This inspection revealed the presence of 26 leaking tubes.

Specimen/sample characteristics: tubes made of ferritic stainless steel AFNOR Z2 CT 18 (AISI 439L). Outside diameter = 18 mm (0.71''), wall thickness = 0.6 mm (0.024'').

Results

The damaged tubes exhibit ID corrosion craters at the lower generatrix and 50 to 60 mm (2 to 2.4'') distant from the water inlet. In this zone, one can see the grooves generated by the flushing tool used during the condenser fabrication (Figure E-1). A few leaks have also been observed out of the grooved area (Figure E-2).

These corrosion craters are the result of the high sensibility of the AFNOR Z2 CT 18 (AISI 439L) ferritic stainless-steel to pitting corrosion in presence of confined water or under deposits (Figure E-3). On these tubes, the grooves have destroyed the passive film. Therefore, corrosion could initiate in stagnant water or under deposits during outages because of a counter slope, the lower elevation being tube inlet side.

Outlet side, the tubes showing grooves damage also exhibit pitting corrosion but none of the pits is through wall. This incipient corrosion is the signature of future severe pitting corrosion in areas with stagnant water like festooned sections between two support plates.

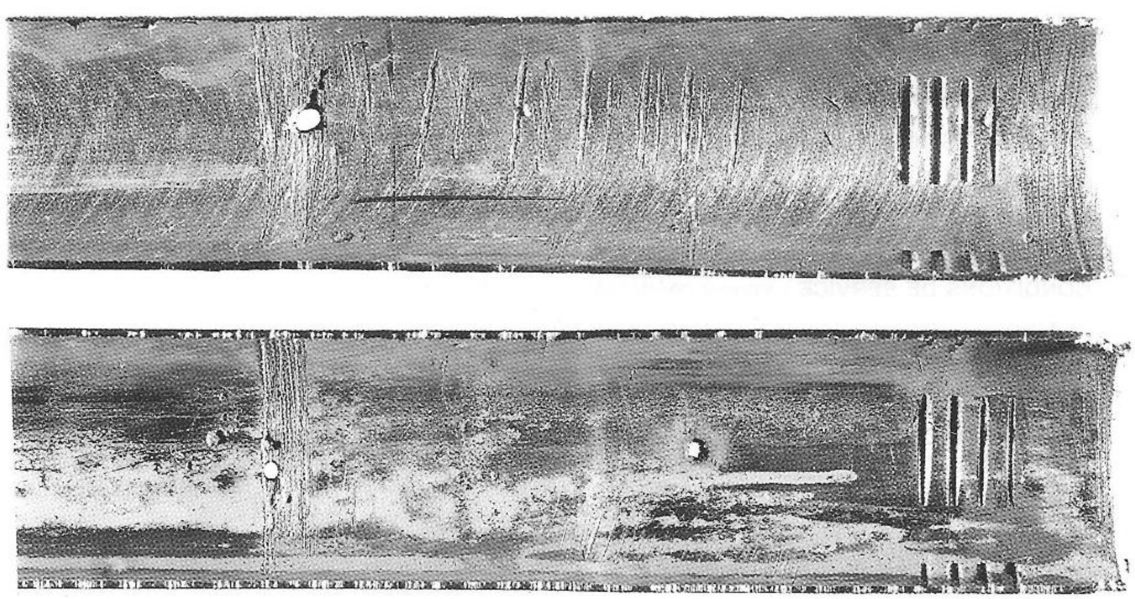

Figure E-1: AFNOR Z2 CT 18 (AISI 439L) ferritic stainless-steel tubes exhibiting pitting corrosion and leaks close to the tube inlet, in a zone damaged by the flushing tool used in fabrication [Cattant, 2021].

Appendix F Some examples of tubesheets and channel head failures

Example #1

Plant main characteristics: fossil fired plant, 250 MWe, France.

Steam characteristics: temperature: 565°C, pressure: 165 bars.

Equipment/Component: condenser, tubesheet, cooling water outlet side.

Operating conditions: cooling water = river water with a high chlorides' concentration.

Time of operation: 55,000 hours.

Failure discovery: degradations have been detected during a planned maintenance outage. The outlet side tubesheet suffers from severe general corrosion, whereas, the inlet side tubesheet has little general corrosion.

Specimen/sample characteristics: the tubesheet is made of carbon steel from the A42 AFNOR designation. Thickness: 35 mm. The tubes are made of arsenical brass (70/30 As).

Results

The observed corrosion under deposits is deeper (10 to 12 mm) around the brass tubes where it propagates from the crevice between the tubes and the tubesheet (Figure F-1). The flow conditions at the outlet tubesheet, along with the presence of chlorides into the cooling water, have likely enhanced the corrosion rate. Moreover, the corrosion rate is also enhanced by the higher temperature at the outlet.

Inlet water side, the tubesheet suffers from uniform corrosion but crater-free.

Remedial action

The outlet tubesheet was sandblasted in order to remove all corrosion products. Then, an epoxy resin based protective coating was applied over the whole cleaned surface. A visual inspection of the repair after 23,000 hours of operation shows the tubesheet is still defect free (Figure F-2).

List of Abbreviations

AFNOR	Association Française de NORmalisation
AISI	American Iron and Steel Institute
ANTI	ANT International
ASTM	American Society for Testing Materials
BBC	Brown Boveri Company
BWR	Boiling Water Reactor
CP2	Contrat Programme n°2
EAC	Environmental Assisted Corrosion
ECT	Eddy Current Test
EdF	Electricité de France
EPRI	Electric Power Research Institute
FAC	Flow Accelerated Corrosion
HP	High Pressure
ICCP	Impression Current Cathodic Protection
ID	Inside Diameter
LD	Localized Damage
LP	Low Pressure
MWe	Mega-Watt electrical
NDE	Non Destructive Examination
OD	Outside Diameter
ppm	parts per million
PREN	Pitting Resistance Equivalent Number
PWR	Pressurized Water Reactor
RCS	Reactor Cooling System
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SHE	Standard Hydrogen Electrode
SS	Stainless Steel
US	United States
UTS	Ultimate Tensile Strength

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