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A Case Study of the French Nuclear Power Industry
Steam Surface Condenser Tubes
Forty Years Later

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Abstract

The French nuclear program began during the 1970's resulting in the construction of 58 Pressurized Water Reactors. These nuclear power-stations currently provide 78% of the electricity needs in France - a world record in terms of percent energy generation. All 58 reactors remain in service today. The creation of Valtimet, a French welded tube manufacturer nearly 40 years ago, was closely linked to this new-born nuclear program. The primary objective of this collaboration was to provide steam surface condenser tubes for all French power stations. Valtimet's close collaboration with EDF (French Electricity Society) remains active today.

In its most fundamental form, the steam surface condenser represents the primary shield preventing cooling water from contaminating the controlled chemistry steam loop flowing through both turbine and steam generator. As a consequence, tube leaks must be avoided at all cost. Condenser tubes are subjected to hostile environments that may include corrosion, erosion and potential vibration issues. As a result, proper material selection must be adapted to not only the design concepts but the cooling water characteristics. It is clear that tube material changes are sometimes necessary due to degradation or other foreseen or unforeseen events.

This paper intends to review the 40 year materials history for condenser tubes and tube plates within the EDF system. In particular, we shall evaluate reasons and observations which resulted in material and design changes, for both sea-water and fresh-water powerplant condensers. Despite the material and design choices, EDF renovation techniques will also be described on specific case studies as well as all the precautions taken during retubing, with the maximum safety against tube leakage.

Condenser Materials History – Fresh Water

At the beginning of the French nuclear program, fresh water condenser tubes were manufactured from brass alloy materials mechanically expanded into carbon steel tubesheet plates. The tube grade chosen by EDF was Admiralty Brass [B70/30AS, UNS C44300 (for loop circuit only)]. Following several operational cycles, tube material degradation symptoms were identified causing not only localized tube wall loss but more pronounced leaks resulting in entire tube failures. We can categorize these phenomena as the following.

Abrasion

Abrasion by cooling water flow can cause a localized or constant thickness loss over the tube ID surface. This phenomenon is more obvious in open-cooling loops. This excessive wall loss can ultimately result in tube leaks but typically reduces the proper tube frequency promoting vibration-zones that can cause tube failure thru fatigue cracking. In addition, brass tubes are susceptible to a vortex phenomenon (vena contracta) which increases localized inlet water velocity causing an erosion-corrosion event on the tube ID.

Steam Erosion

Steam erosion and damage to the brass tubes was noted during the early operational cycles of various units. As a result, anti-erosion grids composed of 304 stainless steel tubes were rapidly installed and visual-tactile test campaigns were scheduled. Any tube having abnormal roughness was preventively plugged. This was an interim step as replacing the impact tubes with more resistant but not immune titanium or stainless steel tubes (0.5mm/0.020" wall and 0.7mm/0.028" wall for impact tubes), to reduce steam erosion would result in considerable expense.

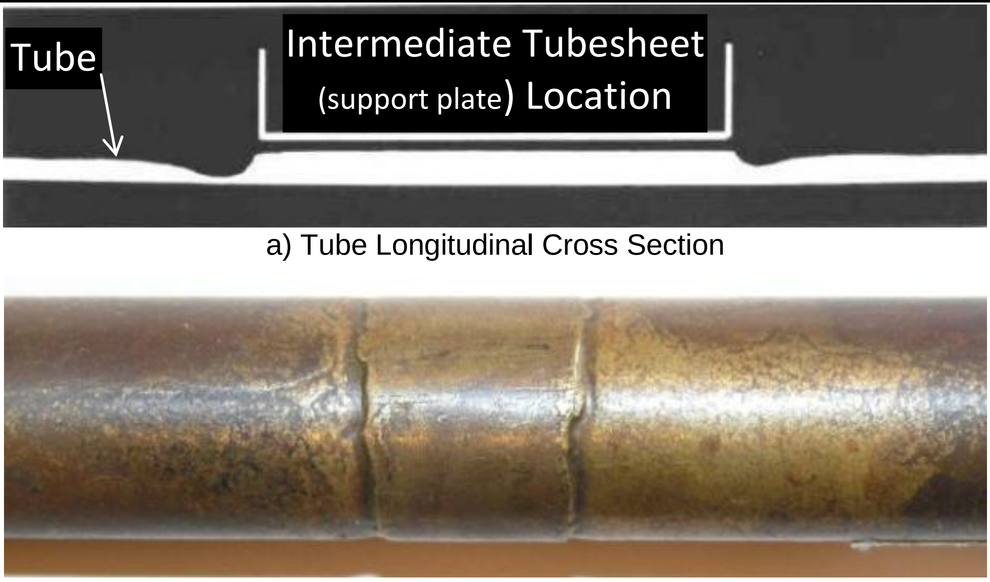
Stress Corrosion Cracking (SCC)

Stress corrosion cracking (SCC) of the brass tubing was also observed on the cooling water side at the expansion interface of the tube-to-tubesheet joint. This observation led to the enforcement of a new rule: the hardness increase during expansion process (i.e. the difference of hardness between tube cold worked surface, and regular tube surface) must be limited to +30 HV5 (Vickers Hardness), for regular brass tubes of ~100 HV5, with serration.

Ammonia Corrosion

It was confirmed that the most severe degradation observed on the first generation brass tubes justified replacement with stainless steel because of ammonia-induced SCC. Hydrazine is often used for hotwell oxygen scavenging and breaks down into non-condensable ammonia liquors. This ammonia steam can accumulate in the air cooling zone and promote ammonia grooving of the copper alloy tubes at the tube/support plate interface stress point. A consequence of ammonia-driven SCC is shown in Figure(s) 1 & 2 (B70/30A Brass) and can result in tube leakage if not detected in time. Stainless steels and titanium tubes are of course not subject to ammonia corrosion.

Figure 1: Ammonia-corrosion on a B70/30AS tube[2]



a) Tube Longitudinal Cross Section

b) tube external view

Most of the above described ammonia-induced illnesses are inherent to brass condenser tubing material. The palliative or immediate remedies such as tube plugging, anti-erosion grids or tube lining were not considered long-term solutions. These fixes could temporarily prolong the condenser life until the scheduled renovation. Moreover, brass tubes required a regular maintenance inspection and follow-up as further degradation was anticipated. This additional maintenance included both visual and physical inspection and testing including accelerated

NDE campaigns. It was concluded that when 50% of brass tubes wall thickness loss was reached, a condenser renovation procedure would be engaged.

Stainless Steel Tubes

Austenitic surface condenser tubes produced as 304L were used from 1981, especially for both the impact tubes (erosion issue) and the air-cooling tubes. Ferritic TP439 tube material was also tested in 3 powerplants. However, pitting corrosion was soon observed on both 304 and TP439. As a consequence, 316L has been used from 1989. Most of the 316L tubes are still in service today (more than 21000 km's / 69 million feet).

Duplex Tubes

After almost 20 years of service with 316L impact tubes, EDF switched its preferred material to Duplex 2205 in 2007 (first used at Chinon Station). A compelling reason for this change was an increasing and problematic calcareous scaling of the tube ID. In addition, the cooling water continued to evolve appearing to increase its corrosion potential as a predictable cooling medium.

Duplex 2205 tubes have actually shown practical advantages for the plant operator. The duplex material has higher mechanical characteristics (toughness) which make the tubing operation easier: tubes remain straight and do not grip during insertion into plates minimizing the tendency to gall. Considering the fact that considerable past tube degradation was caused by improper precautions during condenser stoppages (tube cleaning, drying, etc.), the duplex material is predicted to better cope with such conditions as a result of its improved corrosion resistance over 316 and the brass alloys. Finally, duplex 2205 represents an interesting technical-commercial alternative to both 316L and titanium. To date, more than 4,300km's (14 million feet) of duplex tubes are in service offering a trouble-free return in the experiment.

Brass Tubes – A Return

For environmental and legislation reasons linked with limitations to water treatment, today, EDF is reconsidering a return to brass tubes at certain specific power-stations. Actually, brass tubes are combined with duplex tubes, for the biocide effect provided by copper ions released into the circulating water loop. These installations are limited by the following strictly enforced EDF doctrines.

1. Brass is used only in case of necessity. It is not used in the air-cooler or impact zones of the condenser
2. Brass tubes must be welded and not seamless (seamless brass tubes have been identified with recorded metallurgical defects as well as stress corrosion cracking issues)
3. Hardness increase after expansion must be limited to +30 HV5
4. The tube plate epoxy coating is extended inside the tubes to protect inlet and outlet from abrasion

Condenser Materials History – Sea Water & Titanium

In France, the original design for sea water cooled nuclear power-plant condensers has carried forth even to present day designs. The most important aspects of this design includes the following.

- → **Tubes:** ASTM B-338 Gr. 2 welded titanium
- → **Tubesheets:** Copper Aluminum 5% Nickel (Cu Al9 Ni5 Fe3 Mn) tubes mechanically expanded

→ **Tubesheet Design:** Double or honeycomb tubesheet employing deionized water circulation

The new generation powerplants such as the Flamanville (EPR) are designed with stainless steel plates and titanium cladding on the cooling water side. This concept is used to allow tube-to-plate welding and expansion as titanium can only be welded to titanium. Given titanium's acknowledged immunity to cooling water corrosion activities, the material can experience issues not typically associated with the brass alloy family.

As noted above, the main issue is not corrosion as titanium is totally immune to such conditions that exist in the cooling water. However, vibration-associated events can be triggered that would place the condenser in harms way. There can be 3 types of vibratory failures.

1. Fatigue rupture of a tube which is excited to the proper (natural) frequency
2. Fretting between tubes along a specific generatrix,
3. Radial wear-out at the intermediate plate junction. To prevent these failure modes, plastic or metallic laths are usually inserted between tubes.

Secondly, the use of titanium tubes, coupled with a component of a less noble material (tubesheets or waterboxes in Cu or carbon steel) can precipitate a galvanic activity issue. This phenomenon can appear when both materials are in intimate contact and immersed into the cooling water (no coating). To limit or mitigate this risk, current best practices employ the use either a sacrificial or a cathodic or impressed current (IC) protection system. However, cathodic protection is a highly engineered product requiring an elevated level of know-how or expertise. Clearly, if not designed and operated properly with automatic potentiometer control, elevated SCE levels can exceed recommended thresholds and lead to titanium polarization resulting in a potential excessive hydrogen absorption risk. The results of this may include hydriding and a loss of titanium ductility. This hydriding can apply to both titanium and the more noble stainless tubing materials.

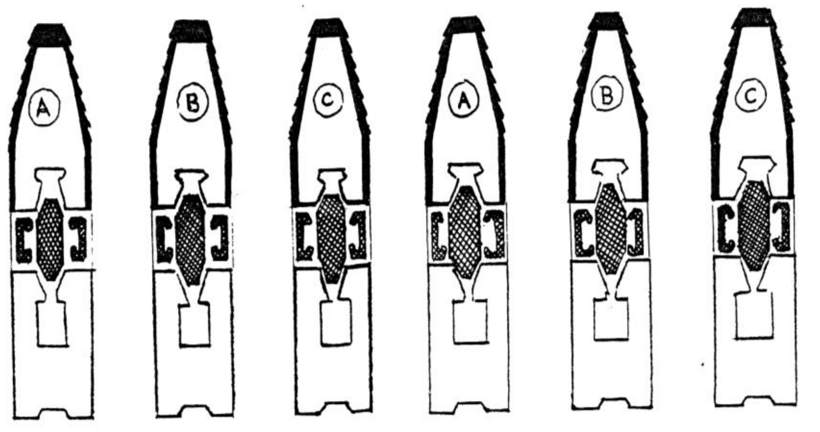
EDF is fully aware of these issues and their respective remedies. Yet despite these items, titanium tubes have left a perfect return of experiment, with absolutely no corrosion observed since 1980.

Retubing Method History

As explained earlier and as part of a comprehensive maintenance program, EDF orders periodic NDT campaigns. Comprehensive reports are submitted to maintenance experts who schedule a condenser renovation if specific indicators are reached (such as 50% thickness loss) Renovations were initially modular retubing then evolved in some cases to the "tube-to-tube" retubing technology.

To understand the different retubing methods, an explanation of the different condenser designs is necessary. The first generation of power-plant condensers (CP1) had "cathedral shaped" tubes bundles (Figure 2). "Reboiling" or reheat steam was necessary to allow the incondensable products extraction (by fresh steam injection at the condenser bottom), especially considering that there was no deaerator on CP1 design.

Figure 2 [1]



CP1 Cathedral Design

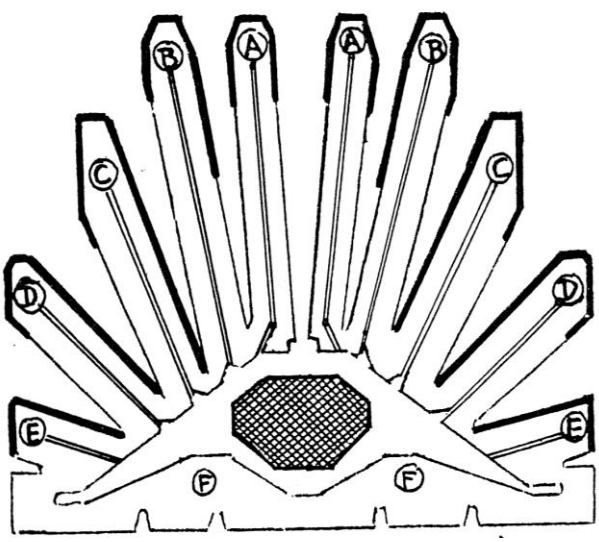
When renovation on those first generation condenser became necessary, follow-on bundle design iteration was developed entitled the “radiant” concept (Figure 3). The modular renovation method on those CP1 condensers was the traditional method used. This process changes out or replaces the existing tube bundles with redesigned and upgraded entire modules including new tubes, tubesheets and support structure. Clearly, this promoted improved performance by including the upgraded “radiant” bundle renovation design.

The main benefits of using the radiant design were:

- → Overall 6 MWe performance gain
- → Improved extraction of incondensable products, allowing removal of reboiling, and to gain about 6 MWe again.

The total, overall gain was about 12-14 electric MW, after a “modular” renovation on each CP1 condensers with the “radiant” design.

Figure 3 [1]



CP2 Radiant design

When the second generation of power-plants condenser (CP2) needed renovation, a technical-economical analysis did not justify an entire modular replacement, and some innovations permitted to proceed to tube-to-tube replacements. Indeed, the tubes bundles were already optimized with a “radiant” design, and the sites already possessed deaerator on the water loop.

Original tubesheets were in carbon steel. For modular renovations with stainless steel tubes, the new tubesheet installed were in carbon steel with stainless steel cladding. Serrations into plate bores and tube-to plate welding were performed to enhance sealing and pull-out loads. For tube-to tube replacements, provided the old carbon steel plates were in good condition, the tubesheets were not replaced but coated with epoxy. For the duplex tubes, it was necessary to change the tubesheet material: the steel must have minimum 480 MPa Yield strength (69.6 ksi), to obtain a correct mechanical expansion of tubes into plates.

Current Retubing Efforts – Methods & Organization

A typical CP2 condenser represents a minimum of 70,248 tubes (Figure 4). A single retubing operation represents anywhere from 35,000 (half a condenser) to 70,000+ tubes where all work must be performed during a maximum outage window. In order to complete all work during this schedule, 3 shifts of 60 to 80 persons (either 2x10h or 3x8h) are employed by the retubing company.

Figure 4: CP2 condenser tubesheet[3]

At this point in the paper, certain specific particulars of the EDF French retubing method should be highlighted. This is not meant to be an all encompassing statement but merely identifies critical areas that are required proven to be successful in the retubing operation.

No 1: The retubing company is required to be fully compliant with both the EDF and the Specification requirements.

No 2: The retubing company must offer a “turn-key” solution including logistics, handling, scaffoldings and all auxiliary and integrated services.

No 3: All retubing is performed tube-after-tube, one tube at a time. This insures better visual control and limits the risks regarding an Eddy Current control extention.

No 4: The condenser shall remain fully open including but not limited to man-holes and ingress and egress entry ways (figure 5). This practice has proven to be advantageous allowing improved access facilitation, enhanced lighting, better aeration and improved safety issues relating to entry/exit, evacuation, etc.

Figure 5: Open condenser view [3]

Specific NDE Testing

The tubing is performed employing an elevating platform, in front of the tubesheet, to allow a tube insertion in a convenient position, thus avoiding external shocks and pinching. After tubes insertion, expansion (welding for titanium tubes), non-destructive Eddy Current (NDE E-C) inspection is performed on a random basis. Each tubesheet is divided into 6 lots; on each lot (generally, about 2000 tubes), 10% of the tubes are inspected (100 to 200 tubes). For each lot, if more than 2 or 3 tubes (depending on the size of the lot) are not acceptable, the control is extended to 100%. Any rejected tube must be replaced, whatever the external defect nature is.

For the duplex tubes, the internal probe is of coil type with a permanent magnet (Figure 5). The control mode is differential. This control is performed in two steps. First, a basic frequency is used to detect eventual defects. The threshold level is 0.5 V, on a 0 - 2 V scale. This threshold tension corresponds to a critical reference defect (visual-tactile reference defect). Then, when a defect is detected, a “quadrature” (phase-shifted) frequency is added, to distinguish internal defect from external defects. If internal, the tube is imputed to the tube supplier, and replaced. If external, the detected defect is of the retubing company responsibility.

Figure 6: Eddy Current testing [3]

This control is very restrictive, because if more than 10% of the tubes are rejected, control extensions to 100% are triggered and it delays the whole operation. A consequence of this strain was the development of Valpack® offer.

Valpack®" Retubing Optimization

In collaboration with EDF, Valtimet has developed a special service offer identified as Valpack®. This offer presents several process service improvements over current retubing practices. It is designed to provide the maximum support and security to both the site contractor and utility alike during the duration of the retubing operation. Among others, several examples can be identified that have proved to be particularly invaluable at the jobsite.

In collaboration with the utility, the retubing company and the Valpack® optimization concept, additional process steps can further strengthen the retubing operation. The below items are merely noted at this point in the paper as specific particulars of the EDF French retubing program and not meant to be an all encompassing statement. They merely identify critical areas that have proven to be successful and could be considered by others to reinforce project goals.

- Internal Eddy Current probe inspection (ID E-C) is performed by an independent third party directly at the tube manufacturing facility and prior to shipment (boxing).
- Special packaging includes a metallic box frame to secure transport, handling and stacking of the tube boxes.
- A Valtimet staff member is present during the discharging (unloading), box opening, tube removal and tubing operations. This presence can augment and insure Best Practices Guidelines are enforced potentially avoiding problems and resolving conflicts between the participants. Potential tubing problems are better resolved at the source rather than later.

Case Study 1 - Renovation in Duplex, Chinon B4 unit

The Chinon B4 reactor was went commercial in 1988. It was originally designed with brass tubes except for Impact and air cooler tubes made of ferritic TP439 . In 2008-2009, the limit of 50% wall thickness losses has been reached and the renovation process was then triggered. This total renovation started in 2010 to replace brass & TP 439 tubes with duplex tubes employing the tube-to-tube replacement.

Eventually, 100% of the condenser was renewed which represented 70248 tubes of 20 mm OD, 0.5 and 0.7 mm wall, 13.6 m length, distributed into 4 bundles of single compartment design. This intervention also included a tubesheet replacement, and a water-boxes and tubesheet coating.

In terms of the retubing organization & schedule, the first phase, namely tubes removal and replacement, was performed in three, 8 hour shifts, 6 days a week, during 25 days. The remaining intervention was performed with 2 shifts. Within 45 days, the condenser tubing changeout was complete. Tube expansion and Eddy Current testing was performed to allow watering the steam-side for hydro-test. After 57 days, half of the condenser was coated, allowing restarting one CRF pump if needed. The intervention was finished after 69th days.

Case Study 2 - Renovation in Titanium, with on-sites orbital welding - Cattenom 4

This tube-to-tube renovation was performed in 2010, on 1/6th of Cattenom 4. In total, 21,414 tubes of 18 mm OD, 0.5 and 0.7 mm wall, 13.75 m length were replaced (also in single compartment design). In addition, two tubesheets, and two water-boxes were coated. An innovative on-site, tube-to-tubesheet orbital weld procedure was a première event and gave a very good return of experiment. Tubes were in titanium Gr. 2 and plates were titanium clad carbon steel. A 100% die penetrant inspection of the welds on both tubesheets plus a final static hydro test validated the condenser leak tightness.

A total of 56 days (8 hours shifts, 6 days a week) were necessary to perform the complete retubing operation, testing, waterbox coating and a return to unit leak tightness.

Figure 7: on-site orbital welding [4]

Summary & Conclusion

The paper provided a brief overview of the 40 year materials history for condenser tubes and tube plates within the EDF system. We also evaluated, in particular, reasons and observations which resulted in material and design changes, for both sea-water and fresh-water powerplant condensers. Specific material selection criteria design choices and EDF renovation techniques were covered using specific case studies. Of paramount importance throughout the exercise were precautions taken during the retubing with maxim emphasis on safety against tube leakage.

In collaboration with EDF, Valtimet developed and expanded on special service offers identified as Valpack®. The offer purports to present several process service improvements over current retubing practices designed to provide maximum support and security to both the site contractor and utility alike during the duration of the retubing operation.

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