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Technical challenges of retubing the Électricité de France (EDF) Belleville Unit 2

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Belleville Nuclear Plant is a PWR operated by Électricité de France (EDF). Since beginning commercial operation in 1989, it has been rated at a nominal capacity of 1,300 MW. The turbine unit consists of one high pressure (HP) and three low pressure (LP) turbines.

Belleville station is cooled by two large cooling towers. Each condenser consists of 6 bundles serving the three low-pressure turbines. Each bundle contains 21,242 tubes, that are 13.75 m (45.1´) long.

Project description

The work consisted of retubing three condenser bundles, each having 21,414 tubes 13.750 m long (45.1´). Six tubesheets were replaced, each one measuring approximately 4.4 x 4.4 m (14.4´ x 14.4´). See Figure 2.

The tubesheets were reverse engineered from scanned copies of old drawings. EDF required an analysis be performed to verify the tubesheet's strength with thin wall tubes and with a postulated increase in hydrostatic pressure. A pullout test was performed to demonstrate that leak tight joints could be produced to satisfy EDF's criteria.

Materials chosen consisted of two bundles of 1 mm (0.039˝) CuZn30As (similar to arsenical admiralty) tubes, and one bundle of 0.5 mm (0.0197˝) X2CrMoNiN 22-5-3 duplex stainless steel tubes. Peripheral tubes and air cooler sections in all three bundles were tubed with 0.7 mm (0.0276˝) duplex stainless tubes. EDF plans to use duplex stainless tubes for all the tubes in the mid- to long-term; however, they decided to keep two of the three bundles in brass due to its proven biocidal nature until

Figure 1. Belleville Nuclear Station

Figure 2. Tubesheet awaiting installation

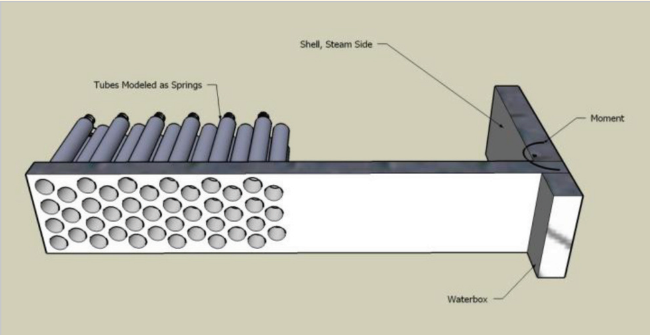

Figure 3. Beam strip model representation (horizontal strip shown)

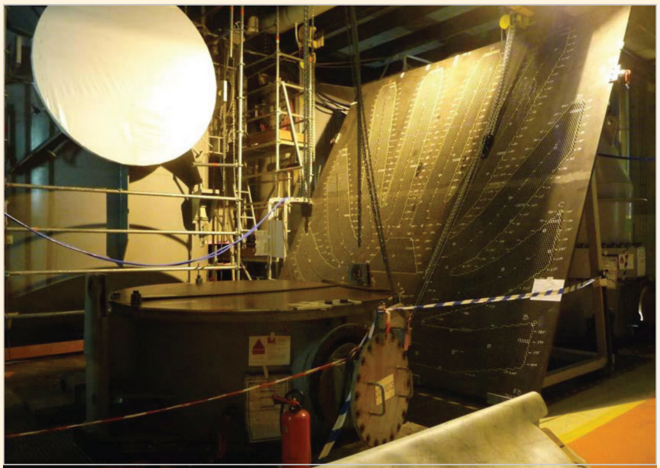

Figure 5. Outlet tubesheet awaiting final placement

Figure 6. Tubesheet target illuminated by laser 5

further experience is gained with the stainless steel tube material.

Technical challenges

Major technical challenges included:

- Performing a tubesheet stress analysis on the tubesheets using a higher hydrostatic pressure and thinner wall tubes.
- Assuring new tubesheets were drilled identically to the existing tubesheets.

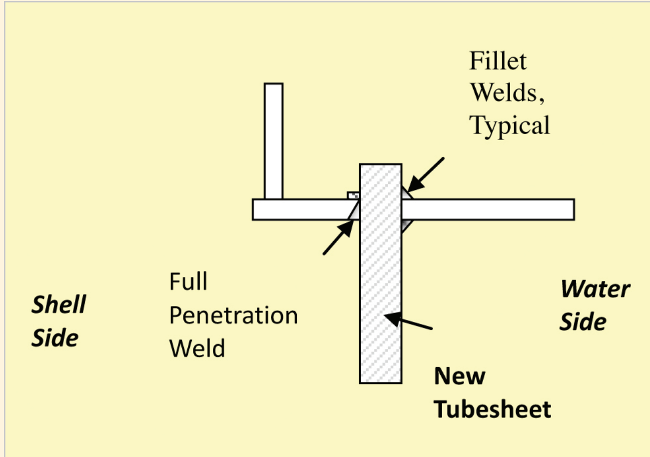

Figure 4. New tubesheet attachment

- Aligning new tubesheets to the support plates accurately and efficiently.
- Rolling brass tubes into the tubesheet with acceptable work hardening of the material.
- Selecting torques that would provide leak tight joints and demonstrating this in shop tests.
- Preventing tube vibration.

Meeting technical challenges

***Tubesheet stress analysis* –** The tubesheet stress analysis demonstrated the thin wall tubes would provide adequate support for the tubesheet and ensured an acceptable safety margin to preclude any potential failure. The analysis was performed with a tubeside pressure of 5 bars (72.5 psi), well above the design pressure of 2.9 bars (42 psi), using 0.5 mm stainless tubes in the main condensing zone and one row of 0.7 mm stainless tubes in the periphery.

The Heat Exchange Institute's Beam Strip Analysis provided the methodology. The tubesheet is modeled as horizontal and vertical strips extending from the edge of the tubesheet. Each tube is modeled as a spring supporting the tubesheet. See Figure 3.

***Reverse engineering of tubesheets* –** Reverse engineering was used to create new CAD based drawings for manufacturing the new tubesheets. In addition to recreating the old drawings, it was necessary to address other key factors. The first issue was that of material. The original tubesheets were manufactured to AFNOR E.26.3-A36; a specification replaced by new European standards. It was recommended that the plates be fabricated of P295GH steel, which is similar to A-516, Grade 70 steel.

The original tubesheets were welded flush on the outer perimeter with the waterbox and shell; however, given access, time and fit-up constraints, the joint was redesigned to utilize a slightly larger tubesheet connected to the shell with a full penetration weld from the inside of the condenser. The additional width of the tubesheet permitted drilling of holes to mount lifting hardware for rigging the tubesheets into position.

Several months prior to the outage, a study was made which showed there was less than 15 cm (5.9″) of clearance to rig the new tubesheets into place. Due to careful planning, the tubesheets were successfully rigged into position. Figure 5 shows the tubesheet rigged to move behind the large waterbox.

To recreate the tubesheet drawing, the locations of various holes were shown on the original drawing. Using these locations and a diagram detailing the tube pitch, the location for each tube relative to another was determined, and a CAD image created of the original tubesheet. To ensure the new tubesheets matched exactly, Power Resources independently verified each tube hole location and dimension.

Aligning tubesheets – Exact positioning of the new tubesheets was essential. If the tubes were difficult to push, it would slow progress. If the tubesheets were not aligned properly, the tubes could become scratched from forcing them through the tubesheets and support plates, causing them to fail eddy current testing.

A variation in condenser design was noted. To allow draining of the tubes, the condenser was constructed with a 0.5 percent slope. Therefore, the tubesheets and support plates are not vertical, but perpendicular to the sloped tubes. To ensure the tubesheets were placed in their original plane, stop blocks were welded inside the waterboxes and the shell against the existing tubesheet. After waterboxes and tubesheets were cut from the condenser, the new tubesheets were placed tight against these blocks.

To align the tubesheet holes with the support plate holes, DZ Atlantic and Power Resources developed a prototype laser alignment system of 5 lasers mounted in the support plates. Mounted three support plates away from the tubesheet, the laser self-centered in the tube holes and was adjustable both horizontally and vertically. Five targets were located on the support plate closest to the tubesheet, and 5 targets were mounted on the outside face of the tubesheet.

The lasers were aligned with the first set of targets centered in holes on the support plate. The beams passed through these targets to the second targets located in corresponding holes in the tubesheet. By observing the location of the beam on the tubesheet targets, it was possible to determine what adjustments were needed to align the tubesheet with the support plate holes.

As a result, all 6 tubesheets were aligned quickly with less than 3 mm deviation in any tube location.

An example of a target with the laser illuminating the crosshairs is shown in Figure 6. Note that the backscat-

ASME Power Division: Heat Exchangers

A Message from the Chair

The ASME Power Division's Heat Exchanger Committee is a dynamic forum organized to advance the art and science of heat exchanger technology in the power generation industry. Through peer reviewed technical publications, panel discussions, meetings and short courses, the committee organizes the introduction of innovations in relevant technology, case and application studies and industry best practices, which are shared with ASME members, conference attendees and the public domain.

During the year, committee members interact with each other to solve operation and maintenance issues on the systems and equipment within this committee's focus via phone calls and/or e-mail. The committee is developing an interactive ASME Peerlink web based forum/bulletin board as a resource for exchange of information among our members. We invite you to join us at our meetings, simply contact me, another ASME member you know or the Heat Exchanger Committee Membership Coordinator, Jim Mitchell, at JEMPlastocor@aol.com or 724-942-0582.

This committee explores and disseminates specific state-of-the-art and technically diverse information focusing on, but limited to, related areas for: steam surface condensers, air-cooled condensers, balance of plant (BOP) heat exchange equipment, service water heat exchangers, feedwater heaters, cooling towers and heat exchanger construction materials.

Our committee members are knowledgeable, committed and include a cross-section of industry acknowledged experts in their respective fields. The committee maintains active relationships with other industry organizations such as HEI, EPRI, ASTM and CTI. This interface ensures a continuous and timely update of information on standards, codes and industry events. We meet twice annually to organize the delivery of valuable conference content.

Thank you and please consider joining us. When you have the opportunity, check our website at *http://divisions.asme.org/Power/Heat_Exchangers.cfm.*

Sincerely,

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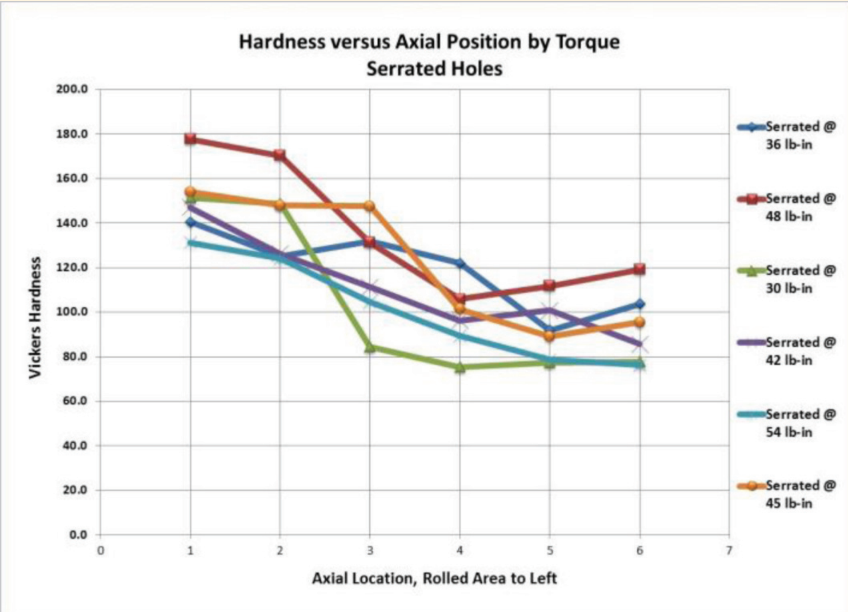

Figure 7. Axial hardness readings

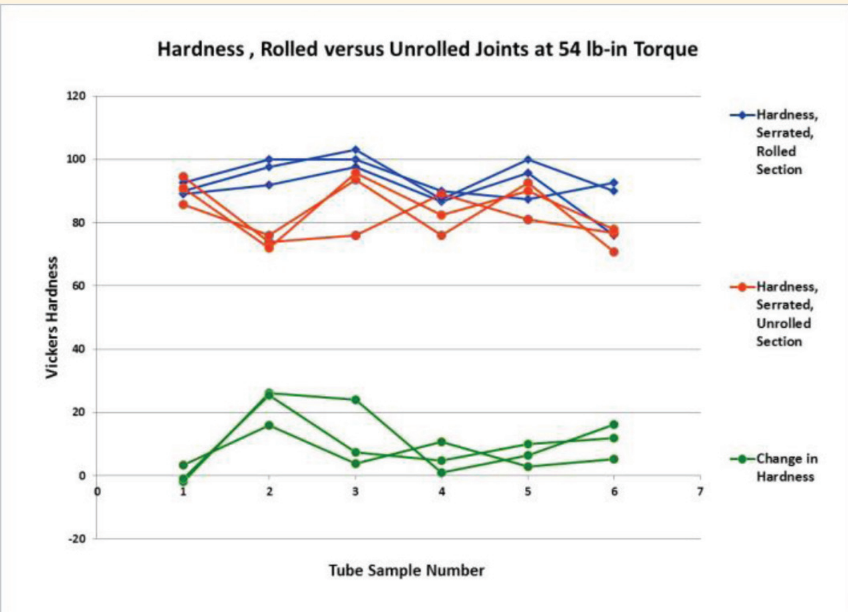

Figure 8. Hardness retest results

tering shown in the photo was minimal when viewing the target with the unaided eye.

Rolling brass tubes and avoiding work hardening – EDF's experience with brass tubes shows a strong correlation between the hardness of brass tubes and their susceptibility to ammonia-induced stress corrosion cracking.

Using the Vickers hardness scale designated Hv, EDF required that tube hardness due to rolling did not increase more than 40 Hv, or less than 20 Hv, with an average increase between 25 and 30 Hv. To measure this, tubes used in pullout testing were split after extraction, and the hardness measured at 12 locations on each half tube – 6 measured in the rolled zone and 6 measured in the unrolled zone. Tubes also had to meet minimum requirements for pullout strength and leak tightness.

The pullout tests were designed to determine the best torque values for tube expansion. Tubes were rolled into mockup tubesheets at various torques, and then pushed out of the tubesheets to determine the force required. It was discovered that the force required to push the tubes out created more work hardening than the rolling operation itself. The following graph (Figure 7) illustrates the effect of the pullout test on the hardness.

Based on this evidence, additional tubes were expanded into a mockup tubesheet at torque levels of 54 and 60 in-lb (62 and 69 Kg-cm), cutting the tube behind the tubesheet, and sawing a slot axially in the tube to allow removal from the tubesheet. These sections were hardness tested.

Results of the retest were dramatic. Previously, at 54 lb-in, the maximum hardness reading in the rolled section averaged 130 Hv, and the average in the unrolled section was 83 Hv. These values declined to an average of 92.4 Hv in the rolled section and remained nearly constant at an average of 83.1 Hv in the unrolled section. The increase between the rolled and unrolled section was less than EDF expected, but was considered an improvement compared to the specified values. The high pullout strength with serrated tubesheet holes allowed a lower torque to be used than if smooth tubesheet holes had been used; this, undoubtedly reduced the amount of work hardening due to rolling. A sample of the retested hardness data is shown in Figure 8.

Selecting the optimum rolling torque to provide leak tight joints – A pullout test was performed for each tube material and wall thickness to determine the optimum rolling torque for tube expansion. The test tubes were rolled into a mockup tubesheet at a range of torques and then pressed out using a hydraulic ram. The pressure in the hydraulic line was monitored with a digital pressure gauge that recorded peak pressure readings 5,000 times/second. Peak pressure occurs at the point where the tube begins to slip in the tubesheet. Using the area of the hydraulic cylinder's piston and the peak pressure, the force required to break the tube loose can be calculated. Dimensions of tubesheet hole diameters, tube wall thicknesses, and rolled tube inside diameters are recorded. This data is reduced to graphs showing apparent wall reduction vs. torque, pullout force vs. apparent wall reduction, and pullout force vs. torque.

The DZ Atlantic practice uses Excel spreadsheets with various graphs preprogrammed so that as data is entered in the computer, the graphs are automatically created. This allows the immediate review of trends. In some cases, it alerts the engineer early to conditions that warrant a change in the test protocol.

Figure 9 is an example of data provided to the customer upon conclusion of the test. In this case, the serrated holes, as-machined smooth holes and holes with a better finish were compared. The as-machined 'smooth' holes in the test plate were estimated to be 250 rms finish and the 'polished' holes were estimated to be better than 125 rms.

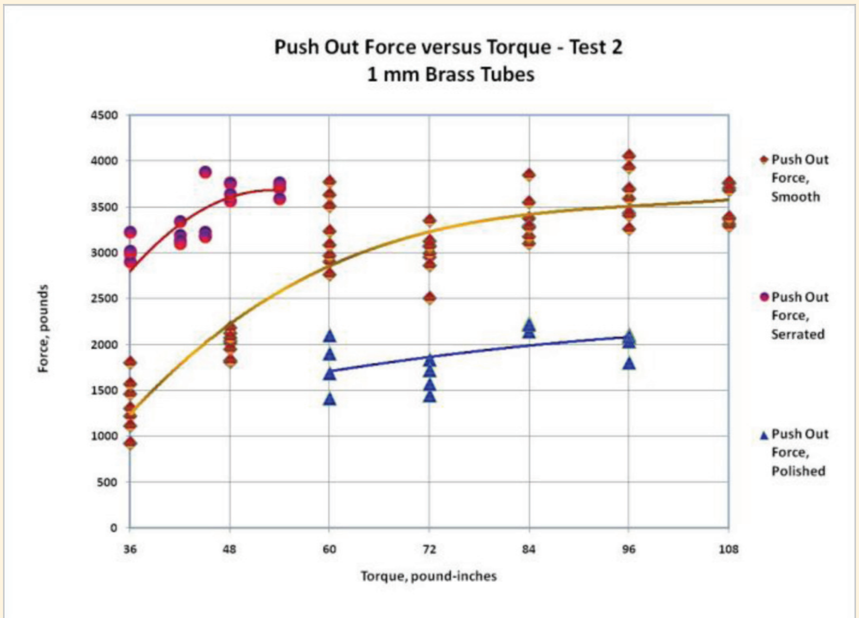

Figure 9. Pushout forces at various torques

The recommendation was made to roll the tubes at 54 in-lb (62 Kg-cm) of torque in serrated tubesheet holes based on the combined results of the pullout and hardness tests.

Figure 10. Test plate bolted to pressure chamber

Figure 11. Leak test in progress

Following the pullout testing, EDF required additional testing to demonstrate the leak tightness of the tube-to-tubesheet joints made at the recommended torques. The test protocol was to roll 40 tubes into a test tubesheet at the nominal torque and at plus and minus 5 Kg-cm. A plug was welded into the end of each tube. The test plate was manufactured with normal, undersized and oversized holes. A rim was machined in the top of the tubesheet to hold water. After rolling the tubes into the tubesheet, the tubesheet was bolted onto a small pressure chamber and pressurized with air to 1 bar (14.7 psi) and the upper end of the tubesheet covered with water. The joints were observed for leaks for 30 minutes. Separate tests were done for the brass, the 0.5 mm stainless and the 0.7 mm stainless tubes. Figure 10 shows the test plate and chamber ready for the test. Figure 11 shows the test plate during the test.

No leaks were observed in any test. After the leak test under water, the water was drained, the chamber was depressurized, and then filled with helium to a pressure of 1 bar (14.7 psi). The helium test did find small leaks emanating from inside two tubes where the plugs were welded into the tubes. These leaks were easily isolated from the joints and no leaks in the tube-to-tubesheet joint were found.

Preventing tube vibration – When installing thin wall tubes in condensers, the potential for tube vibration must be considered.

The Heat Exchange Institute Standards provide guidance on allowable support plate spacing to prevent vibration damage. If the calculations with a new tube material show that the maximum allowable spacing is less than the actual support plate span, staking is needed. In the case of Belleville, EDF designated where stakes were to be installed based on their internal criteria. DZ Atlantic produced its Cradle-Lock®. Using a mockup of three bays of tubes which duplicated the tube hole diameters, support plate spacing, tube pitch and tube material, the stakes were designed and tested. Using a raised 'dimple' on each side of the stake, Cradle-Lock's design prevents the tubes from sliding parallel to the stake (Figure 12). This 'dimple' provides an area of contact both above and below the tube to lock it in place. This is in contrast to most stakes which provide only line contact with the tubes.

Belleville was staked from top to bottom in alternate bays. The staking required the design, manufacturing and installation of a total of 24,360 stakes. Figure 13 shows a typical bay of stakes during installation at Belleville.

Conclusion

The Belleville retubing project provided numerous logistical and technical challenges. However, with planning and teamwork the project was accomplished in the scheduled duration and with excellent results. New tubesheets were successfully reverse engineered and analyzed for

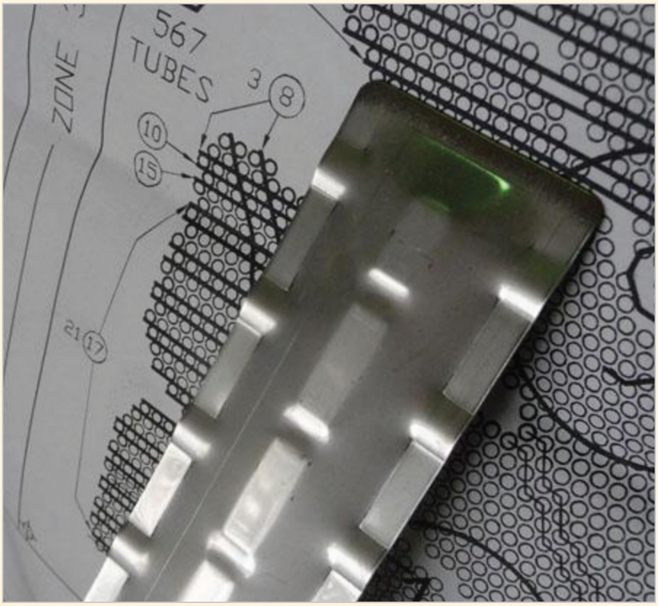

Figure 12. Cradle-Lock® stake

Figure 13. Partially staked bay

stresses with higher design pressures and thinner wall tubes. Through numerous tests, rolling parameters were selected that produced a minimum of work hardening for the brass tubes while providing strong tube-to-tubesheet joints. The rolling parameters produced leak tight joints demonstrated by pneumatic and helium leak tests. Vibration concerns were eliminated by the use of Cradle-Lock stakes. The use of a prototype laser system resulted in excellent alignment of the tubesheets, preventing delays due to difficulty in installing the tubes or creating damage causing the tubes to fail the stringent eddy current testings. In all areas, the project team met the technical challenges through a combination of sound engineering and innovation.

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