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TUBE PULLOUT TESTING EXPERIENCE

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ABSTRACT

This paper provides an overview of the use of pullout testing to determine the optimum parameters for assuring reliable tube to tubesheet joints in condensers and heat exchangers. The test is described with typical test methods, equipment and test precautions. Numerous examples of data from a variety of units, tube materials, and tubesheet materials are presented. Also included are unique tests which were performed to qualify the tube expansion procedures prior to use in nuclear facilities. These tests include mockups for pneumatic and helium leak testing, and hydrostatic testing of mockups with rolled test joints at over 600 psi. Examples will include testing with 3 roll expanders compared to 5-roll expanders in heavy gauge titanium tubes, test results with a double tubesheet arrangement, and high strength joints with thin wall titanium tubes in brass tubesheets. An example comparing the pullout forces determined with a HEI beam strip analysis to the actual pullout test data is also discussed.

INTRODUCTION

Tube pullout testing is an established method for determining the strength of joints between a tube and tubesheet, particularly for roller expanded joints. Although pullout testing does not provide a direct measure of leak tightness, it is often used as a surrogate for leak tightness. This is because a tube-to-tubesheet joint is subjected to a range of forces due to fluid pressure on the tubesheet faces, pressure or vacuum conditions in the shell, and expansion forces associated with temperature changes in the heat exchanger. A joint that has insufficient strength to withstand these forces will eventually fail and leak. Strong joints can be expected to provide long term protection against leaks.

The ASME *Boiler and Pressure Vessel Code* provides methods of calculating the allowable strength of tube-to-tubesheet joints based on the material properties and joint type. These calculations are used for tubes which are used in stayed construction, that is, an arrangement in which the tubes provide support to the tubesheet. This is typical of most straight tube heat exchangers, and is particularly important in the design of surface condensers. Condensers, particularly for large utility steam units are characterized by having large thin tubesheets with a vacuum on the shell side, and pressures on the water side ranging from near atmospheric to 50 pounds per square inch for some cooling tower installations. To withstand these pressure forces would require either thick tubesheets, or the use of other measures to reinforce the tubesheets. Due to the cost of providing thick tubesheets, and, the effort to drill holes in the thick tubesheets, typically the least expensive method is to use the tubes to support the tubesheet.

Over the past two decades or so, there has been a strong emphasis by utilities to replace brass tubes with other materials deemed to be more corrosion resistant. These materials include titanium, traditional stainless steel alloys, and proprietary alloys such as AL-6X, 29-4C, and Sea Cure. These materials do not have the same conductivity as brass, and therefore are generally installed in thinner gauges. Use of the thinner gauge materials may reduce the allowable joint strength. Pullout tests and the analysis of the data taken during the test provides a means of comparing the joint strength with new tube materials to the joint strength used for the original design basis.

Although it is often expected, considering how many tubes have been replaced in condensers and other heat exchangers, that the correct parameters for expanding a tube would be well known, this is not necessarily the case. This is because there are so many combinations of tubesheet materials, tube materials, tubesheet thickness, tubesheet hole diameters, tube gauges, and variations in material strength and tempers. In addition, small differences in the actual tubesheet drilling such as inlet flare depth or the addition of various grooves or serrations may affect the choice of rolling parameters. Finally, the purpose of the pullout test is not to simply determine a rolling torque, but rather is designed to determine the optimum rolling parameters for each specific tube-to-tubesheet joint.

TESTING

Tube pullout testing is generally done by rolling a number of tubes at varying torque levels into a mockup of the actual tubesheet, and then pushing them out of the tubesheet while measuring the force required to remove the tubes. Numerous dimensional measurements are made during the process to allow correlation of the amount of wall thinning of the tube with torque and joint strength. Although the term pullout test is generally used, more typically the tubes are pushed out of the tubesheet during this test.

Mockup tubesheets are specified to be as close to the actual tubesheet as possible. This includes the material, the grade of material, hole diameters, flares or chamfers, hole finish and tube pitch. The number of test holes is often chosen by the customer; however, from the standpoint of the engineer analyzing the data, more holes are always better. Most tests use 50-150 holes, and sometimes use two or more plates. Figure 1 shows a typical mockup tubesheet.

Figure 1 – Typical Mockup Test Plate

When using different materials or gauges for a retubing project, such as for peripheral or air cooler tubes it is important to perform the test on those tubes as well as for the main material. It is also a common practice to drill the mockup tubesheet with some oversize holes. Data from these oversize holes provides useful information in the event a number of such holes are discovered in the field. Tubes used for the tests are typically taken from the same lot as supplied for the retubing.

Prior to performing a pullout test for a retubing, the mockup tubesheet is ‘conditioned’ or ‘work-hardened’ by rolling tubes into the tubesheet similar to the ones that were originally installed and at torque levels similar to what was used for the original tubes. These tubes are then extracted before inserting the new tubes. The purpose of this step is to simulate the condition the tubesheet will be in when the retubing begins. Two changes occur during this step. First, the holes are stretched to a larger diameter, and second, the material of the tubesheet becomes harder and stronger. Following this step, the holes are cleaned and new diameter measurements are taken. If the condenser has been tubed multiple times, it may be necessary to repeat the work-hardening process.

Measurement accuracy is important for a pullout test, particularly for thinner tubes. This is because the wall reduction that occurs as a tube is rolled is very small. For example, consider a 22 BWG tube with a tube wall thickness of .028 inches. If that tube is expanded to 8% wall reduction, the thickness decreases by 0.00224 inches. If the tube is expanded to 10% wall reduction, the thickness decreases by 0.00280 inches. The difference between these two numbers is .00056 inches, or just over ½ of 1/1000th of an inch. Based on diameter measurements, the difference between the two rolled diameters is just over 1/1000th of an inch. Obviously, the need for accurate, repeatable measurements is of paramount importance.

In practice, it is difficult to determine actual changes in wall thickness, so the term Apparent Wall Reduction or AWR is generally used. AWR includes any increase in the tubesheet hole diameter due to rolling. AWR is calculated by the following formula.

$$\text{AWR (\%)} = \frac{[(2 \times \text{wall thickness}) - \text{tubesheet hole diameter} + \text{tube rolled ID}] \times 100}{(2 \times \text{wall thickness})}$$

Note that three measurements are needed to calculate AWR. These are the wall thickness, the initial tubesheet hole diameter, and the final inside diameter of the rolled tube. The tube outside diameter does not affect the calculated value of AWR using this method. Wall thickness measurements are averages of multiple readings taken around the circumference. While it is possible to calculate wall thickness using the difference between the outside and inside diameters, this is usually not feasible with the thin wall tubes used in condensers. This is because slight variations in wall thickness or ovality of the tubes is introduces a greater uncertainty into the measurements than using several direct measurements of wall thickness.

After a set of tubes is expanded into the mockup tubesheet and final dimensions are taken, the tubes are pushed from the tubesheet. Figure 2 shows a test stand used for this process.

In the photo, a mockup tubesheet for a heat exchanger is ready for pushing out the tubes. The tube ends are seen below the steel tubesheet. A hydraulic ram located above will be used to push the tubes out. Typically tube ends are sealed either by crimping or with welded plugs, and then partially filled with sand. Hydraulic pressure is monitored by a digital pressure gauge that records the peak pressure in the system just prior to the tube breaking free from the tubesheet. Using the area of the piston in the hydraulic ram and the peak pressure, the peak force is then calculated.

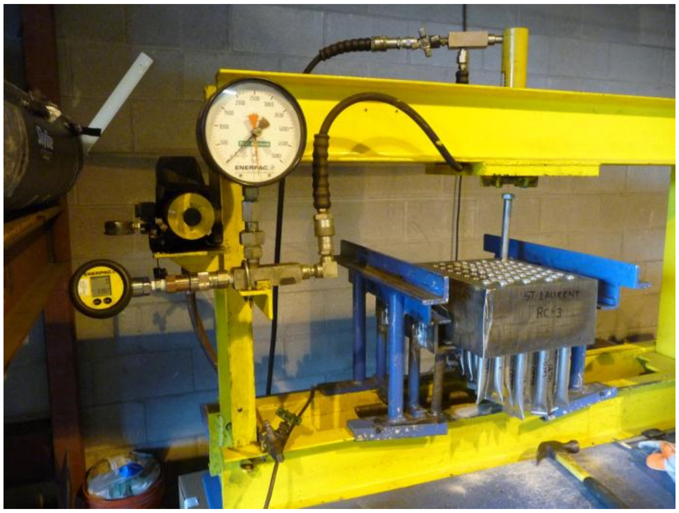

Figure 2 – Test Stand

PRECAUTIONS

There are several precautions when performing a pullout test. First, although the test is not particularly hazardous compared to many routine shop processes, basic safety precautions need to be observed. Personal protective equipment consisting of safety glasses, hearing protection and gloves should be worn for most of the activities. Personnel should be familiar with the hydraulic equipment and safety practices. Where possible, hoses and electric cords should be routed to minimize tripping hazards.

The next precaution is to have a well-defined procedure. This procedure should identify the equipment, materials, and steps to be followed during the test. There are many steps during a test that must be done in sequence, and a procedure is key to proper execution of a test.

Finally, it is important to assure that all equipment is properly calibrated and that the technicians taking the measurements are familiar with the methods of taking accurate measurements with the measuring tools.

ADDITIONAL TESTS

As noted in the Introduction section, pullout tests do not directly measure leak tightness. As a result, some customers have added requirements to the pullout tests for additional tests to verify leak tightness. These include individual tube leak tests, pneumatic leak tests, helium leak tests, and hydrostatic leak tests. Leak tests require that the tube stubs are sealed at the far end with welded plugs.

Individual leak tests are performed with a leak testing device that seals the inside of the tube, draws a gasket tight against the tubesheet, and then pulls a vacuum between the tube and the tubesheet. Any drop in vacuum indicates a leak in the joint. Figure 3 depicts an individual leak tester in use.

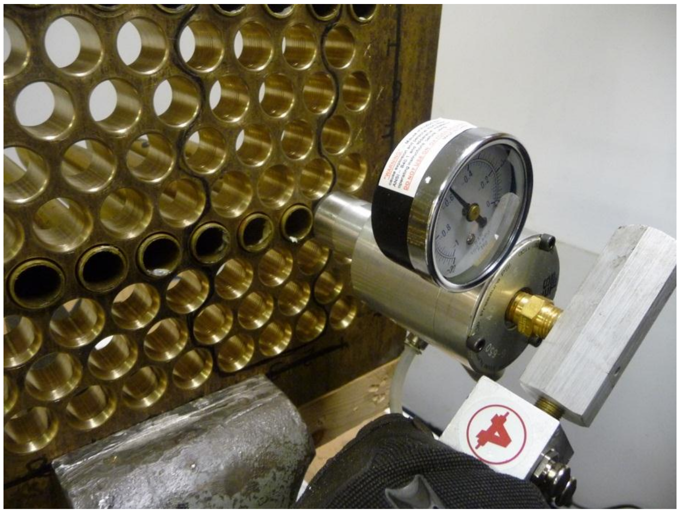

Figure 3 – Leak Tester

Pneumatic tests are performed using a small pressure vessel and a flanged mockup tubesheet. Pneumatic tests are inherently hazardous due to the large amount of energy that can be stored in a pressurized vessel. Accordingly pneumatic tests should only be used at low pressures and with carefully engineered vessels. Pneumatic tests performed in our shop have utilized a machined rim to hold a leak detection solution so any leaks may be detected by bubbles. To date all pneumatic tests have been successfully passed. Figure 4 shows a pneumatic test in progress. This test was performed at a pressure of 15 psig.

Figure 4 – Pneumatic Test

Helium leak tests are another option for detecting very small leaks. To perform a helium leak test the pressure vessel is pressurized with helium. A mass spectrometer is used to detect any leaks. Helium is well-suited to these tests since it is not explosive or corrosive and is well tolerated when breathed by humans. Helium is very sensitive to leaks because it can be detected in very small amounts using a mass spectrometer and because the small helium molecules are able to pass through cracks or pits which would block larger molecules. The only difficulty we have had with helium leak testing of mockup tubesheets was due to small leaks where the far end of the tube was closed with a welded plug. These were relatively easy to isolate, however, and the test found no leaks in the tube-to-tubesheet joints.

Hydrostatic tests are the preferred method for testing for leaks at higher pressures. Hydrostatic testing is inherently safer because water stores little energy due to its incompressibility. Figure 5 shows a mockup tubesheet being prepared for installation in a pressure vessel for hydrostatic testing. This tubesheet had a total thickness of 5.3 inches and was rolled with four steps.

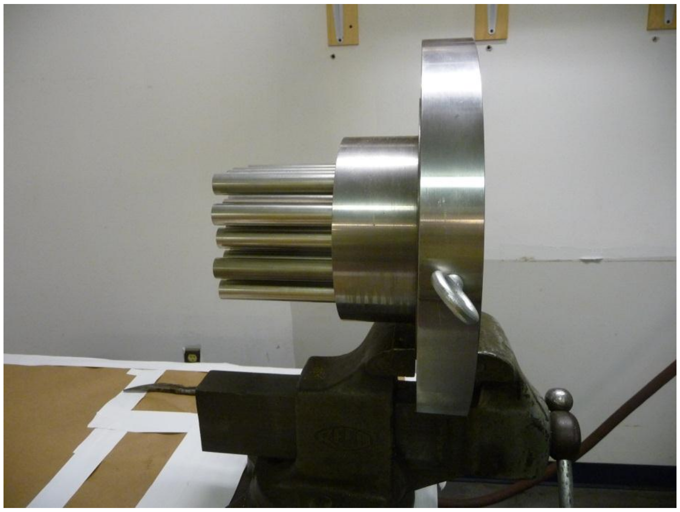

Figure 5 – Tubesheet for Hydro Test

Figure 6 shows the tubesheet bolted into the pressure vessel and ready for testing. This assembly was tested at over 600 psig with no leaks.

Figure 6 - Hydrotest

CASE HISTORIES

Thin Wall Titanium in a Brass Tubesheet

An application that pushed the boundaries of wall thickness that is considered acceptable for application in utility condenser service used 7/8 inch 24 BWG titanium tubes in a 1-1/4 inch thick Muntz metal tubesheet. Prior to installation of these tubes a pullout test was performed.

The test produced very consistent results showing increasing joint strength with increasing rolling torque. Although there is limited experience with rolling 24 BWG titanium into Muntz metal tubesheets, no issues or problems with this combination was found during the test. Interesting findings during this test were made with regard to the use of three different hole configurations -- smooth, single groove, and multi-groove serrated. The single groove configuration did not increase joint strength above that of the smooth hole. In fact, in several cases, the test showed lower push out force was required to extract the tube from a grooved hole than from a smooth hole.

Tubes extracted from holes serrated with the multi-groove tool had significantly greater pullout strength in all torque levels and with both 24 and 20 BWG tubes. In many cases the pullout force was over two times higher with the multi-groove serrations. Figures 7 and 8 are graphs of push out force as a function of torque for the inlet and outlet configurations.

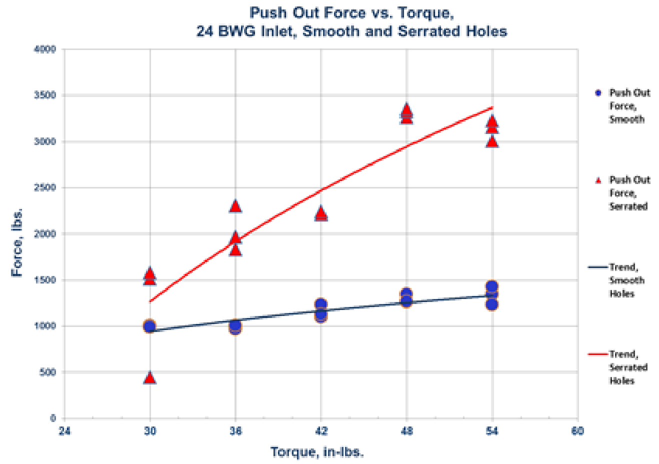

Figure 7- Test Plot - Inlets

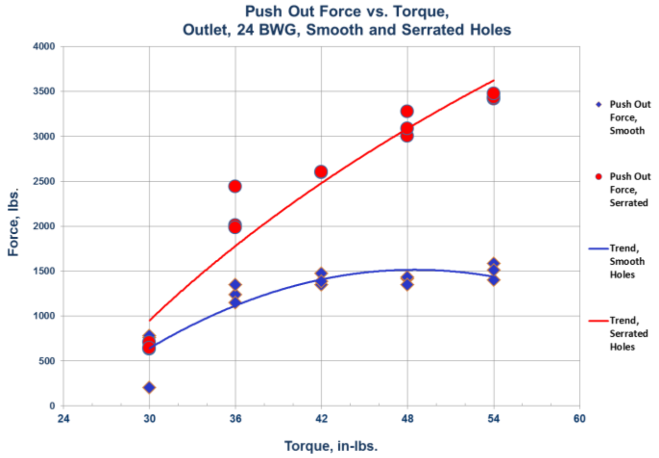

Figure 8 – Test Plot - Outlets

Tables 1 and 2 provide other information on the rolling parameters which were recommended in the report of this test. Although the recommendation was to use serrated holes, the strengths suggest that smooth holes would have provided sufficient strength for this application.

Smooth Hole Data Summary				
Tube Gauge, BWG	**Inlet / Outlet**	**Torque, In-lbs.**	**AWR, %**	**Joint Strength lbs.**
24	**Inlet**	**45**	**12**	**1200**
24	**Outlet**	**45**	**11**	**1300**
20	**Inlet**	**45**	**10**	**1400**
20	**Outlet**	**48**	**10.5**	**1550**

Table 1

Serrated Hole Data Summary				
Tube Gauge, BWG	**Inlet / Outlet**	**Torque, In-lbs.**	**AWR, %**	**Joint Strength, lbs.**
24	**Inlet**	**45**	**18**	**2700**
24	**Outlet**	**45**	**15**	**2700**
20	**Inlet**	**45**	**10**	**3400**
20	**Outlet**	**48**	**11**	**3700**

Table 2

Allowable Loads

The ASME Section VIII, Division 1 provides criteria for establishing maximum allowable joint load that can be used in stay-supported construction. This means that the designer cannot use a higher value for the joint strength when calculating the thickness of the tubesheet. However, joints that have test values that exceed the ASME allowable joint load area always better than ones that meet the calculated value.
The basic equation used is

$$L_{max} = A_t \text{ x } S_a \text{ x } F_e \text{ x } F_r \text{ x } F_y,$$

where,
L_{max} is the maximum allowable axial load on the joint,
A_t is the cross-sectional area of the tube wall in square inches,
S_a is the ASME Code allowable stress in tension at the operating temperature of the material,
F_e is a factor for the expanded length of the tube,
F_r is the joint efficiency. This is a calculated factor equal to $L_{test} / (A_t{*}S_t{*}F_e{*}F_y)$, and
F_y is a ratio of the tubesheet yield stress to tube yield stress, or 1.0 whichever is less.
S_t is the minimum tensile strength of the tube material

For this test the original design basis joint strength (**L**$_{max}$) was calculated based on an assumed joint efficiency of 0.50. A second set of allowable loads (**L**$_{max}$) was calculated from the test data and compared to the original design basis as well as the actual test values. The values are presented in Table 3 below.

	Estimated Original Basis with 18 BWG Al-Br Tubes	Allowable Design Load based on test data with Titanium, Serrated Holes	Test Loads with Titanium, Serrated Holes
Inlet 24 BWG Titanium	**125**	**540**	**2700**
Outlet 24 BWG Titanium	**154**	**540**	**2700**
Inlet 20 BWG Titanium	**125**	**680**	**3400**
Outlet 20 BWG Titanium	**154**	**740**	**3700**

Table 3

HEI Beam Strip Analysis

Another method of considering the loads on a tube-to-tubesheet joint is with the use of the HEI Beam Strip Analysis method, or, as is also done, a finite analysis of the tubesheet. In the Beam Strip method, strips of tubesheet from the top and bottom as well as the sides are modeled. Tubes are modeled as axial springs that provide support to the tubesheet. This method can then be used to calculate the load on individual tubes based on the distance from the tubesheet edge. Table 4 is an example of the results of a Beam Strip Analysis. This example used 0.7 mm thick duplex stainless steel tubes for the periphery, and 0.5 mm thick tubes for the main bundle. The Beam Strip Analysis estimated the pullout loads of the edge tubes at 457 – 464 pounds, and the main bundle tubes between 223 – 241 pounds, depending on location of the strip which was modeled. For comparison, the tested values for pullout joint strength were 5196 pounds for the edge tubes, and 3109 pounds for the main bundle.

	Top / Bottom Strip	Middle Strip
Tubesheet, Max Bending Stress, ksi	**34.6**	**29.7**
Edge Tubes, Max Pullout Force, lbf.	**464**	**457**
Main Tubes, Max Pullout Force, lbf.	**241**	**223**

Table 4

Heavy Wall Titanium with 3-roll and 5-roll Expanders

One of the rules of thumb that is often used in the retubing industry is that thick wall tubes are rolled with 3-roll expanders, and thin wall tubes are rolled with 5-roll expanders. However, a second rule of thumb is to use 5-roll expanders when rolling materials such as stainless steel and titanium. These materials are subject to triangulated rolls, or poor sealing if rolled with 3-roll expanders. So, when using titanium in a heavy gauge, which rule of thumb applies?

Tests were conducted using two expanders; identical except one was a 5-roller configuration and one was a 3-roller configuration. Figure 1 shows that the 3-roll expander produced much stronger joints when rolling 18 BWG tubes into an Aluminum Bronze tubesheet than a 5-roll expander. This test was conducted on 1-1/4 inch tubes. Note that this test was not designed to test one expander versus another, and tests were conducted several days apart. This is why the range of torque and number of data points is different.

The Apparent Wall Reduction was generally higher with the 3-roll expander at any given torque. No cracks or other issues were found on careful examination of either set of joints. The most significant finding is that it was not possible to reach the torque necessary for the optimum joint strength without using a larger rolling motor. In this instance the 3-roll expander was selected with a recommended torque of 126 in-lbs. which resulted in a nominal AWR of 6%, and a pullout force 5,000 pounds greater than a 5-roll expander at the same torque.

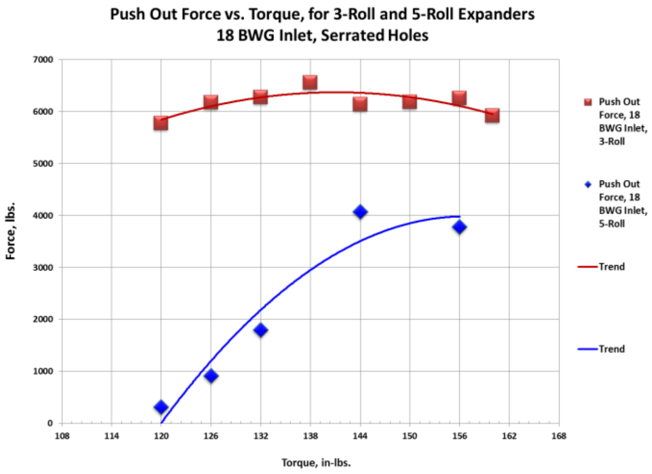

Figure 9

Double Tubesheet

An interesting test was performed on a unit with a double tubesheet. In this case, a ‘picture frame’ steel tubesheet was used to provide additional support for the brass tubesheet. This secondary sheet extended for ten rows of tubes around the periphery. It is important to control the rolling in these peripheral tubes so the backer plate will provide support to the tubesheet around the periphery. This area typically has the highest bending moments on the tubesheet, particularly with a cooling tower and the higher pumping head associated with most cooling towers.

The challenge for this test was to develop strong joints in both the brass sheet and the steel sheet. A second challenge was how to measure the pullout strength in the steel tubesheet only, while maintaining the same rolling parameters in the combined tubesheets.

The recommended rolling procedure uses a somewhat unconventional two-step process using a step roll of the steel sheet, followed by a full depth roll of the brass and steel sheet combined. This method was chosen because it provided a smooth tubesheet ID, was simple to set up, and gave exceptionally strong joints in both the steel and brass tubesheets. One concern was that rolling across the slight gap between tubesheets could create cracks in the tubes. When the tubes were pushed from the tubesheets the forces were so high that the tubes exceeded their yield strength and stretched before they pulled out the sheets. These areas were examined closely for evidence of cracks, and none were found. Our preference is to bond the two sheets together so strongly that they function as one, thereby preventing cracks. Figure 10 is one example of the pushout forces found for two initial torque levels (the step roll of the steel sheet) and four final torque levels (full depth roll of brass and steel tubesheets.) In this case the torque combinations include: 72/72, 84/84, 84/96 and 84/108 for the initial/final torques. There is also one point for the steel tubesheet which was rolled with an initial torque of 72 in-lbs. and a final torque of 72 in-lbs. This test point had a pushout force of 5750 lbs. for the steel plate alone.

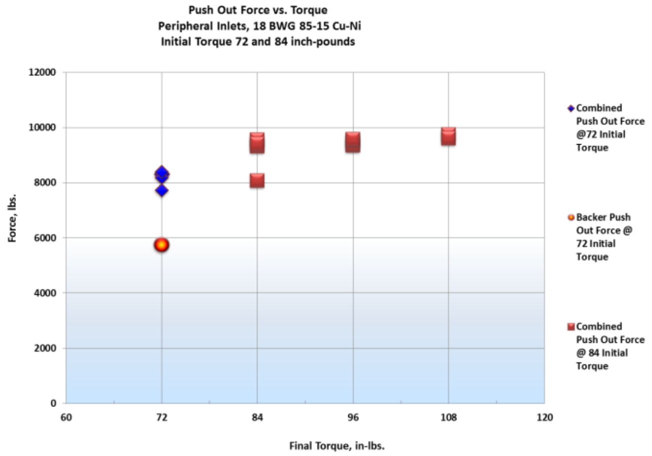

Figure 10

The measurement of the steel tubesheet’s pushout force separate from the brass tubesheet was done by cutting a small ring from a tube, which was equal to the thickness of the brass tubesheet. This tube was inserted in the brass tubesheet, and the remaining tube inserted in the steel tubesheet. The two pieces of tube were rolled with a flush collar expander just as if they were a single tube. However, when the ram was used to push the tube out of the tubesheet, it was actually only pushing it out of the steel sheet, since the ring was rolled in the brass tubesheet.

Minimizing Work Hardening of Brass Tubes

One case that illustrates other potential benefits of pullout testing was a test that was designed to determine the joint that would provide the minimum amount of work hardening in the rolled joint of replacement brass tubes. In this case, tubes were tested in a conventional test, extracted and hardness tested at several points in the rolled and non-rolled sections of the tubes. The first attempt at this provided poor data as the extraction process created more work-hardening of the tube that the rolling. However, it did provide very useful data for retesting some joints. In the retest, the joints were rolled, then the tube stubs were cut from the tubesheet and tested. This provided the data illustrated in Figure 11. This data shows that there was relatively little work-hardening with serrated joints at 54 in-lbs. of torque.

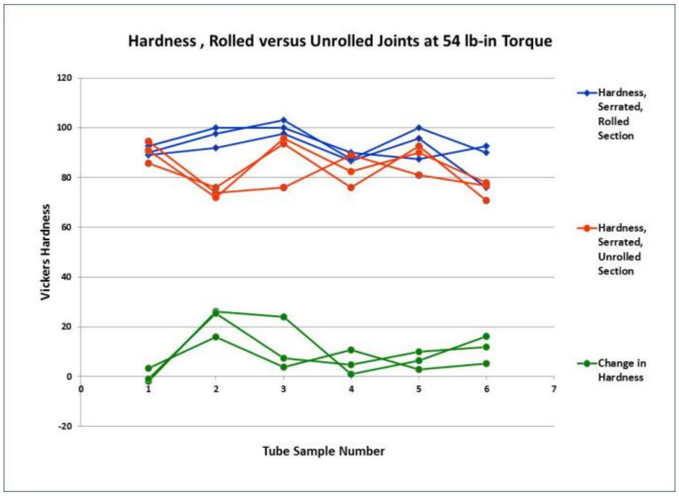

Figure 11

Figure 12 shows additional data from this test that compared the pullout strength of several tubesheet hole conditions. Typical, as-machined ‘smooth’ holes with an estimated surface finish of around 250 rms, ‘polished’ holes with an estimated surface of better than 125 rms, and multi-groove serrated holes were compared. In this case, the serrated holes provided the highest pullout strength at a given torque, and also produced low levels of work-hardening.

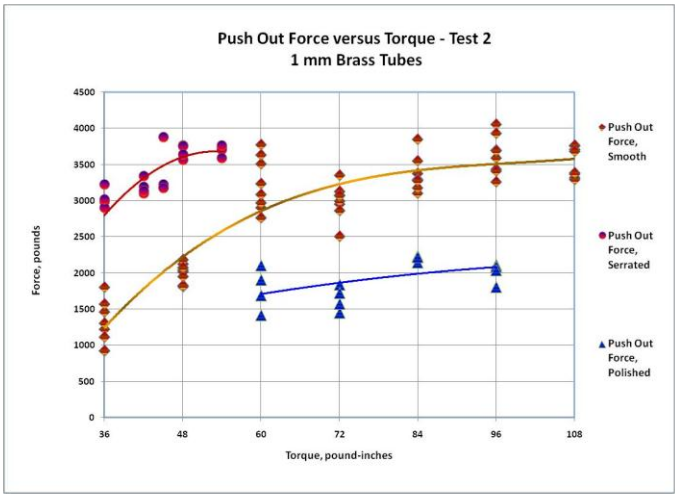

Figure 12

Heat Exchanger with Step Roll

This example is for a heat exchanger which required step rolling to develop a strong joint to a depth of 75 mm (~ 3 inches). The rolling process was governed by the customer’s specifications that required longer overlap than most specifications. This resulted in rolling these tubes in 4 equal steps with an effective roll length of 18.75 mm each. The tests demonstrated high pullout loads, (Figure 13) and even with a high strength stainless alloy, the tubes had noticeable necking down after being pushed out of the tubesheet. (Figure 14) A joint that has necking such as shown here is at the maximum practical limit for joint strength. In this case, the joint was obviously stronger than the tube. It is likely that some yielding of the tube within the joint caused its eventual failure. These joints were later qualified for use in a nuclear facility by exposing them to hydro test pressures of up to 800 psig. (Figure 15).

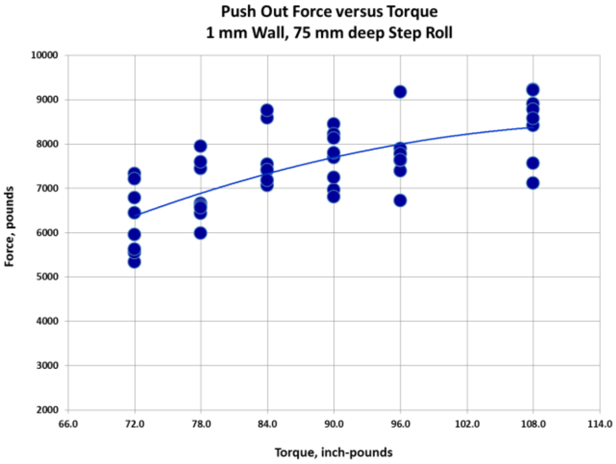

Figure 13

The data shown below is typical of the data from a good test. Although there is a lot of scatter in most tests, the trends are indicative of what is actually happening.

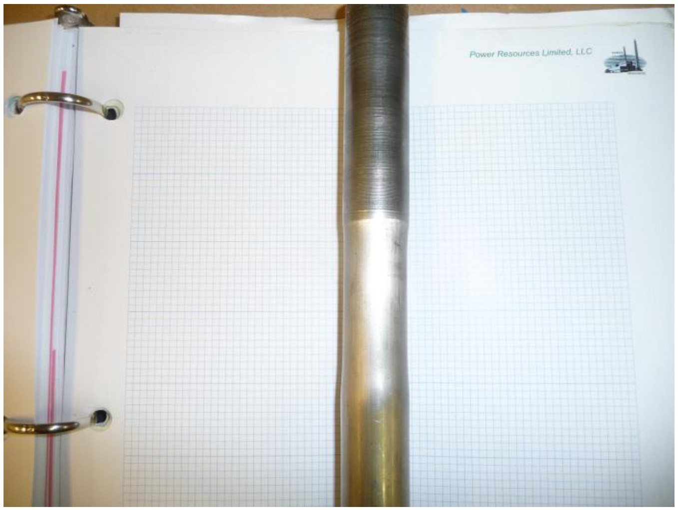

Figure 14 – Tube Necked Down After Test

Figure 15 – Hydro Test Gauge.

CONCLUSION

These case histories have illustrated the range of information that can be developed from pullout testing. The use of these tests should be considered as an important engineering tool in preparing for a retubing project, particularly a project that has unique features or objectives. These tests are also an important tool in the design and testing of new heat exchange equipment. With the proper use of testing, material selection, engineering, and quality installation practices, retubing projects can be completed with high strength, reliable leak tight joints.

REFERENCES

Standards for Steam Surface Condensers, Tenth Edition, Heat Exchange Institute, Incorporated

Boiler and Pressure Vessel Code, Section VIII Division I Appendix A, **“Basis for Establishing Allowable Loads for Tube-to-Tubesheet Joints”.** American Society of Mechanical Engineers

GENERAL REFERENCES

Technical Challenges of Retubing the Électricité de France (EDF) Belleville Unit 2, Proceedings of the ASME 2011 Power Conference, POWER 2011

Retrofitting Titanium Tubes into Copper Alloy Condenser Tubesheets, ASME Joint Power Generation Conference, Miami, Florida, 1987