

High Pressure Heat Exchanger Diaphragm Removal/Retrofit Using Double Tapered Pressure Seal

Abstract

This conference paper describes the successful removal of a tube side cover plate diaphragm (gasket) from a high pressure heat exchanger. The diaphragm was replaced with a double-tapered, metal pressure seal. This seal has been utilized in multiple piping and off-shore applications throughout the world for several years; however, this was the first known application on a heat exchanger of this magnitude within a refinery. Using creative thinking and taking the initiative, a reoccurring reliability issue (diaphragm weld cracking and subsequent process leakage to atmosphere) was resolved, all during a turnaround window (an opportunity!). Modification of the cover plate to accept the double-tapered, metal pressure seal eliminated the need to re-install the metal diaphragm gasket, thereby saving 75% of the reassembly cost of the exchanger. Utilized in conjunction with mechanical multi-jack bolt tensioners, this innovative retrofit has eliminated a reoccurring costly problem (in both maintenance cost and loss of opportunity). This additional reliability coupled with the significant future cost savings from less downtime justified the retrofit – not including the cost savings foreseen by preventing unplanned outages from the exchanger. The success of the first application led to the successful retrofit of a second exchanger. Currently planning is underway to retrofit the remaining 12 high pressure, critical service exchangers. This will occur during the next two turnarounds (2007 and 2010). It is anticipated that this modification could eventually change the way refiners will specify how high pressure heat exchangers in hydro cracking services are designed and constructed.

The Problem

It is not uncommon for diaphragm plates in high pressure heat exchangers to develop cracks in their seal welds. The diaphragm, which is generally a thin plate of alloy steel serves as the gasket and corrosion resistant liner for the channel cover (Figure 1). This arrangement is common for heat exchangers in hydrogen services at

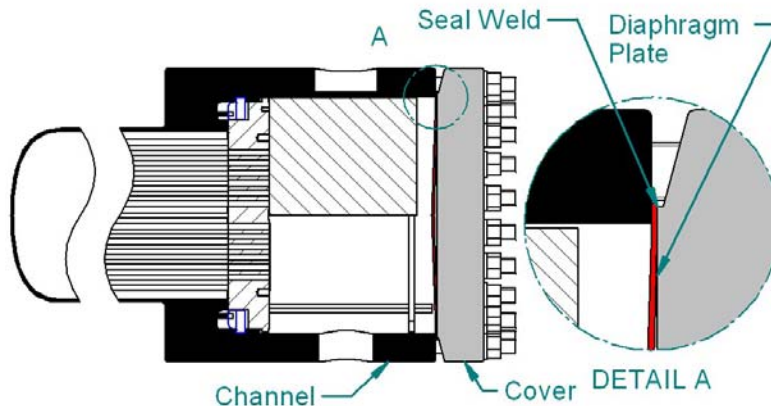


Figure 1 – Schematic of exchanger design with diaphragm

operating pressures above 1600 psig in our refinery's Gas Oil Hydrotreater (GOHT) unit. We have had multiple diaphragm leaks over the past several years.

Until recently, our repair process had been the same. It entailed removing the diaphragm, machining the channel face, welding and re-machining a nickel "butter-coat" layer on to the channel face, and finally welding on a new diaphragm under controlled heat. This repair would suffice for a time, until some process upset or other anomaly would create another cracking "event."

This procedure had become our normal, standard operation of repair and in turn, our “insanity clause.” We continued to perform the same repair steps repeatedly, and yet, after returning the exchanger to service, would expect a different result.

Criticality of Process¹

Hydrotreater units are expensive to build. Their high pressure and elevated temperatures necessitate heavy wall vessels, piping and ancillary equipment. Their severe service often requires exotic metallurgy. The preferred method of fabrication is butt-welding due to material and equipment costs and to prevent possible leak locations. These constraints often minimize block valve installations between equipment and any possibility of isolating or “bypassing” equipment, without taking the complete unit down.

Hydrotreater units are expensive to start up and shutdown. They are labor and maintenance equipment intensive. Large volumes of inert gas are required to cool and protect the multi-million dollar catalyst beds and equipment. There is always some associated risk involved in starting up or shutting down a hydrotreater unit. Rapid thermal gradients can damage equipment and the repair or replacement time could be several weeks or months.

From a business perspective, hydrotreater units required to meet the low sulfur fuel specifications that are now in effect. Hydrotreater units are critical to a refinery's balance sheet. The cost associated with taking one out of service can be dwarfed when compared to the potential lost income. Hydrotreaters are often large volume units. The 3-2-1 and 2-1-1 crack spreads have been favorable for refiners in the recent years; even further elevated the last few years following both hurricanes Katrina and Rita.

Hydrotreaters process feedstock for Fluid Catalytic Cracking Units (FCCU) and Hydrocrackers. The economic impact of these conversion units are crucial to a refinery's profit and loss statement as well, maybe even more so than hydrotreaters. Downtime in a hydrotreater forces refinery logistical issues such as throughput curtailments in the FCCU and Hydrocracking units. Their close integration to each other (and the bottom line) emphasizes the need for unit availability. Equipment reliability is critical to success.

Diaphragms and Why they Crack^{2, 3, 4}

Diaphragms are generally fabricated from thin stainless steel (SS) sheets (0.100"-0.125") such as 304 or 304L. Diaphragms are GTAW fillet welded to exchanger channels in a lap-joint configuration along the edge of the diaphragm plate. This joint configuration has limited transverse strength due to the limited size of the effective fillet leg or cross sectional area of the fillet weld reinforcement. Because of the thin diaphragm, there is high welding residual stress adjacent to the weld.

There are several reasons why cracks can develop. Reasons include the following:

- Tensile overload caused by differences in the thermal expansion of the low alloy steel channel (carbon or Cr-Mo) and the SS diaphragm. Some exchanger channels contain effluent streams up to 730 degrees F and diaphragms can be over 80 inches in diameter.
- Chloride Stress Corrosion Cracking (SCC) – A salt which drops out in hydrotreater effluent exchangers is ammonium chloride. The diaphragm is susceptible to this failure mode due to its high residual stress. The crevice between the diaphragm and channel contain concentrated chlorides and aggravate the cracking mechanism.
- Polythionic Acid Stress Corrosion Cracking – Hydrotreater effluent systems use austenitic SS for sulfidation resistance. Polythionic acids are formed in the process during shutdown periods when the prevalent metal sulfide scale react with oxygen and water condensed during the steam out cleaning process. These acids cause SCC in SS which is sensitized from welding or from operating temperatures in excess of 750 degrees F.

SCC is the result of combined mechanical stresses with corrosion reactions. The combination of a susceptible alloy, sustained tensile stress, and a particular environment lead to the eventual cracking of the alloy.

It is difficult to alleviate the environmental conditions that lead to SCC. Chloride levels required to produce stress corrosion are very small, generally below the macroscopic yield stress. The stresses are often externally applied but are quite often residual stresses associated with fabrication, welding or even thermal cycling. Unfortunately stress relieving heat treatments cannot completely eliminate all the residual stress.

Knowing, and ultimately reducing (or eliminating) the important variables of SCC propagation is the best avenue for success. These variables again are:

- The level of stress,
- The presence of oxygen,
- The concentration of the chloride
- The elevated temperature, and
- The conditions of the heat transfer (often the design).

This failure mode is not uncommon for exchangers of this age, design, and service. Diaphragm fillet welds encounter high stresses from the combination of high hoop stress and large compressive stresses generated from the cover plate bolting. This cracking is common in the diaphragm welds of high-pressure heat exchangers in hydrotreating units throughout our nations' refineries and abroad.

Double Taper Seal Technology

Faced with repeated failures of the diaphragm welds in our hydrotreater exchangers (fourteen exchangers, seven in two separate trains – Figure 2) and the economic impact of these exchangers to the refinery, developing a solution to this phenomenon became a priority.

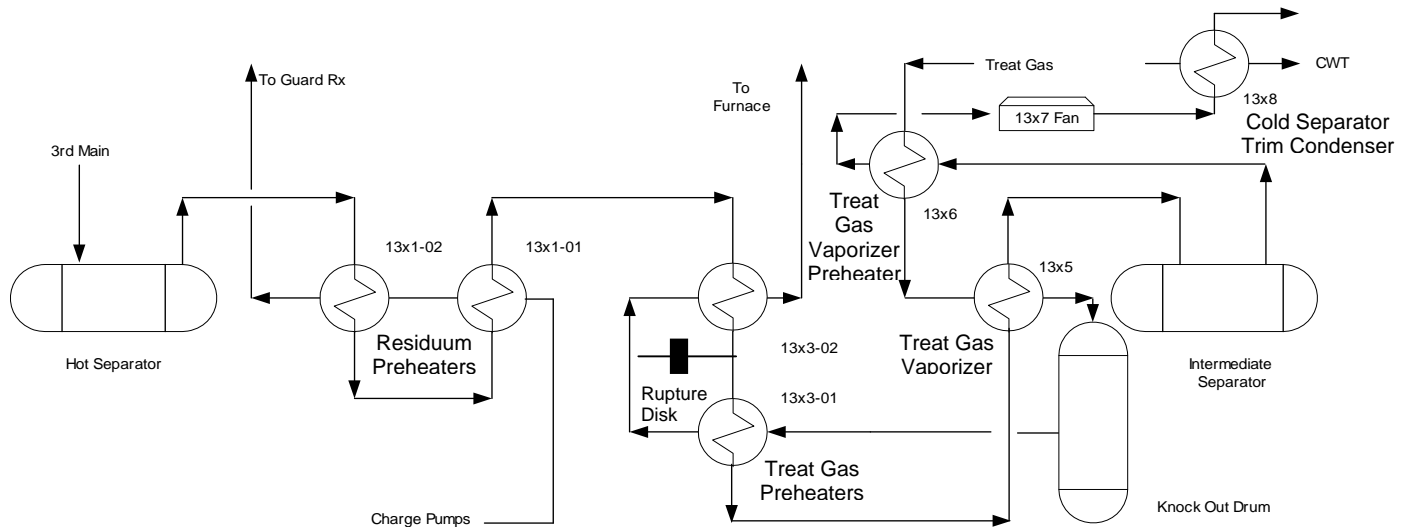


Figure 2– Process schematic of GOHT single train high pressure heat exchanger section

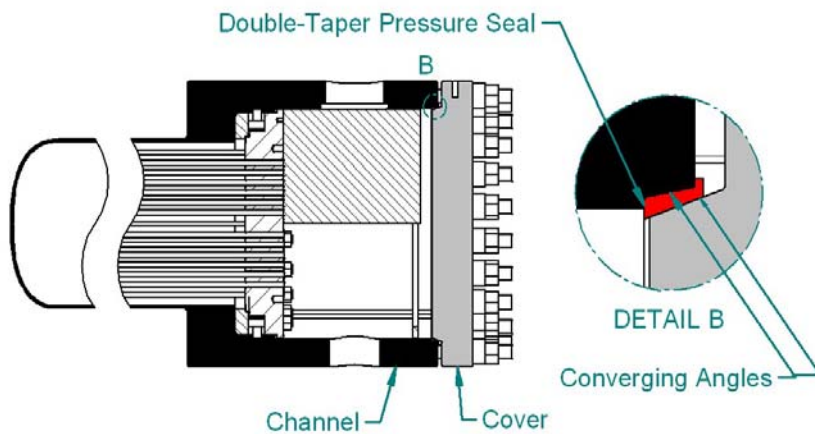


Figure 3 – Schematic of exchanger design with double taper pressure seal⁵

The Reliability and Maintenance groups designed or investigated a handful of possible solutions; however none of them received total buy in. Following several months of study, an innovative, alternate solution was identified. The solution involved eliminating the diaphragm plate entirely and replacing it with a double-tapered, self-energizing metal pressure seal (Figure 3).

The solution was simple, effective and quite field compatible within the timeframe of a shutdown.

Seal Concept

The double-tapered, self energizing metal pressure seal was designed to use on piping applications for topsides of offshore platforms, flow lines, production risers, manifolds, chemical plants, refineries, power generation, supercritical wet oxidation, and numerous other practical applications. Most assemblies consist of a male flange, female flange, seal ring, and a set of studs and nuts. The double-tapered seal seats into a pocket in the female flange and is wedged and seated by a male nose located on the male flange.

Utilizing this concept the exchangers channel cylinder would contain the female pocket while the channel cover would have the male nose geometry.

In the pre-bolted condition, the seal ring lip stands off of the face of the channel. The converging seal surfaces are brought together like a wedge during bolt up. This wedging motion forces the seal ring onto the male nose and into the female pocket forcing a compressive hoop stress. Minimal bolt load is required to achieve the required contact stress on the seal surfaces.

The converging angles of the seal ring create a wedge or “door stop” effect. As the equipment internal pressures increases the seal seats tighter into this sealing wedge.

The seal is made from the same material as the process equipment (exchanger channel and cover) to ensure that thermal expansions are consistent across all components. The effects of bi-metallic (galvanic) corrosion are eliminated. A baked-on moly coating is applied to the seal to prevent galling.

This promising sealing technology required minor modifications to the heat exchangers. It was simple, reusable, provided a metal-to-metal seal, and took very little time to make the modification. However, this application would be unique in that there was no published history utilizing the seal on a refining exchanger of this pressure and severity.

Reliability Assessment and Risk Mitigation of Seal

Since this could possibly be the first use of this type of seal on a fixed equipment cover, a reliability assessment had to be conducted, and the risks needed to be identified and subsequently mitigated.

All known applications for double-tapered pressure seals were researched. It was discovered that these seals had been used in many different types of connections that included:

- weld neck flanges
- blind flanges
- closures
- clamps
- swivel flanges
- misalignment flanges
- tube sheets

The seals had performed well in temperatures from cryogenic to 1600 degrees F and at pressures to 40,000 psig. Applications of note included:

- heat exchanger internals
- hydrogen processing
- high temperature measurement equipment
- offshore (both sub-sea and topside)
- high pressure compressor connections

A study conducted by JP Kenny proved to be helpful. It compared the double-tapered pressure seal to standard ANSI bolted connections. While the study did not focus on welded diaphragm connections it did point out some of the beneficial characteristics of the seal. The results of the study showed that the pressure seal was preferable to ANSI standard gaskets connections (Table 1).⁶

JP Kenny Connector Evaluation Data

JP Kenny gathered and assembled data for both ANSI and Taper-Lok flanged connections and developed a Rank Scale for final evaluation of each system. Results were as follows:

Large Diameter Flanges: Technical Evaluation

		ANSI Flange	Rank	Taper Lok	Rank
1	Flange Material ⁽¹⁾	ASTM A350 LF 6	A	ASTM A350 LF 6	A
2	Gasket Material	RTJ gasket will be made from softer material than the flange material.	C	Gasket material is same as the flange material.	A
3	Bolt Material	ASTM A193 Gr-B7	A	ASTM A193 Gr-B7	A
4	Corrosion ⁽²⁾		C	Lesser exposure to corrosion ⁽²⁾	A
5	Bolt Tension	Requires higher bolt tension to keep the RTJ gasket in contact with the gasket groove.	B	Smaller bolt tension because the pressure energized seal and less likelihood of separation due to the tapered seal surfaces.	A
6	Bolt Diameter	Code specified bolt & bolt circle diameter.	B	Size optimized to fit pressure end load of flange and bending loads.	A
7 a	Make up gap	About 3/4" for 48" flange.	A	About 1 1/4" for 48" flange.	B
7 b	Misalignment	Zero misalignment capability.	B	Some misalignment capability because of the tapered gasket design.	A
8	Bending Moment Capacity	Smaller bending moment capacity because inability to misalign w/o breach of seal.	B	Higher bending moment capacity because of ability to misalign slightly and maintain full contact of seal surface around gasket diameter.	A
9	Bolt relaxation	Possible because the gasket is plastically deformed during make-up.	B	Less likelihood of relaxation because the gasket loads remain below 90% of yield.	A
10	Design Flexibility	No flexibility because the dimensions are specified by the code.	B	Flexible design, dimensions can be changed to match the requirements.	A
11	Flange Weight	Flange size is fixed by B16.47 or SP-44.	B	Smaller and lighter than ANSI flange.	A
12	Availability of misalignment flanges	Misalignment Flanges up to 10 degrees are available.	A	Taper Lok make flanges with max. 10 deg misalignment.	A
13	Susceptibility to damage	Mating flange may hit the projected half of the RTJ gasket.	B	Male flange has a projection that may hit the female flange.	C
14	Leak Test	Requires pipeline to be pressured.	B	Seal can be tested without pipeline pressure.	A
15	Pressure energized seal	No	B	Pressure acting against seal drives seal tighter into converging tapered seal surfaces.	A
16	Made up gap	Need to check for uniform made up gap.	B	Need to check for uniform made up gap.	B
17	Effect of Check Valve Clapper Impact Loads.	Bearing stress may exceed allowable.	B	Bearing stress is within allowable.	A
	TOTALS	4 A's, 12 B's, and 2 C's		15 A's, 2 B's, and 1 C	

⁽¹⁾ Flange material was changed to ASTM A694 F65.

⁽²⁾ If Taper-Lok flanges are used, there is no galvanic corrosion problem. The ring is cut from similar/same chemistry material as the flanges, hence there is no dissimilar metal-to-metal contact between the ring and flange. If another flange design is used (such as Taper-Lok) which employs a ring material that is not low alloy steel (higher alloys such as stainless steel, or a nickel base alloy such as Inconel) there is a potential for a galvanic couple to be set up between the ring and the flange. In this scenario the ring would be the cathode and the flange would be the anode. This creates the potential for corrosion on the flange (internally) in the area around the ring. If they inlay the ring groove with the same material as the ring (Inconel 718 is very similar to 625 from an electrochemical standpoint) this will prevent the seal area from corroding which is critical. However, there will be a galvanic couple between the inlay (cathode) and the flange (anode). However the flange is large compared to the cathode (seat inlay) so the corrosion will be spread out over a large area and will be inconsequential.

There will be no galvanic corrosion externally anywhere. All the steel will be polarized to anode potentials. Internally there will only be the potential for corrosion in the water phase if there is one.

Table 1 – JP Kenny connector evaluation data

A design of the seal for one of our heat exchanger was created and calculations according to ASME Section VIII, Division 1 Unfired Pressure Vessels⁷ were conducted to ensure code compliance. Because the seal is self-energizing the gasket factor “m” and the minimum design seating stress “y” are both zero which reduce the required bolt load to equal only the hydrostatic end load of the closure.

A finite element analysis (FEA) was conducted by an independent third-party engineering firm.⁸ Analysis consisted of both 2D and 3D nonlinear models with contact elements. Both models showed a wide contact area with pressures at the sealing surfaces to be in excess of 20ksi (Figure 4). The analysis verified that the seal would be kept

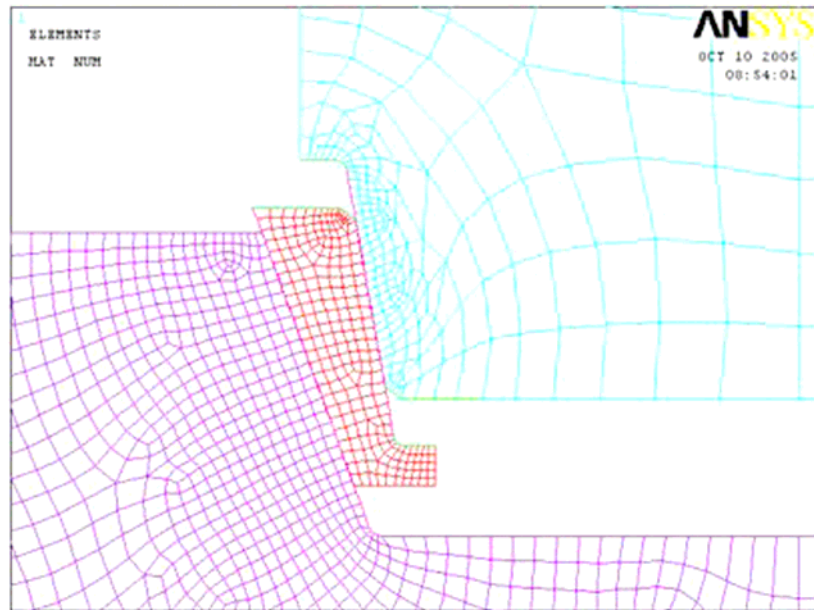


Figure 4 – FEA of pressure seal illustration of mesh used in the analysis

in an elastic state and that the stresses in the components

would be below code allowable limits (Figure 5).

Even though all data suggested that this seal would work in our application we were still concerned with the possibility of a leak or failure of some sort. Without published history, we needed a fall back plan. It was determined that when we implemented this sealing system in one of our exchangers, we would build a new channel cover with the male nose geometry as opposed to retrofitting our

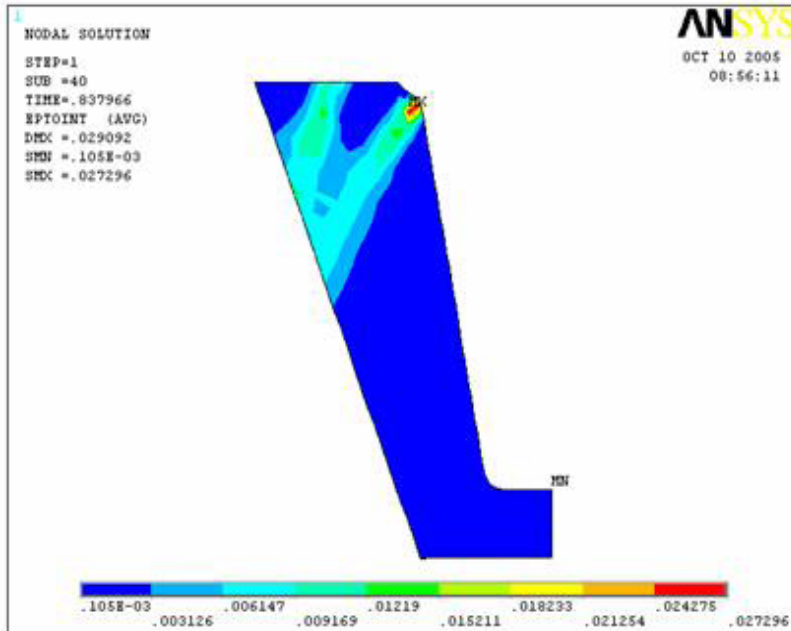


Figure 5 – FEA of pressure seal illustration of strain on seal

existing closure. This would then require only the cutting of the female pocket into the

exchanger channel. In the event of something unforeseen becoming obvious during the retrofit we could reuse the old closure and weld back a diaphragm plate and seal the opening as we had always done.

Opportunity for implementation

During the refinery start up following hurricane Rita (from which we were gratefully spared) in September, 2005 a leak occurred in our GOHT Cold Separator Trim Condenser (Figure 2, previous). The leak was from a small crack in the diaphragm weld just in front of the tube side cover plate.

Hurricanes Katrina and Rita crippled plants along the gulf coast. Refineries were requested to restart operations as quickly and safely possible to provide fuel for the clean up. Our refinery was up to the task, until the diaphragm crack became evident.

With an entire train down to repair one heat exchanger, the refinery Leadership Team decided to remove the diaphragm from the exchanger and implement the double-tapered pressure seal.

Timing affects everything! The double tapered pressure seal was engineered, fabricated and installed during the next three days.

Implementation

Description of Modification

The modification centered on the elimination of the welded diaphragm gasket and implementation of the double angled pressure seal.

Simple Modification Procedure

Remove/Replace Channel Cover Plate

A new channel cover plate was fabricated to reduce downtime. Originally, the existing channel cover plate was to be modified via a rapid turnaround machining effort to allow the cover to accept the tapered pressure seal; a minor effort that was not difficult. The original channel cover plate was salvaged for modification and installation on the sister exchanger in the second train. It was also available to re-install if any unforeseen problem existed with the retrofit.



Figure 6 - Machining pressure seal female pocket with ID mounted tool

Remove Metal Diaphragm Gasket/Seal

The diaphragm seal was removed in a multi-step process that began with drilling a hole through the diaphragm and performing a safety check for any residual hydrocarbon. Once complete, the center of the diaphragm was removed by arc gouging, being careful not to cut close to the inside diameter of the channel. The remaining diaphragm including the fillet weld that attaches the diaphragm to the channel were machine cut from the channel. The channel was also faced to insure a true, flat surface.

Field Machine Female Pocket Into Exchanger Channel (Figure 6)

The double angled pressure seal geometry requires two sealing surfaces. One, a female pocket, the other a male nose. The female pocket was machine cut into the exchanger channel while the new, fabricated channel cover plate featured the male nose. During assembly, an additional benefit to the design was observed. This male nose on the channel cover plate configuration acted as a guide.



Insert Pressure Seal Ring Into Pocket (Figure 7)

Since the geometry of the female seal pocket is angled, the seal ring was installed into the female pocket and held in place by friction, providing a hands free, safe installation of the channel cover plate.

Figure 7 – Inserting pressure seal into female pocket

Insert Channel Cover Plate On Studs and Pressure Seal

Pre-tension studs (Figure 8)

To ensure that the channel cover plate was assembled square and free from misalignment and to reduce bolt interactions, hydraulic tensioning equipment was utilized. Four (4) tensioners were used at ninety (90) degrees and the tensioners were kept under load while all nuts were installed and hand tightened.



Figure 8 - Hydraulic tensioning and installation of mechanical tensioners

A second deviation from the exchangers original design was applied at this time. In lieu of the traditional heavy hex nuts,

mechanical multi-jack bolt tensioners were utilized. This also proved quite fruitful as torque wrenches were then used to apply the proper torque required to seat the double angled pressure seal. The traditional impact (and accompanying crane used to hold it in place) was rendered obsolete.

Hot torquing was not necessary after the installation, even after the unit had gone through a few cycles. This is attributed to the spring affect the seal and component geometry create during and after seal seating. This spring effect refrains the bolts from relaxing.

Conclusion

Several benefits were realized from this retrofit. The largest being the elimination of the cracking which in turn increased equipment reliability and unit availability. Having the seal fabricated from the same material as the pressure parts (channel and cover), bi-metallic or galvanic corrosion cannot occur. All thermal expansion observed during operation is constant. The seal or "gasket" is in compression and in an elastic state. The seal is self energized, creating a tighter seal with any increase in pressure. Elements that promote the cracking are eliminated.

A second exchanger was retrofit in Mach 2006. The remaining twelve exchangers are scheduled to be retrofit during the next two scheduled GOHT outages.

Additional benefits, some initially unforeseen, were the reduced cost or downtime from several items such as the following:

- the reduction in the exchanger turnaround time from six shifts to three shifts
- the utilization of one crane in lieu of two (1 for cover plate and 1 for impact)
- the elimination of any hydrogen bake out from weld contamination and weld dilution on alloy exchangers with a stainless steel corrosion overlay
- the elimination of machining of weld build up (Nickel butter coat)
- the elimination of seal weld and metal diaphragm seal
- the elimination of NDE to search for cracking throughout the entire process

Downtime has decreased since the root cause of the process leaks (cracking of diaphragm welds) at the cover have been eliminated. The retrofit was deemed a success. No downside opportunities have been observed or foreseen.

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