

Large Titanium Heat Exchangers Design, Manufacture, and Fabrication Issues

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Titanium shell and tube heat exchangers are frequently required for high pressure, highly corrosive processes. Typical applications for the equipment include manufacture of PTA and pressure acid leaching of metals. These titanium tube exchangers typically require a combination of solid titanium and titanium-steel clad components, including tubesheets, shells, and bonnets. The clad components can present unique issues for clad manufacture, forming, and fabrication. The high operating temperatures and pressures can present unique design considerations to accommodate the thermal expansion mismatch between titanium and steel. Three recent projects, which have presented relatively unique design requirements, are discussed. The first two required titanium on all tubeside surfaces. Although these units are for identical service, they differ significantly in configuration, design choice, and in backer materials. The third involved very high pressures in combination with aggressively corrosive conditions both tubeside and shellside. The most economical solution was a solid titanium tubesheet and tube bundle in a titanium clad shell. The inter-relation between design, manufacture, and inspection issues and the related equipment performance considerations are presented.

Use of Titanium in Heat Exchanger Design

Titanium is used in heat exchangers for the same reasons that it is used in other process equipment – for handling of corrosive fluids effectively with minimal equipment degradation. While the material choice for heat exchangers often follows that of other equipment, the choice of titanium affects the mechanical design and manufacture of shell and tube heat exchangers in unique ways. Additionally, shell and tube heat exchangers have many configurations depending on the service, temperature range, and type of fluids handled. These configurations are also affected by the use of titanium. These are discussed below in order of complexity.

Titanium Clad Tubesheets

Tubesheets represent the most common and simplest utilization of titanium clad components with the titanium on the tubeside of the heat exchanger. The reasons for clad tubesheets are several. First, a choice of titanium for the tubes to handle corrosive conditions leads to a clad tubesheet in order to facilitate the tube-to-tubesheet joining and sealing. Rolled-only joints are generally not acceptable for titanium tubes due to the material's relatively high yield stress and its 'elastic memory.' Due to these properties the tubes tend to shrink or contract after rolling, creating leaks. Welding of the tubes to the tubesheet is, therefore, required and this requires a titanium face to the tubesheet.

A second reason for the use of titanium clad tubesheets is to bridge the difference between the material requirements of the shellside and the tubeside of the heat exchanger. In the chemical process industry, the process fluid is often the corrosive fluid and the heat exchanger is configured for this fluid to be on the tubeside for cleaning and maintenance. This fits well with heat exchanger thermal design as cooling water, condensing steam, boiling water, and hot oil are all heating or cooling media that work well as shellside fluids. These also have minor or manageable corrosion issues and are usually handled with steel. Titanium clad tubesheets form an excellent link between the steel and titanium sides of a heat exchanger.

Titanium clad tubesheets are manufactured by explosion welding. Explosion welding is a unique technology which uses the energy of a chemical explosive to create fusion and welding conditions. The extreme rapidity of the process does not permit sufficient time for formation of deleterious intermetallic compounds which occur during other, slower technologies. Explosion cladding is a well developed and industrialized manufacturing technology. Explosion clad materials are manufactured by a limited, but worldwide, group of specialists with the combined explosive and metallurgy expertise required to assure product reliability.

The backer material for clad tubesheets is not always carbon steel. The alloy used may be varied to match the material requirements of the shell side. Stainless steel and other alloy backers are frequently used. In the case of a shellside condenser for anhydrous acid, Hastelloy G-30 was the material of choice for the shell and zirconium for the tubes – zirconium clad on a Hastelloy G-30 backer was used for the tubesheets. Severe service conditions on the shellside may call for the tubesheet to have butt-welding hubs. Forged tubesheet discs are required by the ASME Code for this kind of construction. Cladding of a non-hub side of a forging is not significantly different than cladding a plate material. Explosion cladding of the hub side is considerably more complex, and is rarely used. When cladding of the hub side is mandatory, unique design concerns at the clad perimeter must be addressed.

Cladding Metal Thickness Considerations

The titanium that is explosively clad to the tubesheet disc is generally thicker than what is used for cladding on cylinders and heads. The thickness is selected to accommodate the tube to tubesheet welding and any gasket surface machining that is required on the titanium face. The Standards of the Tubular Exchanger Manufacturers Association sets minimums for cladding thickness. TEMA paragraph RCB-7.8 sets the minimum nominal cladding thickness at 3.2 mm [1/8 in] when the tubes are welded and 8 mm [5/16 in] when they are not. This is a starting point for the consideration and the actual joint configuration and the tube to tubesheet welding technique must be considered. The depth of this chamfer for either seal or strength welding plus a machining tolerance and some allowance for weld penetration sets the real minimum titanium cladding thickness in the tube field. If in the design of the tube to tubesheet joint, it is determined that a tubehole groove should be placed in the cladding, the thickness is increased even further, typically to 13 mm to 16 mm [1/2 in to 5/8 in].

The required machining on the tubesheet face also affects the titanium cladding thickness, and is often a major determining criterion. Several factors are at work: the flatness of the disc that can be achieved by the producer; the requirements for gasket surfaces and pass partitions, whether confined gasket joints are required; and whether the full face is required to be machined flat. When working with low cost metals, the cladding face is commonly machined flat; it simplifies assembly. When working with expensive metals, such as titanium, zirconium, and the nickel alloys, the assembly advantages rarely out-weigh the added metal cost; most fabricators experienced in these metals do not completely machine tube sheet faces. Generally, tubesheets with titanium clad on the tubeside have a gasket surface for joining with the bonnet or channel – otherwise little or no machining is required. Pass partitions when present, require gasket surfaces to be machined across the center of the tubesheet; whereas without them, machining is required only for the pressure gasket surface is around the periphery of the disc. The requirement for a confined gasket joint is set by service level, usually categorized by the TEMA classes R, C or B. For severe services, corresponding to TEMA R, paragraph R-6.5 requires confined joints. For moderate and chemical process services, corresponding to TEMA C and B, respectively, paragraph CB-6.5 leaves the decision to the user. The effect of confined joints on the thickness is to add 4.8 mm [3/16 in] of cladding material for producing the groove.

A clad tubesheet disc is manufactured to be flat within a specified tolerance which is determined by press capacity and technique limits. This tolerance can range from as little as 3 mm [1/8 in] on tubesheets under 1500 mm [60 in] diameter up to as much as 13 mm [1/2 in] on tubesheets over 3000 mm [120 in] diameter. Without pass partitions, an out of flatness condition can be tolerated, thus the center of the tubesheet doesn't require machining.

For example, cladding thickness determination for a 2000 mm [78-3/4 in] tubesheet with TEMA R pass partitions and confined gasket joints would be as follows and as shown in Figure I. (The specified out-of-flatness of the product permitted in the cladding specification, ASTM B898, Section 10.3.1.2, is 5.5mm [0.220 in].)

- Minimum cladding (TEMA): 3.2mm
- Allowance for gasket and pass partition confinement (TEMA): 4.8mm
- Allowance for face out-of-flatness (B898): 5.5mm
- Undergauge tolerance from nominal (B898): 1.5mm

The sum, 15 mm, is the nominal titanium thickness that is required prior to clad manufacture. Assuming standard inch-dimension sizes, the thickness would be adjusted upward to the next standard which is 16mm (0.625in). The only possibility to reduce this is to improve flatness of the clad disc, which can sometimes be negotiated with the clad manufacturer.

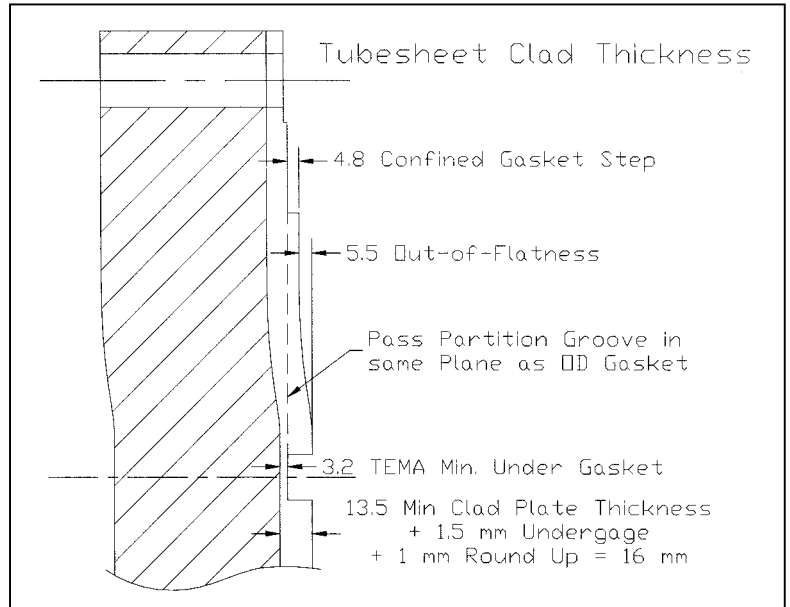


Figure I – Tubesheet Cladding Thickness

For a second example, consider a tubesheet the same as above, except without the pass partition. The requirement for added thickness for the contained gasket is at the tubesheet perimeter only. More specifically the disc needs to be flat within an agreed amount in this area only. Typically the clad manufacture would commit to improved flatness in the gasket area only, likely reducing the required nominal thickness to 12.7mm [0.50 in].

Inspection Considerations

A titanium clad tubesheet introduces minimal additional inspection points into either the fabrication or maintenance of the heat exchanger. During the manufacturing of the clad tubesheet disc, the bond between the titanium and the backer is tested and proved for its soundness. ASTM Specification B-898 requires that all clad plate be ultrasonically tested for bond quality. Two acceptance standards, A and B, are applicable for tubesheets. B898 also specifies that the manufacturer shall assure that the clad shear strength be no less than 140 MPa [20,000 psi]. When supplementary requirement S1 is specified the clad manufacturer is to measure and report the shear strength of the product. Once these inspections have been performed, the disc may be treated as essentially solid during both manufacturing and operation.

Size Considerations

The size of the tubesheet is limited by the availability of the backer material. Because of welding and weld quality concerns, the base metal should generally be of one piece. Although cladding alloys are not normally available in the large sizes typical for steel, this is rarely a size limitation. Since the cladding layer is not part of the design strength requirement, it may be pieced together by welding to achieve any size of tubesheet disc. The use of titanium clad tubesheets is appropriate in heat exchanger sizes ranging from 150 mm to 5000 mm [6" to 16 ft] in diameter and for fixed, floating, or u-tube configurations. Tubesheets with titanium clad on the tubeside are a good solution for tube attachment issues and for joining sides of differing metallurgies. Tubesheets with titanium clad on the shellside may also be used and these are discussed below in the section on titanium shellside construction.

Titanium Clad Tubeside Fabrication Concepts

The configuration of the bonnets of a heat exchanger is guided, but not restricted, by the presence of titanium clad tubesheets. A bolted joint between the tubesheet and the remainder of the tubeside allows full freedom for material choice. The bonnet may be coated or bare steel, stainless or nickel alloy, or titanium as required by the process material evaluation. Titanium clad bonnets occur often where titanium is specified, as even moderate pressures shift the material choice toward titanium clad for large titanium bonnets.

Conventional bonnets with either clad flat covers or clad dished heads are used frequently. Fabrication of these items involves the standard weld seam batten strip, nozzle liner, and flange face details for covering exposed backer surfaces. Batten strap, or liner, design issues can get quite complex, particularly when pressures and/or temperatures are high. The coefficients of expansion and the elastic moduli of titanium (and the other reactive alloys) are appreciably different from steel. The designer and fabricator are cautioned to adequately consider these design issues to assure long, maintenance-free equipment performance.

Where bonnets of non-standard configuration are required, such as bonnets for separating drums on vertical tubeside condensers and bonnets with mitered elbows on thermosyphon reboilers, custom batten details may be developed to cover the uneven joints between adjacent shell sections. The batten strips covering seams between a cylinder and a cone or between sections of a mitered elbow require complex forming, but with care and attention to the final fit of the parts the joints will provide reliable service.

These loose lined parts are subject to special care and attention during fabrication as well as causing additional inspections for proving the integrity of the fabrication and for ensuring the continuing integrity during operation. Typically holes are drilled through the steel into the region where the titanium will be welded. This provides a means of providing purge gas to the backside of the titanium weld. The titanium welds that attach and seal the liners are 100% liquid penetrant tested and helium mass spectrometer leak tested. The purge holes can be used as tell-tale holes are drilled into every space behind the liners, both for the helium leak detection testing and for leak detection during operation. In operation, visual inspections for signs of process fluids leaking out through these holes should be performed regularly. Timely identification of liner failures will minimize backer repairs as the process fluids are highly corrosive to the backer and may quickly degrade the area under the liners. Hot gas cycle testing during fabrication is used to minimize the occurrence of such operational failures. In this test, the titanium clad component is heated and pressurized to operational conditions

and cycled, typically, twice, which stresses the titanium liner attachment welds. Afterwards, the integrity of these welds is checked again by the helium leak testing method.

Head Considerations

Dished heads from titanium clad plates are generally produced by hot or warm pressing. The cold forming or spinning processes are less used as they induce excessive shear between the backer and the titanium, which can cause disbonding. The pressing equipment of the head former limits the size and shape of the heads available, but standard sized flanged and dished, ellipsoidal, and hemispherical heads are available. For heads larger and thicker than are available from one-piece pressings, segmental heads may be used. In this way a large head may be assembled from a center dish piece and multiple petal pieces. While larger titanium clad heads and heat exchangers are made possible by this method, the increased number of parts that make up the head also increases the length of weld seams. As each seam requires custom batten strips, this greatly increases the amount of inspections required during fabrication and during operation. Cones, mitered elbows, and smooth elbows may also be formed by cold rolling or hot pressing and lined in a similar way. For all formed parts, the layout of the weld seams should be designed with the lining process in mind.

Internal Attachment Issues

Internal structures, such as pass partitions, separation baffles, demister supports, and vortex breakers fabricated from titanium may be directly attached to the internal clad surfaces. These items should be anchored substantially on the integrally clad plate rather than being attached primarily to the loose liners. These internal structures are subject to large thermal stresses that are due to the difference between the thermal expansion of the backing steel shell relative to the titanium internals. Carbon steel expands about 40% more than titanium and stainless steel expands about 80% more than titanium. Special attention must be paid to design of structures that are installed across the whole diameter of the vessel. Flexible sections or bolted joints are helpful for alleviating these stresses. Properly designed internal structures will avoid distortion of the structure, detachment of liners, or disbonding of clad during service.

Titanium Clad Tubeside Case Studies

Case studies for two large heat exchangers with titanium clad construction on the tubeside are presented below. These exchangers illustrate some of the concepts of fabrication and design described above. Both units are 1st Reactor Condensers in PTA plants and both use boiling water as the cooling medium on the shellside. However, choices of configuration and materials produced very different units.

Vertical Reactor Condenser

The first unit discussed is a vertical BEM unit with a separation drum as the bottom bonnet – see Figure II. Its shell diameter is 2550 mm [100-3/8 in] and has (5540) 19 mm [3/4 in] OD by 1.24 mm [0.049 in] wall by 7500 mm [295-1/4 in] long tubes. The shellside functions as a vertical thermosyphon boiler. In the PTA process, the reactor condensers are arranged as a series of partial condensers, each stage cooling the off-gas and condensing a portion of the mixture. Thus the outlet bonnets of these units function as drums to separate the liquid product from the uncondensed gas. This unit has moderate design conditions of 1960 kPa g at 252°C [285 psig at 486°F] with an operating temperature of approximately 175°C [350°F].

In consideration of the potential corrosion of the backer material from flange and loose liner leakage, the backer material for this unit was chosen as 316/316L stainless steel. The tubeside heads, cone, and cylinders as well as the tubesheets were SB-265 Gr.1 titanium explosion clad onto SA-240 316/316L stainless steel. The loose lined nozzle forgings were also SA-182 F316/316L stainless steel. As noted above, this material combination of stainless steel and titanium has a large difference in thermal expansion, which is taken into account in the design.

Per standard construction, the bonnets were joined to the tubesheets using flanges. These girth flanges, being for 2550 mm [110-3/8 in] shells, are large and difficult to handle. However, as the unit is vertical field fit-up is not overly difficult. In order to avoid the cost of such a large stainless steel forging, a lap joint design with a painted carbon steel flange and stainless steel lap ring was used. Consistent with the backer corrosion concern, the lap ring and the titanium flange face are extended past the bolt holes to the OD of the flange.

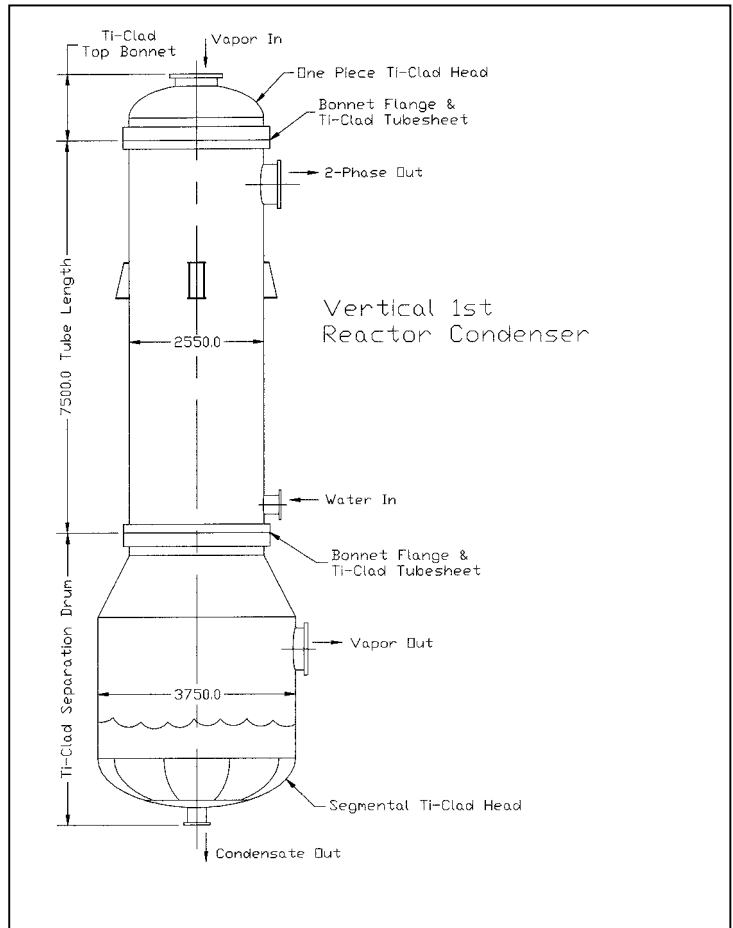


Figure II – Vertical Reactor Condenser

The top bonnet consists of the 700 mm [28 in] NPS inlet nozzle, a formed head, a short cylinder and the girth flange. This ellipsoidal head, being 2550 mm [100-3/8 in], is of such a size that it is able to be pressed in one piece and is 20 mm [0.790 in] minimum thickness stainless steel with 3 mm [1/8 in] thick cladding.

The bottom bonnet uses the same flange as the top bonnet, but with a cone, expands to a diameter of 3750 mm [147-5/8 in] for the separating drum. This ellipsoidal head exceeds the size limit for one-piece heads and is formed in sections. Its crown plate is 1991 mm [78 in] in diameter and it has eight petals for the knuckle – it is 29.7 mm [1.17 in] minimum thickness stainless steel with 3 mm [1/8 in] cladding. This head and the drum transition cone, with its five segments, add a large amount of backer welding and batten strips lining that is due to its large size and clad construction. While more small units of solid titanium construction would relieve the complexity, the one large unit provides overall economy of design.

The tubesheet is a large, 2781 mm [109-1/2”] OD by 152 mm [6 in] thick, disc from plate. The flatness available on a plate of this size is flat within 9.5 mm [3/8 in]. As the gasket joint was not required to be confined and there are no pass partitions, only a minimal amount of material beyond the thickness is required for gasket surface cleanup. It was ordered with 14.3 mm [9/16 in] nominal titanium plate: 3.2 mm [1/8 in] minimum material under the gasket surface, 0.8 mm [1/32 in] excess for cleanup, 9.5 mm [3/8 in] for flatness, and 0.8 mm [1/32 in] for material loss in the explosion cladding process.

The vertical separation drum allows the separation of the liquid and gas using very few internal structures. A small box is constructed as a shroud around the gas outlet nozzle to prevent the condensed liquid droplets from exiting. For this plant, the 2nd Reactor Condenser had a requirement for a divided sump in its separating drum. This involved a titanium plate across the diameter of the tank. For flexibility, two convolutions were formed in the plate. This compensated for the difference in thermal expansion between the stainless steel shell and the titanium divider plate.

Horizontal Reactor Condenser

The second unit discussed is a horizontal BKM unit – see Figure III. Its tubeside diameter is 3175 mm [125 in] and has 8232 tubes, each 19 mm [3/4 in] OD by 1.65 mm [0.065 in] wall by 8000 mm [315 in] long. The shellside kettle is 4877 mm [192 in] ID and functions as a pool boiler. As in the first unit, the outlet bonnet of this unit functions as a drum to separate the liquid product from the uncondensed gas. This unit has moderate design conditions of 2400 kPa g at 250°C [348 psig at 482°F] with an operating temperature of approximately 175°C [350°F].

Although this unit handles the same corrosive components, and the backer is subject to the same potential for corrosion due to leakage, the material choice was made for carbon steel backers. Steel is less expensive than stainless steel and there is less of a difference in thermal expansion between steel and titanium than between stainless and titanium. These positive benefits are set off somewhat by the need for heightened inspection vigilance for potential leaks in loose liners.

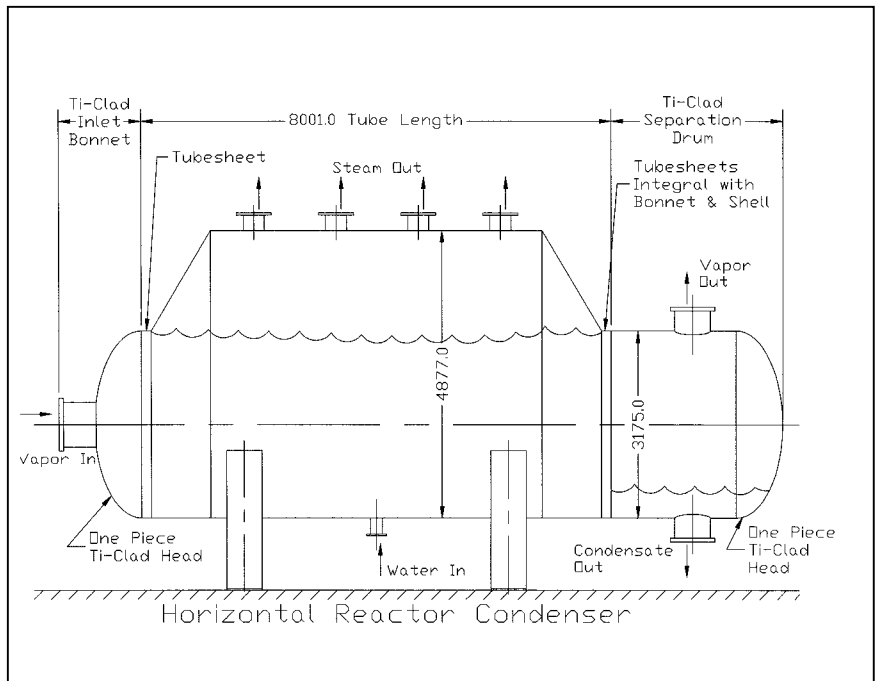


Figure III – Horizontal Reactor Condenser

The tubeside diameter is 3175 mm [125 in]. This is a large dimension for a girth flange and since the bonnets are horizontal, the field fit-up of such flanges would be difficult.

With this in mind, the flanged connection between the tubesheets and the bonnets was eliminated – this is a deviation from standard tubeside titanium clad construction. The carbon steel backer of the cylinder welded to the carbon steel backer of the tubesheet easily as a corner joint. This joint was covered using a specially formed angle-shaped batten strip. As with all other batten strips, tell-tale holes were drilled behind the strip and the joint was hot gas cycle tested and helium leak tested, proving the joint before operation. As on the other unit, the nozzle flange faces were extended to the OD of the flange to provide corrosion protection for the backer due to leakage.

The rear bonnet, functioning as a separation drum was the same diameter as the front head. Both heads, at 3175 mm [125 mm] were within the limits for one-piece pressing, which greatly simplified the welding and batten strip application. Furthermore, as the girth flanges were eliminated, the front

head was welded directly to the front tubesheet, eliminating a shell course. The large size of this unit, providing the possibility for the titanium welders to work inside, makes this possible.

The tubesheets for this unit were produced from forged discs. To facilitate welding to the kettle cones on the shellside, butt-welding hubs were machined in the tubesheet, requiring the use of forgings. The use of forgings and the absence of any gasket surface on the tubesheet eliminated any flatness considerations for the selection of the titanium clad thickness. However, for maintenance reasons, the end user specified a minimum clad thickness of 10 mm [0.394 in]. With an allowance for material loss during the explosion bonding operation, 11.1 mm [7/16 in] nominal titanium cladding plate was used.

For a horizontal bonnet to operate effectively as a separator drum, internal baffling was required. Incorporated into this baffle was a set of demister pads. The support arrangement for these demister pads was arranged so that no parts were fixed across the diameter of the bonnet. The internal baffles were bolted and the demister pads were clamped into place; both designs accommodate the differential expansion.

These two vessels, identical in service, but different in design approach, illustrate the fabrication issues involved with titanium clad construction on the tubeside of heat exchangers. In both of these designs process, mechanical, and material criteria were all satisfied by creative design solutions.

Titanium Clad Shellside Fabrication Concepts

While less common than tubeside titanium clad construction, shellside clad construction is possible and is used. The use of titanium as the material for the shellside of a heat exchanger would rise from heat transfer considerations during design. Condensing or boiling of a corrosive process fluid could lead to a titanium shellside. As shellside of a heat exchanger is generally not appropriate for fluids containing particulates or requiring frequent cleaning, the placement of these fluids on the tubeside could also lead to a titanium shellside.

For low and moderate pressures, a fully titanium shellside with solid titanium tubesheets, cylinders, baffles, and tubes is fabricable using standard techniques. For higher pressures or large diameter units with moderate pressure, clad construction for the shell becomes more economical. With this economy comes restrictions on the heat exchanger configuration, fabrication, and tubesheet design. These are discussed below.

Heat Exchanger Configuration for Shellside Titanium Clad

The shellside performs all of the vital functions of a shell and tube heat exchanger. The baffles and support plates guide the fluid to obtain the desired heat transfer and support the tubes against vibration. All of the loads within a heat exchanger, shellside and tubeside pressures plus differential thermal expansion, act on the shellside. Designing the titanium clad shellside to accommodate the differential expansion, plus consideration of the fabrication sequence, will restrict the heat exchanger design to either floating tubesheet or u-tube configurations.

When required by calculation, fixed tubesheet heat exchangers are fitted with expansion joints to compensate for differential thermal expansion. These expansion joints are either thin-walled bellows type or flexible shell elements per TEMA. Unless severe forming issues are overcome, titanium clad flexible shell elements are not feasible. A bellows type expansion joint would entail direct attachment of the titanium joint convolutions to both the clad surface and to loose liners. This would be very problematic in operation and should not be done.

Even for fixed tubesheet heat exchangers without expansion joints, titanium clad shellside construction is not possible. The fabrication sequence of a fixed tubesheet heat exchanger ends with the final closure seam of the shell being performed blind. The installation of the bundle inside the shell leaves no access for finishing the seam internally. For solid steel and alloy materials this poses no restriction. Titanium clad construction, however, requires extensive internal finishing of all backer welds and covering with batten strips. Internal access is required for titanium clad construction and floating tubesheet and u-tube configurations provide this.

Although the heat exchanger configuration is restricted to floating tubesheet and u-tube construction, many options remain for thermal and mechanical design. The TEMA shell types with single pass flow E, J, K and X are easily constructed. The multiple pass shell types F, G and H could also be constructed, however, the complexity involved in the arrangement of the longitudinal baffles renders these configurations less common. The packed floating heads, TEMA head types P and W, are not appropriate for clad construction because of the batten strip liners; plus the pressures that make clad construction economical exceed the limits of packed construction. The TEMA type S 'floating head with backing device' and the type T 'pull through floating head' are both appropriate head designs. The S type head is more complicated than the T type head, but for the same tube-field yields a smaller shell size and less peripheral open space. This would benefit thermal designs with segmental baffles while the T type head with its larger shell and more peripheral open space would benefit thermal designs such as pool boilers and surface condensers. See Figure IV for descriptions of the TEMA configurations.

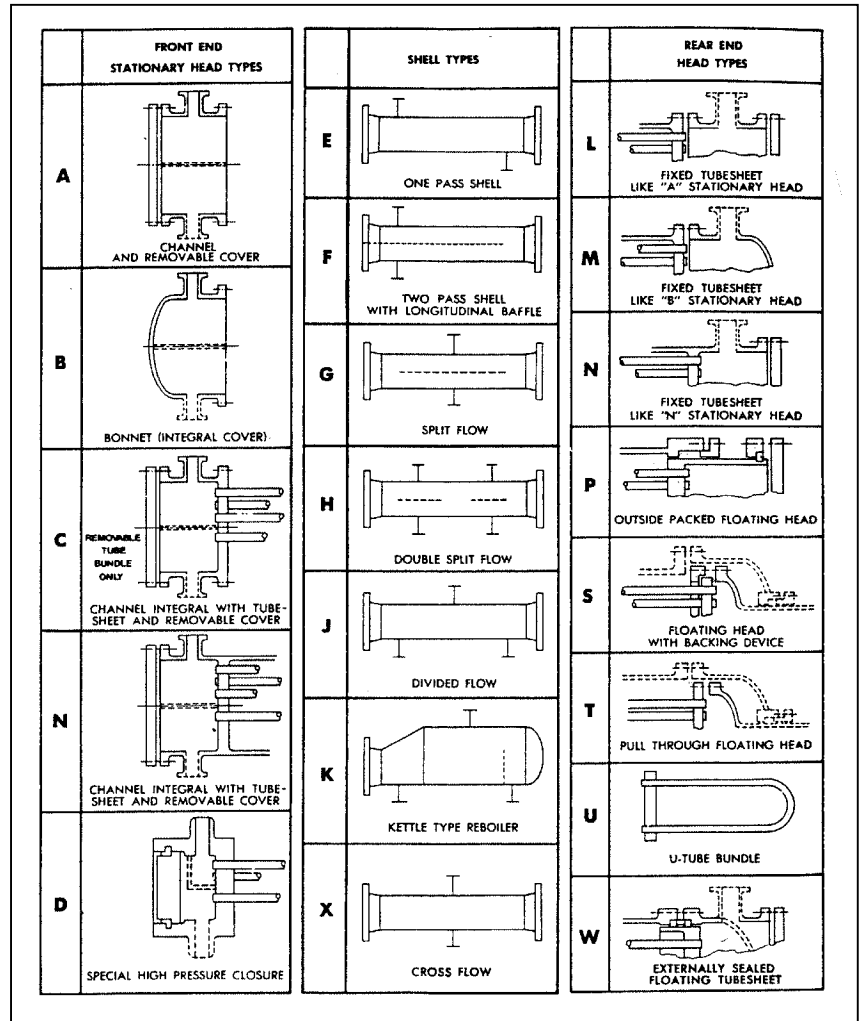


Figure IV – TEMA Heat Exchanger Configurations (TEMA Figure N-1.2)

See Figure IV for descriptions of the TEMA configurations.

Fabrication of the titanium clad shell cylinder uses the standard weld seam batten strip, nozzle liner, and flange face liner construction and inspection as the titanium clad tubeside described above. The shell will have one flange to the tubesheet and usually another flange at the cover for access to the floating head. Because of these liners, the inside of the shell surface is now uneven and has numerous sites for snagging the bundle as it is inserted or removed. Bundle runners, lead-ins, and ramps to guide the bundle over the batten strips will have to be incorporated into the titanium liner and baffle designs. Bundle to shell clearances greater than those recommended in TEMA paragraph RCB-4.3

should be added to compensate for the height variations of the liner application. Careful consideration of the combined complexities of titanium clad construction and of heat exchanger shellside configuration will result in a sound design and reliable service.

Tubesheets for Shellside Titanium Clad

The design of the tubesheets to accommodate shellside titanium clad construction merits some discussion. As titanium has been selected as the material of construction for the shell and the tubes, the remainder of the bundle is also required to be titanium. Baffles, tube supports, and tie rods are easily made from titanium using standard construction practices. The tubesheets and floating head components also require a titanium surface for the shellside fluid.

Double-Clad Tubesheets: Specifying a double-clad tubesheet with the titanium clad on both the shellside and tubeside is a viable option. This option, however, brings with it significant complications in fabrication and maintenance that must be overcome. The shellside clad complicates the attachment of the titanium tubes to the titanium layer of the tubesheet. Unlike tubesheets with titanium clad on the tubeside, the access to the titanium face is severely limited and unless ID welding of the tubes is employed, the seal between the tube and titanium layer must be performed by tube expansion – see Figure V. To facilitate shellside sealing, a thicker than normal titanium shellside clad would be used. Plates 19 mm [$\frac{3}{4}$ in] or thicker would be required to generate sufficient tube expansion length in the titanium portion to achieve a seal. The titanium clad on the tubeside is used to weld the tubes for the tubeside seal and for strength, but it is important to seal the titanium to titanium at the shellside face to prevent corrosion of the tubesheet backer material. Although titanium has a high yield stress and elastic memory, this seal can be achieved in the shop. It is, however, potentially prone to leakage under the normal fluctuations that occur in operation. Although there is minimal potential for migration of corrosive media and corrosive products, this could lead to degradation of the backer or localized tube collapse in some environments. The cladding industry is seeing an increase in use of the double-clad design in upstream oil and gas service where the shell side media is seawater. In these cases, the backside cladding thickness has been increased further to allow for one or two ring grooves in the titanium.

One method for alleviating the tube sealing problems incurred in a double-clad tubesheet construction is to sleeve the tubeholes with titanium. This method takes advantage of the titanium clad to both sides of the tubesheet. The tubeholes are drilled larger and titanium sleeve with an inside diameter to match the tube OD is welded to both the shellside and

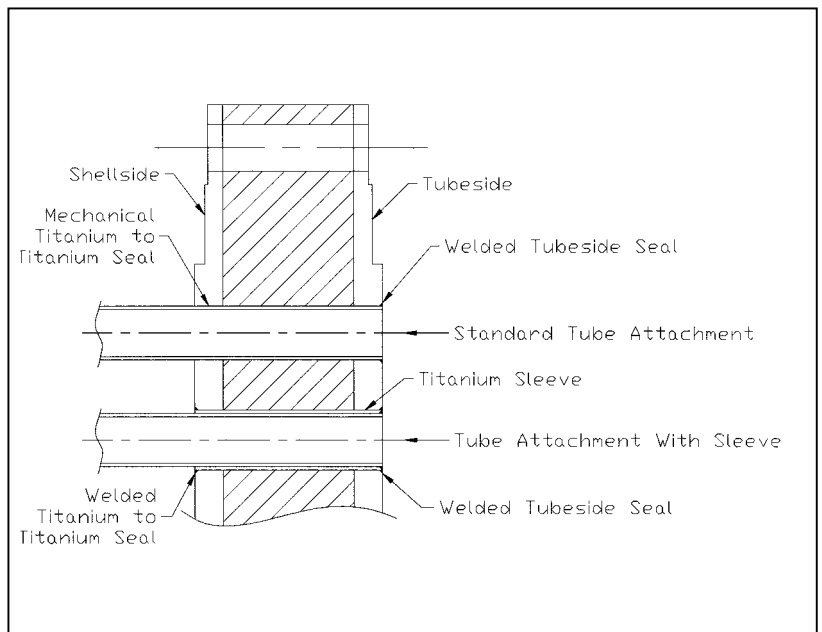


Figure V – Double Clad Tubesheet

tubeside faces. The tube sealing is then simply accomplished by welding on the tubeside face and both the tube and sleeve are expanded together into the tubesheet to close the gap on the shellside – see Figure V. This method adds significant complexity and cost to the fabrication of the tubesheet. Additionally, it affects the heat transfer and overall size of the heat exchanger as the pitch of the tubes

has to be increased to accommodate the thickness of the sleeve. The larger tubehole reduces the ligament efficiency which increases the thickness of the tubesheet. However, the operational reliability of the double-clad tubesheet would be significantly improved by sleeving the tubeholes.

Solid Titanium Tubesheets: The complexity and reliability questions of the double-clad tubesheet can be avoided by using a solid titanium tubesheet. In this method, standard tube attachment details may be used and the possibility of corroding the tubesheet by accidental leakage is eliminated. Commercially pure (CP) titanium (grade 2) with its associated palladium and ruthenium grades (7, 16 and 26) is significantly weaker than steel and the tubesheet thickness increases quickly with diameter and pressure. SB-381 forgings of over 190 mm [7½ in] in thickness and 1000 kg [2200 lb.] have been produced in these grades, which allows design of heat exchangers of significant pressure and diameter. Heat exchangers that have titanium clad on the shellside often have such pressure and size that the availability of solid tubesheets becomes the limiting factor. Double-clad tubesheets, while complex, are available in sizes up to 5000 mm [16 ft] or more, limited only by the steel backer. Higher strength grades of titanium are available and these extend the application range of solid titanium tubesheets. 3 Al – 2.5 V grade 9 titanium is accepted by the ASME Code and has been found in the stress tables since 1995. The associated ruthenium grade 28 has been approved for use in the ASME Code under Code Case 2425 and the palladium grade 18 could also be included, pending fabrication interest. These alloys have allowable stresses that are significantly higher than steel and can be used in many situations where the pressure and diameter have made shellside clad construction economical. To date, SB-381 forgings of over 220 mm [8¾ in] in thickness and 1700 kg [3750 lb.] have been produced in these grades. While the benefits of thinner components seem great, the substitution for a high strength grade for a commercially pure grade should not be done automatically. While the corrosion resistance properties of grade 2 and 7 are well known, they are not for the higher strength grades. The use of these higher strength alloys should be done only after careful metallurgical study of the application. If a specific corrosion analysis indicates that the 3 Al – 2.5 V alloys are suitable, these will provide reliable operation and will simplify and economize fabrication.

The use of shellside titanium clad construction in a heat exchanger to optimize its thermal performance presents many complex design and fabrication issues. These arise from the interaction between the heat exchanger mechanical design and standard titanium clad construction details. Careful consideration of these issues together with the available material choices will result in economical and reliable designs.

Titanium Clad Shellside Case Study

A case study for a high pressure heat exchanger with titanium clad construction on the shellside is presented below. This exchanger illustrates some of the concepts of fabrication and design described above. The unit described here is an ore slurry heater in a hydrometallurgical process. Both sides of the heat exchanger operate at high pressures – the tubeside is designed for 13500 kPa g [1958 psig] and the shellside is designed for 5782 kPa g [838.5 psig]. The unit is designed for a severe service with its design temperature above 260°C [500°F].

The design of this unit by Hatch International for a nickel mining project by INCO balances many diverse design constraints. The slurry, although of only moderate corrosiveness, had a high solid load and was inappropriate as a shellside application. The available heating fluid was condensing steam, which was ideal for shellside application. This steam, however, was potentially very corrosive and consideration of this by detailed corrosion evaluation led to the choice of titanium for the shellside. The pressures and size of the unit made shellside titanium clad construction the economical choice.

In consideration of shellside clad construction, fixed tubesheet designs were not used. Additionally, the solids load in the slurry mandated a design to accommodate easy tubeside cleaning. Because of this cleaning criterion, the u-tube configuration was passed over for a floating tubesheet design. The removable floating head and the straight tube design allows blocked tubes to be cleared. As the shellside contains condensing steam, a tight clearance between the tube field and the shell was not required, so a TEMA T-type pull-through floating head design was selected; an overall BET configuration – see Figure VI.

For ease of bundle insertion and removal several features were incorporated into the design. Bundle runners with ramped ends were provided to bear the weight of the bundle and the lead the tube supports over the batten strips and flange faces. Ramped guides were placed on the floating head and tubesheet for the same purposes. Correspondingly, where the bundle runners were to pass over these parts, the welds were blended out to provide a gentler passage over. To further ease the bundle's passage, the bundle to shell clearance was increased beyond the 6.4 mm [$\frac{1}{4}$ in] required by TEMA to 16 mm [$\frac{5}{8}$ in]. This allows for the variations in liner thickness and application.

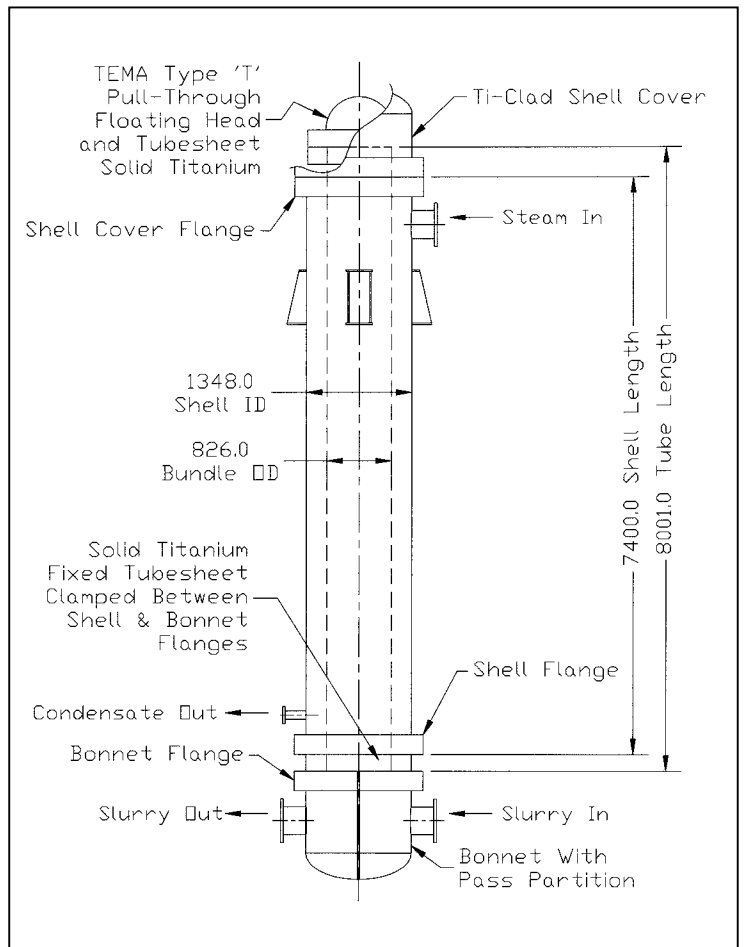


Figure VI – Shellside Ti-Clad Heat Exchanger

These corrosion studies showed that titanium Grade 17, unalloyed titanium Grade 1 with the addition of 0.06% Palladium, was an appropriate cladding material for the process environment. Clad fabrication practices that have been well developed for Grade 1 are fully applicable for this alloy. The titanium grade 17 was specially ordered with yield strength requirements below the specification upper limits. Explosion clad manufacturers have observed that lower yield strength and the corresponding higher ductility result in improved cladding process reliability. Over 250 clad plates and 51 formed clad heads were required for the 51 heat exchangers. All required 100% ultrasonic inspection and 100% bond shear strength testing in accordance with ASTM B898 Class A and S1 (restricting nonbond indications to 25mm [1.0 inch] maximum and shear strength to 140 MPa [20,000 psi] minimum.) There were no rejectable nonbonds and no low bond strength values on the complete project; 100% of the clad plates were delivered on schedule. This uncommonly good performance supports recommendations to reduce upper yield strength for the explosion cladding grade alloys. Welding on grade 17 is performed with ERTi-7, high palladium-content filler wire.

To avoid the complexity and reliability issues of double-clad tubesheets, higher strength titanium alloys were investigated for the tubes and tubesheets. It was found that titanium grade 28, a ruthenium bearing variety of grade 9, was appropriate for the tubes and tubesheets. This material was also used for the floating head flange, cover, and bolting. The selection of such a strong and corrosion resistant

material for all of the tube bundle parts simplified the mechanical design. The high pressure and temperature of the unit required the following thicknesses:

Tubesheets – 1470 mm [58 in] OD by 220 mm [8¾ in] thick

Tubes – 25 mm [1 in] OD by 2.77 mm [0.109 in] wall

Floating Head – 32 mm [1¼ in] minimum thick hemi-head

Floating Head Flange – 230 mm [9 in] thick

Floating Head Bolts – 76 mm [3 in] diameter studs

The robust nature of these components reflects the design emphasis on reliability and serviceability. The assembly of these parts required relatively little welding; the floating head to flange and the tube to tubesheet welding. As the pressures required strength tube to tubesheet welds, these were welded with ERTi-28ELI filler wire, as was the floating head weld.

The use of shellside titanium clad construction in these heat exchangers achieved an overall economy of design. Without its consideration, an intermediate heating fluid between the steam and the slurry would have been required, plus additional equipment. This heat exchanger design is successful, as in combining titanium clad shell construction with a solid titanium tube bundle, it balances many competing criteria. Corrosion and process requirements are accommodated, thermal and mechanical designs are optimized, and fabrication and inspection issues are addressed.

Conclusion

The use of titanium clad construction in heat exchangers requires attention to details of configuration, fabrication, and inspection beyond that of solid construction. As the discussion and case studies presented above show, including titanium clad in the design broadens the range of application of titanium to larger and higher pressure heat exchangers than otherwise possible.

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