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Heat-exchanger tube-to-tubesheet connections

Stanley Yokell, Energy and Resource Consultants, Inc.

Heat-exchanger tube-to-tubesheet connections

Most heat-exchanger failures occur at the point where the tube is secured in the tubesheet. If you want tight, long-lasting joints, you must specify the proper manufacturing and quality control procedures.

Stanley Yokell, Energy and Resource Consultants, Inc.

☐ The connection of the tubes to the tubesheets is the most critical element of a shell-and-tube heat exchanger because its reliability depends upon the integrity of the many parallel tube-to-tubesheet joints. Consequently each of the many joints must be virtually free of defects.

The part of the tube held to the tubesheet is stressed more severely than the main body of the tube. The configuration of joints allows only limited nondestructive examination. For these reasons, the tube-to-tubesheet joint is the site of most failures.

To understand the degree of reliability needed, consider the functions of the joint and the consequences of failure.

Joint functions and requirements

The main function of tube-to-tubesheet joints is to seal the tubes tightly to the tubesheets. And for most equipment, an additional major function is to support the tubesheet against pressure-induced loads.

Leaking joints may cause:

- Erosion of tube ends and tubehole walls.
- Corrosion of the lower-alloy side.
- Poisoning or fouling of the atmosphere.
- Fire or explosion.
- Tube-wall fouling.
- Catalyst poisoning.
- Product adulteration and degradation.
- Yield reduction.
- Power-generation-capacity reduction.
- Plant shutdown and power outage.

When joint leakage is intolerable, consider using double tubesheets. You can justify the extra cost: (1) when the hazard caused by a leak is great; (2) when joint failures are more probable than failures in tube bodies.

The degree of tightness you need depends upon the service conditions. Minor leaks in commercial low-pressure water heaters may be tolerable. Here, if you see a drop of water at the tube joint after a half-hour on hydrostatic test, it is hardly significant. To try to reduce the leakage rate below watertightness would hardly be worthwhile.

On the other hand, consider that the permissible chloride ion concentration in a surface condenser is 0.1 ppm. A typical brackish cooling-water supply might have a chloride ion concentration of 5×10^{-3} ppm [*1*]. A surface condenser producing 5,000 gpm (3.15 m^3/s) of condensate could therefore tolerate a total leak of approximately 0.1 gpm (6.3×10^{-6} m^3/s) of brackish water. The number of tubes in a two-pass condenser that could handle the steam load would be approximately 50,000, making the average permissible leak of brackish water through each joint 10^{-6} gpm (6.3×10^{-9} m^3/s).

Measuring joint tightness

One way you can assess the quality of joints is to measure how tight they are. It is reasonable to assume that if you set the acceptable measured leak-rate below what you can tolerate in service, you will assure that high-quality joints have been made.

Depending upon the service conditions, you may use the following to gauge tightness:

- Visual observation during liquid pressure-testing.
- Bubble-formation testing.
- Halogen-leak testing.
- Helium-leak testing.

Liquid pressure testing—For most equipment, the *Pressure Vessel Code* [2]* hydrostatic test is adequate. When you remove the channels or bonnets, the tube ends are visible. You can then see any leaks of pressurized shell-side water. You may be satisfied that if no leaks appear after a specified time (one-half hour is the minimum acceptable period), the joints will be watertight.

However, when the tube-side design pressure is higher than that of the shell side, the direction of leakage will probably be from the channel or bonnet into the shell. When you hydrostatically test the tube side, small leaks behind the tubesheet are hard to see in U-tube and floating-head units; they are impossible to see in fixed-tubesheet exchangers.

For these conditions, test for joint leakage indirectly by measuring loss of pressure over an extended period

*Hereafter, this ASME publication will be referred to simply as the *Code*.

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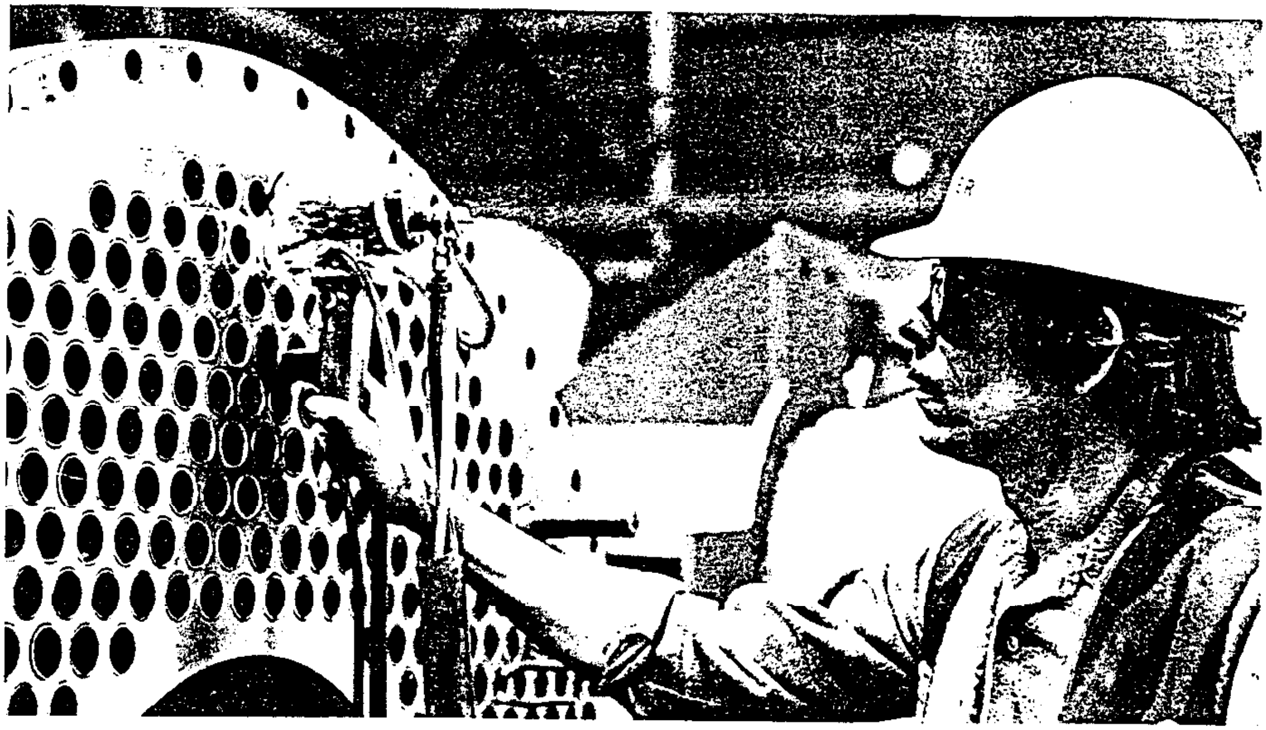


The Kynex Corp.

(usually 24 h). If the pressure falls, assume there is a leak. However, you must remember that: (1) ambient temperature changes may cause the pressure to vary; and (2) small leaks in fittings and connections may falsely indicate joint leaks.

By using a test fluid more searching than water, you may test for a higher level of tightness than with the extended-time hydrostatic test.

Bubble-formation testing—After you test the shell side hydrostatically, you may further test tube-joint tightness by performing the leak tests described in Article 10 of Section V, "Non-destructive Examination," of the *Code.*

To perform a gas-and-bubble-formation test, fill the shell with inert gas or air at the design pressure. After 15 min., flow bubble solution over the joints and tube ends. The joints are acceptable if there is no continuous bubbling.

The test solution must not break away from the test surfaces or break down rapidly because of air drying or low surface tension. Household detergents and soap solutions are not suitable. You may obtain proper test solutions from suppliers of materials for nondestructive examination.

Halogen leak-testing—For exchangers handling lethal or noxious fluids, halogen diode-detector testing may be suitable. For *Code* purposes, the method is not considered quantitative. However, with a 10% (by volume) tracer-gas concentration, the largest actual measured leak-rate allowed in *Code* tests is 1×10^{-12} std m^3/s.

The detector or "sniffer" sucks air through a tubular probe and then passes it over a heated platinum element (the anode). This element ionizes the halogen vapor. The ions flow to a collector plate (the cathode). Current, proportional to ion-formation rate, is indicated on a meter.

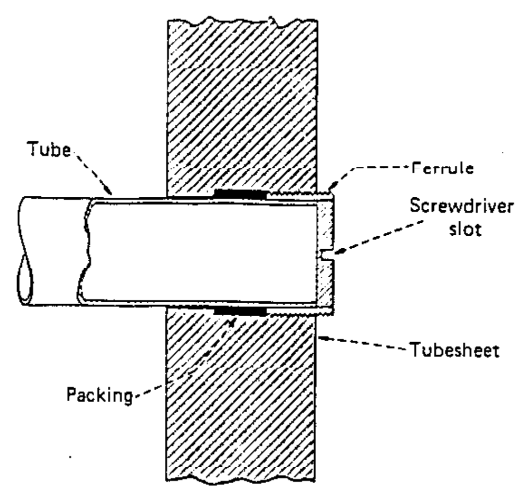
The sniffer must first be calibrated against a capillary halogen standard that has a leakage rate of 0 to 1×10^{-14} std m^3/s of refrigerant gas, and again at intervals of not more than 2 h during use.

Specific test procedures vary; a typical procedure follows: Clean and dry the shell. Fill it with a mixture of 10% (by volume) tracer gas and clean, dry air or inert gas, usually at 30 to 50 psi (207 to 345 kPa). Allow at least 30 min for tracer dispersion. Traverse each weld and insert the probe into each tube end. Be careful to keep the probe tip within ⅛ in. (3.2 mm) of the test surface.

Determine the scanning rate by passing the probe over the leak-standard orifice at a rate that detects leakage of 1×10^{-13} std m^3/s.

Alternatively, encapsulate each tube with a funnel connected to the probe. Determine the response time by encapsulating the standard and measuring its response time.

The preferred tracer-gas is Refrigerant 12, but you may substitute Refrigerant 11, 21, 22, 114 or methylene chloride.



Components of a typical packed joint Fig. 1

Helium leak-testing—When the hazard presented by a leak is unacceptable, or when the effect of a leak can justify a higher testing cost, consider helium mass-spectrometer leak-testing.

Helium-leak testing is done with portable mass spectrometers sensitive to minute traces of helium. Two methods are used. The cheaper one is the "sniffer" method. The more-costly hood method can detect smaller leaks than the sniffer.

The sniffer method is not considered quantitative for *Code* purposes. However, with a 10% (by volume) helium tracer-gas concentration, the largest actual measured leak-rate allowed in *Code* tests is 1×10^{-13} std m^3/s.

The hood method is quantitative. The *Code* acceptance standard, total allowable, integrated leak-rate is 1×10^{-14} std m^3/s, unless otherwise specified. However, the method is difficult to apply to individual tubes.

Testing joint strength [*3*]

The pull-out or push-out strength of a tube-to-tubesheet joint cannot be conveniently measured directly in a heat exchanger. Therefore, to find the typical strength of a given joint, you must test joints in a model. The parameters of the model—tubesheet and tube materials, tube diameter and gage, tubesheet thickness, hole-drilling tolerance and surface finish, hole grooving, weld procedure, etc.—must match those of the production exchanger.

A shear-load test [*4*] is used. Both the size of the model and the number of tubes tested affect the significance of the results. Results also vary because of the effects of the range of tolerances in hole drilling, tube manufacturing, material specifications, and joint-producing techniques.

Heat-exchanger manufacturers should have test results available to support their tube-to-tubesheet-joint procedures. When you specify or buy equipment, scrutinize the joint-fabrication procedures and supporting test results at least as carefully as you scrutinize mill test reports of the chemical and physical properties of the metals and the welding procedures.

When you do a shear-load test at room temperature, you do not account for the effects of operating temperature [*5*]. At operating temperature, the different expansion rates in the tubes may combine with reduction of tube and tubesheet strength to produce an unsatisfactory joint. So for critical service, consider performing tests at operating temperature.

In cyclical operation, joints may be periodically loaded and unloaded, or the direction of the load may be reversed. Hence, failure may occur well below the point of failure in a static test. When the operation of an exchanger is to be cyclical, calculate the joints' required load-bearing capacity [*6*]. Test specimens by alternately loading and unloading to this value, or by reversing loads until they fail. Determining the number of cycles to failure in this way is expensive, but it may avoid serious problems.

When you test tube-to-tubesheet specimens, the effects of tubesheet deflection, interpass temperature differences, tubesheet temperature gradients, and vibration are excluded. You must consider these effects when you design an exchanger. If you do not consider them during design, you may have to consider them when the exchanger fails.

How tube-to-tubesheet joints are made

Tube-to-tubesheet joints are made by:

- Stuffing the space between the tube and the hole with packing.
- Sealing the tube to the hole with an interference fit.
- Welding or brazing the tubes to the tubesheets.
- Using a combination of methods.

Packed joints

Fig. 1 is a sketch of a typical packed joint. At the inner side of the tubesheet, the clearance between the tube and hole is just enough to let the tube slide through. The counterbored recess at the outer side of the hole is threaded for approximately half its depth. A slotted, threaded ferrule is used to squeeze packing rings into the chamber. The friction of the compressed packing against the tube and hole determines the strength and tightness of the joint.

The advantage of packed joints is that they are easy to assemble and retube. The tradeoff is that either the tubesheet ligaments are thin or the tube pitch is spread. The first alternative requires you to use thick tubesheets. The second reduces the number of tubes you can install in the shell and also may reduce the shell-side coefficient.

It is not always as easy to replace tubes as you may have assumed when you decided to use packed joints. The threaded connections may become frozen. Consequently, you may destroy the ferrules when you try to remove them. Also, the packing may dry out, becoming stiff and hard to remove.

More economical and positive methods have largely replaced packed joints. Aside from some small auxiliary exchangers, their principal current use is in vertical, low-pressure heat recuperators. In this equipment a hot gas, which may be laden with pollutants, flows down through vertical tubes. Cold combustion air flows upward through the shell. Baffles in the shell direct the air back and forth across the tubes.

Pollutants may settle on the walls nonuniformly, resulting in different rates of fouling that may cause the average temperature of adjacent tubes to be markedly different. If the tubes are firmly fastened to both tubesheets, the forces created by differential expansion may rupture the joints, damage the tubesheets and buckle the tubes.

With loosely packed joints at the lower tubesheet and welded joints at the upper, tubes may expand individually. You can pack the joints loosely because heat recuperators usually run at low pressure, and some hot and cold stream mixing is generally acceptable.

The tubes of many heat recuperators are large enough for the ferrules to be designed as stuffing-box gland followers with wrench flats.

Alternatives to packed-end recuperator joints are: (1) expanding the lower tube end to sliding contact with the tube hole; and (2) making each lower tube-to-tubesheet connection through a bellows expansion joint.

Interference-fit joints

If you were to shrink the holes in a tubesheet onto the tubes, interference between the tubes and holes would create interfacial pressure. The hydraulic tightness and strength of the joints would depend upon:

- Interfacial fit pressure.
- Surface finish of the tube and hole.
- Static coefficient of friction.
- Length of tube embedded in the hole.
- Hole diameter.
- Poisson's constant.
- Other properties of the pair of metals.

An equation that relates fit pressure of shrink-fit joints to the interference, when the tubes are thin-walled (ratio of diameter to thickness more than 10), is [7]:

$$P_o = \frac{IE_t}{2\phi_t(1 + E_t\phi_p/E_p\phi_t)} \qquad (1)$$

where: P_o = interfacial fit pressure, psi (Pa); I = interference, in. (m); b = outside tube radius, in. (m); E_t = tube elastic modulus, psi (Pa); E_p = tubesheet elastic modulus, psi (Pa); $\phi_p = b(1 + \nu_p)$; $\phi_t = a^2(1 - \nu_t)/2(b - a)$; ν_p = Poisson's constant for the tubesheet; ν_t = Poisson's constant for the tubes; and a = inside tube radius, in. (m).

The pullout force is related to the interfacial fit pressure by:

$$F = 2\pi P_o b(1 - e^{-\alpha f l})/\alpha \qquad (2)$$

where: F = pullout force, lb (N); $\alpha = \nu(c^2 - b^2)/b(c^2 - a^2)$; c = radius of an imaginary ring of tubesheet surrounding the tube, equivalent to a shrunk-fit ring, in. (m) (c may be chosen to be b + the ligament); f = static coefficient of friction; and l = thickness of tubesheet, in. (m). Other symbols are as previously defined.

In the derivation of this equation it was assumed that Poisson's constant was the same for both tubes and tubesheet. The effects of the assumption are inconsequential if you use the average value.

The tensile force that will cause a tube to yield is:

$$F_{yt} = \pi(a + b)(b - a)S_{yt} \qquad (3)$$

where: F_{yt} = force to cause tube-yield, lb (N); and S_{yt} = yield stress of the tube, psi (Pa)

If you set the pullout force calculated by Eq. (2) equal to the force that will cause tube-yield, calculated by Eq. (3), you can determine the interfacial fit pressure associated with the strongest joint. This is:

$$P'_o = \alpha(a + b)(b - a)S_{yt}/2b(1 - e^{-\alpha f l}) \qquad (4)$$

where: P'_o = fit pressure for strongest joint, psi (Pa).

By rearranging Eq. (1) and substituting P'_o for P_o you can estimate the interference needed to produce the strongest joint, based on an assumed coefficient of friction.

$$I' = \frac{2P'_o(1 + E_t\phi_p/E_p\phi_t)}{E_t} \qquad (5)$$

In this equation: I' = interference to make the strongest joint, in. (m).

It would appear that this could be obtained by shrink fitting. However, the sum of the hole-drilling and tube-diameter tolerances is greater than the interference that gives the strongest joint. For example: Based on a friction coefficient of 0.4, 1-in. (25.4-mm) O.D. tubes and 1-in. (25.4 mm.) thick tubesheets, the strongest joint interference for various tube gages and metal pairs varies in the range 0.0005 in. (0.013 mm) to 0.0015 in. (0.038 mm). The permissible tube undersize is 0.006 in. (0.1524 mm). The permissible hole oversize is 0.002 in. (0.0508 mm) for 96% of the holes and 0.01 in. (0.254 mm) for 4%. The combined tolerance is 0.008 in. (0.2032 mm) to 0.016 in. (0.4064 mm). Therefore, in spite of attempts to size holes and tubes, shrink fitting has not been a commercial success.

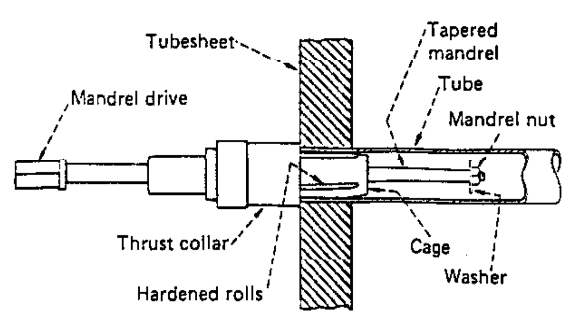
The practical way to achieve an interference fit is to expand the tube into the hole. To create interference, the tube must be permanently enlarged to a diameter greater than the hole. You do this by applying radial force inside the tube.

When you first load the tube into position there is clearance between the tube and hole. As you apply pressure, the tube bulges out. If the tube contacts the hole before the expanding pressure enlarges it beyond its elastic limit (yield stress/$\sqrt{3}$) and you then release the pressure, the tube will spring back to its original dimensions.

However, if the pressure needed to cause contact exceeds its elastic limit, the tube will be stretched permanently. Now, if you release the pressure, the tube will recover somewhat, but not to its original size. The amount of recovery depends upon the tube properties and tube and hole dimensions.

The recovery is elastic. If you reestablish the pressure and again release it, the tube will return to its previously relaxed size.

Measurements of the tube before and after you



Tube-roller in tube, before expanding **Fig. 2**

stretch it permanently will show that the increase in diameter is accompanied by a length reduction and by barely perceptible wall thinning. The relative amounts of these dimensional changes are determined by Poisson's constant, the length of tube-end expanded, tube diameter and wall thickness.

After contact, as you raise the pressure, the stress distribution in the tube changes. If you ignore the effects of adjacent holes and differences between tube and tubesheet properties, you can imagine the assembly as a large plate with a hole in its center, with pressure acting in the hole.

With increasing pressure, enlargement continues and the plastic zone spreads outward. Beyond the plastic zone, the stress is elastic. The stress in the elastic zone corresponds with the stress at the boundary of the plastic zone, not the pressure in the tube. When the plastic zone reaches the tube exterior, the pressure on the hole is equal to the tube elastic-limit stress.

In the model of a hole in a large plate, the plastic zone radius increases beyond the outer tube-wall radius as you continue to raise the pressure in the tube. When the plastic zone radius reaches 1.75 times the hole inside radius ($1.75a$), you cannot obtain further enlargement because the tube interior begins to extrude. The corresponding expansion pressure is 2(tube yield stress)/$\sqrt{3}$, or 1.155 S_{yt}.

After you release the pressure, there is some recovery, which is very nearly elastic. The inside of the tube is now larger than when you started. The assembly is permanently strained and there is a zone of residual stress beyond the interior of the tube. Residual stress increases from zero at the inside of the tube to a maximum, then declines with increasing radial distance.

The residual stress at the outside tube radius is the interfacial fit pressure, analogous to the pressure you would get by shrink fitting.

Expanding pressure is probably seldom applied to the point of fully developing yield in the tubesheet, because the resulting tubesheet distortion may be unacceptable. Furthermore, the permanently enlarged holes could make it difficult to retube a unit.

When the tube and tubesheet materials are different, differences in modulus of elasticity, yield stress and Poisson's constant affect the residual pressure. The fit pressure is also affected by the ratio of outside to inside tube radius (b/a).

At one extreme, the plastic limit may be reached in the interior of a thick tube, while there is not enough stress at the outer wall to deform the hole. At the other, a thin springy, strong tube may enlarge elastically enough to permanently deform a surrounding hole in a low-yield-strength, high-elastic-modulus tubesheet. For such a metal pair, when you release the pressure, the tube recovers its original size, but the hole does not; therefore clearance is *increased*. At neither extreme can you produce an interference fit.

When you use Appendix A, Sect. VIII, Div. 1 of the *Code* to establish allowable loads in expanded tube joints, it is prudent to establish reliability factors for conditions near these extremes by test.

Expanding is the most frequently used way to join tubes to tubesheets. It is the standard method used for exchangers built to TEMA Standards [*9*].

Tube expanding methods

You may use the following ways to obtain an interference fit:

- Expanding the tube by rolling.
- Exploding charges in the tube ends.
- Compressing an elastomer axially in the tube ends, to create radial pressure.
- Applying hydraulic pressure directly to the tube end.

Roller expanding

The tube roller shown in Fig. 2 consists of a cylindrical cage with equally spaced longitudinal slots. Three to seven rollers, nested in the slots, are made of hardened steel. The tapered mandrel fits between the rolls. The drive end of the cage is threaded to receive a thrust collar and locking nut. You adjust the position of the rolls in the tube by adjusting the position of the thrust collar.

To expand the tube, you push the mandrel forward, driving the rolls outward to press on the tube, and then rotate the mandrel. Friction between the mandrel and rolls causes the rolls to turn.

Before the advent of power-driven rolling, hammer blows were used to drive the mandrel forward, and you turned the mandrel with a wrench. In power-driven tube rollers, torque is supplied to the mandrel. As the mandrel tightly presses the rolls to the tube, the surface under each roll is slightly depressed. The tube wall is squeezed as the rolls ride up the side of the depression.

You can supply the force to insert and retract the mandrel by a self-feeding arrangement. If you set the slots in the cage to make an angle with the longitudinal axis of the cage, the mandrel will self-feed. You withdraw it by reversing the direction of rotation.

However, setting the rolls at an angle changes the motion of the rolls to a combination of sliding and rolling. If the tubes are soft and the tubesheet hard, self-feeding may cause the tube to take an hourglass shape. The opposite condition may cause a barrel shape. Either reduces the amount of contact surface, making the joint less satisfactory.

With self-feeding, the tube is pulled in reaction to the thrust of the rolls. You can use the thrust collar to hold the tubes in their axial position as you expand.

Torque is supplied by electric, air or hydraulic motors. Hydraulically driven equipment is shown in Fig. 3. Unlike self-feeding rolling tools, its roll slots are in line with the tube length. You insert and retract the mandrel hydraulically. There is no roller thrust or reaction collar, so you must hold the tube in its axial position some other way.

When you roll a tube, the effect of the high contact-pressure of the rolls on the tube is added to the effect of radial stretching. There is markedly more tube wall reduction than if you apply pressure uniformly. This is accompanied by axial extrusion of the tube end.

It is hard to measure the *actual* wall reduction. In production, you deduce the reduction by measuring the hole and tube before rolling, and the tube interior after rolling. However, the after-rolling measurement includes the stretching of the hole. Therefore, what you measure is more appropriately termed "apparent wall reduction."

Wall reduction and tube extrusion have each been used as indicators of joint strength. However, when you roll thin, springy, strong tubes into a tubesheet, the reduction may be too small to be a significant indicator of rolling degree.

To establish a repeatable procedure, you sense the torque being drawn by the roller, and set the control to stop rolling torque at a predetermined value. Many shops determine the torque cutoff point from measurements of wall reduction produced at a given torque level. The wall reduction is in turn correlated with strength and tightness tests. However, the current trend is to relate torque values directly to strength and tightness tests.

Roller expanding demands careful attention to:

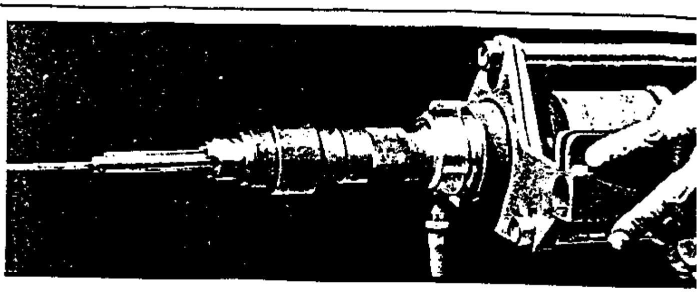
- Cleanliness of the roller, tube interior, and exterior tube hole.
- Number of rolls.
- Angle of rolls relative to tube axis.
- Roller rotational speed.
- Lubrication and cooling of the roller.
- Condition of cage, rolls and mandrel.
- Shape of rolls.
- Measurements.
- Maintenance of precise torque cutoff settings (using a torque analyzer).
- Technique of rolling.
- Effects of worker fatigue.

When you have a heat exchanger with thick tubesheets it is customary to limit the depth of hard rolling to the amount that provides a joint strength equal to tube strength. This is considered to be achieved at a depth of $1\frac{1}{2}$ to $2\frac{1}{2}$ in. [*10*].

The current practice in the U.S. is to expand the tubes for a length not less than 2 in. or tubesheet thickness minus $\frac{1}{8}$ in. for TEMA Class R and B exchangers, and the least of twice tube diameter, 2 in., or tubesheet thickness minus $\frac{1}{8}$ in. for TEMA Class C.

However, to avoid crevice corrosion you may have to bring the tube into contact with the hole for the full thickness of the tubesheet.

A less obvious reason for full-depth contact is that when you consider the tubesheet to be a perforated plate, the effective size of the perforation is the inside diameter of the tube where it is in intimate contact with the hole. But, where there is clearance between the tube and hole, the effective perforation size is the diameter of the hole.


Vernon Tool Co., Ltd., Oceanside, Calif.

Vernon hydraulically driven tube roller **Fig. 3**

If you are concerned only with sealing the unexpanded space, the two alternatives are: (1) Roll the tube into the tubesheet at the shell-side face. Then roll the tube into the tubesheet at the tube-side face. This procedure leaves the intervening space unexpanded; and (2) Expand the full depth.

The maximum practical depth that can be rolled in one step is about 2 in., because of the torque required and tube extrusion. The first alternative (above) lets you seal the front and back of the tubesheet without excessive tube compression resulting from extrusion.

The second alternative requires special attention to the rolling technique. If you do the first step at the inner end of the joint and successive steps progressively outward, the tube end can move out of the hole without causing the tube to be compressed.

Extrusion caused by roller expanding will cause tubesheets to cock if an improper technique is used. You should establish the sequence of rolling with the fabricator as part of the procedure for tubing or retubing a unit. A typical recommended sequence is shown in Fig. 4.

When you roll tubes into double tubesheets, the effects of extrusion are intensified. The life of the exchanger will be shortened if the tubesheets are not set parallel with each other or if corresponding holes in adjacent tubesheets are not aligned accurately.

The sequence that will avoid these problems is:

(1) Fix the tubesheets at each end parallel with each other, with tube holes aligned.

(2) Set the pair of tubesheets at each end parallel with those at the other end, with holes aligned.

(3) Tube the bundle, following the specified cleaning procedure.

(4) Tack-expand the tubes in the front inner tubesheet in the order shown in Fig. 4.

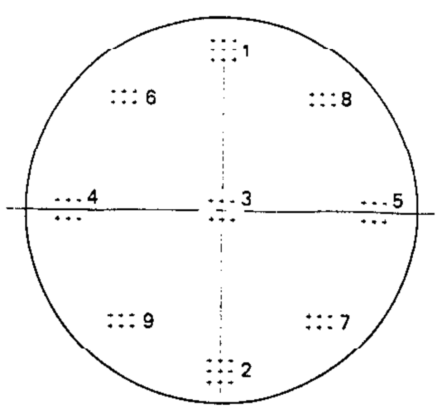
(5) Fully expand the tubes in the front inner tubesheet, using progressive step rolling.

(6) Repeat Steps 4 and 5 at the rear inner tubesheet.

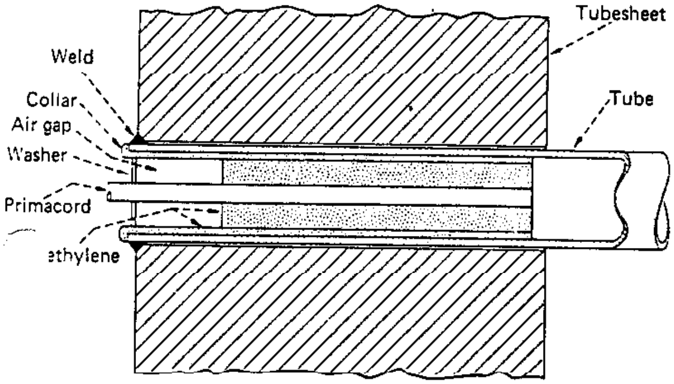
(7) Test the shell side.

(8) Repeat Steps 4 and 5 at the front outer tubesheet.

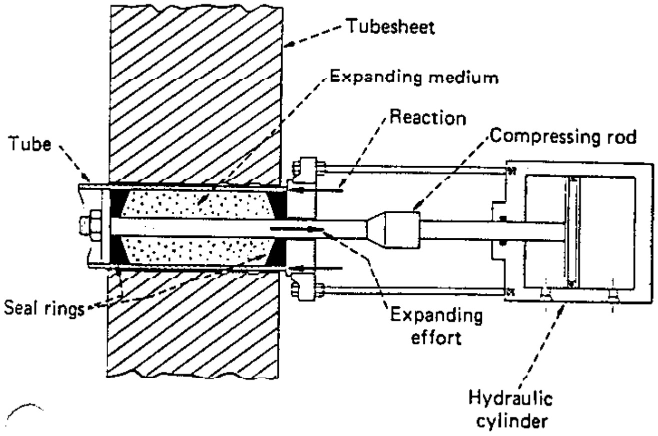
(9) Test the gap, if it is possible, or the channel side if the gap is exposed.



Typical sequence of tack-expanding tubes before beginning production expanding Fig. 4



Explosive insert in tube-to-tubesheet assembly Fig. 5



How Hitachi rubber expanding works Fig. 6

(10) Repeat Steps 8 and 9 for the rear outer tubesheet.

When you fix the tubes at one end, then roll the tubes at the other, the friction of the rolls may cause the tube to twist. As a result, the bundle may have a noticeable twist after rolling is completed. You can avoid this problem by using a tapered drift pin to lock the tubes to the second tubesheet.

The other ways to expand tubes—exploding charges in the tube ends, compressing an elastomer in the tube ends, and directly applying hydraulic pressure—apply expanding pressure uniformly.

Exploding charges in tube ends

Setting off of a charge in the tube ends is called near-contact forming, kinetic expanding, near-explosive expanding or, Detna-forming* [*11*].

In kinetic expanding, the tube is the workpiece. The tubesheet and the air gap in the clearance between the tube and hole make up a forming die. The explosive-charge package consists of Primacord contained in a cylinder of polyethylene. The polyethylene medium transmits the expanding force to the tube in a controlled way.

Polyethylene is used because it: (1) is cheap; (2) is available; (3) is easy to handle; (4) is flexible; (5) resists attack by water and most solvents; (6) has fairly high density; (7) has a high-enough melting point; (8) does not react with the tube metal; and (9) does not create a cleaning problem after expanding.

From the control standpoint, polyethylene is desirable because: (1) it is resilient, accommodating large elastic strains without cracking or bursting; and (2) stress waves are rapidly attenuated as they are propagated through it. The resiliency makes removing the insert easy. The rapid diminution of stress waves minimizes shocks to the tubes and tubesheets.

To get consistent expansions in the desired expansion region, you must fit the Primacord carefully into the polyethylene insert, leaving no air gap.

The pressures generated when you set off an explosion decrease very rapidly with distance, especially very close to the explosion. This makes it possible to control precisely the length of tube that you expand. You may contact-expand tubes into a tubesheet after you make a primary front-facejoint weld. Precise control of expanding distance lets you avoid deforming the weld.

Fig. 5 is a cross-section through a portion of a tubesheet into which a tube has been welded. It shows the arrangement of Primacord, polyethylene medium wrapper and air gap for controlled contact expanding of the tube without stressing the weld.

To establish the charge size, perform pull-out load tests. You may substantiate the charge size by measuring the strain in unrestrained tubes that have been expanded by setting off the selected charge.

The detonation in the tube produces less-severe surface distortion on the inside of the tube than does rolling. The tubesheet is not injured by the explosion in the tubes. The process is applied mostly to thick tubesheets.

The manufacturer must work out the expanding pro-

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*A trademark of Foster-Wheeler Energy Corp., Livingston, N.J.

cedure. If you review the manufacturer's procedure, points of attention are: (1) how the charge is established; (2) what steps are taken to ensure that the connections to the charges are secure and reliable; (3) how misfires are to be prevented; (4) how misfires are to be corrected; (5) how the joint is to be tested; and (6) what is the procedure for cleanup after expansion.

One of the uses of near-explosion expanding is the contact expanding of previously welded-in tubes into thick tubesheets of high-pressure feedwater heaters. Another important use is to make expanded-only joints in low-pressure feedwater heaters.

A unique advantage in making explosive-expanded-only joints is that with one explosion you can apply full expansion pressure in the vicinity of annular grooves in the tube hole, and contact-only pressure in the balance of the tube end [*12*].

The other uniform-pressure expanding methods are more common.

Compressing an elastomer in the tube

Hitachi calls its procedure for compressing an elastomer in the tube ends to achieve radial expanding force, "rubber expanding." Fig. 6 is a schematic drawing, showing how the Hitachi Rubber Expanding Machine works. The expanding medium is a cylinder of elastomer. The pressing rod, connected to the hydraulic cylinder, passes through the medium. When you hydraulically retract the pressing rod, the medium is compressed. It bulges radially, exerting pressure uniformly on the tube interior. The radial force is uniform at any section perpendicular to the tube axis. However, it probably varies with axial distance in the medium.

The seal rings at the inner and outer faces of the elastomer cylinder prevent it from extruding during compression. The nut and washer on the inner end of the pressing rod transfer compressing force to the medium. Reaction to the compressive force is contained by the thrust bushing seated in the retainer held to the hydraulic cylinder by the tie rods.

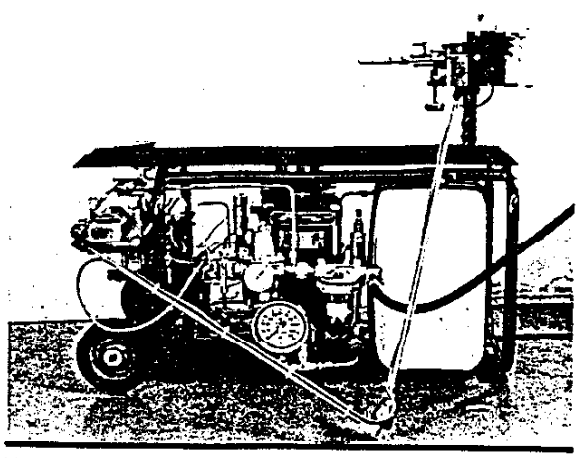
When you rubber-expand, the degree of expansion is related to the hydraulic cylinder retracting pressure. However, you cannot directly measure the expansion pressure in the tube end.

Applying hydraulic pressure directly

You can supply expanding force by applying hydraulic pressure directly in the tube ends [*13,14*]. Because there is no intervening medium, you can directly measure and precisely control the pressure. Furthermore, you can repeat the pressure within a very narrow range.

In direct hydraulic expanding, the working fluid is demineralized or distilled water. The basic system consists of a two-stage pump and reservoir assembly, operating gun, and mandrel, plus needed hydraulic piping.

Fig. 7 shows the HydroSwage* power unit with housing removed. The compressed-air-driven Haskel hydraulic water-pump feeds a fixed-ratio intensifier to produce hydraulic expanding pressure of approximately 40,000 psi (275 MPa). Adjusting the input to the intensifier lets you precisely control the expanding. To make the operation of the unit flexible, you may connect the low-pressure side to the intensifier by an umbilical hose.



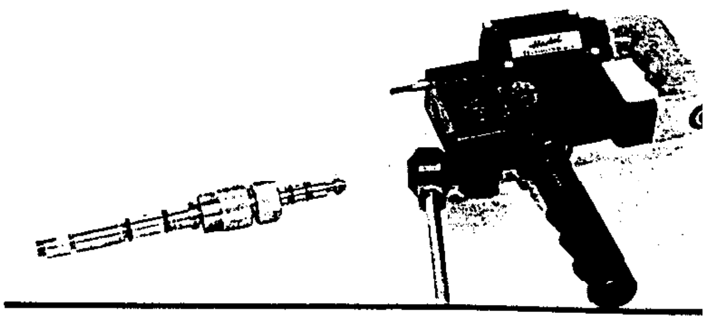
Haskel HydroSwage power unit, swivel fittings with hydraulic tubing, gun and mandrel Fig. 7

High-pressure water is conveyed to the gun and mandrel through sections of hydraulic tubing joined by the four-axis swivel fittings shown in Fig. 7. To provide flexibility, you place the fittings on the power unit, between equal lengths of hydraulic tubing, and on the gun (or you can use flexible capillary tubing).

The gun accepts mandrels sized for all tube diameters, gages and expanding-lengths. It has three signal lights to indicate the stage of operation. An amber light on the bottom shows the start of expanding. A green light on the top signals completion of the cycle. A red light in the middle comes on only when there is a problem in reaching the preset expanding pressure. It lights up when the intensifier has completed its stroke without attaining the pressure setting. This may result from a defective tube, or a need for new mandrel seals.

A gun and mandrel are shown in Fig. 8. The finger that projects at the forward end of the gun operates an adjustable pressure switch. It must be depressed by contact with the tubesheet to activate the switch and turn the gun on.

The mandrel has front and rear O-rings with backup



Haskel HydroSwage and mandrel Fig. 8

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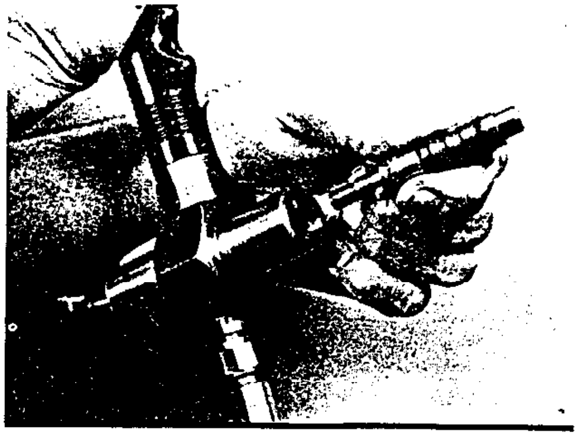
*A trademark of Haskel Inc. The worldwide distributor for HydroSwage equipment is Torque and Tension Equipment Inc., Campbell, Calif.



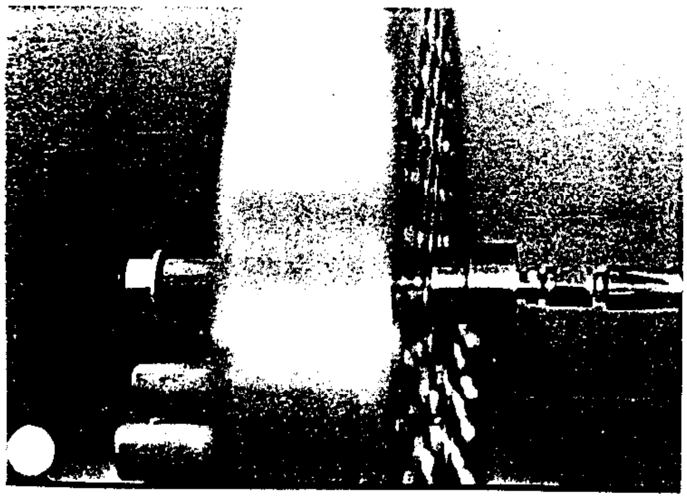
Haskel tube-lock tool Fig. 9

rings. You can set the O-rings to seal on the tube interior exactly where you want expansion to stop. O-ring life is affected by the bead height if you use welded tubes. There is no limit to the mandrel length, therefore you can expand the full depth of the tubesheet in one operation.

The mandrel of the HydroSwage system has a self-centering feature that allows the inside tube diameter to increase as much as 0.010 in. (1.016 mm) during expansion, with one mandrel.

When you apply pressure to the tube, the changes in the condition of the tube metal do not take place instantaneously. Therefore, the gun is provided with an adjustable timer, which you set to an experimentally determined dwell time.

Use the following sequence to expand tubes with the HydroSwage: (1) thread the mandrel into the gun; (2) insert the mandrel into the tube; (3) depress the operating trigger button; (4) remove the mandrel when the green light comes on. If the red light comes on, investigate the cause. Correct it and repeat the procedure.



How the Haskel tube-test tool is used Fig. 10

When you are swaging, the mandrel is too tightly locked to the tube to be moved manually. The axial forces are balanced, therefore you do not have to resist thrust.

You have to lock the tube in position before you make a uniform-pressure expanded joint, a joint made by a hydraulically driven roller with inline roll slots and a welded-first joint. For this purpose you may use a tapered drift pin, but if a power unit is available, it is more convenient, cleaner and faster to use the tube-lock tool illustrated in Fig. 9.

The tube-lock tool operates from the low-pressure side of the power unit. A hydraulic cylinder causes the polyurethane segments to expand when you apply pressure. After you release the pressure, the tube has been bulged out enough to hold it axially. However, the tube is not in contact for the full depth of the hole, nor is it tightly sealed.

You may use the tube-test tool to verify the pressure given in the expanding-procedure specification. The tool, pictured in Fig. 10, consists of a mandrel threaded at one end, and with a boss on the other. An O-ring is provided as a seal between the rod and tube near the threaded end. A second O-ring seals the back of the boss to the face of the tubesheet in the ligament space surrounding the tube.

The testing procedure is: (1) insert short stubs of tubing from the same production heat into the tubesheet; (2) insert the tool into tube end and tighten the nut against the thrust washer bearing against the tube stub; (3) introduce high-pressure test water through the mandrel; (4) inspect for leaks.

Although the manufacturer supplies the tool as part of a system, you may use it to verify the tightness of roller-expanded joints, welded- or brazed-only joints and welded- or brazed-first, expanded joints.

How temperature affects expanded joints

The effects of metal temperature on expanded tube-to-tubesheet joints have not been adequately investigated. Still, the following elementary discussion may be useful as a guide.

You expand tubes into tubesheets at room temperature, but usually operate heat exchangers at other temperatures. The temperature change affects the joint strength and tightness. Of concern are:

- Differences in expansion between tube and hole.
- Changes in metal properties.
- Creep.
- Changes in coefficient of friction.

As the temperature changes, if the tube expands more than the tubesheet, the joint becomes tighter until there is inelastic deformation. In the opposite case, the joint becomes looser. You can calculate the change in interference by using the following equation:

$$\Delta I = 2b\,(T_o - T_r)\,(\psi_p - \psi_t) \qquad (6)$$

where: ΔI = change in interference; T_o = operating temperature, °F (°C); T_r = room temperature, °F (°C); ψ_p = tubesheet mean coefficient of thermal expansion, in./(in.)(°F) or m/(m)(°C); ψ_t = tube mean coefficient of thermal expansion, in./(in.)(°F) or m/(m)(°C).

You can then appraise its effect by using Eq. (1) and (2).

The tube and tubesheet may also expand at different rates along the axis of the tube. Imagine a stainless-steel tube stub in a hole in a steel tubesheet, with the ends of the stub flush with the tubesheet faces. If you heated the assembly, the tube stub would expand more than the tubesheet and protrude from each face. The force to restrain this movement is supplied by friction.

You can appraise this thermal effect by estimating the interfacial pressure and interference needed. If you make the simplifying assumption that the tube is held in a ring of tubesheet having a radius equal to half the pitch, you can develop an equation for the unit equilibrium force or contact pressure. You can substitute this value in rearranged Eq. (1) to calculate the associated increase in interference needed.

The equations developed this way are:

$$P_o'' = \frac{(\psi_p - \psi_t)(T_o - T_r)(r^2 - b^2)(b^2 - a^2)E_pE_t}{fb[(r^2 - b^2)E_p + (b^2 - a^2)E_t]} \qquad (7)$$

In this equation: P_o'' = interfacial pressure required to prevent axial movement of tube relative to tubesheet, psi (Pa); and r = one-half tube hole pitch, in. (m).

The interference that will develop this pressure is:

$$I'' = \frac{2P_o''(1 + E_t\phi_p/E_p\phi_t)}{E_t} \qquad (8)$$

where: I'' = interference to create pressure psi (Pa), in. (m).

You can include the effects of temperature on metal properties by choosing the values of yield stress, modulus of elasticity and mean coefficient of thermal expansion at the anticipated operating temperature.

The main impediment to using expanded tube joints at high temperatures is the tendency of the strain to relax with the passage of time. This tendency to creep is enhanced as temperature increases. You may test the creep behavior of the pair of metals by simulating operating conditions in a model.

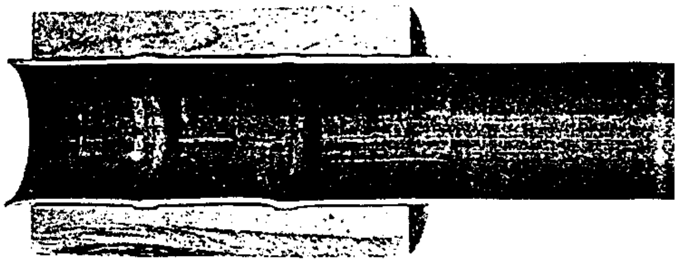
There does not appear to be much information available on the variation of friction coefficients with temperature. Values of the coefficient could readily be determined at various temperatures for given surface conditions and pairs. However there may not be a direct relationship between these values and the actual conditions after you expand a tube into a hole.

Probably the best way to determine the effect of temperature on expanded joints is to perform pull-out or push-out tests at the proposed design temperature after a suitable period of heat-soaking.

Grooves, flaring and beading

A general rule of thumb for expanded joints is that rough tube-holes make strong joints, and smooth holes make tight ones. You can enhance the strength and tightness of the joints by providing annular grooves in the holes.

Tests of the effects of grooving on roller-expanded boiler-tube joints showed a 39% enhancement for one groove and 53% for two [*15*]. When you roll tubes into grooved holes, the tube metal extrudes into the grooves. The shape of the extruded metal is approximately rectangular. Overexpanding, which causes axial tube extrusion, tends to shear these keys, resulting in weaker, less-tight joints.



Specimen of a tube expanded into a double-grooved hole by uniform pressure **Fig. 11**

When you use one of the uniform-pressure expanding methods, the tube bulges into the groove as shown in Fig. 11. The metal-to-metal interference at the points where the nearly parabolic shape of the tube-bulge meets the groove edges is responsible for making the joint tight.

Many groove configurations have been used. The TEMA Standards for Class R exchangers state, "All tube holes for expanded joints shall be machined with at least two grooves, each approximately ⅛" wide by $\frac{1}{64}$" deep. When integrally clad or applied tubesheet facings are used, all grooves shall be in the base material unless otherwise specified by the purchaser." The standard for Class B units is identical except that ". . . by the purchaser" is deleted, and the standard for Class C equipment requires grooving for tubes ⅝ inch O.D. and larger for ". . . design pressures 300 psi and/or temperatures in excess of 350°F . . ."

Because uniform-pressure expanding bulges the tube into grooves in the hole (in contrast to the extrusion that rolling causes), you can use explosive, rubber or hydraulic means to expand tubes into the gap between integral double tubesheets [*16*].

In uniform-pressure expanding, the groove width, depth and position affect the strength and tightness that you achieve [*17*].

You obtain the optimum width when the product βW is in the range of 1.5 to 3.0. Here:

$$\beta = \sqrt[4]{3(1 - \nu)^2/R^2t^2} \qquad (9)$$

where: W = width of groove, in. (mm); R = mean tube radius, in. (mm); and t = tube wall thickness, in. (mm).

The joint strength varies almost linearly with groove depth. The minimum depth of groove that you should specify for uniform-pressure expanding is $\frac{1}{64}$ in. (0.4 mm).

For maximum pull-out strength, locate the grooves near the outer tubesheet face. For maximum push-out, position them near the inner face. For alternating service place one groove near each face.

If the direction of the forces resulting from pressure on the tubesheets is outward, you will enhance the joint strength and tightness by flaring or beading the tubes.

In flared-end tubes, you increase the strength by the force needed to draw the tube down to its original size. On beaded-end tubes, you raise the strength by the force that will shear the bead.

Flaring and beading make the tube interfere with the outer edge of the hole. This metal-to-metal interference is a further barrier to leakage.

Another use for beading-over the tube ends is to provide a weld-joint preparation. When you do this, the beaded and welded joint is tight and strong in both directions.

Tube ends are sometimes flared or beaded to ease tubeside entrance effects. You may accomplish this more effectively by expanding the tubes flush with the front face of the tubesheet, then machining a smooth taper or radius from the bore of each tube to a point just short of the middle of the ligament.

Welded and brazed joints

Use welding, brazing, or welding and brazing to join tubes to tubesheets when:

- The operating metal temperature is high.
- Operation is highly cyclical.
- Helium-leak tightness is specified.
- Quality assurance requires nondestructive examination of each joint.
- The dimensions and properties of the joints are unsuitable for expanding.

When you choose to weld or braze the tubes to the tubesheet, consider the following questions:

- Can the metals be joined by welding or brazing?
- What is the most suitable process?
- Has a qualified procedure been established and used successfully in the shop and field?
- How will the dimensions of tubes and tubesheet and hole layout affect the welding or brazing?
- Will the proximity of the shell or pass partitions to tube holes interfere with producing good joints?
- Will it be necessary to preheat or to post-weld heat-treat the joints? If so how will the exchanger be affected?
- What nondestructive examinations can be used?

These questions cannot be answered independently of each other. Whether or not metals can be joined by brazing or welding is partly a question of metallurgy, but it is also a question of process and dimensions. It is not possible, for example, to fusion-weld titanium tubes to steel tubesheets, but they can be successfully explosion-welded. However, if the tubesheets are thin and the ligaments small, explosion-welding is not feasible.

The size of the exchanger may affect the procedure. In brazing and fusion-welding it is desirable to have the tubesheets horizontal (i.e., with tubes vertical) when you do the work. The advantage of this arrangement is that the position in which you work on the tube end is constant. By contrast, when the tubes are horizontal, your position continually changes as you traverse the tube.

However, few shops have facilities for setting large exchangers vertically. Furthermore, heat exchangers are usually horizontal during hydrostatic testing. Therefore, it may be impractical or too costly to use the most desirable fusion-welding or brazing position.

Basic information on welding and brazing is given in the "Welding Handbook" [*18*]. In addition, the American Welding Soc. (AWS) publishes articles and discussions in its *Welding Journal*. The New York-based Welding Research Council (WRC) pursues new developments. The council issues progress reports and interpretive reports. When a conclusion has been reached on a new process or development, the Council publishes a final report in a WRC bulletin.

Brazing and welding processes

The processes used most often to bond tube ends to tubesheets are: (1) brazing; (2) fusion-welding processes; and (3) explosive welding.

In brazing, you produce coalescence by heating the assembly to a temperature above 800°F (427°C). This melts a nonferrous filler metal that flows into the space between the tube and hole by capillary action. The base metals have higher melting points than the filler and do not melt.

The operating temperature at which you can use brazed joints depends on the filler metal as well as on the base metals. If you qualify a procedure satisfactorily under Section IX of the *Code*, then under Sect. VIII, Div. 1, the filler metal is considered to be suitable for operating temperatures of 200°F (94°C) or less.

You may use certain classifications of brazing filler metals for service temperatures as high as 300°F (204°C) if you meet additional conditions listed in the *Code*.

You must use a suitable flux, atmosphere or flux-atmosphere combination to exclude atmospheric gases that can oxidize or embrittle the braze metal. You can braze either with a torch or in a furnace. Furnace brazing may be in an open-flame or a closed furnace.

The joint design and brazing technique must ensure flow of braze metal into the joint. You cannot easily see evidence of such penetration. Consequently, it is prudent and customary to reduce the joint efficiency factor. You can use a higher efficiency by preplacing braze-metal rings behind the tubesheet and having visible evidence that the braze metal penetrated to the front.

If you follow the latter procedure, you eliminate the crevice between the tube and hole. Therefore, it may be done to prevent crevice corrosion. When you make the primary joint by front-end welding, you may eliminate crevice corrosion by back-brazing. However, the shell-side process fluids must be compatible with the braze deposit.

Cleanliness of the parts is essential in successful brazing. If there is any oil, grease, oxide scale or foreign matter present, you will get porous joints. When you examine a brazing procedure, be sure that a cleaning specification is part of it.

The *Code* prohibits using brazed joints for lethal-material service and for unfired steam boilers.

Most metallically bonded joints are made by fusion welding. The technology is highly advanced. Technical institutions, welding equipment manufacturers, fabricators and technical societies continually work to improve the processes and techniques. Here is a brief summary of the fusion-welding processes and their application to tube-to-tubesheet joints.

When you fusion-weld, you bring the base metals to a molten state. The metals then fuse, forming complex solutions.

You may supply heat-of-fusion by: (1) burning a mixture of gas and oxygen at the joint; (2) applying a voltage gradient to the parts, causing current to flow against resistance; (3) inducing an electric current to flow in the metals; and (4) striking an arc across a gap subjected to a voltage difference.

In fusion-welding tubes to tubesheets, the electric arc processes are normally used, sometimes supplemented by gas welding.

Electrodes intended to be melted into joints are termed consumable. Electrodes meant to be used only as terminals are called nonconsumable; if they melt into the molten puddle, they make inferior welds.

When you use nonconsumable electrodes, you may fuse the base metals only, or you may provide filler metal. Filler may be fed continuously from spools of wire at rates controlled to match welding speed, or you may manually feed a rod of filler metal. In some joints it is advantageous to set rings of filler in place before striking the arc.

Arc welds can be made in the atmosphere, but they tend to become oxidized, embrittled and porous. Therefore, air is excluded from the molten metals by fluxes or shielding gases. You may also use fluxes to contribute metal elements to the weld.

The fusion-welding processes used to bond tubes to tubesheets are:

- Shielded metal-arc welding or SMAW ("stick").
- Gas tungsten-arc welding or GTAW (or TIG, tungsten inert gas).
- Gas metal-arc welding or GMAW (or MIG, metal inert gas).
- Oxyfuel gas welding or OFW.

When you use shielded metal arc (SMAW), you clamp a stick of flux-coated metal rod in the jaws of a welding handle. The process is manual, which puts a premium on welding skill. The welder must follow the specified procedure faithfully. Joint quality varies with the skill and the physical and emotional state of the welder.

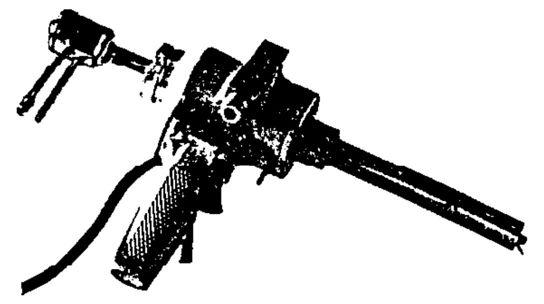
You need an adequate ligament width to stick-weld tubes to tubesheets; the welds are fillet welds. Their best application is welding heavy-wall tubes to tubesheets.

The largest number of welded tube-to-tubesheet joints is made by using the gas tungsten-arc welding process. The nonconsumable electrode is thoriated tungsten. You shield the weld from the atmosphere by blanketing it with inert gas (helium, argon, CO_2 or mixtures). The gas flows at a controlled rate through an annular space between the electrode and surrounding nozzle. You may also blanket the back side of the joint with shielding gas.

You must take great care not to let the electrode touch the weld puddle, because tungsten inclusions embrittle the weld.

A projection of the tube may melt to act as filler metal in the joint. You may also feed filler metal from a wire spool continuously through the nozzle, or hand-feed straight lengths to the arc.

A variety of systems is available for automatically welding tubes to tubesheets by the GTAW process [19].


Kynex automatic welding gun for welding tubes to the back side of the tubesheet Fig. 12

The Ciber-Tig* system consists of a gas-tungsten-arc welding machine, programmer, automatic tube-to-tubesheet welding head, and motor speed controller.

The system automatically controls the flow of pre-purge gas, shielding gas and post-purge gas, wire feedrate, rotational speed and weld voltage buildup and decline. Various accessories are available to control the welding remotely, stabilize the arc and record arc voltages, currents and sequences. The latter accessory is extremely valuable for establishing welding procedure specifications and controlling their application.

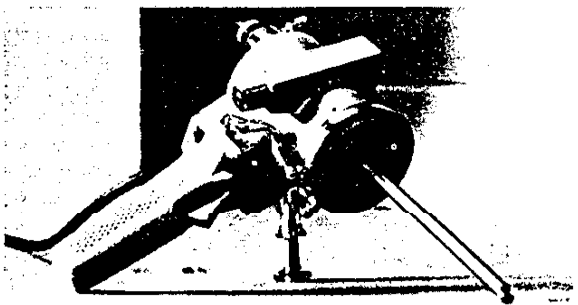
You can join the tubes to the front or rear face of the tubesheet by using the GTAW process. If you forge tube-hole projections on the rear face, you can butt-weld the tubes to the projection. This permits you to radiograph the tube-to-tubesheet weld [20,21].

When you weld the tubes to the back side of the tubesheet, the perforation in the tubesheet is the same as the tube I.D. This gives you flexibility in making future repairs.

Kynex Corp. of Rome, N.Y., provides an onsite automatic tube-to-tubesheet joint-welding service. Fig. 12 shows the Kynex GTAW process gun for welding near the back side of a tubesheet. Fig. 13 shows the Kynex automatic face-welding gun for performing welds where the tubes are flush with the front face.

In the gas-metal-arc welding process the electrode is consumed. You feed it from a spool through a nozzle. Shielding gases flow around the electrode through the nozzle. You may use gas up behind the joint as in

*A trademark of Hobart Bros. Co., Troy, Ohio.


Kynex automatic welding gun for welding tubes to front tubesheet face **Fig. 13**

GTAW. Or the electrode may be a small tube, filled with flux that contributes alloying elements to the weld. This is called flux-cored wire.

The most suitable use for GMAW is to make fillet welds that join large-diameter tubes to front tubesheet faces.

Reliable fusion welds must be free of porosity, nonmetallic inclusions, and cracks. To achieve this quality, you must meet the following conditions: (1) the base metals must be compatible; (2) the tube ends and holes must be *completely* free of foreign matter; (3) the environment must be clean and dry; (4) the flux on coated rods must be dry; (5) shielding gas must be bone-dry; (6) the base-metal grain structure must be uniform; (7) gases generated by welding must be able to escape the weld puddle; (8) the tube-to-tubesheet temperature must be kept nearly constant after you begin welding; (9) you must exclude condensation moisture when you interrupt welding; (10) you must not let the voltage and current output of the welding source fluctuate; and (11) you must keep the welding area free of stray magnetic fields.

Metals to be fusion-welded must be able to form tough, crackfree solid solutions. When the tube/tubesheet pair does not meet this requirement, you may clad the tubesheet face with a metal compatible with the tubesheet and the tubes.

If the tube and tubesheet are not scrupulously clean before welding, you can count on porosity at best and complete joint failure at worst. Be sure that any weld procedure that you review requires mechanical cleaning of the tube ends and holes, followed by washing with a volatile chloride-ion-free solvent. To assure the quality of the joint, make this a quality-control hold point.

Ordinarily, clean, untreated atmospheric air is a suitable welding environment. But for some base metal pairs you must surround the work area with uniform-temperature, controlled-humidity, filtered air. You may do the work in a special room called "clean room" or in a housing that surrounds the tubesheet.

The consumables—weld rods and shielding gases—must be dry. When you evaluate a shop's capability of making sound tube-to-tubesheet fusion welds, make certain that it is standard shop practice to store opened containers of flux-coated rods in moisture-excluding ovens. On the working floor, opened packages of loose rods ought to be held in portable rod-warmers. Note also that, before a cylinder of shielding gas is connected to the welder, it should be tested with a moisture-sensitive paste.

The grain structures of tubesheets made from large rolled plates or forgings may vary across the surfaces. If a tube hole pierces the tubesheet where an unsatisfactory local condition exists, it can cause a faulty weld. This may show itself at a spot where the local carbon content is too high to make a tough weld. You can surmount this problem by cladding the tubesheet with a thin layer of weld deposit of acceptable composition before you drill it.

If the gases produced by fusion welding cannot freely escape from the weld puddle, the tube-joint welds may be porous and predisposed to cracking. When you make the joints at the front face of the tubesheet, using the geometries shown in Fig. 14, you must hold the tubes in place. You may do this by tack-welding the tubes, expanding the tube ends with a drift pin to make line contact, or using a device like the previously described Haskel tube-setting tool.

The practice of setting tubes by lightly rolling them before welding is likely to cause trouble by: (1) not permitting an adequate escape path for welding gases at the root of the weld; and (2) introducing foreign matter to the surfaces to be welded (lubricants and flakes from the roller and cage of the expander).

If you let the tubesheet temperature vary widely during welding, the size of the root opening will vary from joint to joint. As welding heat spreads throughout the tubesheet, the holes deviate from roundness. The amount they recover depends on the change in radial temperature gradient. As the welds solidify they shrink, which further distorts the holes near the joint being made. To reduce the amount of distortion, keep the tubesheet at a uniform temperature.

When welding is interrupted, it is advisable to warm the tubesheet before restarting. Re-start warming is separate from pre-heating and post-weld heat-treating, which serve different purposes. The re-start warming also helps to dispel condensation moisture.

If you interrupt the welding for a long time, condensation moisture may settle in the unwelded joints. It can make subsequent welds porous when the moisture vaporizes. Good practice is to put a cloth bag of desiccant in a plastic wrapping around the assembly.

Although you might not notice it, the line-voltage fluctuates. These variations may change current and arc-gap length, and cause unseen changes in the weld penetration and metal deposits. For best results use a voltage regulator on the supply to the welding machine.

Shops are full of stray magnetic fields (often generated by neatly coiled leads of welding cable). External magnetic fields add to the effect of arc blow, a deflection of welding current in direct-current welding caused by variations of magnetic flux in the work piece. Arc blow may cause skips and uneven tube-joint welds.

The reliability of fusion welds also depends upon the joint design. When you design a joint, major factors to consider are the leak path and the strength of the weld.

For tightness, the leak path through the weld throat should be at least as long as the tube wall thickness.

You can design the weld joint to be as strong as the tube in resisting axial loading, or to just meet the *Code* requirements. Tube welds probably fail more from localized stress than from axial loading [*22*]. Simply adding weld metal does not always help.

The joint design should allow the basic weld configuration to be replicated easily. Furthermore, there are so many joints that you have to consider it likely that some will fail on test or during the life of the exchanger. Therefore, joint geometry should permit repairing.

For joint designs for high-pressure exchangers or those in nuclear or other hazardous service, consider also [*22*]:

- Joint weld-stress due to tubesheet flexure.
- Interactions between the tubes and tubesheet resulting from differential thermal expansion.
- Residual welding stress.

- Effects of combining welding with expanding.

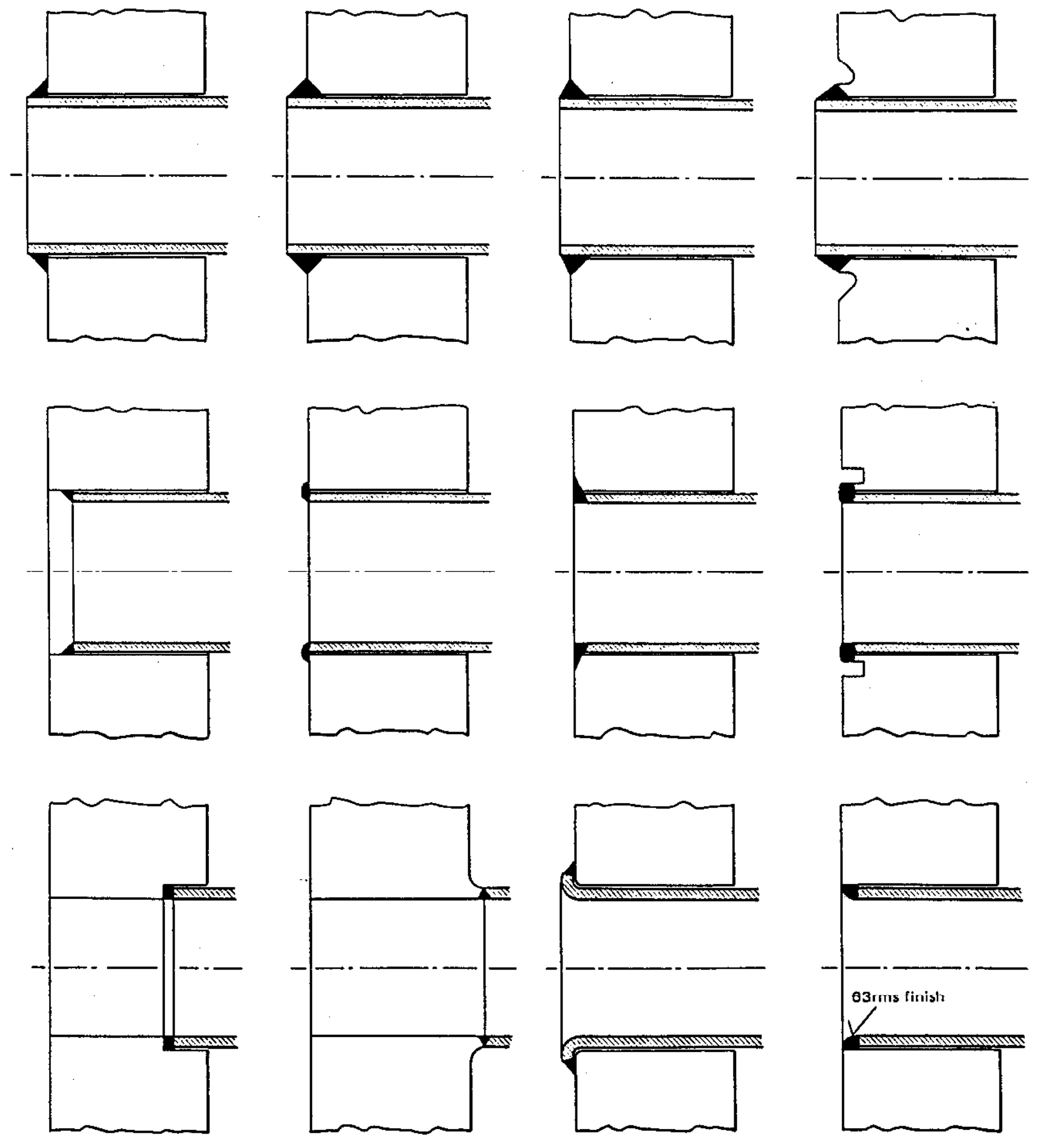
You may examine the fatigue strength of specific joint designs by using *Code* methods for these service requirements.

Explosive welding

When the metals are not compatible for fusion welding, but you need the tightness and strength of welded joints, consider explosive welding.

The AWS defines explosive welding (EXW) as [*18*] "a solid-state welding process wherein coalescence is effected by a high-velocity movement produced by a controlled detonation."

There are three requirements for explosive welding [*23*]. One, you must progressively bring together the two components, thereby producing a collision front that traverses the surfaces to be joined. Two, the velocity of the collision front must not exceed 120% of the



Some typical weld-joint configurations

Fig. 14

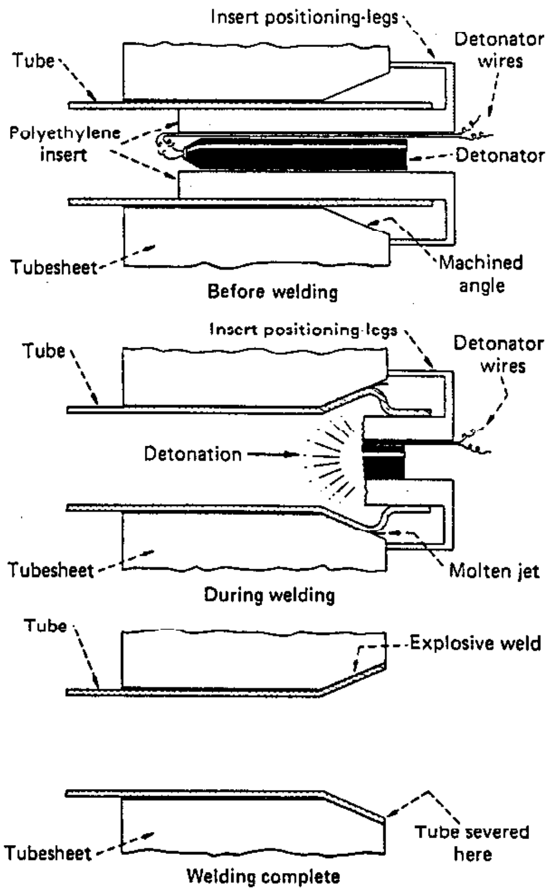
sonic velocity of the materials. And three, the pressure created at the interface must be several times the yield strength of the materials.

If you meet these conditions, the component surfaces become molten at the collision front. The molten metal, together with any surface contaminants, is propelled before the collision front in the form of a jet. The jet is ejected from the interface at the tube end. Upon passage of the jet, the cleaned surfaces, in contact under high pressure, diffuse into each other to form a metallurgical bond. Any tube projection is severed at the tubesheet face.

The bond interface has the shape of a sinusoidal wave. This prevents complete molten-metal ejection because some is entrapped by the vortices associated with the wave peaks and troughs.

Although the velocity front must not exceed 120% of the sonic velocity, explosives that produce a higher-velocity front are cheap and easy to handle. To use them you must make an angular joint preparation.

Fig. 15 is a schematic representation of the process. The tube hole, tapered outward toward the front face, makes an angle with the tube. When you detonate the explosion near the junction of the tube and the untapered part of the hole, the blast makes the tube collide with the hole. The distance the tube must travel to the collision point is progressively greater along the tube because of the taper. This reduces the collision-point velocity below the detonation velocity and makes it possible to use high-velocity-front explosives.



Adapted from Hardwick, R., Methods for Fabricating and Plugging of Tube-to-Tubesheet Joints by Explosion Welding, *Welding J.*, Apr. 1975.

Explosive tube-welding sequence Fig. 15

The increasing gap between the tube and hole limits the surface area you can weld. However, this is acceptable because you can get enough welded surface to attain full weld strength.

The depth of the countersunk taper usually is $\frac{1}{2}$ to $\frac{5}{8}$ in. The angle used lies between 10 and 20 deg. High angles produce larger wave lengths than do smaller ones, and this causes less jet-metal entrapment at the interface. Therefore, you should use high angles when the combination of molten tube and tubesheet materials produces a brittle intermetallic.

However, when you must have small ligaments, you have to reduce the angle to machine less metal out of the ligament. You must make a compromise between the geometry and metal requirements.

The tube-wall thickness mainly governs the ligament thickness needed to avoid deforming the hole. Because thick tubes accelerate more slowly than thin ones, they need higher charges to reach the collision velocity required for explosive welding. If the tube wall-mass accelerated to this velocity distorts the ligament, the collision pressure will be reduced.

You may partially circumvent this problem by putting tapered plug supports in adjacent unwelded holes. Another expedient is to reduce the tube wall in the region of the joint. Tube-wall thicknesses versus ligament widths for unsupported and supported ligaments have been experimentally determined and tabulated [*23*].

Fig. 16 is a photograph of a cross section of an explosively welded tube-to-tubesheet joint.

Inspecting brazed and welded joints

The configuration of brazed and front-face fusion-welded joints restricts your ability to perform significant nondestructive tests.

An experienced welding inspector, using a strong light, can detect most surface flaws. Properly done, fluid-penetrant examination can reveal surface porosity and cracks that might not be found on the visual examination. Neither visual inspection nor fluid-penetrant examination will disclose the presence of subsurface porosity, inclusions and cracks. Nevertheless, they are important because: (1) surface defects reasonably may be assumed to indicate internal defects; and (2) these checks are simple to do.

Weld metal in which surface defects have been found should be removed until sound metal is found. Before a repair is attempted, take extreme measures to make sure the parts are cleaned meticulously. When visual examination under strong light discloses no visible evidence of foreign matter, clean the surfaces with at least three washes of distilled water. Follow this with three solvent washes and clean-air drying. Acetone has been used successfully. However, it is highly flammable and exposure to its vapors is undesirable; use it carefully.

You can examine radiographically joints made by welding the tubes to the rear tubesheet face [*24*]. Placing the film and source in the nest of tubes is difficult. There is also more complexity in interpreting the radiographs than in isolated butt-welded pipe joints.

Butt-welded joints made internally, socket-welded joints and explosively welded joints can be examined ultrasonically. Interpretation requires preparation of models with standard discontinuities for comparison.

You may visually examine inner surfaces of internal and rear-face joints with optical devices.

Combining joining methods

When you make the primary joint by welding at the front tubesheet face, you obtain the following benefits by also expanding the tubes to make light contact with the hole walls:

- You close the crevice between the tube and hole. For the purpose of eliminating crevice corrosion, this is preferable to boring enlarged holes in the tubesheet behind the joint.
- You reduce the effective perforation diameter, thereby increasing the tubesheet stiffness and its load-bearing capacity.
- You isolate the weld vibration, thus increasing resistance to fatigue failure [*25*].
- You reduce discontinuity flexural stress between tube and ligament.

In addition to these benefits, you make a tighter, stronger joint, and isolate the weld from axial loads when you strength-expand (expand enough to develop full expanded joint strength) the tubes after welding.

However, if the tube and tubesheet have different linear coefficients of thermal expansion and the operating temperature is high, the restraint of the strength-expanding will impose thermal stress on the weld.

If you make the primary tube-fastening by expanding, seal-welding provides a second barrier to leakage.

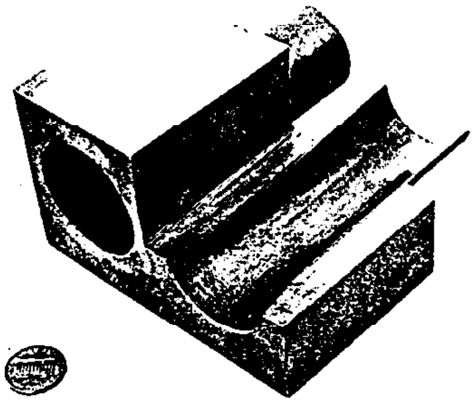
The sequence in which you combine welding with expanding may determine the results you get. There are several reasons to weld first. Foremost is the need to provide welding surfaces that are totally free of foreign substances. If you use hydraulic or rubber expanding you may obviate this problem.

There are other reasons to weld first. The previously discussed restraint of differential axial thermal expansion between tube and tubesheet may cause weld-root tears and cracks if you expand first. In addition, when the tube is tightly pressed against the hole wall, gases produced by welding must escape from the surface of the weld puddle. This increases the prospect of porosity.

If the tube-joint welding procedure requires you to post-weld heat-treat, there is no point in expanding first. The heat treatment will relax the tube.

It is inconvenient to weld first because weld metal may overlap the tube end, and weld shrinkage may reduce the tube I.D. so that it is difficult to insert expanders. Deal with these problems by reaming out excess metal at the tube mouth.

In non-U-tube exchangers, another way of combining joining methods is to weld the joints at one end and expand them at the other. You may choose this construction because one end operates at a high temperature and the other end is cool, or because the fluid environment makes it desirable.



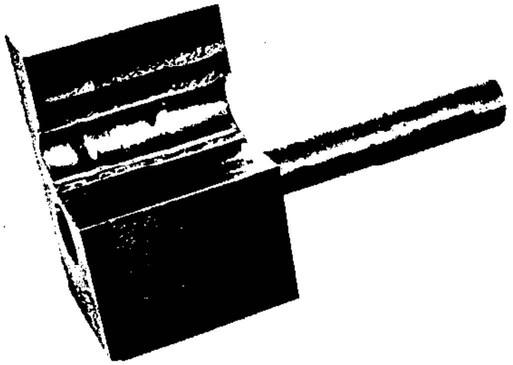
Section through explosively welded tube-to-tubesheet joint Fig. 16

Explosive Fabrications, Inc., Louisville, Colo.

Joints can be made by combining expanding and packing (gasketing) [*26*]. Fig. 17 is a photograph of a section through a joint in an explosively clad tubesheet. To make this joint you prepare the hole by machining an annular groove into the base metal and another in the alloy cladding. The grooves are somewhat deeper than the TEMA standard depth, but are limited by the ligament thickness. A suitable rubber gasket (usually temperature-resistant silicone) is inserted into the grooves. The tube ends are cleaned, inserted, and the tube is expanded by one of the previously described methods.

The specific application of this combination is to deal with the case of high-strength, thin-walled, low-elastic-modulus tubes to be joined to low-strength, high-elastic-modulus tubesheets. When you design this kind of joint, you cannot assume that the tubes support the tubesheet.

A modification of this combination is to use O-ring grooves and O-rings. You do this at one end of a two-tubesheet unit, while fixing the other end. Each tube may then float individually to accommodate differential expansion between adjacent tubes.



Expanded and gasketed joint Fig. 17

Explosive Fabrications, Inc., Louisville, Colo.

Failures in tube-to-tubesheet joints

You will find most failures in the region of the rear face of the tubesheet. That is where most tubes are anchored to the tubesheet and receive bending and torsional loads. Also, if the tubes are subjected to vibration, this area may fail.

When the tubes are expanded into the holes, there is a transition from the expanded diameter to the original diameter near the back face. This is also the location of the highest fluid shear on the tubewall and consequent erosion/corrosion in the tubes.

In thin-walled tubes, an error in expanding technique in which the tubes are expanded beyond the rear face may lead to cracking.

If you use a regressive (front to rear) roller-expanding technique, you will create compressive loads in the tubes and the reaction will be taken here.

Inside the tube, failures may result from work-hardening, stress-corrosion-cracking and fatigue. Outside the crevice, corrosion may attack.

When you fusion-weld austenitic stainless-steel tubes to tubesheets, there may be precipitation of complex carbides in a heat-affected zone behind the weld. An atmosphere that the stainless steel ordinarily resists may corrode this zone.

When a tube-joint welding procedure requires preheat or post-weld heat treatment, the emplacement of thermocouples to control temperature is critical to avoiding distortion and undesired metallurgical changes.

Fusion welds may fail because of: (1) hidden porosity or large gas pockets; (2) blowholes caused by burn-through of the tube wall; and (3) root bead tears.

Root bead tears may cause stress risers. Grain-boundary precipitation, underbead cracking, and thermal stress compound the effect.

High stresses in the joint may cause cracks to grow normal to the tube wall. Base metals sensitive to fissure cracking may sensitize the weld metal. Root tears may open the way to weld failures.

Summary

Pay careful attention to the design and production of tube-to-tubesheet joints, because their functions are essential and the consequences of failure are dire.

Make adequate tests of tightness and strength. Be sure to qualify testing and manufacturing procedures and personnel.

Relate the kind of joint, manufacturing processes, testing and nondestructive examinations to the service of the unit. Consider the size and shape of the exchanger when you select a joint design and joining method. Remember that the way the joints are made affects the overall structure of the equipment.

To produce acceptable joints, cleanliness and faithful adherence to qualified procedures are essential.

Take advantage of the best features of different kinds of joints by combining them.

Pay special attention to the part of the joint where the tube emerges from the rear face of the tubesheet, because it is the most likely place for failure to occur.

Roy V. Hughson, Editor

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