

EPRI Feedwater Symposium

August 22-23, 2007

**New low-pressure feedwater heater
and condenser tube plug
will not leak or fall out
for the life of the exchanger**

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New low-pressure feedwater heater and condenser tube plug Will not leak or fall out for the life of the exchanger

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Abstract

This paper describes a new technology called “Insta-Plug™.” The plug is designed not to fail like other mechanical tube plugs with thermal cycling over a wide range of temperatures and pressures. The recently developed plug is made from a novel, engineered alloy originally created by the Naval Ordnance Laboratory from a combination of nickel and titanium metals. This metal has two very unique properties: it is super-elastic and it “remembers” the original shape made prior to its expanded state.

The plug in its martensitic or “shrunk” specially deformed state can be introduced into the end of a tube or tube sheet and then heated and allowed to expand to its high temperature, stable austenitic or “expanded” state. The installed plug will maintain a tension on the tube or tube sheet through thermal cycling resulting in a continuous leak free seal.

The paper describes the underlying engineering design and tests conducted including finite element analysis (FEA) for strain and stress on the tube and tube sheet. A comparative analysis will be made with other tube plugs on the market.

Plugging tubes: a problem with many solutions

Any leaking between the fluids of a heat exchanger is a failure that can rapidly compromise its effectiveness and, in turn, the overall efficiency of system containing the unit. The costs associated with the continued operation of an inefficient system weigh against the costs of fixing the leaks. While scheduled maintenance shutdowns afford the best opportunity for complete repairs, it can be very cost effective when quick, positive measures can be applied to stop the leaking during unscheduled maintenance interruption. It is well-established practice to isolate such leaking tubes in shell and tube heat exchangers by plugging both ends of the offending tube(s). Plugging, while generally regarded as a non-permanent solution, is widely used because it is a rapid and positive fix that minimizes system interruption.

While there are a wide variety of plugs available that will provide isolation, there are only two functional categories of plugs: (1) those employing metallurgical bonding and (2) those employing a mechanical interference. Metallurgical bonded plugging is accomplished by forming a metallurgical union between the tube and the plug by explosive, welding or (usually hard) soldering means. Mechanical interference is accomplished by an intimately forcing of the outer surface of a plug with the inner surface of a tube, usually by some type of a wedging action.¹ A large number of specific plugs and plug methods have evolved within the two functional categories, and no one mechanical press fit plug is a perfect solution for all situations.

¹ In the most general sense, even the force induced by the threads on a screw can be regarded this way if the screw threads are characterized as a wedge or incline wrapped around a cylinder.

Metallurgical (kinetic) bonding is usually reserved for the highest pressure, most critical situations, and all forms of this kind of a fix are more extensive and reserved for tube sheets having a thickness of 3" or greater. Mechanical plugging, on the other hand, is rapid, economical and more than adequate for most plugging situations². Mechanical plugging, and particularly a new plug that minimizes the chances of coming undone during operational cycling, is the focus of the discussion that follows.

The basics of mechanical plugging

The simplest mechanical plug is a tapered pin, and the static engineering analysis of the plug is sensible and easy to understand. In fundamental engineering mechanics (e.g. Statics 101), most readers will remember a problem from the second or third hour exam that looked like:

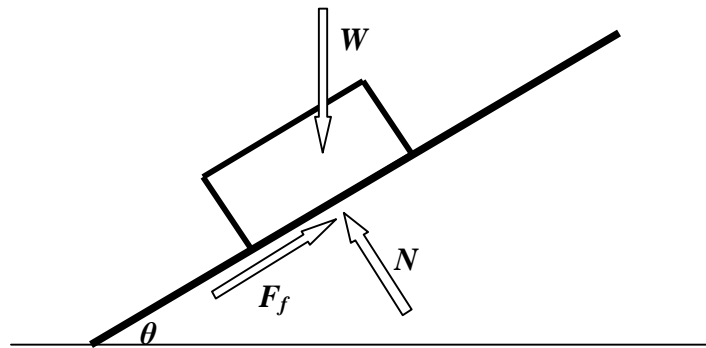


Figure 1. Incipient motion against friction example: block on an inclined plane with dry static friction surfaces.³

with the problem asking for what angle would the block just start to break loose and slide down the plane. The solution was found by solving the static equations for equilibrium:

$$\begin{aligned} \Sigma F_x &= 0 : \\ -W \sin \theta + F_f &= 0 \end{aligned}$$

$$\begin{aligned} \Sigma F_y &= 0 : \\ -W \cos \theta + N &= 0 \end{aligned}$$

where:

$$W = \text{weight}$$

$$N = \text{normal Force to the plane}$$

and

$$F_f = \mu N$$

$$\mu = \text{the coefficient of dry static friction}$$

² Book on heat exchangers chapter 10 page?

³ Reference 2, p.276

Then solving for μ , the coefficient of dry static friction between the block material and the material of the plane,

$$\mu = \tan \theta$$

or

$$\theta = \arctan(\mu)$$

For static coefficients of friction between 0.2 and 0.5, the corresponding angles would be 11.3° and 26.6° , the angle at which motion ensued was a single function of the coefficient of friction.

The critical taper for a plug to be “locked” statically into a tube has a very similar solution; the free body diagram of this situation is shown in Figure 2:

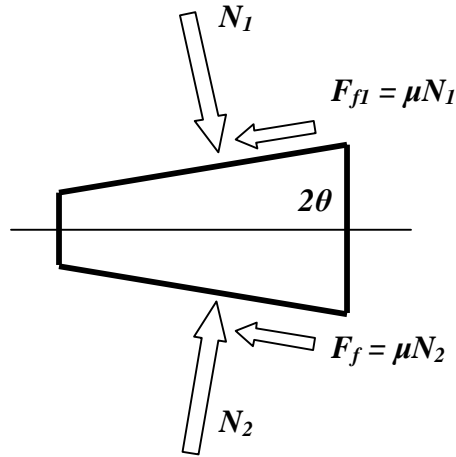


Figure 2. Free body diagram of contact forces on a wedge (no “blowout” forces shown.)_

and noticing that the included angle of the taper is 2θ , the relationship between the plug’s just sticking in the tapered hole is related to the coefficient of friction as:

$$\theta = \arctan(\mu)$$

Notice that the lowest generally accepted ranges for coefficient of dry static friction (0.2), the tapered pin plug should stay locked in for any taper angle less than 11.3° .⁴ In practice, all real tapered pin plugs use a much shallower angle than this theoretically acceptable pitch, and according to static engineering analysis, they should never come undone. In everyone’s experience, however, they do.

A dose of the real world

In practice, static behavior of the plug is only a first consideration of all of the effects associated with curing a leaky heat exchanger. Like the doctor whose first mandate is to “do no harm” the

⁴ The pressure force trying to “blow out” the plug can easily be considered but it is not important to and complicates the exposition here. It could be additive to or subtractive from the condition shown, with the “blowout” force being equal the pressure in the tube times the projected cross section of the plug surface exposed to the pressure. If the narrow end of the taper were toward the pressure side, the “blowout” force would tend to extract the plug. If the narrow end of the taper were away from the pressure side, the “blowout” force would tend to seat the plug harder.

“repair” also must not only accomplish the plugging, but it also must do no further damage to the device, to the system nor to the people who are effecting the repair or running the system. It is important that the plugging process does not cause damage to the ligaments of the tube sheet, the surrounding tubes, or to any of the other construction of the heat exchanger. It is of paramount importance that the installation of the plug does not inadvertently create fire or explosion situations, and that the plug, once installed, cannot become a hazard (a missile) once in operation or when plugging additional tubes at a later date. These are obvious realities.

Less obvious are the situational realities associated with operations. To return a minute to the engineering statics problem of the block on the incline, the problem never asks the question, “What happens if we change the incline dynamically, tap on the box, or pour penetrating oil on the interface --- and then that we do all of these things cyclically?” It’s not a question for the elementary statics, but in life’s experience, it can be guaranteed, at some point, under some circumstance, the box will move.

For mechanical plugs, because to one degree or another they depend on the competing forces of friction and the resultant of the “squeeze”, there is an opportunity to the “squeeze” winning out – to squirt the plug loose like a pumpkin seed squeezed between finger and thumb into flying through the air. In a heat exchanger, the static force conditions that are achieved at installation of a mechanical plug represents the best plugging condition that the plug will experience in its operation; this is always true if the plug material and the tube/tube sheet materials are identical or if they have very similar coefficients of thermal expansion. It is not quite true if the plug has greater coefficient of thermal expansion than does the tube/tube sheet material, but for the considerations of this expository, the assumptions are “close enough.”

During every operational thermal cycling of the heat exchanger, the various parts experience different rates of heating with sometimes-large differences in temperature of those parts. Once at the equilibrium of operating service, the differences tend to be less severe, and always more stable. But during heat up and cool down portions of the cycle, the differences in temperatures accentuate a natural phenomenon of a plug in a hole. Even when the materials are identical, the hole will expand further than the plug, a well-known experience to anyone who has heat-shrunk a wheel on an axle. If enough differential heating occurs, or if the heating is sufficiently high, and/or if heating diminishes the coefficient of friction between the mating surfaces, the normal (contact) force between the plug and tube can be lost, at least transiently, and in that instant, even gravity forces can cause the plug to retreat from its “locked” position. Once the lock is broken, the plug, by virtue of its taper, cannot recover its seal. The unlocking can occur a little at a time, as is most often the case, with the plug being relaxed from the tube a little amount with each cycle, until the seal is finally broken.

Insta-Plug™ an irreversibly installed mechanical plug

There is a way to avoid the pitfalls of existing mechanical taper plugs. Using a very special alloy, NiTiNol, it has been possible to create a very simple, non-tapered plug that does not suffer from inherent “reversing” deficiency of the tapered plugs. This new plug utilizes two aspects of NiTiNol to achieve its function: the material’s “super elasticity” and its “memory,” both of which come from the material’s inherent atomic structures. NiTiNol is a Nickel Titanium alloy

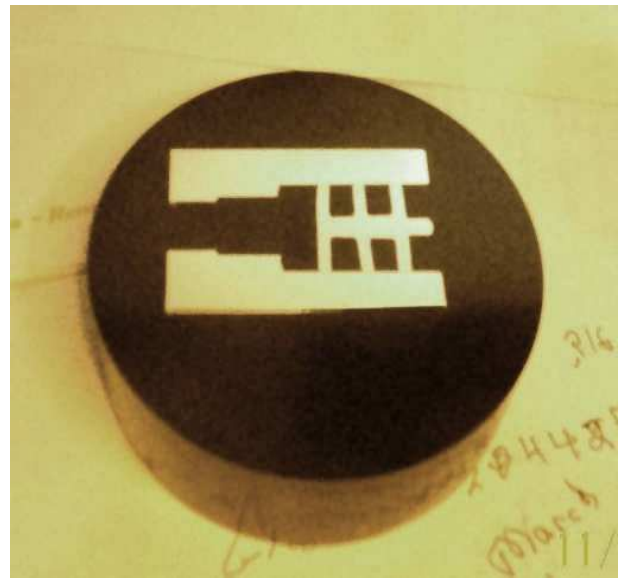
whose composition and properties were discovered at the U.S. Naval Ordnance Laboratory nearly forty-five years ago. The atomic lattice structure of the material exists in two allotropic forms, a higher temperature “austenitic” form and a lower temperature “martensitic” form, and these forms have an overlapping temperature range where either form can characterize the material.⁵ If the material is cut or otherwise produced in a particular shape in one condition, and if the material is subsequently converted to the other allotropic condition and then deformed, then when the material is again converted back to its first allotropic condition, the geometry of the original form will be faithfully and forcefully restored. The following steps emphasize the requirements for making a practical Nitinol plug:

1. Create a shape
2. Assure that shape is the form in a first allotropic condition
3. Convert the material to its other allotropic condition (by a type of heat treatment)
4. Deform the original shape while in the second allotropic condition
5. Reconvert (by a type of heat treatment) the part to the first allotropic condition
6. The original shape (in 1.) is restored automatically, and with considerable force.

Insta-Plug™ is a single piece of NiTiNol whose geometry typically consists of three circular fins on a central cylinder. A typical Insta-Plug™, deformed to reduce its outer diameter, is shown in the photograph of Figure 3(a), and a metallurgical cross section of early, very high pressure (>10,000 psi) test results.



(a)



(b)

Figure 3. Photos of Insta-Plug™ (a) freestanding in its pre-installation form, and (b) in a post-test, metallurgical cross-section installed into the high-pressure test fixture used in the experiment

⁵ Both of these names come from the individuals who first discovered the forms, and both appear in the literature with capitalized and non-capitalized, as here, presentations.

Drawings showing plug in its machined state, and in an exaggeration of the pre-installation deformed state to show how its effective diameter is reduced are shown in Figures 4(a) and 4(b) respectively.

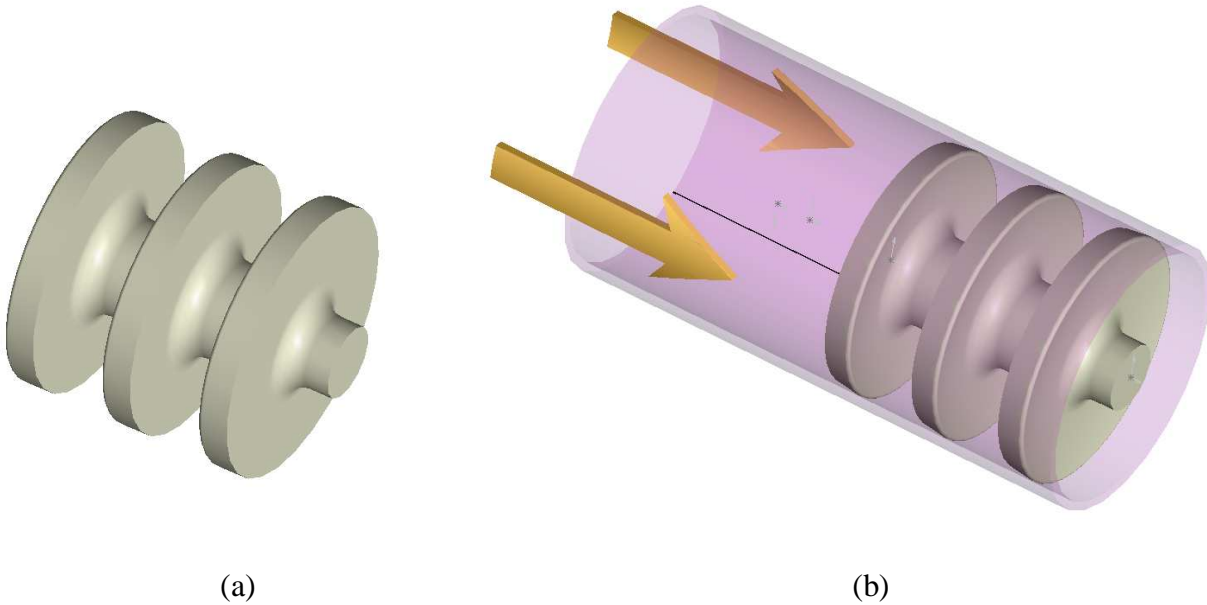


Figure 4. Drawings showing plug in its machined state (a) and in an exaggeration of the pre-installation deformation.

The plug shape is created for the desired tube size, heat treated to assure its shape is remembered in the austenitic state, and then it is subsequently chilled to transform the atomic structure. While in this allotropic martensitic state, the plug is driven through a swaging die to reduce the effective outer diameter of the fins, much like taking down an umbrella. The product is shipped in this condition. At the application site, the tube surface is prepared by removal of all scale and the assurance of a clean metal tube surface free from oils, etc. Then the Insta-Plug™ is inserted into the tube within the tubesheet length and heat is applied to bring the Insta-Plug™ to a temperature well above its austenitic (finish) temperature, and for practical purposes, above 300°F.⁶ Heating is most typically achieved by a simple propane torch, but alternative ways of heating the plug also are used and include hot air guns and electric resistance heating.

Unlike every other “mechanical” plug, the Insta-Plug™ does not degrade with thermal cycling; it actually improves its holding power. The installation assures that the first of the three fins (the fin closest to the heating source) will be restored to an “interference” of 0.002 to 0.005 inches, i.e. the original plug size is at least that much larger than the prepared interior lumen of the tube. Typically the second and third fins are only minimally recovered to their austenitic form on initial installation, but upon virtually any exposure to normal operating temperatures, the second and third fins as well as the central cylinder do convert to the austenitic form, and they remain

⁶ The actual austenitic start temperature for the Insta-Plug™ is about 120F, but for assurance of full conversion of at least the outermost fin of the part, the temperature in the body of the text is used.

converted even as the heat exchanger is returned to room temperature. It is essentially a one-way conversion after application. The super elastic properties of NiTiNol provide for a much greater reserve of residual force in the Insta-Plug™, because the stress strain curve for the material has two distinct slopes, a first elastic modulus that occurs much as any normal material out to a fraction of one percent, and a much flatter modulus line that occurs above 50 ksi and extends *elastically* to six percent and beyond – eight times the extension of common structural metals.

The effect of the “memory” and “super elasticity” properties is to give the plug both a sufficiently large recovery range to accommodate typical tube variances while providing nearly constant force (owing to the low slope of the secondary modulus) over that entire recovery range. The net result is a plug that produces a sufficient plugging force over a wide range with the minimum of risk of overstressing ligaments and other parts of the critical structures. The plugs will very reliably block 1000 psi in a 5/8 inch diameter tube with only the first fin recovered (as in installation) and they have been tested for blowout reliably above 5000 psi (with many exceeding 10,000 psi) when the entire plug is recovered from operational temperature exposure.

Installation of Insta-Plug™ should be considered to be irreversible, i.e. “permanent” for all of the reasons just described. Further contributing to that permanence are the physical properties of the plug material itself. While NiTiNol’s superelasticity gives the product the ability to accommodate differences in coefficients of thermal expansion between the plug and virtually any tube material, the nickel-titanium alloy is itself very non reactive, chemically or electrically (galvanic) with virtually any of the common tube materials. (The non-reactance of NiTiNOL to environments as hostile as the human body is well known in its application of medical stents for opening blocked arteries.)

Removal of Insta-Plug™ is just as permanent. On removal, the plug is destroyed by a single plasma cut using an available special guide fixture that assures the central core of the plug is blown out without endangering other structures. Once the central core is gone, the remaining fins, now rings, are extracted with a conventional spear.

Practical engineering considerations for Insta-Plug™ devices

The behavior of NiTiNol is not simple, and it does not lend itself well to some of the assumptions that make dealing with typical structural materials considerably easier. In the development of the Insta-Plug™, finite element techniques have been used both to predict thermal flows and to analyze and refine the plug geometry. In the latter case, the analysis has been used to optimize the amount of stress in the material and the distribution of that stress so that a maximum of material can be engaged in the active process that restores the fins to the interference fit. This same design consideration, coupled with the peculiarly flat, second modulus permits designs that provide adequate blowout resistance while avoiding overstressing of tubesheet features, most especially the tubesheet ligaments. Representative models for the finite element analysis are shown in Figure 5 on the following page.

Hollaender Enterprises, who developed the Insta-Plug™, continues to improve the shape and controlled behavior of the plug, as have most other novel plugging manufacturers with their own products (e.g. Pop-a-Plug II.) Insta-Plug™ plugging devices are manufactured and sized

using proprietary methods. The presently marketable Insta-Plug™ products are very conservatively designed, with specific plug size ranges for each typical tube diameter being provided in 0.015 maximum intervals. The theoretical effective range for the plugs far exceeds this interval, but as a relatively new entry into the tube plugging markets, a conservatively sized, very reliable plug, which will not fail, has been the driving product consideration.

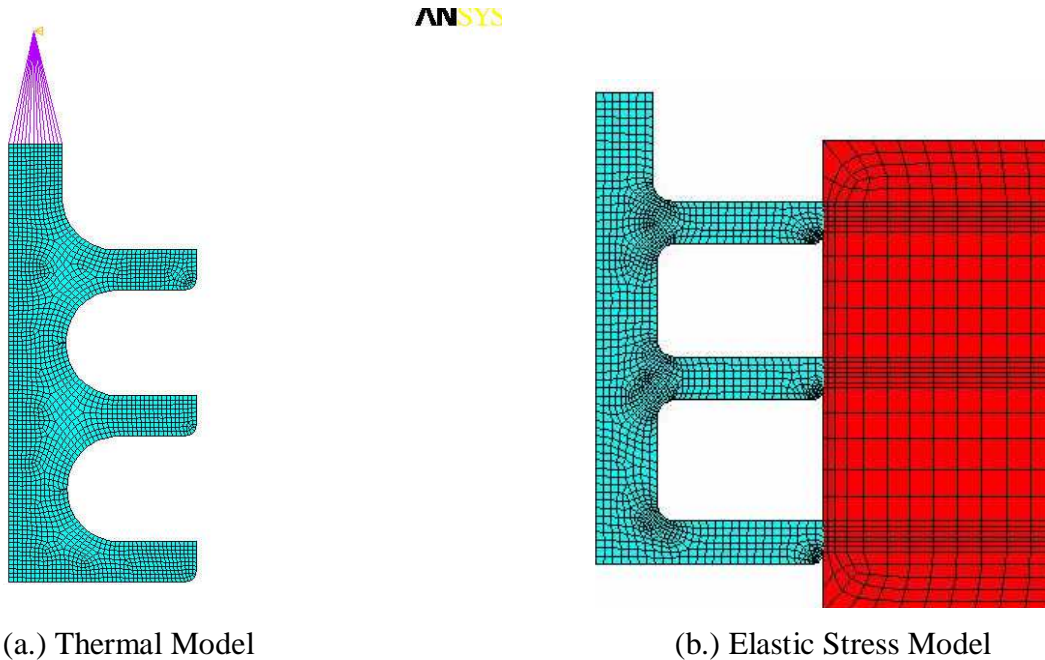


Figure 5. Representative models from the various finite-element engineering analyses conducted on Insta-Plug™ of tubesheet features, most especially the tubesheet ligaments.

Field applications

Insta-Plug™ is a new solution to mechanical tube plug failures. Its one-piece simplicity contributes to a reasonable cost for the product. It is the only mechanical method that we have found which does not have susceptibility to working itself loose and leak or fall out. With the plug being at least as easy to install and quick to apply as its alternatives, the total installed plug is cost effective.

Several applications of the plug have been made into a variety of operating heat exchangers. However, we have targeted our present use of the plug to LP feedwater heaters, condensers, oil coolers, hydrogen coolers, cooling water coolers, and other process heat exchangers -- applications where the pressure requirements are below 2000 psi, the operating temperatures are sufficiently high to assure complete transitioning of the NiTiNol from austenite to martensite, and where a forced outage or unexpected downtime is critical for heat exchangers that are not easily isolated from the main plant system.

Conclusions

After years of development, we believe that we finally have a mechanical plug that has the attributes we have long desired and that will not fail in service and survive the full useful life of the exchanger. We believe that we now have cost effective, and reliable means in the Insta-Plug™ that will:

- not fail in service regardless of the cycling conditions
- provide for installation that is fast, safe and simple
- be cost competitive to other mechanical plugs on the market.
- account for real world service demands by retaining super-elastic (“spring”) energy that prevents plugging force degradation during thermal cycling

We intend that Insta-Plug™, like our long experience with explosive plugs for high pressures and/or more extreme temperatures has demonstrated, fills our other plugging applications with the confidence that it too, “lasts the lifetime”⁷ of heat exchanger

References

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⁷ See APS explosive plug experience and our guarantees for the explosive plug service.