Advances in InstaPlug™ for Low/Moderate Pressure Heat Exchangers, e.g. Condensers and Feedwater Heaters

Roger A. Adelman, Ph.D., P.E.
V.P. Engineering, Douglas Hollaender Enterprises, Inc.
and
Daniel D. Bina
President, American Power Services Inc.

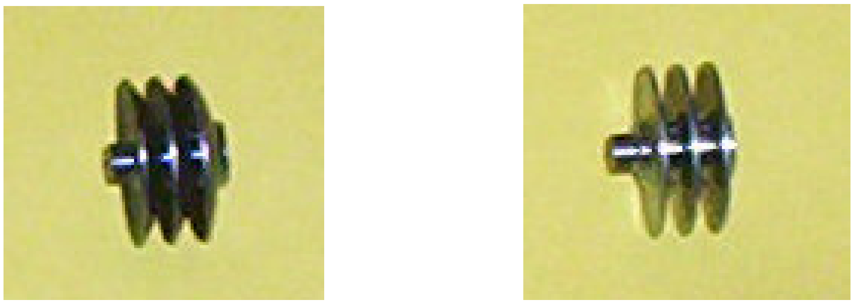
1. Abstract

Mechanical tube plugs have been susceptible to plug failure due to thermal cycling because of their inherent friction fit designs. Over time mechanical tube plugs will work loose, begin to leak and completely fail. This paper describes why friction fit mechanical plugs will eventually fail and the advances in a new technology called "InstaPlug™." InstaPlug™ is the first mechanical plug that will flex as the tube sheet and tube flexes. The sealing pressure remains constant on the tube or tube sheet wall as the heat exchanger cycles. The plug's special metal alloy and its mechanical design make "InstaPlug™ very effective in applications where erosion has caused large variation in tube diameters and where the normal heat cycling can cause variations in a mechanical tube plug's holding forces.

Since its introduction last year, the product has been refined, better utilizing the underlying metallurgy and employing engineering design and analysis that provide for enhanced tolerance to tube erosion, improved ease of installation, and providing a part more consistent with the changes that occur with repeated thermal and pressure cycling. Reported are a synopsis of the underlying metallurgical fundamentals, the design considerations, and the analytical and experimental tests conducted on the advanced technology InstaPlug™. Our early experience with actual field installations from Beta site testing is also reported here. Finally, a summary tabulation of InstaPlug™ attributes is provided in comparison with other mechanical plugs.

2. The InstaPlug™

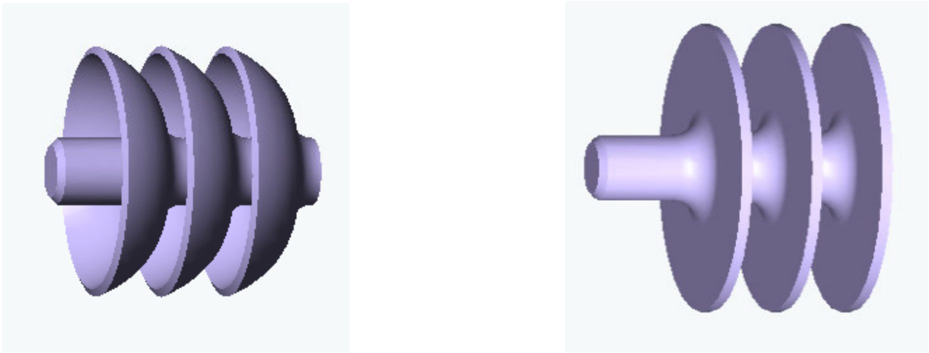
InstaPlug™ is a simple, one-piece component of NiTiNOL alloy, and it consists of a core and three fins, that are sized to produce a predetermined interference fit when it is installed in a prepared, leaking tube. It is one of the simplest and easiest plugs to install, and it is extremely tolerant of the variations from erosion and other factors in tube size diameters. It has the least amount of volume to surface ratio of any of most utilized mechanical plugs, and it is inherently able to "breathe" with changes that occur during thermal transients without losing its contact force and seal. On installation, the InstaPlug™, in the first of its allotropic metallurgical forms, is introduced into a de-scaled and cleaned, prepared tube and moderate heat is applied (ideally with electric resistant flameless, arcless low voltage high current heat) for less than a minute. The heating causes the alloy of the plug to change to its other metallurgical form, causing the InstaPlug™ "remember" in an effectively irreversible way, its interfering (plugging and sealing) form. A photograph of a plug in its form prior to installation is shown in Figure 1a, and another photo of the plug "converted" to its interfering, or sealing form is shown in Figure 1b.



a. As received prior to plug insertion b. As-installed, interfering shape after heating

Figure 1. Pictorial of InstaPlug™ in its first and second allotropic metallurgical forms

Pictorial representation of these two plug conditions are provided in a somewhat exaggerated form in Figures 2a, and 2b to emphasize the deformed to expanded allotropic forms of the plug.



a. As-received prior to plug insertion b. As-installed, interfering shape after heating

Figure 2. Actual photos of InstaPlug™ in its as received, and its installed, fully expanded forms.

Lastly, a picture showing the plug's dynamics in response to installation heating is shown in Figure 3 where the "ghost" images show intermediate expansion of the plug. Until the plug hits the tube wall, its internal stress is essentially zero. Once contact is made with the tube wall, wherever that may be within the expansion of the plug, the internal stresses will increase until they reach a stress level of about 70,000 psi, along in the super plastic range of the material. The combination of the material stress and the geometry of the fin in turn cause a consistent seal owing to superelasticity – the atomic "springiness" inherent in the NiTiNOL.

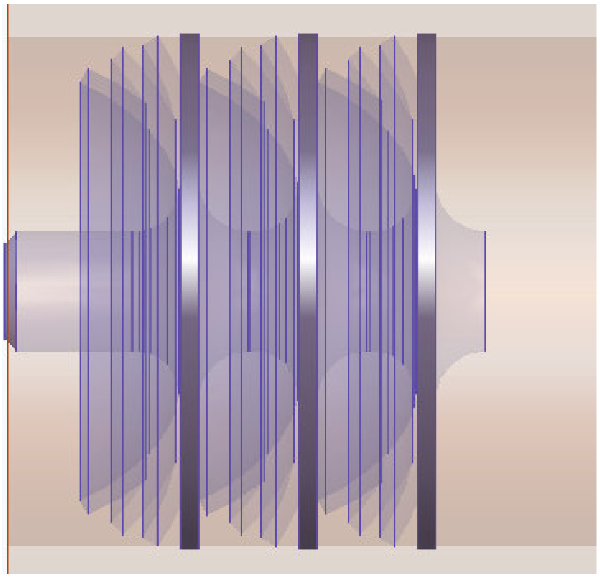


Figure 3. InstaPlug™ plug dynamics on moderate heating during installation.

3. NiTiNOL an Unusual Alloy

NiTiNOL is one of the best in class of the so-called “memory metals,” materials that are characterized by their ability to memorize and reproduce a given geometry after an intermediate, typically severe, distortion is imposed on a structure. **NiTiNOL** was invented in the late 1960’s when **Ni**ckel and **Ti**tanium were combined in a special way at the **N**aval **O**rdinance **L**aboratories. In addition to its “memory” capabilities, the metal also possesses superelasticity – the ability to be deformed more than eight per cent (typical metals are less than 0.8 per cent,) and return time after time to its undeformed state. Yet another quality of the material is its inherent ability to dampen sound; under specific heat treatment, a bar will not “ring” but will instead “thud” – as if it were made of lead – when struck.

The underlying reason for this unusual set of properties is that NiTiNOL can exist in either of two fundamental crystalline structures: a lower temperature arrangement of atoms called Martensite, and a higher temperature arrangement called Austenite. Very importantly, there is also an intermediate temperature range where the material can exist in stable form as ***either*** Martensite or Austenite. Typically this range is around room temperature, and it can be accurately reproduced through the careful control of the atomic percentages of the alloys (to 1/100th per cent) and other processing variables. The atomic lattice structures of Austenitic Nitinol and Martensitic Nitinol produce very different material properties.

Austenitic NiTiNOL has the form of a cube within a cube, not unlike Austenitic iron, except that in NiTiNOL two elements, nickel and titanium (instead of all being all one element as in iron) form alternative cubes as shown in Figure 4a. In this form, each atom of titanium has a set of eight atoms of nickel as its nearest neighbors, and likewise, each atom of nickel has a set of eight atoms of titanium as its nearest neighbors. It is a very stable arrangement where any pull on the material is resisted only by the elasticity of the atomic bonds between the atoms. The visualization of the Austenite matrix of atoms is itself rather challenging, but the visualization of the arrangement of atoms Martensite is yet more difficult, and we’ll progress through it in steps so that the material behavior can be related to it.

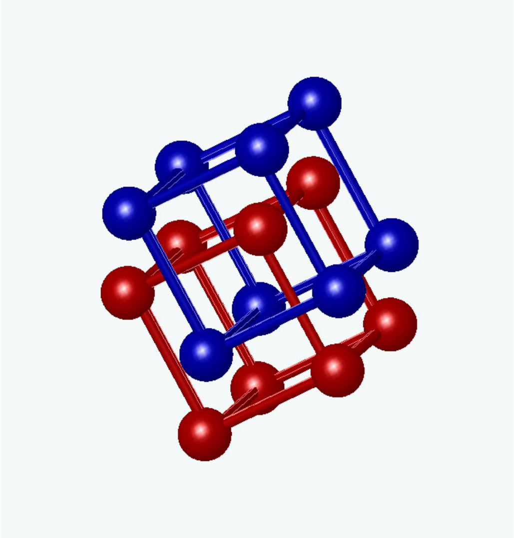


Figure 4a. Pictorial representation of the cubic nature of NiTiNOL in its form as Austenite

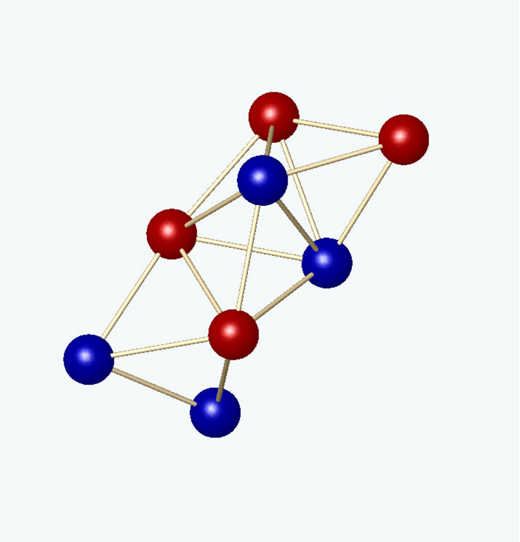
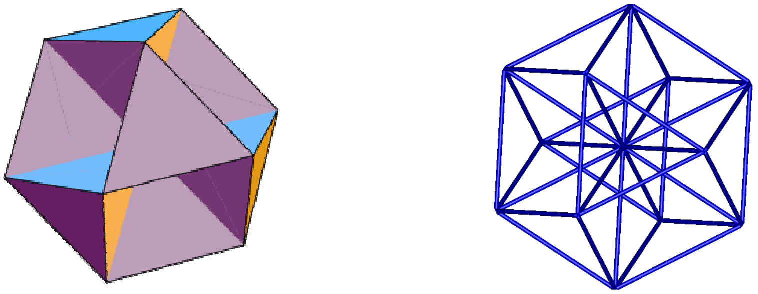


Figure 4b. Pictorial representation of the the sub unit tetrahedron in NiTiNOL as Martensite.

The Martensitic form of NiTiNOL is based, in part, on a tetrahedral arrangement of the nickel and titanium atoms as shown above in Figure 4b. But this is only part of the repeating atomic structure. In the real (as well as the mathematical) world, a general closed solid with equivalent boundaries cannot be formed by tetrahedrons alone. Unlike the simple cubes of Austenite, where a solid may be built of so many cubes stacked side by side and one atop the other, tetrahedrons of Martensite won't form, for instance, to build a straight wall or a sphere with such a regular surface.   Other structuring units, in addition to the tetrahedrons are required, such as the four-sided pyramids which alternate with the tetrahedrons in the octatethahedral structure shown in Figure 5.



a. tetrahedral + pyramidal

b. projections of vertices

Figure 5. The uniform polyhedron $U_{3,}$ also called the octatetrahedron, whose dual polyhedron is the octahemioctacron. It has Wythoff symbol 3/2 3|3. Its faces are 8{3} + 4{6}. It is a faceted cuboctahedron. For unit edge length, its circumradius is R= 1.   See reference (1)[1]

Referring back to Figure 4a, the atoms in the cubic Austenite arrangement are tightly bound, and every titanium atom has nickel atom-neighbors that are all at their closest proximity, and each nickel atom is identically surrounded by titanium atoms that are at uniquely located at closest proximities.   Like water that has run downhill into a (bounded) pool, the atoms in this position are at their lowest energy state, and if they are to be moved, it will require the input of some energy, even if it is to push the atoms slightly – elastically – apart. Continuing the water analogy, it is like trying to move the water to one side of the pool: when the moving is stopped, the water comes back to its original position. However, if the water had been pushed so violently that it splashed outside the pool boundaries, then not all the water would return – and this is analogous to what happens when the material is stretched so far that it will not return to its original condition, i.e., to its non-elastic or plastic behavior. Here's the point: In Austenite, every atom, titanium or nickel, has eight neighboring atoms of the other kind, and each of these neighbors can ONLY be at a single, unique position. That's Austenite.

Martensite is an entirely different story.

Referring back to Figures 4b and 5, the central portion of the arrangement of atoms in Figure 4b demonstrates an almost "square" projection of the atoms. In that figure, the atoms belonging to the square are, though not entirely obvious, in different planes. But their individual displacements from the plane is slight, and it would (correctly) suggest, that if they were in that particular plane, their resulting formation would somehow resemble the nicely closed solid octatetrahedron shown in Figure 5. The Martensitic structure is *something like* that solid, with tetrahedral bonds between some atoms, and pyramidal relations between others. While the actual Martensitic structure of NiTiNOL is still a matter of some debate, it achieves its combined atomic bonds in a form called "twinning," where the weaker bonds form in mirror-like fashion. A pictorial approximation of the repeating, atomic lattice pattern of Martensite is shown in Figure 6.

---

[1] The "Octatetrahedron"

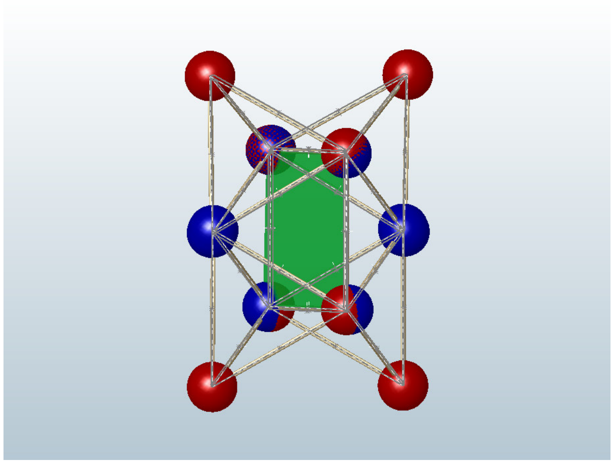
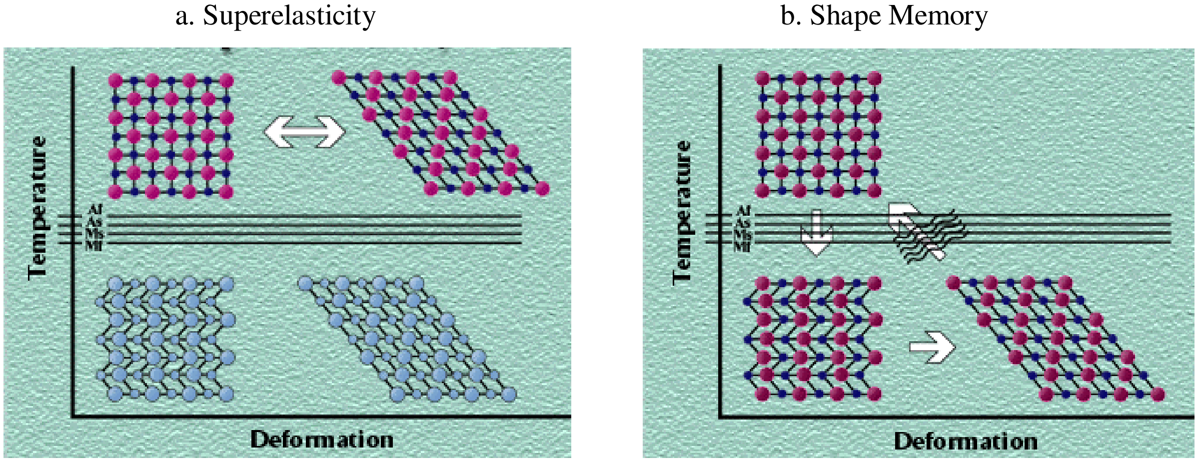


Figure 6. Three-dimensional picture of the elementary half twin structure of Martensitic NiTiNOL.

Note in this figure, the green, central plane. It identifies four atoms, which have been dual colored to set them apart, and which uniquely in the figure lie at the corners of a planar square. (It is seen as going backward into the paper, but it is nonetheless a square.) All of the other atoms form tetrahedrons, which have equilateral triangular sides. Because they are equilateral triangles, they cannot be distorted – both their angular and distance relationships are fixed, and any "stretching" would amount to a traction directly on the interatomic bonds. The square that is identified by the green color is different: it can be angularly distorted, fairly easily, to form a rhombus. This is the basis of the superelastic AND the memory aspects of Nitinol. It is also a very, very difficult 3 dimensional picture to visualize.

An easier way to visualize the effect (fortunately!) is shown in Figure 7 which is a 2-dimensional pictorial of the functionality that happens in NiTiNOL, and graphically explain the superelastic (and sound deadening) attributes of NiTiNOL, and in part, the story behind NiTiNOL's ability to memorize a shape, become distorted, and return to its memorized form. In both figures, NiTiNOL below a transformation temperature and unstrained is in the Martensitic form, with the zig-zag pattern corresponding to the twinning distortion that occurs. Similarly, the unstrained material above the transformation temperature



a. Superelasticity

b. Shape Memory

Figure 7. The mechanisms of NiTiNOL (Courtesy NDC Corp. Fremont, CA.)[2]

---

[2] Courtesy NDC Corp. Fremont, CA

represent the cubic form of Austenite. In Figure 7a, under the influence of large deforming stresses, the Martensitic form responds by straightening out the zigzags as in the array at the bottom right. What happens to the material at high temperatures is a little more curious – it transitions to a Martensitic-like structure under when subjected to high stress, and the atomic lattice looks much the same as the straightened out zigzags of Martensite.

Memory is a little more complicated. If the material is used to make a particular geometry as Austenite, then it starts out as the cubic structure at the top of Figure 7b. Chilling the material (and the part) will convert its internal atomic structure to Martensite in the lower left-hand corner of Figure 7b. While the atomic structure has been transformed, the geometry of the part is unaffected because no external, distorting forces have been applied. In the Martensitic state, the part then can be deformed by external, distorting forces. This will stretch the zigzags of the Martensite, the parts of the lattice that correspond to the square-to-rhombic condition shown previously in the 3-d model. Finally, if the part is heated while it is in its distorted condition, the internal atomic structure will reverts to the Austenitic condition where every atom is in a cubic lattice at a uniform distance from every other atom. Because this is exactly where each atom was when the part was initially produced in Austenite, the original gross geometry of the part is "remembered."

The atomic properties of NiTiNOL would be unidirectional if the material were made of a single crystal of atoms, and all the behavior would align itself with the atomic lattice. In practice, however, NiTiNOL is always severely "worked" – forged or cross rolled or any of the other ways that fine grain structure is obtained. The resulting fine grains result in the atomic lattices of the individual grains to be oriented at virtually every possible angle, and the NiTiNOL achieves isotropic behavior characteristic of any poly-grained metal. It is important that in subsequent processing of NiTiNOL that the fine grain structure is preserved.

NiTiNOL's stress strain curve reflects the unusual nature of the alloy, and a representative curve is shown with some annotations worth elaborating in Figure 8.

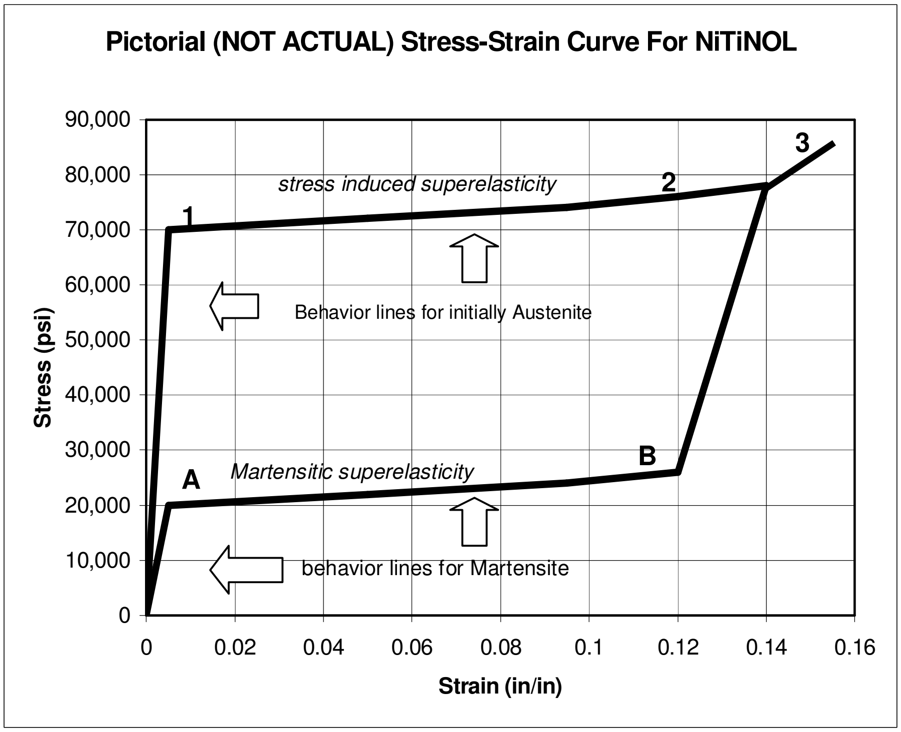


Figure 8. Representation of NiTiNOL stress-strain curve at constant temperature.

The material starts at zero stress and zero strain (point "0" on the graph) as Austenite. It goes from "0" to "1" in a linear fashion exhibiting a typical Young's modulus line of about 22 million psi reflecting the elastic response of the Austenite cubic atom structure having its atoms stretched apart along straight force lines. At somewhere above ~70,000 psi (point "1") the material curve sharply breaks over, and elongation continues for a long distance (to point "2"), but again as essentially a straight line (a secondary modulus) in excess of eight per cent strain. What has happened is that the energy imparted to the Austenitic structure has caused a stress-induced transformation to the Martensitic form, and the "vee" relationships between atoms in the Martensitic form are straightened out like an accordion bellows, as additional stress is applied. The very low value of the secondary modulus (the slope of line 1-2) occurs because it takes very little stress to produce a great deal of strain during the "straightening" of the "vee" bonds. This behavior continues until the "vees" are virtually flattened to straight lines at (2). From that point (2) to failure at (3) the lines between atoms are straight, and the sharply rising modulus line (2-3) reflects it. As the stress continues toward (3), the material is stretched beyond elasticity, at which point irretrievable, plastic deformation occurs until failure.

Still referring to Figure 8, if the material had been Martensitic to start with, it would have followed the path from (0) to (A) as the Young's modulus for that form of Nitinol, which, as in the Austenitic form, is the elastic stretching of bonds between atoms. Once the stresses reach point (A), then the material exhibits "superelasticity" as before (by the mechanism of the flattening of the "vee bonds") up to point (B). From point (B), the Martensitic form strains plastically with further increases in stress until the material fails at (3).

The stress-strain behavior is a key to the ability to assure a seal that is dominated by the stress levels of Austenite corresponding to the (2) – (3) range. That material behavior also lets the InstaPlug™ accommodate a very large range of tube dimensional variations, with one plug size accommodating more than 1/32 of an inch diametral variation for sizes larger than ⅝ inch outer diameter.

The ability of NiTiNOL to change from Martensite to Austenite is the key to the "memory" process. Once the NiTiNOL is obtained in its basic poly-grain Austenitic form, it can be cut and shaped into the desired form to be "memorized." The material is then annealed (still as Austenite) at 500ºC to relieve any residual stresses from the formation of the geometric shape. This anneal "sets" the material's memory, with each atom inside each grain being at the closest proximity to its eight nearest neighbors (of the other element.) The formed and memorized part is then chilled until the atomic structure becomes Martensite. Once in the Martensitic state, the bonds between the tetrahedral atomic substructure, the "vees", can be deformed elastically. Over the summation of all the microscopic grains of a submicroscopic Martensitic atomic arrangement, the gross deformation of the part can be substantial, and in the InstaPlug™, the deformation pushes the fins backward, with a resulting decrease in the plug's effective diameter. When the material is then forced back to becoming Austenite, with its atoms being held to their original specific minimum distances, then again over the summation of all of the grains (etc.) the part will return to its "memorized" shape. And that is exactly the "magic" of the material that enables InstaPlug™.

One last note about the metallurgy: NiTiNOL is inherently resistant to both chemical and galvanic corrosion. Both titanium and nickel have such corrosion neutrality, and their binary combination into NiTiNOL preserves the corrosion neutrality of its element constituent parts. To complete the NiTiNOL picture, a summary of its properties is presented in Table 3-1.

Table 3-1 Selected Properties of NiTiNOL DO NOT USE FOR DESIGN[3]

	SI UNITS				ENGLISH UNITS			
Transformation Temperatures and Strains								
Transformation temperature range	-200	to	110	°C	-328	to	230	°F
Transformation enthalpy (specific heat)	0.47	to	0.62	kJ/kG-˚C	0.113	to	0.149	Btu/lb-˚F
Transformation strains								
up to 1 cycle	8			%	8			%
up to 100 cycles	5			%	5			%
up to 100.000 cycles	3			%	3			%
above 100.000 cycles	2			%	2			%
Physical Properties								
Melting point								
Density	6.45			kG/dm^3	0.233			lb/in^3
Thermal conductivity of the Martensite	9			W/m˚C	62			Btu/hr-ft^2°F
Thermal conductivity of the Austenite	18			W/m˚C	124			Btu/hr-ft^2°F
Electrical resistivity	50	to	110	μΩ/cm	1524	to	3353	μΩ/ft
Coefficient of thermal expansion, Martensite	6.7			(m/m)/˚C	3.7			(in/in)/˚F
Coefficient of thermal expansion, Austenite	10	to	11	(m/m)/˚C	5.6	to	6.1	(in/in)/˚F
Corrosion properties and biocompatibility				Excellent				Excellent
Magnetic permeability	1.002							
Mechanical Properties								
Young's modulus of Austenite	70		80	GPa	10.2		11.6	million psi
Young's modulus of Martensite	23		41	GPa	3.3		5.9	million psi
Ultimate tensile strength (cold worked condition)	1900			MPa	276,000			psi
Ultimate tensile strength (fully annealed condition)	900			MPa	131,000			psi
Plateau stress (Pseudo-Yield stress) Martensite	70	to	200	MPa	10,000	to	29,000	psi
Plateau stress Austenite	200	to	650	MPa	29,000	to	94,000	psi
Yield stress Austenite	550	to	700	MPa	80,000	to	102,000	psi
Poisson's ratio	0.33				0.33			
Tensile strain (fully annealed)	20	to	60	%	20	to	60	%
Tensile strain (cold worked)	5	to	20	%	5	to	20	%
Hot workability				Reasonable				
Cold workability				Difficult (work hardening)				
Machinability				Poor, grind or use non-trad				

4. Engineering Design

The alloy has enabled the creation of the plug, but the design gives the plug its utility. InstaPlug™ reflects the design criteria that are called for in real-world, reliable and utilitarian situations. The functional design considerations for the plug are summarized in Tables 4.1

---

[3] Memory-Metalle GmbH Info-Sheet No. 4

TABLE 4-1 Functional Design Criteria

• Pressure	must withstand condenser, LP feedwater and heat exchanger pressures to 250 psi
• Temperatur	must withstand condenser, LP feedwater and heat exchanger temperatures70F to 700F
• Strength	adequate to not fail at application pressures and temperatures
• Versatility	must be able to accommodate new and eroded tube ends
• Corrosion	chemical and electrolytic as good as titanium and/or nickel
• Fatigue	must withstand the growth and contraction of tubes/tube sheets that occurs during transitions from startup to steady state and corresponding cool down

There is a tradeoff among the first four criteria. The InstaPlug™ has been tested to withstand pressures in excess of 13,000 psi.[4] However, in order to achieve such a high pressure (and temperature and strength,) the plug has to be limited to a very small range of size change – on the order of five or ten 1/1000ths of an inch. A much more practical plug was chosen for applications below 1,000 psi, where the reduction in the first three criteria allowed the fourth, versatility, to permit a plug that fits tubes eroded more than sixty per cent of their original wall thickness. This is ideal for condenser, cooling water cooler, oil cooler, hydrogen cooler and LP feedwater heater applications

One of the design attributes intended for InstaPlug™ has been its ability to survive the repeated changes in structures that occur during thermal cycling. The plug was designed with a large surface area-to-mass ratio to help assure thermal growth behavior that closely matched the natural growth that happens in the heat exchanger itself. Further, the geometry of the fins permits the InstaPlug™ to move easily, in a spring-like fashion just like the rolled tubes themselves move with the tubesheet, during the expansion and contraction. This "breathing" with the heat exchanger is due in part to the superelastic nature of NiTiNOL and in part to the low volume, high surface area of the InstaPlug™ design.

InstaPlug™ also had to meet a number of applications, i.e. "practical" criteria as well, and these are summarized in Table 4-2. The application concerns have to do with installation and removal of the plug.

TABLE 4-2 Application Design Criteria

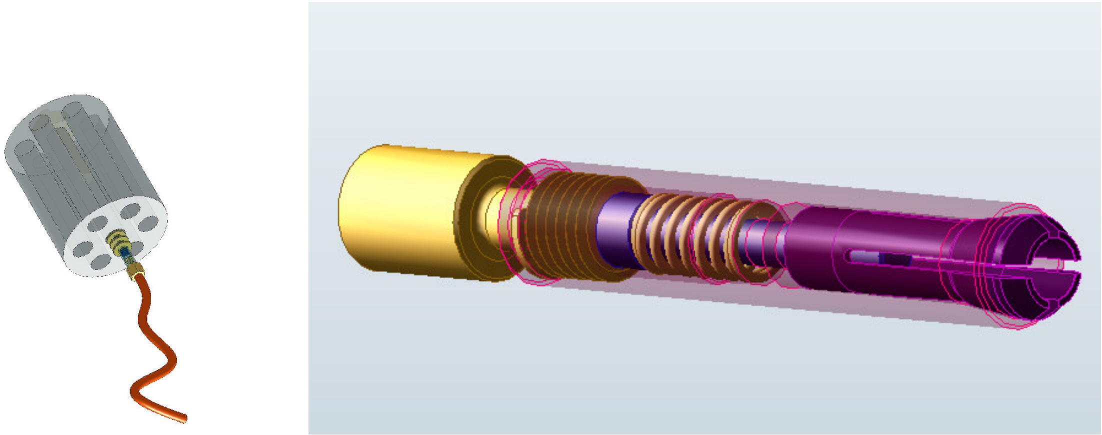
• Installation	• Safety • More than one way to set the device • Ease and reliability of installation • Assurance (in part inherent because first thermal cycle will be high enough to assure complete transition)
• Removal	• Safety • More than one way to remove device • Ease and economy

Certainly safety is at the top of both lists, and versatility and ease of application are what make any plug practical. InstaPlug™ can be set by the application of moderate heat, in virtually any manner usually below 200F. In practice, electrical resistance heating is the easiest, and recommended, way to set the plug. Using an ordinary arc welder – a "buzz-box" – the low voltage (~28V) and moderate current (~180 amps) will set the plug in approximately 40 seconds without arcing or other open flame. InstaPlug™ has

---

[4] Thielsch Laboratories Report to D.L. Hollaender Enterprises, inc.

a specially designed collet (shown in Figure 9) that allows a plug to be set at the opposite end of a tube, many feet distant, by threading only the welding cable down the tube and retracting it after the electricity has been applied. However, InstaPlug™ also is easily set using other heating methods, from low temperature torch to calrod heaters and everything in between. It is only necessary that the plug be brought to a temperature above its Austenite finish transition temperature, a few hundred degrees, for the plug to obtain its fully employed form. Very importantly, once the plug has been set in place initially, every subsequent application of heat assures the complete transformation to Austenite. (It would take immersion in sub zero temperatures to begin to reverse the metallurgical form to Martensite, and even then the plug would retain most of its holding geometry.)



a. b.

Figure 9. InstaPlug™ Electric Heater Collet (a) simulating installation and (b) as transparent drawing of collet assembly (U.S. Patent Pending.)

5. Engineering Analysis

InstaPlug™ was designed using conventional engineering analysis, e.g. strength of materials and elasticity formulas to determine its desired functionality.[5] Post-design analysis was conducted using both conventional stress analysis and finite element analysis methods, and static testing was used to confirm analysis and to establish a sample statistical base. The InstaPlug™ was analyzed for stresses created during its deformation and recovery processes, and particular attention was paid to stresses at the usual offending regions, e.g., the roots of the fins. Separate analyses were conducted to determine thermal flows during the setting of the plug. Most of these had been conducted prior to the installation of the first plugs more than a year ago.

More recently, we have analyzed InstaPlug™ and other means for tube plugging using multiphysics finite element analysis (FEA) to better understand what happens during thermal cycling. That analysis is described in some detail in the following paragraphs.

Finite element analysis is, in its most general form, a computational way for very, very closely approximating solutions to differential equations that describe (what can be very complicated) physics problems applied to very close representations actual parts: The FEA computer method solves real world problems on real world parts. The process for applying this method consists of the following steps:

---

[5] Young, Chapter 10

(a) Determining what physics – e.g. heat flow, material deformation, vibrations – are to be solved
(b) Making a computer model of the geometry of the part under analysis and its surroundings
(c) Identifying the conditions of the physical problem at known places within the problem space as boundary or initial value conditions.
(d) Applying a mathematical model of the appropriate physics, e.g. a change in temperature with time, or the change of position of a geometry, and/or some combination of the problem dynamics
(e) Meshing, where the computer breaks the application space (the part and its surroundings) into a "mesh" of tiny elements, typically in the tens of thousands, and then applies the governing mathematical physics to each "element."
(f) Solving. Every element's individual solution has to match up with every other element's individual solution where the elements are contiguous, and the total solution, i.e. the summation of these individual element solutions, must meet the "boundary" and initial conditions and other criteria set for the whole problem. Presenting the solution in a suitable form. [6]

The examination of the transient behavior of plugged tubes during the heating and cooling cycling is an excellent problem for FEA, and the following describes the analysis as it was established in general for a simple plug in a simple tube situation. The "a, b, c, d, etc. "steps are described for the simple plug, then the geometric and through meshing steps are presented for other analyses currently under way. Then the meshed representations of other plugs, including InstaPlug™ are shown for studies currently being run.

A simple tube plug is shown in Figure 12. It is to be applied into a heat exchanger whose tube sheet is shown in isolation in Figure 13. The configuration is taken so that cooling water at a constant temperature in the space in front of the tube sheet then flows into the tubes which are themselves encased in the tubesheet and otherwise surrounded by steam which can be turned on and off at will. The simple plug is to be inserted into the tube with sufficient force to withstand 1,000-psi differential pressure across its face.

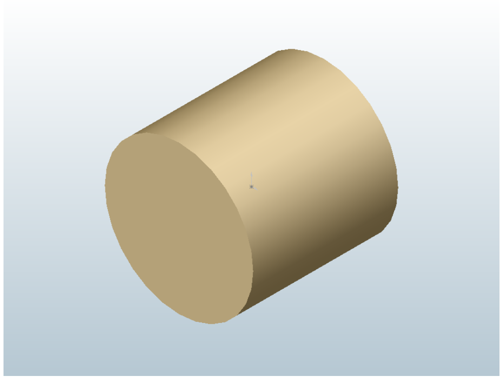


Figure 12. Simple cylindrical tube plug

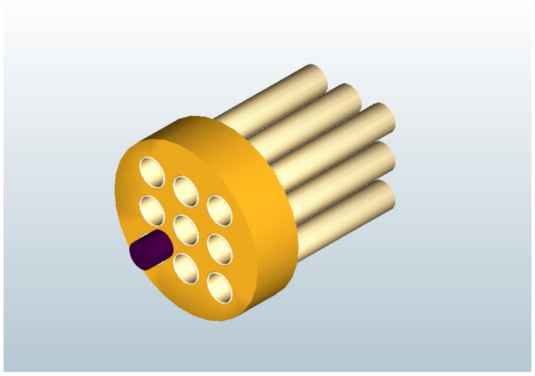


Figure 13. Simulation of plug in tubesheet

The computer assisted drawing (CAD) of the geometrical model is shown in Figure 14. The outlines of the various parts, including the boundaries of the water, the steam, and the rest of the environment all comprise the geometry of the problem. The initial temperatures of the water, air, and hard parts including the interface force between the tube and the plug, and geometric and similar conditions (e.g. the tube to tubesheet modeled as being solidly matched together throughout the problem all constitute the conditions that constrain the problem. The meshed problem is shown in Figure 15.

---

[6] Comsol Multiphysics Modeling Guide, Introduction

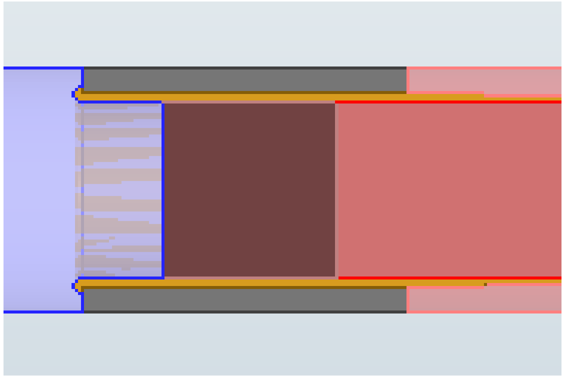


Figure 14. CAD model of the problem

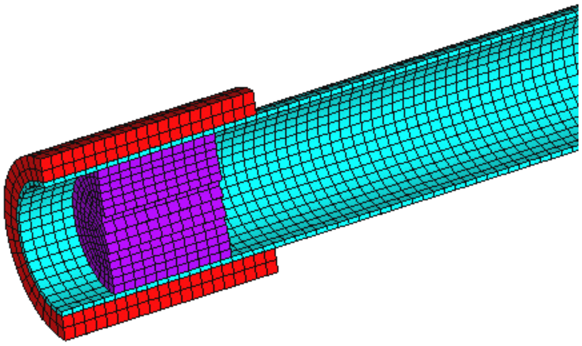


Figure 15. Problem "meshed" into finite elements

The "heat up" problem starts with everything at room temperature, and this is followed by an immediate rush of steam (approximated by a "step" function in time,) and continued until substantially a steady state or very slowly changing temperature distribution is achieved. The particular part of the problem of immediate interest is what happens to the (binding) forces between the plug and the tube during this transient heating period. The "cool down" problem simply reverses the heating situation, starting at the steady state condition, terminating the steam flow, and continuing until the "cooled" state is achieved. The particular part of the problem of interest is again the forces between plug and tube. Other descriptive results are also obtained because many kinds of physics (heat flow, stress analysis, deformation) are all being solved simultaneously. The amount of heat flow and temperature of the various parts are all nearly automatic results of the process because it is part of the "multiphysics," the simultaneous processing of all applicable, interactive physics, that is necessary to obtain any part of the total solution. A solution showing the force between plug and tube is shown in Figure 15, and an intermediate solution to the temperature distribution across the simple plug problem is shown in Figure 16.

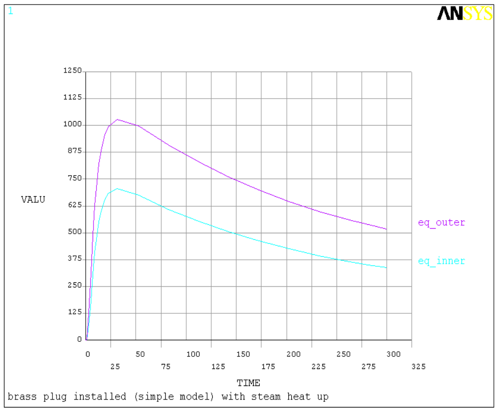


Figure 15. Time dependence of plug to tube interface forces during "heat up."

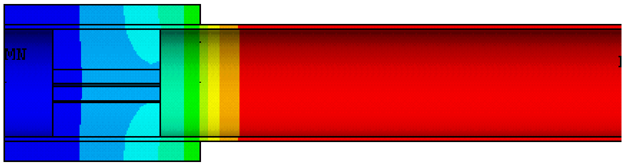


Figure 16. Temperature distribution in the simple plug model at a transition during "heat up."

The actual computation of the solutions for the remaining models is ongoing at the time of writing of this paper. The actual meshed models for the various plugs are shown in Figures 17, 18, and 19.

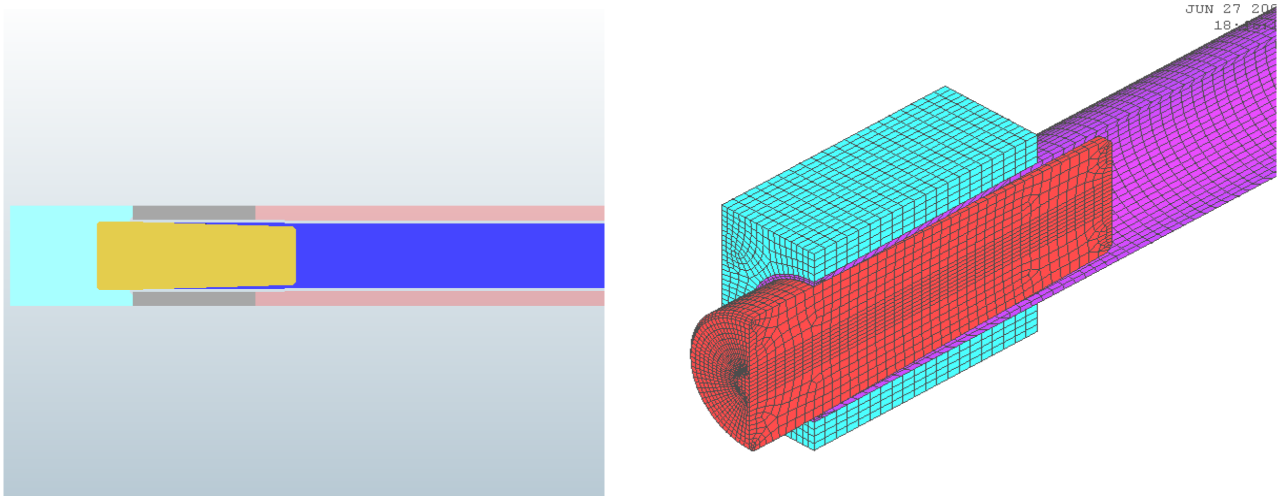


Figure 17. Taper Plug and its meshed model for the FEA problem

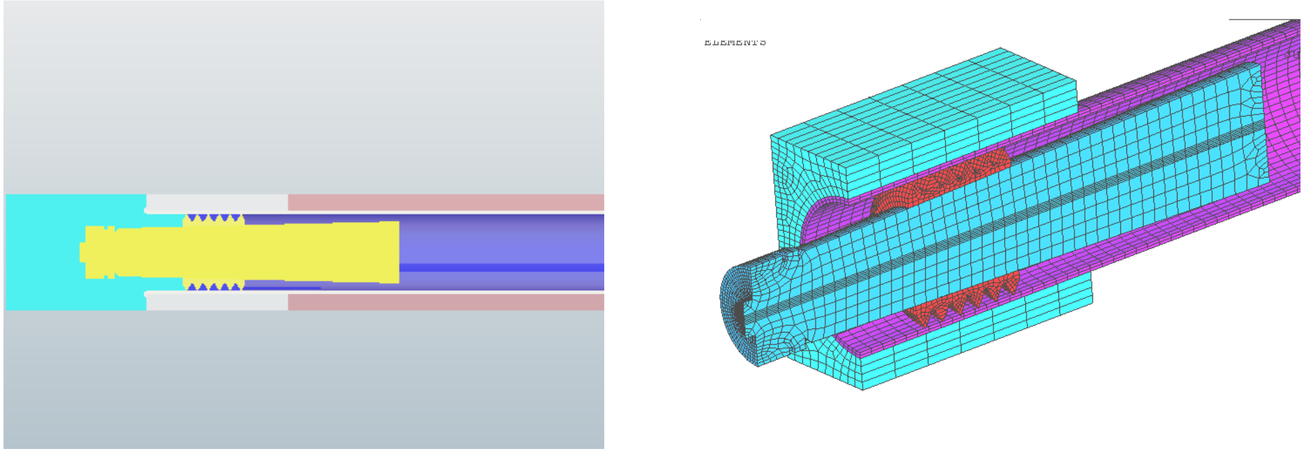


Figure 18. Representative Taper-in-Cylinder Plug and its meshed model for the FEA problem

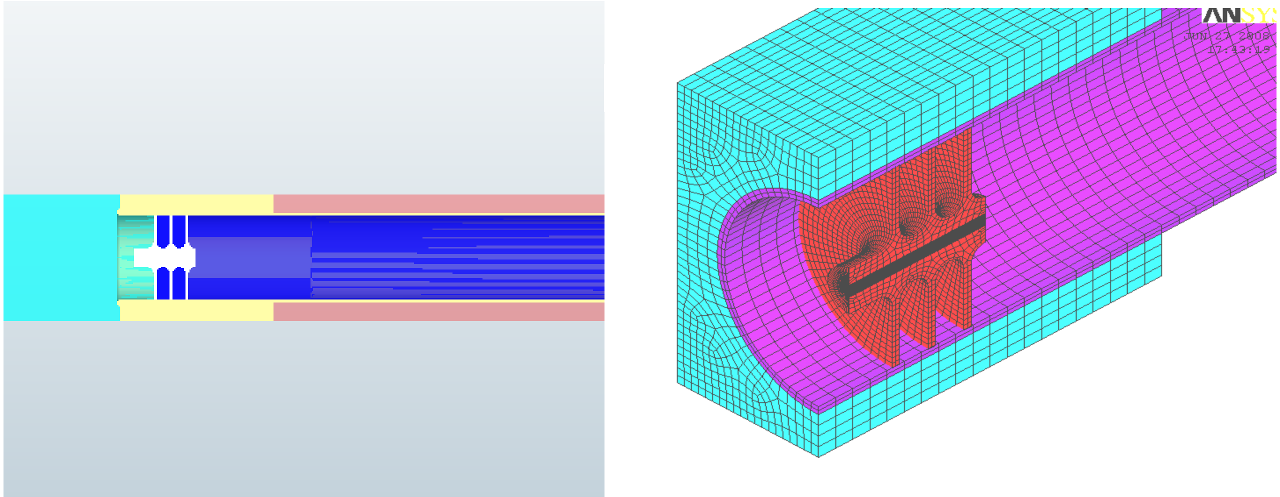
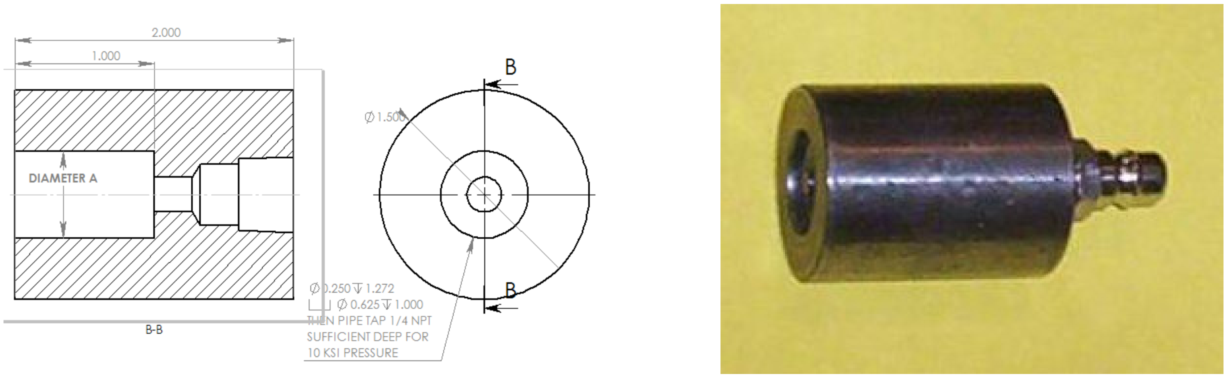


Figure 19. InstaPlug™ and its meshed model for the FEA problem

6. STATIC PROOF TESTING

Static proof tests were used to verify the predicted blowout performance of the InstaPlug™ during its development as an experimental confirmation of the design process, and later, static pressure proof testing, conducted on a sample of every production lot, was accepted as a way to assure the consistent performance of every InstaPlug™.

The tests utilize a hardened steel test cylinder, and the steel used in the test cylinder, the hardness of the steel, and the surface finish of the internal cylinder bores were selected so that the test cylinders (1) would be reusable for essentially an infinite life and (2) would present a consistent installation condition. A typical test coupon is shown in Figure 20 and in the photograph, an installed plug and the ultra high pressure quick disconnect are shown. For every tube size/BWG combination there are three sizes of test coupons that simulate respectively, new installation, half eroded, maximally eroded diameters of the tubes. Water is used as the pressure medium, and great care is employed to avoid air entrapment that might affect test results, but more importantly, would cause an unsafe test situation.



(a.) Engineering drawing of test coupon

(b.) photograph of InstaPlug™ in test coupon

Figure 20 Test coupon used for high-pressure test; note very high pressure quick disconnect.

7. FIELD APPLICATIONS

InstaPlug™ was initially installed in power plants where its progress could be monitored, and where consequences of any failure might be minimized. After some plugs had remained in place for nearly a year without evidence of failure, the field application studies were expanded in a cooperative program between D.L. Hollaender Enterprises, inc., the creator and manufacturer of InstaPlug™, and American Power Services, inc., its first commercial distributor and installer. A Beta Test Program was established with APS providing the field installation and reporting. In exchange for participation in the Beta testing, plugs were provided at significantly discounted rates, and APS provided its customers with the guarantee that ANY failure of the InstaPlug™ would result in a no-cost fix using any of the customer's preferred plugs. Between 300 and 900 plugs were to be installed under this Beta Test Program.

In late 2007, the InstaPlug™ design criteria were changed from it being a plug that could withstand thousands of psi blowout resistance to one that would be initially marketed for applications of 250 psi and 600F maximum. The lower pressure plug permitted the InstaPlug™ to become much more versatile than it was originally, and it easily accommodated as much as 1/32 inch of variability in tube bores for nominal tube sizes of ⅝ to 1 inch, and wall thickness of BWG 16 through 20. This more versatile, low pressure plug is the "advanced" design of InstaPlug™ now being marketed.

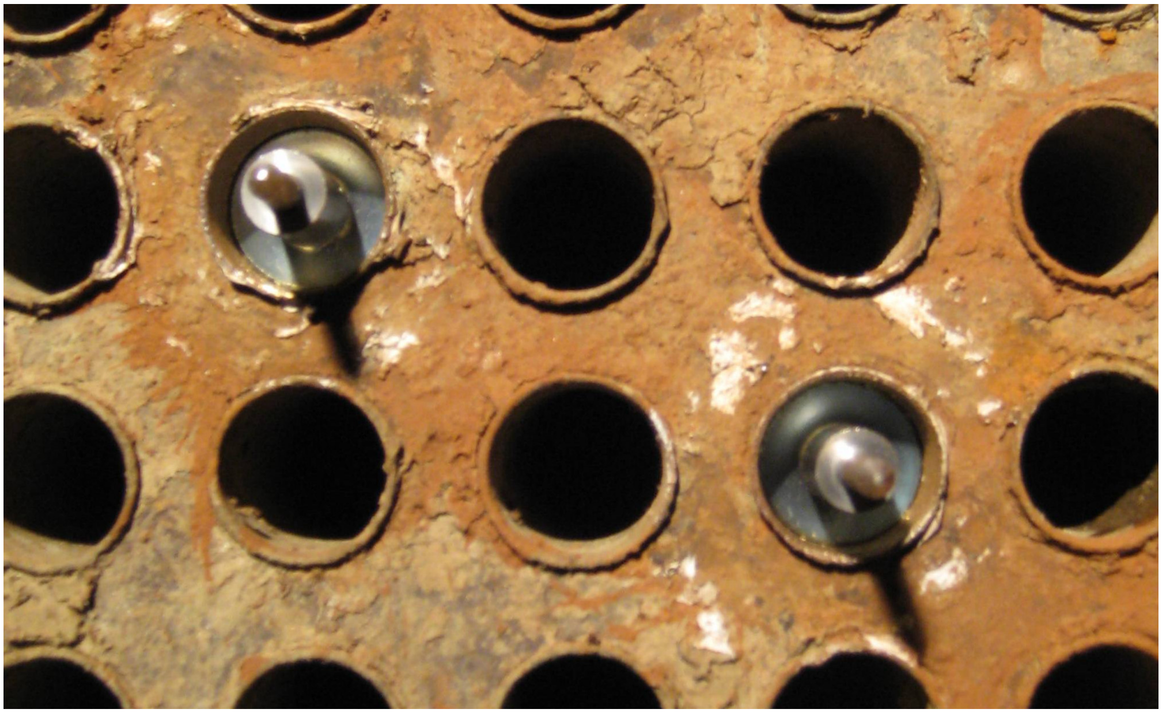


Figure 22. InstaPlug™ installation in APS job J08047 May 2008. Note that curvature of the fin that is visible is still indicating some curvature, a guarantee of residual "springiness". (Installation connectors extending from tubes have not yet been pulled off installed plugs.)

The plug was placed in service by APS using nothing more than the recommended written instructions provided with the InstaPlug™; ***No special training of personnel was required.*** The plugs set at the first of the APS installations are shown in Figure 22, and a summary of the installation practice (DO NOT USE FOR ACTUAL INSTALLATION: SAFETY REFERENCES HAVE BEEN OMITTED) is presented in table 7-1.

Table 7-1 Summary of Installation Procedures
DO NOT USE THIS SUMMARY AS A REPLACEMENT
FOR ACTUAL INSTALLATION PROCEDURES FOR InstaPlug™

---

1. **Identify** the leaking tube. **Inspect** the tube end to determine its size and whether there is any anomaly in the internal surface of the tube that would interfere with the successful installation of the plug. Mark the tube end to be plugged.
2. **Measure** the tube end with an inside tube micrometer or a gauging block to determine the actual diameter of the tube end. **Select** the INSTA-PLUG™ tube plug of the correct size based on that measurement.
3. **Prepare** the inner surface of the tube. Use a Jimmy brush (SS Power Tube Brush) (preferred) or a reamer to thoroughly provide a bright metal surface to the tube.
4. **Clean** the tube end thoroughly. BE ABSOLUTELY CERTAIN THAT THE SURFACE IS FREE FROM ANY LUBRICANTS, OILS, ETC.

Table 7-1 Summary of Installation Procedures (continued)
DO NOT USE THIS SUMMARY AS A REPLACEMENT FOR ACTUAL INSTALLATION PROCEDURES FOR InstaPlug™

5. **Inspect** the tube end to assure cleanliness and the absence of any anomalies
6. **Install** the INSTA-PLUG™ tube plug so that the plug is inserted totally within the tube and that it is set deep enough to be entirely within the tube sheet thickness
7. **Heat** the INSTA-PLUG™ with electrical resistance heating provided by an electric arc welder. There should be no arcing. The heating will occur by the resistance of the plug fins with the tube surface.
    a. Set the welder to 165 amps ± 10%. Do not turn it on!
    b. Establish ground connection on material that will conduct to the tube/tubesheet.
    c. Clamp the welding rod holder to the (removable) small rod extending from the end of the INSTA-PLUG™.
    d. Turn on the welder and allow the current to flow for 45 seconds. The plug should be firmly set at this point.
    e. With a pliers or similar tool, remove the heating extension rod and dispose of it safely.
8. **Test for integrity, and then pressure test.**

Finally, we present our own assessment of our plugging experience. We emphasize this to be our own opinion, but it is based on more than twenty-five years' experience in the maintenance of heat exchangers. The opinion is shown in Table 7-2.

Table 7-2 Plug Comparison

PLUG TYPE	**DESCRIPTION**	**EXPECTED LIFE**	**REASON FOR FAILURE**	**APPROX. INSTALL TIME**
1. Explosive welded plugs	Pure nickel, compatible with all metals used in feedwater heaters, hollow design allows for flex, can be installed in tube or tubesheet.	Life of heaters	Installation error	5-10 per hour
2. Insta-Plug	Nitinol plug material acts as a spring maintaining pressure on the tube/tubesheet. Thermal cycling will not cause a plug to leak. Maintains pressure on the tube ID or tube sheet hole. Compatible with all metals. Allows for tube sheet flex.	Life of heat exchanger	Installation error	10-20 per hour
3. Thimble plug & fusion weld	Hollow design one piece plug is fusion welded into tubesheet hole after tube is removed from tubesheet. Hollow design allows for expansion and contraction	2 to 20 years	Installation fit up, weld porosity and cracking, cleanliness of weld ,installation time is excessive.	2-4 hours each

Table 7-2 Plug Comparison, Continued

4. Two piece serrated taper pin	Variety of materials, installed in tube at any location	3 months to 10 years	Installation error, thermal expansion & contraction pressure cycling; impossible to seal with tube or tubesheet hole out of round	5-10 per hour
5. O-ring plug	Expanded O-ring in tube hole. Removable plug has holding jaws expanded with taper locked expanded with Allen wrench Primarily for temporary plugging	3 months to 1 year	Tube hole fit up, thermal expansion & contraction and pressure cycling.	2-4 per hour
6. Two piece taper pin	Vriety of materials used, installed in front face of tubesheet, expansion of solid ring as tapered pin is hammered into ring.	3 months to 10 years	Installation error, thermal expansion & contraction pressure cycling; impossible to seal with tube or tubesheet hole out of round (reaming or burring may be reqd.)	10-20 per hour
7. Taper pin & fusion weld	One piece taper hammered into tube/tubesheet and fusion welded to the tubesheet overlay	6 months to 20 years	Installation error, thermal expansion & contraction pressure cycling, weld porosity and cracking, weld damage to overlay, cleanliness of weld, installation time is excessive,	1-2 Hr.
8. Elastomeric expansion/rubber expanded plug	Installed in tube and expanded with screw driver, ratchet/socket, torque wrench	3 months to 10 years	Poor friction fit may result in plug blow out, thermal expansion and contraction varies from tube sheet/tube resulting in plug failure.	10-20 per hour
9. Tapered pin	One piece taper hammered into tube/tubesheet Minimum contact area to tube, gradual taper 3-5% Solid metal, wood, rubber.	3 months to 5 years	Thermal expansion & contraction, pressure cycling; impossible to seal with tube or tubesheet hole out of round (reaming or burring maybe required)	5-20 per hour

8. References

1. Weisstein, Eric W. “Octahemioctahedron.” From MathWorld--A Wolfram Web Resource. http://mathworld.wolfram.com/Octahemioctahedron.html

2. “Atomistic Model,” From Nitinol Devices and Components Corporation, Fremont, CA, http://www.nitinol.de, 2006

3. “Info-Sheet No. 4 Selected Properties of NiTi-based Alloys” Memory-Metalle GmbH, http://www.memory-metalle.de/html/03_knowhow/pdf/MM_04_ _properties_e.pdf, 2001.

4. “Report TEi Job No. UES-43-05-0013-1A,” Thielsch Engineering Inc. October, 2005. (Report available from DLH Enterprises, 8900 Glendale Milford Road, Suite 1B, Loveland, OH 45140)

5. Young, Warren, Roark’s Formulas for Stress and Strain, McGraw Hill Book Company, New York, London and other cities, Chapter 10, 1989.

6. Comsol Multiphysics Modeling Guide, Chapter 1, Comsol AB. Stockholm, 2005.