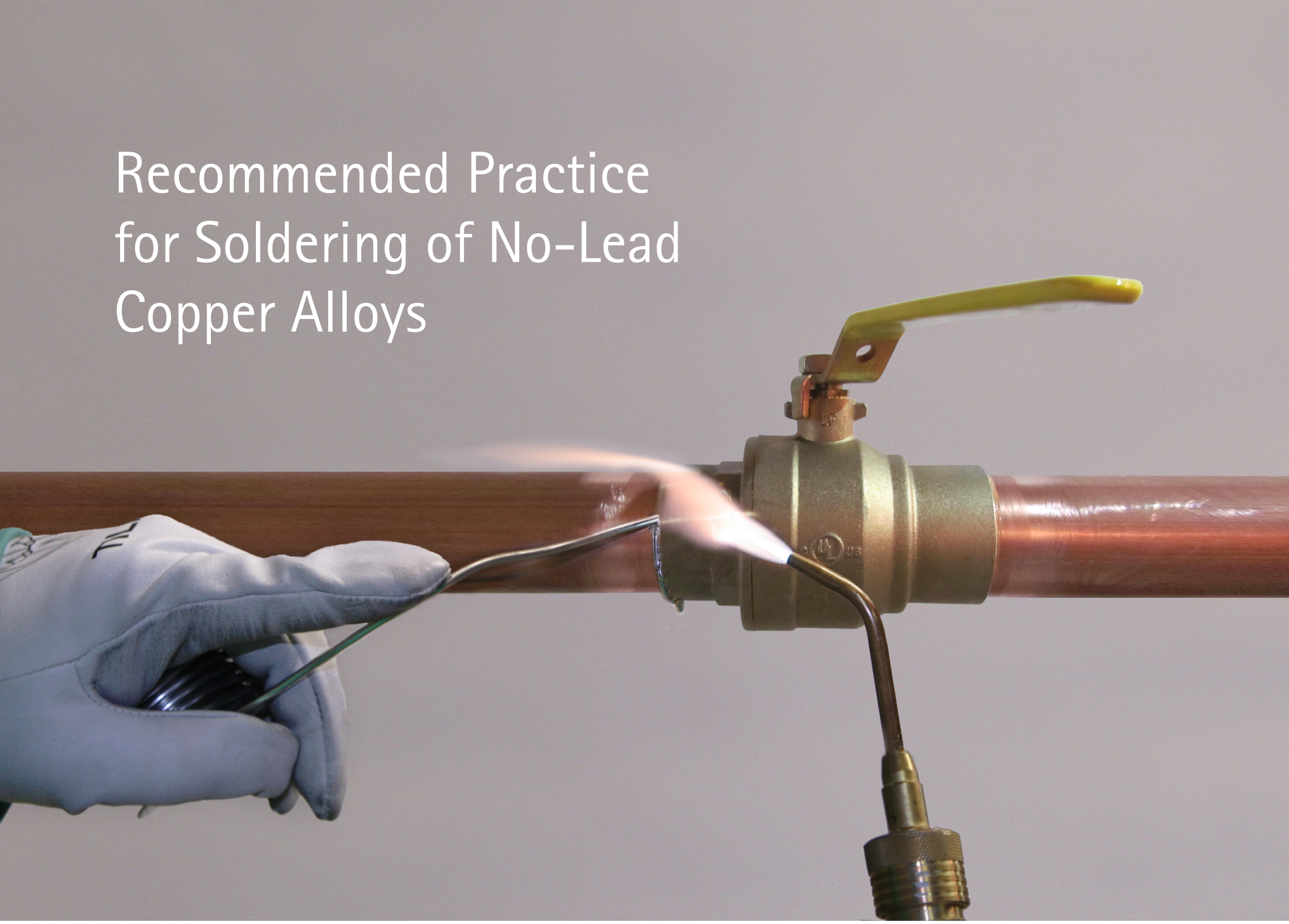
Recommended Practice for Soldering of No-Lead Copper Alloys



Background

On January 4, 2014 new requirements, federally mandated by the implementation of the Reduction of Lead in Drinking Water Act (RLDWA), dramatically changed the definition of no-lead as it appears in the Safe Drinking Water Act (SDWA).

Previously the SDWA definition of lead-free set a maximum limit for lead in pipes, fittings and valves utilized in potable water plumbing applications to a maximum of 8% total lead content, as a percentage of the total mass of the component. Now, rather than defining lead-free by the total composition of the alloy or component, the RLDWA defines no-lead compliance by limiting the amount of lead in contact with the potable water, rather than the entire composition of the component. By the new Act the amount of lead allowed in a component intended for potable water use is limited to a maximum of 0.25% lead calculated as a weighted average of the total surface area of the component in contact with the water (wetted surface area). Components include pipe, pipe fittings, valves and plumbing fittings.

Industry wide, copper based alloys like brass and bronze are the most widely used materials for valves, backflow preventers and other plumbing fittings and faucets. The dramatic reduction in allowable lead content affects the chemical composition of copper alloys like brasses and bronzes that can be used for potable water applications, as well as the design of components using these alloys.

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Results of Changes to SDWA

The change in the allowable limits for lead in piping components can be addressed in two ways.

First, components can be redesigned to reduce the wetted surface area of lead bearing components below the 0.25% limit of the total wetted surface area. For example, a brass-body ball valve with a stainless steel ball may still utilize a brass alloy containing up to 8% lead (the limit in the SDWA), provided that the wetted surface area of that alloy is minimized so that the weighted average lead content of the total wetted surface area (the body plus the ball) does not exceed 0.25%.

Second, component manufacturers can incorporate into their designs alternative copper (brass and bronze) alloys that do not contain lead, or contain significantly less lead. To aid in this effort a number of new copper alloys have been developed that substitute bismuth, silicon, and other alloys for lead to create functional, no-lead copper (brass and bronze) alloys. However, the newer no-lead copper alloys can exhibit properties that are significantly different from the older leaded copper alloys. In particular, differences in the thermal conductivity of some of these alloys, especially those containing silicon, may lead to issues with the solderability or joinability of these alloys in the field.

Background: Installation Concerns

For well over a year CDA, their representatives and members have been made aware of concerns related to the solderability of no-lead alloys by installers of soldered joints between copper tube and these new no-lead copper alloys.

In many cases, reported issues have come along with a variety of theories, misconceptions and myths as to the root cause, and thus the solution to the issue. These myths include, among others:

- Mechanical cleaning of the no-lead alloy with a fitting brush leads to inferior solder joints – FALSE
- Only specific soldering fluxes can be successfully used in joining the no-lead alloys - FALSE
- Tinning fluxes must be used to join the no-lead alloys - FALSE
- Heating the entire joint with a larger torch to quickly bring the entire assembly up to temperature is necessary - FALSE
- Joints must be immediately quenched following soldering to cool the no-lead alloy and keep solder from running out of the joint – FALSE

In case it isn't obvious enough, all of the above are false. High quality solder joints can be made between copper tube and components made of the new no-lead alloys using any previously acceptable cleaning method, any of the commonly used and code-accepted soldering fluxes, using appropriately sized torch tips and without shock-cooling the joint.

So is the solderability of the new no-lead alloys truly problematic? While we wouldn't characterize it as problematic, soldering these new alloys can be more challenging, especially when soldering techniques are applied that do not meet industry standard recommendations as published in ASTM B828. Some of these no-lead alloys are less-forgiving of improper techniques or shortcuts that many installers have grown used to employing with more forgiving joints, such as copper tube to wrought copper fittings.

Issue: Thermal Conductivity and the Heating Process

The challenge in making solder joints with these alloys lies in a fundamental misunderstanding of the thermal properties of the alloys and their subsequent effects on solder joint fabrication. Thorough testing of all of the variables involved in making solder joints between copper tube and the new no-lead alloys including: various base alloys, cleaning methods, fluxes used, size of torch tips employed, order of heating the joint components, post soldering quenching and others, and application of these results to the basic theory of solder joint design and fabrication supports this conclusion. In short, the much lower thermal conductivity of these alloys, especially the silicon-containing alloys, requires strict attention to proper heating and soldering procedure to ensure high-quality solder joints.

After over a year of in-field and laboratory research, Copper Development Association (CDA) is convinced installers' concerns are directly related to a misunderstanding or in many cases the misapplication of the industry standard soldering procedure. This misapplication can have a negative impact on the quality of solder joints made using these lower conductivity, no-lead alloys. The negative experience of installers regarding soldered joints in these alloys has very little to do with the preparation of the soldered joints or the type of flux or solder used in fabricating the soldered joints. In fact, while we could replicate apparent issues related to all of the variables in joints made with improper soldering procedures, once we employed the proper soldering procedure the apparent impact of all of these variables disappeared.

CDA has been the recognized industry expert for over 50 years on the use and application of copper and copper alloys in many applications and especially the joining of copper and copper alloys. CDA was instrumental in the research and development of the soldering standard referenced in every major model plumbing and mechanical code in the US. That standard is ASTM B828 - *Standard Practice for Making Capillary Joints by Soldering of Copper and Copper Alloy Tube and Fittings.* ASTM B828 outlines proven practices required to ensure the fabrication of consistent and repeatable high-quality soldered joints between copper and copper alloy tube, fittings and components. The standard contains several steps that must be completed for every soldered joint:

1. Measuring and cutting
2. Reaming (burr removal from I.D. and O.D.)
3. Cleaning (oxide removal from surfaces to be soldered)
4. Fluxing (thin even film of an approved flux applied to surfaces to be soldered)
5. Assembly and support (ensure equal capillary space around the circumference of the joint)
6. Heating (heating of tube, fitting and capillary space to bring each joint element up to soldering temperature)
7. Application of solder (to displace flux from the joint and fill the joint with solder)
8. Cooling & cleaning (uniform natural cooling and removal of excess flux following completion of soldering process, never quick quench)

In the case of joining copper tube to the new, no-lead alloys particular attention must be paid to step six, the heating process for making the soldered joint. It is important for installers to thoroughly understand the science and metallurgy associated with fabricating any soldered capillary joint. A capillary soldered joint between copper tube and copper or a copper alloy fitting is actually made up of four individual major parts that make up a soldered assembly:

1. Tube
2. Capillary space
3. Fitting, valve, or appurtenance (Copper alloy backflow preventer, pressure reducing valve, etc.)
4. Filler metal (solder)

All four of these components of the soldered joint have distinct and varying physical characteristics, like thermal conductivity, that must be taken into account individually as part of the complete assembly. It is incorrect and problematic to view all four components as a single homogeneous assembly when fabricating soldered joints.

In order to successfully create a high-quality soldered joint, all four parts of the "joint" have to be at or above the temperature where the filler metal will melt, adhere to the base metals (tube and fitting/component), and flow completely into and fill the capillary space in that portion of the joint by capillary action. Not only do all of these components need to reach a temperature at which the solder will melt and flow, they must remain at this temperature to prevent premature "freezing" or solidification of the solder metal before it is able to wet and spread throughout the entire capillary space. It is not enough to simply heat the solder with the torch until it reaches melting temperature. The base metals (tube and fitting/component) must be raised to at or above the melting temperature of the solder and maintained at that temperature so that the solder will be drawn into the capillary space between the two.

Therefore, heating processes must be designed and applied to ensure that all components of the joint assembly are raised to at or above the melting point of the solder and held at that temperature until the solder has filled the capillary space in that portion of the joint. The soldering process outlined in the ASTM B828 standard, the CDA Copper Tube Handbook, and the AWS Soldering Handbook are all the same, and is designed ensure proper heating to create a reliable, high-quality soldered joint.

Unfortunately, based on traditional practices this process is rarely employed accurately or consistently in the field. The inherent forgiveness of joints between copper tube to wrought copper fittings or the no longer acceptable lead-bearing copper alloy (brass or bronze) has allowed installers to devise and employ substandard techniques and still achieve acceptable soldered joints. This is primarily due to the very high thermal conductivity of the wrought copper materials and the lead-bearing copper alloys (see **Table 1** below). The high conductivity of these parts virtually ensured that no matter where the heat was applied to the joint, on the tube surface or the fitting/component surface, the heat from the torch would have a high probability of bringing both of the base metal components and the capillary space up to soldering temperature. Improper heating of these joints, and especially improper heat control during the application of the solder metal is still a leading cause of faulty solder joints. Even though they are more forgiving they are not foolproof and proper techniques should still be followed, see ASTM B828.

In-field research with various and multiple installers, training facilities and contractors throughout the United States over the past year confirms that installers are commonly employing improper heating techniques across the range of solder joints that they install, including those made with the new, no-lead alloys. The most common of these are improper application of preheat (location and duration) and improper application of heat during the application of solder (location and duration). In the first case, installers begin heating the joint by applying the torch directly to the fitting/component cup and ignoring the tube, attempting to bring the entire joint assembly up to soldering temperature through application of heat only to the fitting/component. In the second case, once the joint or a portion of the joint is at soldering temperature installers tend to focus all of the heat at one point at the base of the fitting/component cup while solder is applied either at one point or around the entire joint.

Let us evaluate the problems associated with the improper application of heat in these two cases.

Improper Preheating

If we only try to heat the joint through the fitting there are several factors that are acting to disrupt the easy and clear flow of heat into the three parts of the joint (tube, capillary space and fitting/component). The main disrupting factor is thermal conductivity, or the ability to transfer heat through a material. When applying the torch flame directly on the fitting/component the heat that is being transferred from the torch to the fitting/component would have to heat the fitting/component to soldering temperature, travel through the fitting/component, then the capillary space (an air space that acts like an insulator) and finally into the tube, then bringing the tube up to soldering temperature. In this case, as the installer focuses the heat only on the fitting/component, with no prior preheating into the tube, the fitting/component cup begins to expand thus opening the capillary space and increasing the insulative effect of this space. This effect by itself greatly slows the ability of the torch to raise the tube surface inside the joint to soldering temperature. In addition, some of the new no-lead copper alloys (brass or bronze) and especially the silicon containing alloys have a coefficient of thermal conductivity almost 10 times lower (See **Table 1** below) than copper tube, and 2 – 3 times lower than previous brasses and bronzes greatly slow the transfer of heat through and out of the fitting/component. Because of this, much more heat must be directed into the fitting/component body to begin to raise the temperature of the tube surfaces within the joint. This excessive application of heat required at the fitting/component surface has shown four probable outcomes:

1. The fitting/component surface reaches soldering temperature but the tube surface within the joint does not, so solder melts and adheres to the face of the joint (due to some heat overwash on the tube surface outside the joint) but does not flow into the capillary space;
2. The fitting component/surface reaches soldering temperature and the tube surface inside the joint barely reaches soldering temperature. The solder begins to melt and inherently cool the joint surfaces so the tube surface does not maintain soldering temperature. Solder solidifies without completely flowing/filling the capillary space;
3. The fitting/component surface reaches soldering temperature and the tube surface within the joint reach soldering temperature but it took so much time to bring the tube surfaces up to temperature that the flux within

Table 1: Coefficient of Thermal Conductivity of Copper Tube and Select Leaded and No-Lead Copper Alloys (Brasses and Bronzes). No-lead alloys are highlighted (*).

UNS Alloy Number	Common Name/Use	Coefficient of Thermal Conductivity BTU x ft/(hr x ft^2 x °F) @ 68°F
C12200*	DHP Copper (copper tube and fittings)	196[A]
C36000	Free Cutting Brass (fittings, valves, components)	67[A]
C37700	Forging Brass (fittings, valves, components)	69[A]
C83600	Ounce Metal (fittings, valves, components)	41.6[A]
C84400	Valve metal (valves, components)	41.8[A]
C27450*	Yellow Brass (fittings, valves, components)	67[A]
C69300*	ECO Brass (fittings, valves, components) contains silicon as lead replacement	21.8[A]
C89550*	SeBiLOY III (fittings, valves, components) contains bismuth and selenium as lead replacement	≈58 (see note 1)
C89836*	Copper Bismuth (fittings, valves, components) contains bismuth as lead replacement	41.0[B]
Carbon (Black) Steel	Included for comparison purposes	21[C]

Sources:
[A] ASM Handbook, Volume 2: Properties and Selection of Nonferrous Alloys and Special-Purpose Materials; ASM International: Miami, Florida
[B] Alloy Data Sheet http://www.sipimetals.com/#!c89836/c6ez; Sipi Metals Corporation; Chicago, Illinois
[C] ASM Handbook, Volume 1: Properties and Selection of Irons, Steels and High Performance Alloys; ASM International: Miami, Florida

Notes:
[1] The thermal conductivity of C89550 has not been published. Due to the close similarity of alloy composition this value is an extrapolation based on the thermal conductivity of alloy C89580 as found in Source A.

the joint burns and inhibits effective flow of the solder throughout the capillary space;

4. Both the fitting/component surface and the tube surface within the joint reach soldering temperature, solder flows throughout the capillary space. However, the excessive heat now contained in the fitting/component surface due to the excessive overheating and the low thermal conductivity of the material prevents the joint from cooling quickly. This prevents the solder in the capillary space from freezing/solidifying in the space to complete the joint (i.e. the molten solder metal runs out of the joint).

Improper Application of Heat During Application of Solder

Provided that proper preheating technique is employed (see below) to overcome the issues above, improper application of heat during the soldering process once the joint components are at the melting temperature of the solder can also result in faulty joints. While there are a number of scenarios that can come into play here, we are only going to discuss the two most common: application of heat at only one point while solder is added to the joint; and application of heat only to the fitting/component surface while solder is applied, ignoring the tube surface.

1. Application of heat at only one point (commonly the base of the fitting/component cup at the bottom of the joint) while solder is applied at the opposite side of the joint (commonly the top of a horizontal joint) requires that the temperature throughout the entire fitting/component cup and the joint surfaces between the heat source and the point of application of solder must be above the melting point of the solder. And, they must stay above the melting temperature as the solder is added and begins to flow around and cool the joint. With the lower conductivity alloys, this is difficult to achieve and generally results in one of the four outcomes listed above.

2. Failure to regularly reapply heat to the tube surface as the solder is applied can result in rapid cooling of the tube surfaces within the joint as the solder is applied and can cause incomplete solder flow in the capillary space. Once preheating is achieved, it is necessary to focus the application of heat at the base of the fitting/component cup to ensure filling of the entire capillary space with solder. However, the thermal conductivity of the fitting/component is still low and will prevent maintaining the temperature of the tube when heat is only applied to the fitting/component. Again, this can lead to one of the four outcomes listed above.

Regardless of the manifestation of the problem, or the outcome, all of these issues basically stem from the misapplication of the heating process which is exacerbated by the fact that the lower thermal conductivity of some of the new, no-lead alloys makes the proper application of heat more important. Joints between copper tube and the new no-lead alloys can be, quickly, easily and reliably fabricated so long as the installer follows the heating processes below to ensure that all joint components are brought to and held at soldering temperature throughout the soldering process.

Figure 1: *improperly Heated Solder Joint – Brush marks from mechanical cleaning (stainless steel brush inserted in power drill) still evident in soldered surface indicating inadequate heat in the tube surface leading to a lack of solder fill in the capillary space.*

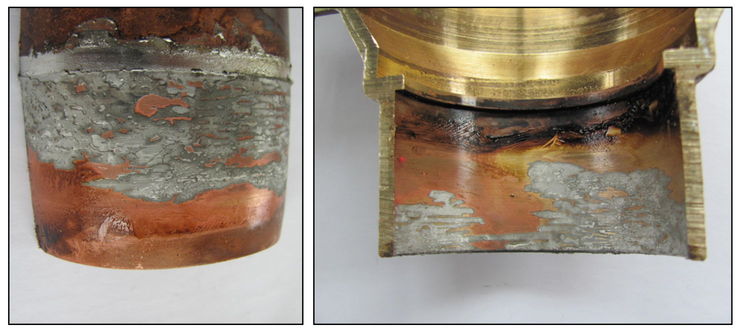

Figure 2: *Improperly Heated Solder Joint – Incomplete solder flow in the capillary space due to inadequate preheating of the tube surface.*

Solution: Recommended and Accepted Joining Procedure

Since our research indicates that factors such as the tube cleaning, fluxes used, post-fabrication cooling, etc. are not the essential variables in successfully making joints between copper tube and the new, no-lead copper alloy (brass and bronze) fittings/components we are not going to cover all of the preparation steps for solder joints here. Instead we are only going to focus on the proper heating processes. For more information on the proper preparation of solder joints refer to *ASTM B828*, the CDA *Copper Tube Handbook* (www.copper.org), or the *AWS Soldering Handbook.*

Once all preparatory steps are completed, the tube is cleaned, fluxed and inserted into the cleaned and fluxed fitting the actual soldering process can begin.

Step One: Preheat the Tube

In order to overcome the difficulties in trying to bring the tube surface up to soldering temperature installers should first focus on adequately preheating the tube to soldering temperature. This does two important things. First, the copper tube has a high thermal conductivity, so heating the tube surfaces immediately outside the joint allows the tube to easily conduct heat along the tube surface within the joint itself, thus raising the temperature of the tube from the front to the base of the fitting/component cup. Secondly, adding preheat to the tube causes the tube to expand radially into the fitting/component cup, thus minimizing the capillary space (gap) between the tube and the fitting and keeping that space within the tolerances necessary to create capillary flow of the molten solder metal.

Our research has shown that with the new, no-lead fittings/components it is beneficial to preheat the tube more than would normally be done. This begins to heat the interior surfaces of the fitting/component with heat from the tube surface. The preheating of the tube should be undertaken with the appropriately sized torch tip directing the flame perpendicular to the tube, about the same distance from the fitting cup as the length of tube that is inserted into the solder cup (i.e. if the fitting cup is 1 inch deep, preheat the tube approximately 1 inch beyond the face of the joint). While there is no definitive time limit on preheating, the tube should be preheated until the flux at the face of the joint begins to become active (begin showing signs of cleaning the tube/fitting surfaces).

Step Two: Preheat the Fitting/Component

Once appropriate preheat has been applied to the tube, move the flame back onto the fitting/component surface to the base of the fitting cup. Preheating of the fitting is most effective if the torch is directed from the back of the fitting cup to the face of the solder cup. This torch position directs the greatest amount of heat from the back of the fitting cup towards the face, where the solder will be applied. This allows for the primary flame of the torch to concentrate heat into the fitting/component while allowing the secondary flame to keep the tube surface at temperature (note: for larger tube/fitting sizes it is beneficial to move the torch in a slow, continuous pattern from the base of the fitting cup to the face of the joint as you work your way around the circumference of the joint). By using this torch position it actually pulls surrounding air around the torch flame, which provides a cooling effect to the area behind the torch flame and the unsoldered side of the joint.

Due to variable environmental conditions it is difficult to describe and exact time or duration of preheating. However, since the tube surfaces inside were already preheated and began to conduct heat into the inner surfaces of the fitting/component, required preheating time on the fitting/component is usually less than that for the tube. Watch for the activity of the flux at the face of the joint and test the solder to see if it melts. If the solder melts it is time to switch from preheating to the actual soldering process. If it does not melt, remove the solder and continue preheating.

Step Three: Apply Heat and Solder

Now that appropriate preheating has been accomplished, choose a spot on the joint to begin soldering. On vertically oriented joints, the starting point is irrelevant in terms of successful completion of the joint so we will focus on the slightly more difficult horizontal joint. For horizontal joints, move the torch to the base of the fitting/component cup slightly off-center of the bottom of the joint (imagine the 5 o'clock or 7 o'clock position if the face of the joint were the face of a clock) and begin adding solder to the face of the joint at this same position.

As the solder begins to melt from the heat contained in the tube and the fitting/component (not from direct heat of the torch) push the solder straight into the joint. Push solder into the joint at this position until the capillary space is full at the current position before you move (solder will begin to run from the front of the joint), then keeping the position of the torch at the base of the cup slightly ahead of the position of the solder metal move the solder metal across the bottom of the joint.

Move slowly but deliberately, as solder fills the capillary space at the point of application it will begin to run out of the face of the joint, your signal to continue moving. Continue across the bottom of the fitting/component and up the opposite side of the joint to the top of the fitting/component. Coming across the bottom of the joint and up the other side, moving the torch along with the solder creates smooth, continuous flow of the solder in the capillary space. While applying the solder move the most intense heat from the torch away from the already soldered portions allowing the solder to solidify. In the case of the horizontal joint, this creates a solder dam at the bottom of the joint.

Now, return to the point of the beginning off-center of the bottom of the joint keeping the torch at the base of the cup and slightly ahead of the solder metal. Overlap the starting position and solder up the remaining side of the joint. Move slowly and deliberately with the torch always slightly ahead of the solder metal to fill the capillary space and prevent remelting of the already soldered surfaces. Once you reach the top of the joint, overlap your previous ending position and then remove both the torch and the solder.

Installers should try to maintain even heating of the joint surfaces during soldering. This can be accomplished by moving the torch closer or further away from the joint so that hotter or cooler portions of the flame are being used. Remember, as you add solder to the joint and it melts, it removes heat from the base metals and acts to cool the joint. By continually adding solder and varying the portion of the torch flame directed at the joint you should be able to maintain the solder at a molten, but still pasty condition allowing for good control of the solder application. Failure to regulate the portion of the torch flame impinging the joint can quickly lead to either overheating or premature cooling of the joint.

Step Four: Cooling and Cleaning

The completed soldered joint should be allowed to cool slowly and naturally. Never quick cool or quench any soldered joint. The new, no-lead alloys may not reject heat as quickly as their predecessors due to their lower thermal conductivity. Therefore, by controlling the amount of heat added to the joint in preheating and making the solder joint to the bare minimum required to facilitate full solder melting and flow, the solder will solidify and cool the joint quickly once the joint is complete and the direct heat from the torch is removed.

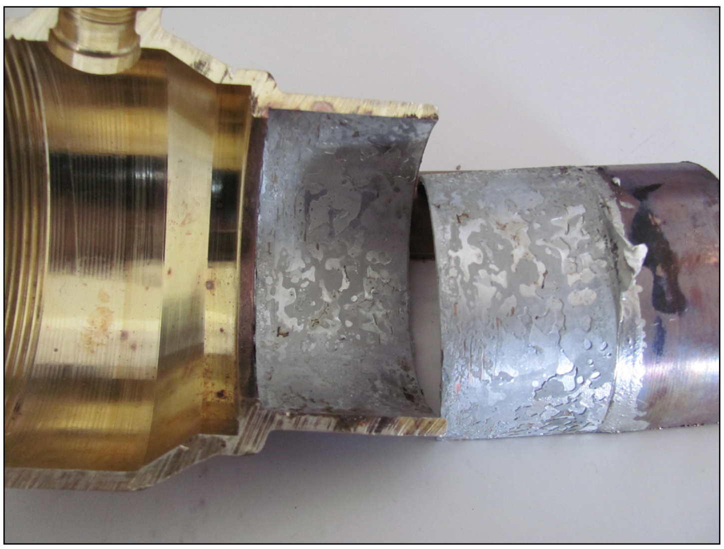

Figure 3: *Properly Completed Solder Joint – Prepared identically to **Figure 1**. Brush marks from mechanical cleaning (stainless steel fitting brush inserted in power drill) no longer evident as proper heating allowed for complete solder flow and fill in the capillary space.*

Conclusion

If the proper procedures are followed, especially in the preheating and heating process, consistent, high-quality solder joints can easily be achieved between copper tube and new, no-lead copper alloy (brass or bronze) fittings/components. Proper heating techniques outlined in this paper are applicable to creating any soldered copper joint and are in complete agreement with the recommended and accepted procedures contained in the code-required *ASTM B828* standard, the *AWS Soldering Handbook*, and the CDA *Copper Tube Handbook*. For more details on the complete soldering process including descriptive photographs and diagrams refer to either of these three documents or visit *www.copper.org* to view an online or downloadable version of the Copper Tube Handbook. You will also be able to view a brief video of the process outlined above for joining copper tube to new, no-lead fittings/components.

References:

1. *ASTM B828, Standard Practice for Making Capillary Joints by Soldering of Copper and Copper Alloy Tube and Fittings;* ASTM International, West Conshohocken, Pennsylvania; www.astm.org
2. The Copper Tube Handbook; Copper Development Association Inc., New York, New York; www.copper.org
3. *Soldering Handbook;* American Welding Society, Miami, Florida; www.aws.org
4. *ASM Handbook, Volume 2: Properties and Selection of Nonferrous Alloys and Special-Purpose Materials;* ASM International, Materials Park, Ohio; www.asminternational.org

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