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Weld Development for Aluminum Fission Chamber

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Introduction

The Sigma welding team was approached to help fabricate a small fission chamber (roughly ½ inch dia. x ½ inch tall cylinder). These chambers are used as radiation sensors that contain small traces of radionuclides (Cf 252, U 235, and U 238) that serve to ionize gas atoms in addition to external radiation. When a voltage is applied within the chamber, the resulting ion flow can be calibrated and monitored. Aluminum has the advantage of not forming radioactive compounds when exposed to high external radiation (except from minor Na alloy content). Since aluminum has not been used before in this application, this presented an unexplored challenge.

The material provided to us for the chamber body was Alloy 6061, and for the tube (used to feed gas and electrical wires into the chamber) was Alloy 3003. Alloy 6061 is generally considered to have very poor weldability when welded without 4xxx or 5xxx alloy filler metal. These filler alloys shift the weld composition into a less crack sensitive regime. Likewise, the hybrid fusion zone alloy formed by welding 6061 to 3003, has even poorer weldability than alloy 6061 alone (i.e. more prone to solidification cracking). Thus, this provided a challenge for weld development. The chamber design evolved into the general configuration shown in Figure 1 (i.e. two coaxial cans), with the requirement that the welds remain leak tight and hold up to 100 psi gas pressure.

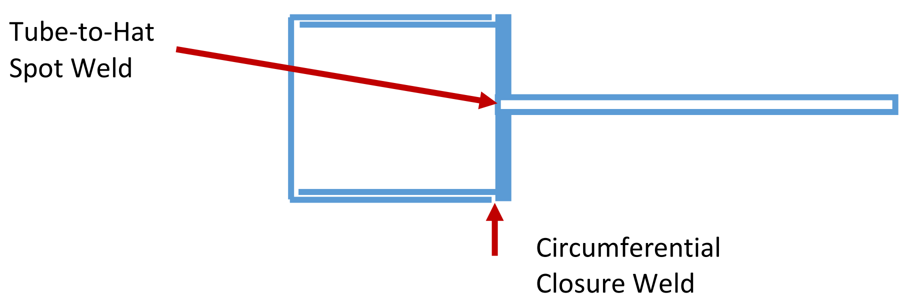


Figure 1: Schematic of fission chamber showing location of welds.

Welding Process

Gas tungsten arc (GTA) welding was selected because it works well for joining aluminum and because we have equipment available to do this. Direct Current DC-GTA welds were first attempted on scrap pipe, but they were found to be too hot, i.e. melting back the thin section aluminum (DC requires the use of helium shielding gas which tends to run hot). Alternating Current AC-GTA welds, made with argon shielding gas, were found to be more suitable. Here we adjusted the most appropriate mixture of Electrode Negative (provides heat) and Electrode Positive (provides cleaning) to give us the desired weld. Pulsing was added to this in order agitate the weld pool to remove porosity. Electron beam (EB) welding was considered as a backup, because it is well suited for welding thin parts, although equipment availability is sometimes a concern.

Tube-to-Hat Weld

Making a gas tungsten arc fillet weld (between tube and hat) on the outside of the cylinder was considered impractical, with no way to add filler metal on that small a weld. Welding in a circular pattern aggravates cracking susceptibility. Likewise, making an annulus weld around a 1/8 inch tube (0.013 inch wall) from inside the cylinder, i.e. inside a 0.432 inch OD cylinder (0.012 inch wall), was deemed impractical, again with no way to add filler metal. What did appear to be possible, was to spot weld the tube-to-hat from the inside by pre-placing a piece of aluminum 4043 or 4047 filler rod in to the tube and fusing everything together (6061, 3003, and 4043) into one weld nugget as suggested in Figure 2. This, of course, requires that the tube hole be reopened by post-weld machining.

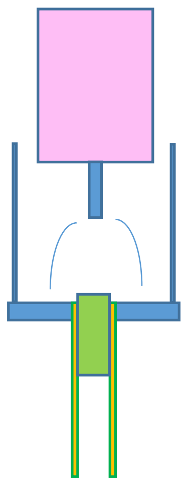


Figure 2: Schematic showing GTA torch and filler metal "plug" placement to make tube-to-hat spot weld.

A photograph of the equipment used to make the spot weld is shown in Figure 3. In Figure 3a, a split-cylinder copper heat sink is held in the jaws of a rotary fixture (no rotation is involved). The outer fission chamber cylinder is located within a slight recess in the copper and the tube to be spot welded extends down into a hole in the heat sink. Tightening the screws serves to hold the assembly in place. A copper ring (to the right in Figure 3a) is placed over the chamber, and the ceramic gas cup of the GTA torch is positioned slightly below the lip of the chamber (Figure 3b). There is a gap between the gas cup and the chamber that allows shielding gas to escape during welding. Figure 3c shows the arc light emitted from an actual weld taking place. Welding parameters are provided in Table I.

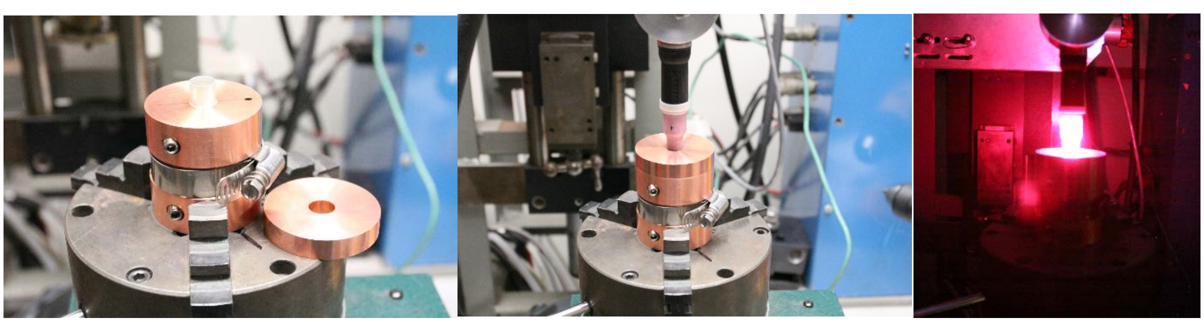


Figure 3: Welding fixture for tube-to-hat GTA weld showing a) chamber, b) assembly, and c) arc light during weld.

Table I: GTA Welding Parameters for Tube-to-Hat Spot Weld

Filler Material	Aluminum 4047 or 4043 Plug
Joint Preparation	Wire Brush + Acetone and Alcohol Wipe
Electrode	1/16th inch Ceriated Tungsten, 45° Tip Angle, No Land
Shielding Gas	High Purity Argon (99.999%), 25 SCFH
Plug Height	0.025 inch above Joint
Power Supply	Lincoln Inverter 205
Polarity	AC, 150 Hz, 85% Electrode Negative
Arc Gap	0.040 inch
Pre-Purge	10 s
Start Current	15 A
Slope Up	1 s
Pulsed Current	
High	135 A (50% on-time)
Low	65 A (50% on-time)
Pulse Rate	5 Hz
Slope Down	1 s
Post Purge	10 s
Total Arc-On Time	9-15 s

Following welding, the spot weld appears as shown in Figure 4 when looking down into the chamber, i.e. weld has a round over-bead. Fine cracks are often observed in the weld center and extensive porosity is observed around the perimeter. This was typical for welds made with 4047 filler rod, believed to contain high hydrogen content. Cross-sectional metallography is given in Figure 5. It is observed that extensive porosity exists in the weld as well as extended regions of cracking, backfilled with eutectic (4047 is an Al-Si eutectic alloy containing 12 wt.% Si). Most of these weld defects will be removed when machining out the tube plug, but there is concern regarding leak tightness. To improve upon this, we extended the arc-on time in order to allow for gas pores to escape the molten pool and to achieve more penetration. Also, use of 4043 instead of 4047 resulted in less porosity.

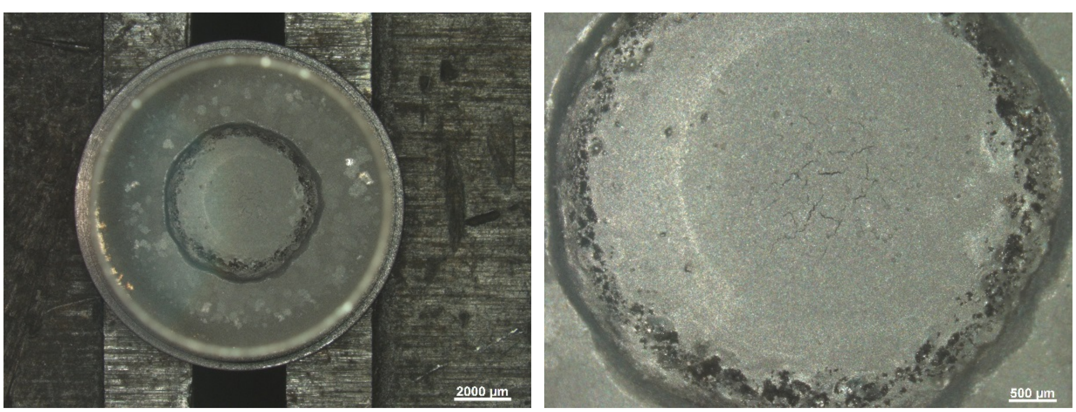


Figure 4: View of GTA spot weld made with 4047 filler plug looking down into chamber with stereo microscope, observed at two different magnifications.

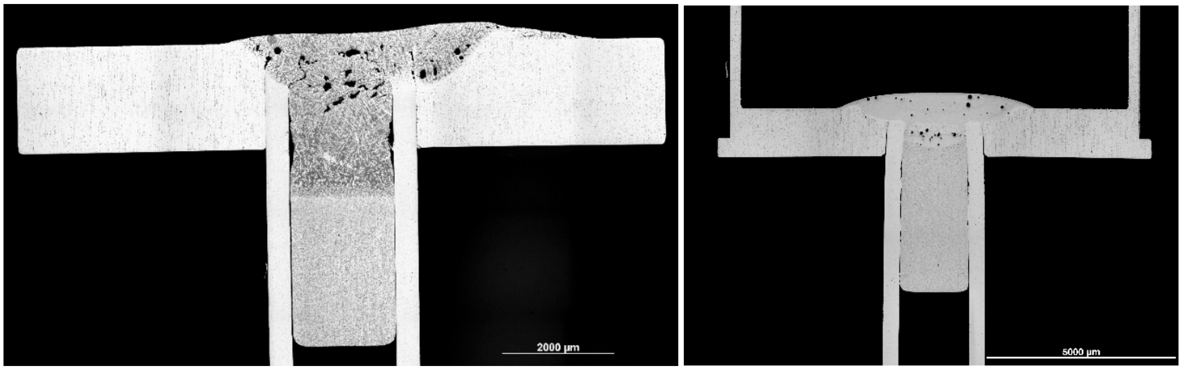


Figure 5: Metallographic cross-section of tube-to-hat spot weld showing a) initial attempt with 9 s arc-on time and 4047, and b) improved performance with 15 s arc-on time and 4043. Observed are molten nugget region with dendritic structure, partially melted plug material, extensive nugget porosity, and cracks back-filled with eutectic.

The set-up shown in Figure 3 was used to make practice welds in order to develop weld parameters given in Table I. Short pieces of tubing were used during this development (approx. 1 inch length). Arc-on time was increased from 9 to 15 s in order to achieve more penetration and a broader nugget. In order to make real parts in preparation for assembly, tubes with 18 inch length had to be used. This required modification of the fixture, using a heavy walled aluminum pipe (18 inch length x 3 inch OD) to extend the copper heat sink above the turn table. When the parameters of Table 1 were applied to the extended fixture, the spot welds were found to run cold (i.e. inadequate penetration) when making these parts. This was obvious from examination of spot size and also from failure of a weld during handling, and appears to be due to better heat sinking of the copper associated with its attachment to the aluminum pipe. To address this shortfall in an expedient manner, the welded assembly parts were re-welded, this time pre-heating the copper fixture to about 250C (measured with thermocouple) with heat applied using a propane torch. Using parameters from Table I, this resulted in a spot size similar to earlier development when viewed from above. No metallography was performed to qualify this new procedure. Helium leak tests were performed on 4 welded parts; 1 passed and 3 failed. One of these welds was later found to fail completely during 100 psi pressurization following assembly and closure weld.

Closure Weld

For the closure weld, the assembly was held in copper heat sinks attached to a rotary fixture. An assembly is shown in Figure 6, where the chamber is held in the copper heat sink on the left, sitting within a recess pocket. The tube extends to the right through a split heat sink (see screws), allowing its removal after welding. Also, there is a split copper sheath placed between the hat and the right heat sink, added to avoid arc-out. With a stationary GTA weld torch, the joint was rotated underneath the tungsten electrode during welding to complete one single weld pass plus a slight overlap. Placement of the electrode was critical to success: positioned slightly to the hat side of the joint. When positioned too close to the chamber wall (as opposed to the chamber hat) the thin chamber wall would melt back. Welding parameters are given in Table II.

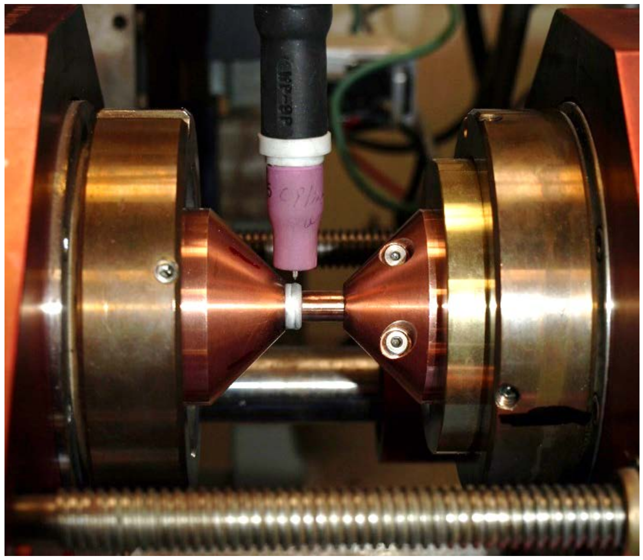
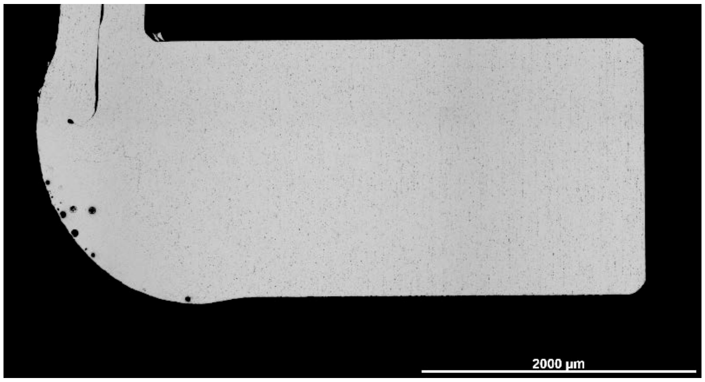


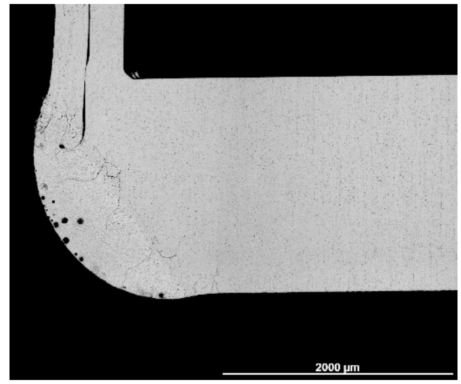
Figure 6: Photograph showing welding fixture used for making GTA closure weld.
The fission chamber is located in the left heat sink and the tube extends to the right.
The torch is held stationary while the part rotates.

Because the torch was positioned to favor the right side of the joint (hat side), it was found that the entire arc tended to jump to the heat sink on the right side (i.e. the split cone). To avoid this, the small diameter split-copper sheath was used to provide distance between the hat and the cone as shown in Figure 6. This still resulted in part of the arc transferring to the sheath.

Table II: GTA Welding Parameters for Closure Weld

Filler Material	None (autogenous weld)
Joint Preparation	Wire Brush + Acetone and Alcohol Wipe
Electrode	1/16th inch Ceriated Tungsten, 60° Tip Angle, No Land
Shielding Gas	High Purity Argon (99.999%), 15 SCFH
Power Supply	Lincoln Inverter 205
Arc Gap	0.020 inch, shifted horizontally 0.025 inch off joint towards tube side
Polarity	AC, 150 Hz, 85% Electrode Negative
Pre-Purge	10 s
Start Current	10 A
Travel Delay	2 s
Upslope	1 s
Pulsed Current	
High	53 A (50% on-time)
Low	10 A (50% on-time)
Pulse Rate	10 Hz
Travel Speed	16.5 s/rev
Down Slope	1 s
Post Purge	10 s
Total Weld Time	19.5 s (includes 1 s overlap)





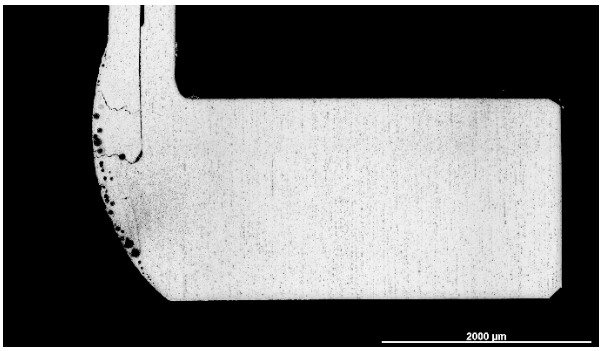


Figure 7: Metallographic cross-sections of a single GTA closure weld showing a) no etch, b) same as “a” but with etch, c) through-thickness crack.

Cross-sectional metallography of a closure weld is provided in Figure 7. A large amount of fine porosity is observed in these welds, collecting along the pool surface. A light etch brings out an elevated level of Si eutectic along grain boundaries (Figure 7b). At some locations along the weld a continuous crack can be found. This reflects upon the poor weldability of alloy 6061 and it is expected that these welds will not be leak tight.

When the time came to make closure welds on 6 actual parts containing radionuclide and electronics, acceptable welds could not be made. Initially we thought that this might be a cleaning issue, as practice parts were cleaned by us, whereas actual parts were cleaned at TA-48. Good cleaning practice involves brushing the joint surface, inside and out, to break up surface oxides, followed by a vigorous acetone wipe to remove residual hydrocarbons. Also, an alcohol swipe immediately prior to welding is often done to remove incidental contamination. On one actual part we brushed the outside joint, followed by an acetone rubdown using a Kimwipe. In this instance, too much acetone was used to wet the Kimwipe, which flowed into the joint and resulted in a blowout during welding.

At this point, the remaining parts were taken back to TA-48 for disassembly and careful cleaning. Just prior to welding the first re-assembled part, the outside of the joint was wire brushed, wiped with alcohol, and left to dry. The weld again was unsuccessful, similar to the initial welds, with the molten pool rolling over (i.e. not wetting both sides of the joint). In essence, cleaning was now ruled out as a source of the problem. We then considered that a charge build-up inside the chamber (associated with coaxial cable) might be deflecting the arc. Recall that the arc location is critical to a successful weld. On the next part, the coaxial cable (running through the tube and connecting to an electrode within the chamber) was grounded to the outside of the tube in order to avoid any electrical charge build-up. The resulting weld was not only unsuccessful, but very abnormal, splitting the weld in two (i.e. two weld beads). This suggests the presence of an internal current loop, generating a magnetic field that interacts with the welding arc, flicking it back and forth.

Weld Strength Calculations

Tube-to-Hat Weld

1. Assume weld failure will occur in shear around the outer diameter of the tube
2. Assume 0.010 inch penetration at the joint
3. Assume that there are no solidification cracks or porosity present
4. Assume yield strength of 4043/6061 weld in tension = 18 ksi (handbook value)
5. Yield strength in shear for 4043/6061 weld = (0.6) tensile yield strength = (0.6)(18 ksi) = 10 ksi
6. Tube area exposed to 100 psi pressure = $\pi D^2/4$ = (3.14)(0.125 in)^2/4 = 0.0123 in^2
7. Shear force = (100 psi)(0.0123 in^2) = 1.23 lbs
8. Shear area = circumference x penetration = (3.14)(0.125 in)(0.010 in) = 0.0039 in^2
9. Shear stress at joint = 1.23 lbs/0.0039 in^2 = 315 psi
   (significantly less than 10,000 psi yield strength in shear: safety factor = 32)

Closure Weld

1. Assume weld will fail in tension across its entire circumferential mid-section
2. Assume 0.010 inch penetration at the joint
3. Assume that there are no solidification cracks or porosity present
4. Yield strength of weld for 4043/6061 = 18 ksi (handbook value)
5. Area of cylinder exposed to 100 psi pressure = (3.14)(0.410 in)^2/4 = 0.132 in^2
6. Tensile force = (100 psi)(0.132 in^2) = 13.2 lbs
7. Load bearing area of weld = circumference x penetration = (3.14)(0.432 in)(0.010 in) = 0.013 in^2
8. Tensile stress at weld = 13.2 lbs/0.013 in^2 = 1,000 psi
   (significantly less than the 18,000 psi tensile yield strength: safety factor = 18)

Recommendations for Future Work

Aluminum Chamber. Ideally, one should use a more weldable alloy such as 5083 for both chamber and tube material. This alloy does not need a filler alloy to prevent cracking. To make the tube-to-hat weld it is suggested that we switch to an electron beam weld (EBW). Welding from the inside, the beam can be deflected to make a circular pattern that follows the tube/hat joint. Some preliminary attempts at this are shown in Figure 8, for both tube-to-hat and closure welds, suggesting that this may be a workable approach. Although, cracking was observed in the closure weld. Electron beam weld parameters are given in Tables III and IV, suggested to us by Dr. Paul Burgardt at LANL.

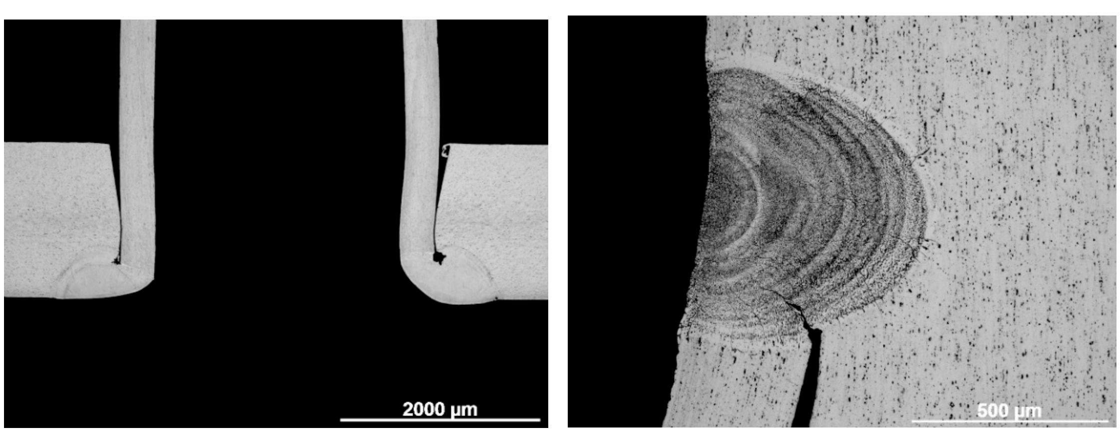


Figure 8: Metallographic cross-sections of a) tube-to-hat weld and b) closure weld made using EBW.

Table III: Electron Beam Welding Parameters for Tube-to-Hat Weld

Work-Gun Distance	12 inches
Filament Current	32.3 A
Acceleration Voltage	100 kV
Focus	Sharp
Circle Frequency	2 Hz (2 rev/weld)
Beam Current	2.5 mA
Travel Speed	2 Hz
Vacuum	5.5×10^{-5} torr

Table IV: Electron Beam Welding Parameters for Closure Weld

Work-Gun Distance	14 inches
Filament Current	32.5 A
Acceleration Voltage	100 kV
Focus	Sharp
Beam Current	2.5 mA
Travel Speed	13 s/rev
Vacuum	1.2×10^{-5} torr

For the closure weld, electron beam is not now recommended due to the internal charge problem (expected to be worse with EB than with GTA). Perhaps arc welding would work better if direct current were used instead of alternating current, using a mixture of argon plus helium shielding gas to adjust heat input. Helium would also be helpful in reducing porosity.9.10. Use of laser welding would be an even better alternative to avoid interference with electric charging altogether. Brazing or soldering the chamber is also a possibility, best achieved by pre-coating the aluminum with copper or zinc, but a problem with residual flux may give problems regarding corrosive attack.

Stainless Steel Chamber. Use of an austenitic stainless steel (e.g. 304L) would make weld development much easier. We could make the tube-to-hat weld from the outside using a commercial tube welder, best achieved using a stub protruding from the hat. Also, sensitivity to burn back would not be as great as with aluminum. However, concern with charge build-up remains a concern if using GTA for the closure weld. Here again, laser welding may provide the best solution.

Electric Charge. Exactly how an electric charge builds within the fission chamber to adversely influence the welding arc is unknown. Perhaps thermionic emission of electrons is at play, or the leaking of current through the insulator. Also, the AC current may be inducing current flow within the coaxial cable. Never the less, there is strong evidence that an effect does exist. This points to laser as an attractive alternative to GTA or EB welding for the closure weld.

Acknowledgements

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