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Title: Formed HIP Can Processing

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Formed HIP Can Processing

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Revision 1

Overview

The intent of this report is to document a procedure used at LANL for HIP bonding aluminum cladding to U-10Mo fuel foils using a formed HIP can for the Domestic Reactor Conversion program in the NNSA Office of Material, Management and Minimization, and provide some details that may not have been published elsewhere. The HIP process is based on the procedures that have been used to develop the formed HIP can process, including the baseline process developed at Idaho National Laboratory (INL). The HIP bonding cladding process development is summarized in the listed references [1-18]. Further iterations with Babcock & Wilcox (B&W) to refine the process to meet production and facility requirements is expected.

Materials

- Formed HIP can (mild steel) – design TBD (Version 1, 2, or 3): most likely V3. To date, these have been produced by Experi-Metal, Inc., Detroit, MI from mild steel sheet that is nominally 0.050 inches thick.
- HIP can lid (mild steel) – to match HIP can design. Simply sectioned (shearing) from mild steel sheet that is nominally 0.050 inches thick..
- Evacuation tube (stainless steel) – 0.25" – 0.125" adapter, 0.125" tube, Swagelok fitting. This diameter was chosen based on a readily available tube crimping device at LANL. The evacuation tube can be larger.
- Strongbacks (stainless steel) – thickness dependent on can filling requirements. Water-jet sectioned from stainless steel plate. Bottom strongback has machined contour to match bottom of can.
- Aluminum sheet (6061-T651) – thickness dependent on fuel plates being HIPed. Water-jet sectioned from aluminum sheet.
- LEU-10Mo fuel foils – size dependent on fuel plates being HIPed.
- MoS_2 aerosol spray parting agent. (note: other parting agents, such as Neolube No. 1 and No. 2, in either aerosol or liquid form, may be used, with consideration of modified bakeout procedure [18])
- Equipment
  - Personal protective equipment
    - Nitrile gloves
    - Safety glasses
  - Cleaning facilities [16]
  - Staging area for cleaned parts.
  - UHV aluminum foil.
  - Masking tape.

- Brown paper roll.
- Fume hood for applying aerosol parting agent.
- Clean surface (we use a roll of paper) in fume hood for drying parting agent on strongbacks and can.
- TIG welder *in argon glovebox* or electron-beam welder.
- Evacuation tube rotary welder.
- TIG welder for evacuation tube-to-can lid weld.
- Bakeout furnace, vacuum pump.
- Crimp welder and TIG welder to seal evacuation tube.
- HIP, HIP furniture.
- Bandsaw.
- Inspection equipment
    - Calipers
    - Deep-throat micrometer

<u>Processing Steps</u>

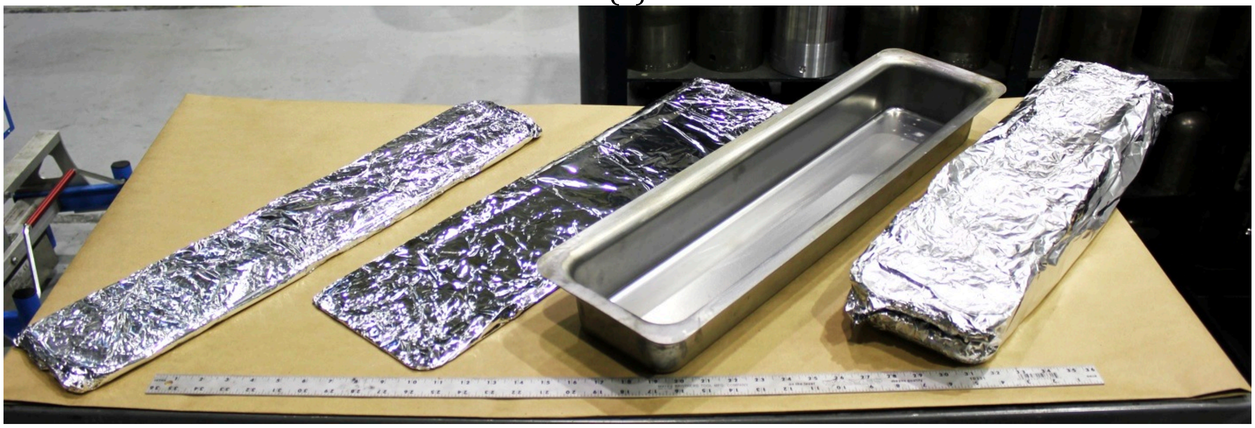
1. Component cleaning
2. Can assembly
    - Apply parting agent to strongbacks and interior surfaces of formed HIP can
    - Air- or furnace-dry strongbacks and can
    - Assemble stackup
3. Electron-beam weld or TIG weld lid to can
4. Bakeout
    - Attach evacuation tube
    - Evacuate
    - Bakeout
    - Crimp weld
5. HIP cycle
    - Load HIP
    - Pressure and thermal cycle
    - Unload HIP
6. De-can
    - Cut open can
    - Stackup disassembly
7. Cleaning/inspection and pass plates to sizing/machining

1. Component Cleaning

Cleaning procedures for each of the six material types (stainless/tool steel, carbon steel, U-10%Mo, Zr foil, Zr-clad U-10%Mo foil, and 6061-T651 aluminum sheet), are detailed in R.L. Edwards et al. [16]. Although no rigorous experiments have been performed to determine the maximum time after cleaning that HIP can assembly and seal-welding should be performed, times have ranged from < 1 hour to 24 hours for assembly, and 24 hours to several days for seal welding, with no obvious change in fuel plate bonding. Figure 1 shows HIP can parts as-received from cleaning. Note that the components are wrapped in UHV

(Ultra High Vacuum) aluminum foil to prevent surface contamination between cleaning step and assembly step.

(a)



(b)

Figure 1. From left to right, 6061 aluminum sheets, formed HIP can lid, formed HIP can version1, and stainless steel strongbacks, as-received from cleaning.

2. Can Assembly

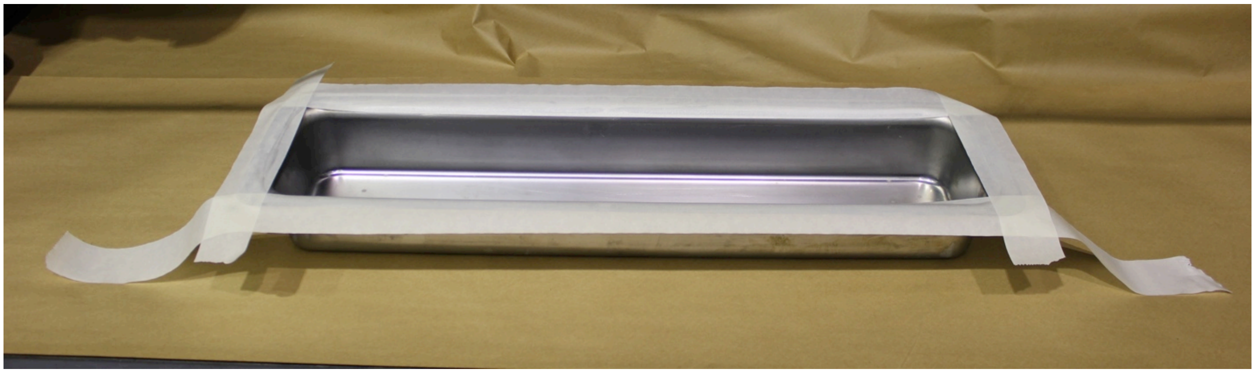
The inside of the formed HIP can is sprayed with parting agent after applying masking tape to cover the can flange surfaces that will subsequently be welded. Strongbacks are sprayed with parting agent on one side, allowed to dry, turned over, and sprayed on the opposite side.

During development experiments, the MoS_2 parting agent has been applied by manual spraying using an aerosol spray can. The manual nature of the spraying process results in variability in the amount of parting agent applied to each component, but becomes more repeatable with operator experience – a more automated process may be desirable.

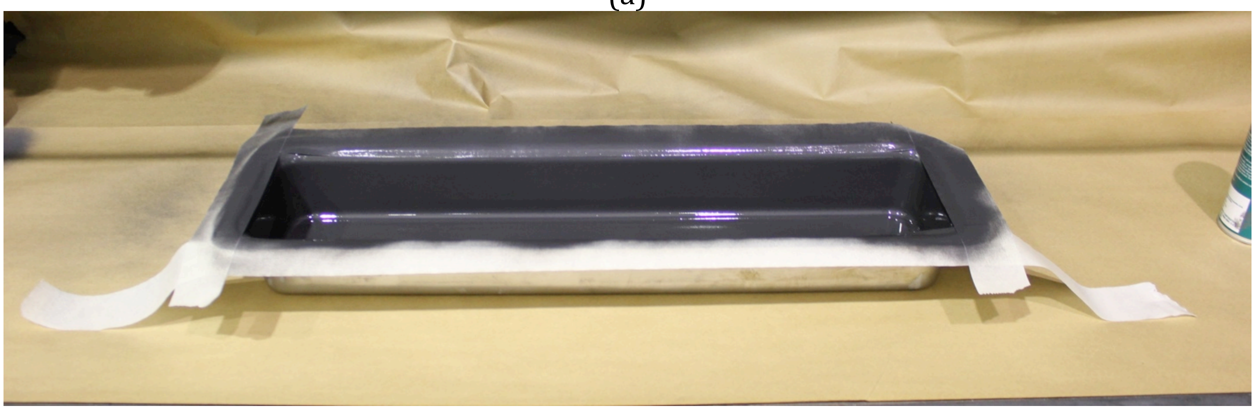
Generally, visual inspection of the plates is used to determine if an appropriate amount of parting agent has been applied. The objective is full coverage of the strongbacks and inside of the formed can, again determined visually.

Experiments to date have been performed after drying in ambient air, although air furnace drying above the parting agent outgassing temperature [18] may be worthwhile. The ambient drying of the parting agent is largely determined by visual inspection, and takes between 30 and 60 minutes, depending on ambient conditions and the amount sprayed.

The images in Figure 2 show a representative Version 1 can during parting agent application and assembly. Cleaned components are received from cleaning wrapped in UHV aluminum foil. Nitrile gloves are used to handle the components during assembly. UHV aluminum foil is used to wrap the can (with lid) after assembly while waiting for seal welding (electron-beam or TIG).



(a)



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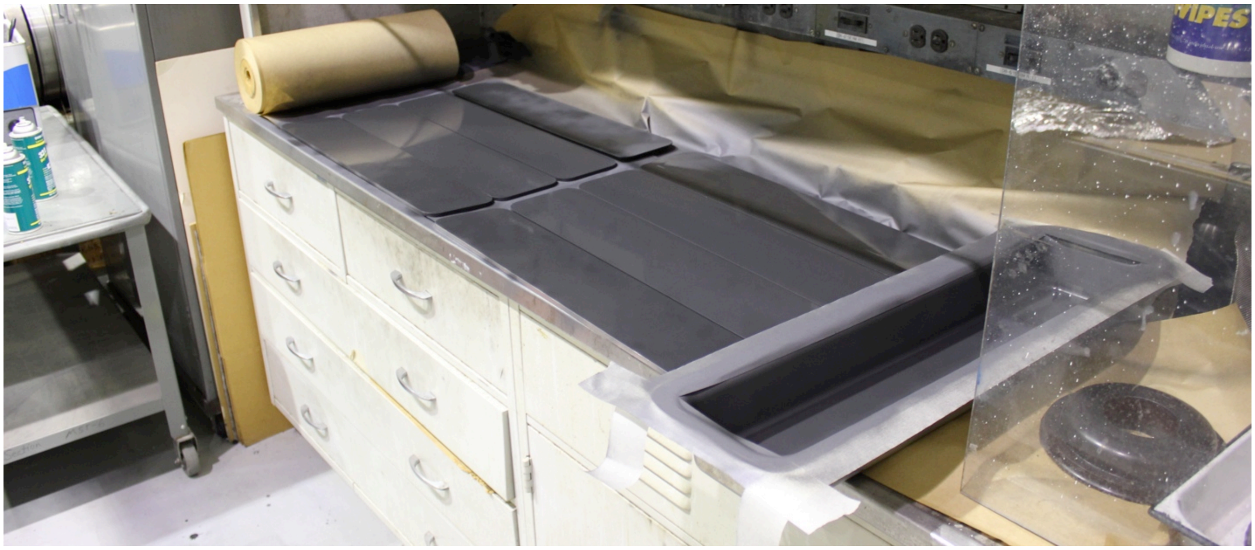

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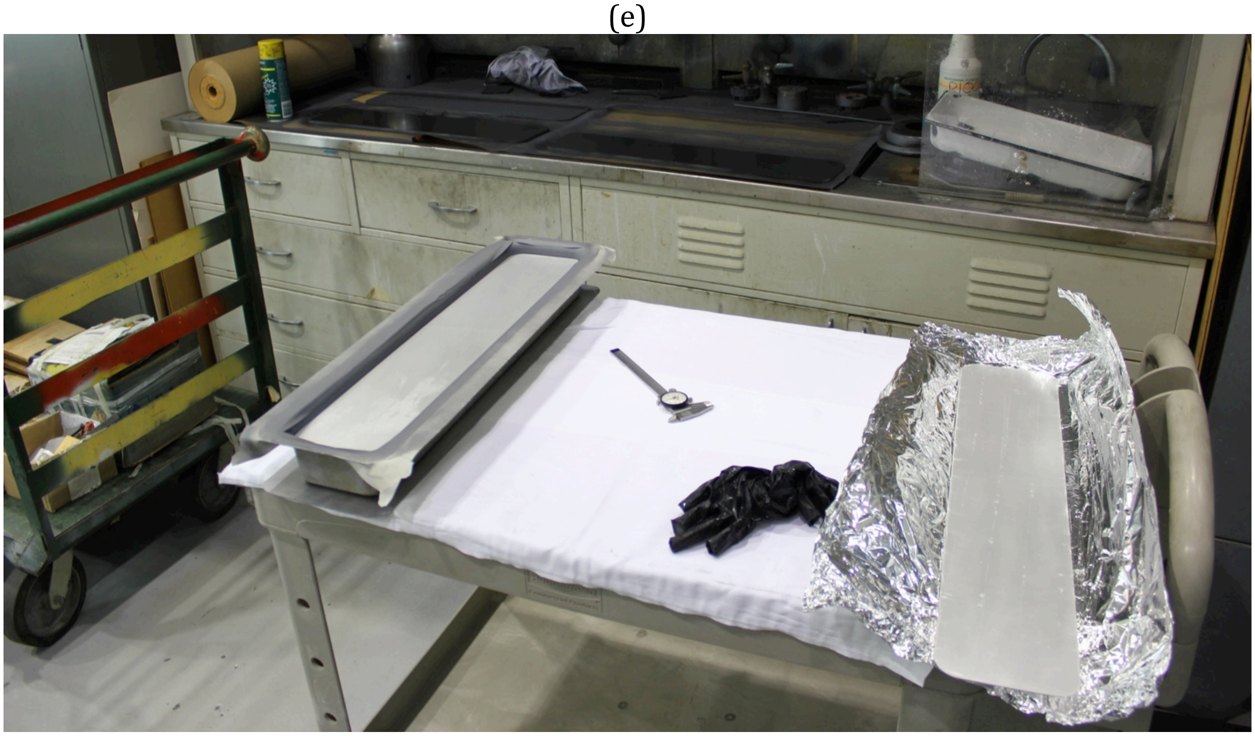


(f)

(g)

Figure 2. Images of a large formed HIP can during parting agent application and stackup assembly. (a-d) Application of parting agent, and (e-g) stackup assembly.

3. Electron-beam or TIG weld lid to can

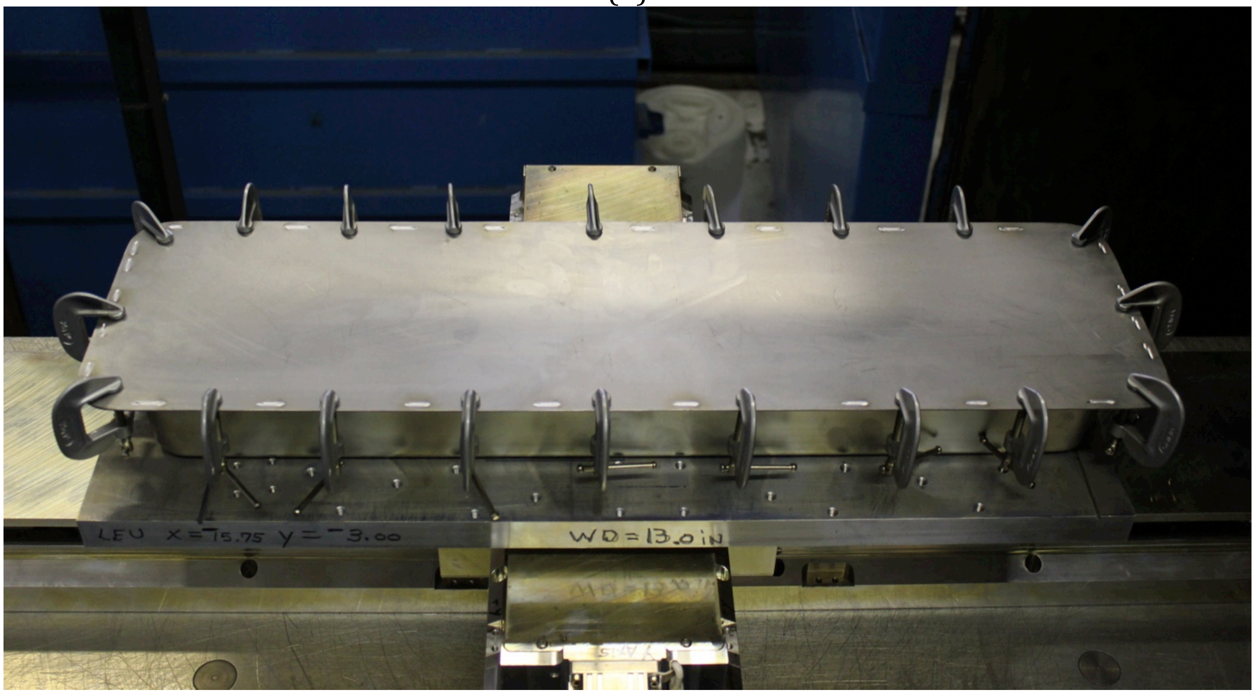
To date, all formed HIP cans have been electron-beam welded to seal for HIPing. However, there is no reason why TIG welding could not be used to seal formed HIP cans, and this viability has been shown on small-scale HIP cans [11].

Figure 3 shows a can being sealed by electron-beam welding. The electron-beam welding is performed in two steps. First, the lid is clamped to the formed can to ensure intimate contact between the lid and the HIP can flange. The lid is then stitch-welded between the clamps in the evacuated electron-beam welding chamber. Note that the lid of the can is depressed outside the chamber after stitch welding due vacuum remaining in the can, suggesting the stitch welds seal the can to some degree. Second, the vacuum chamber is opened, clamps are removed, the can is again placed in the evacuate electron-beam welding chamber, and the full circumference of the HIP can is welded to hermetically seal the can. The full circumference weld is run over the locations of the previous stitch welds. The parameters used at LANL (likely applicable only to LANL electron-beam welding equipment) are as follows:

Working Distance: 15.0 inches
Beam voltage: 110 KV
Beam current: 15.5 mA
Travel: 18 mm/s (0.7 in/s)
Sharp focus

(a)

(b)



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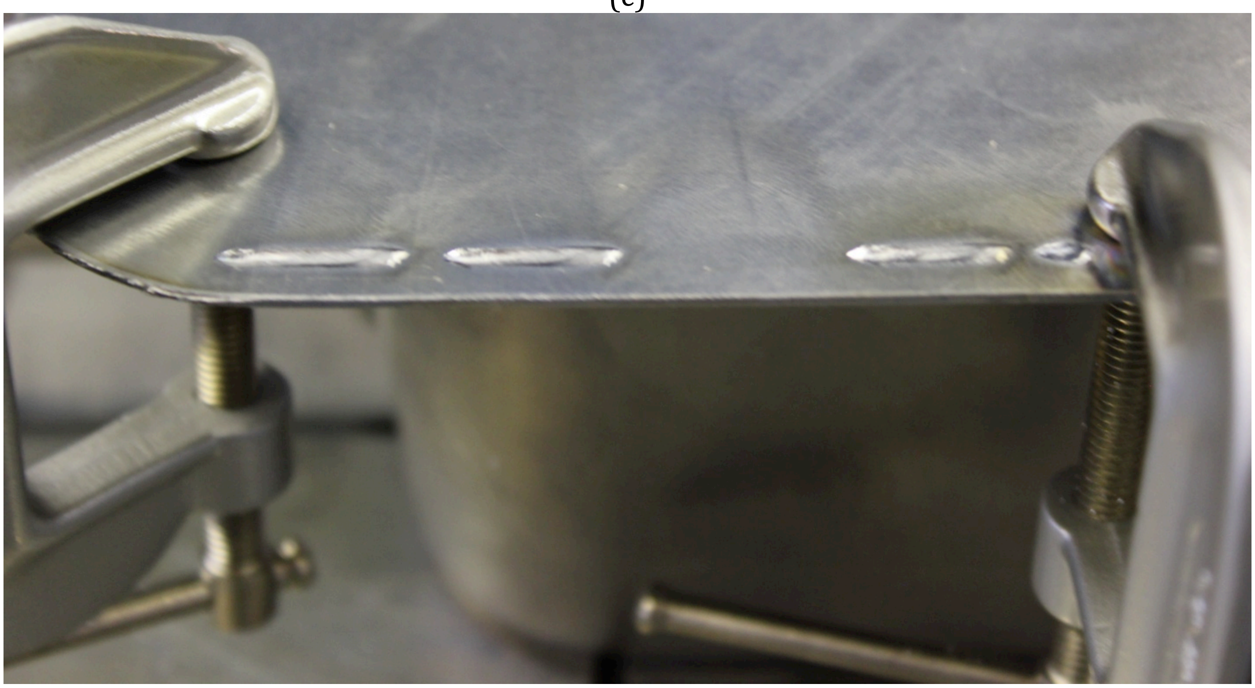

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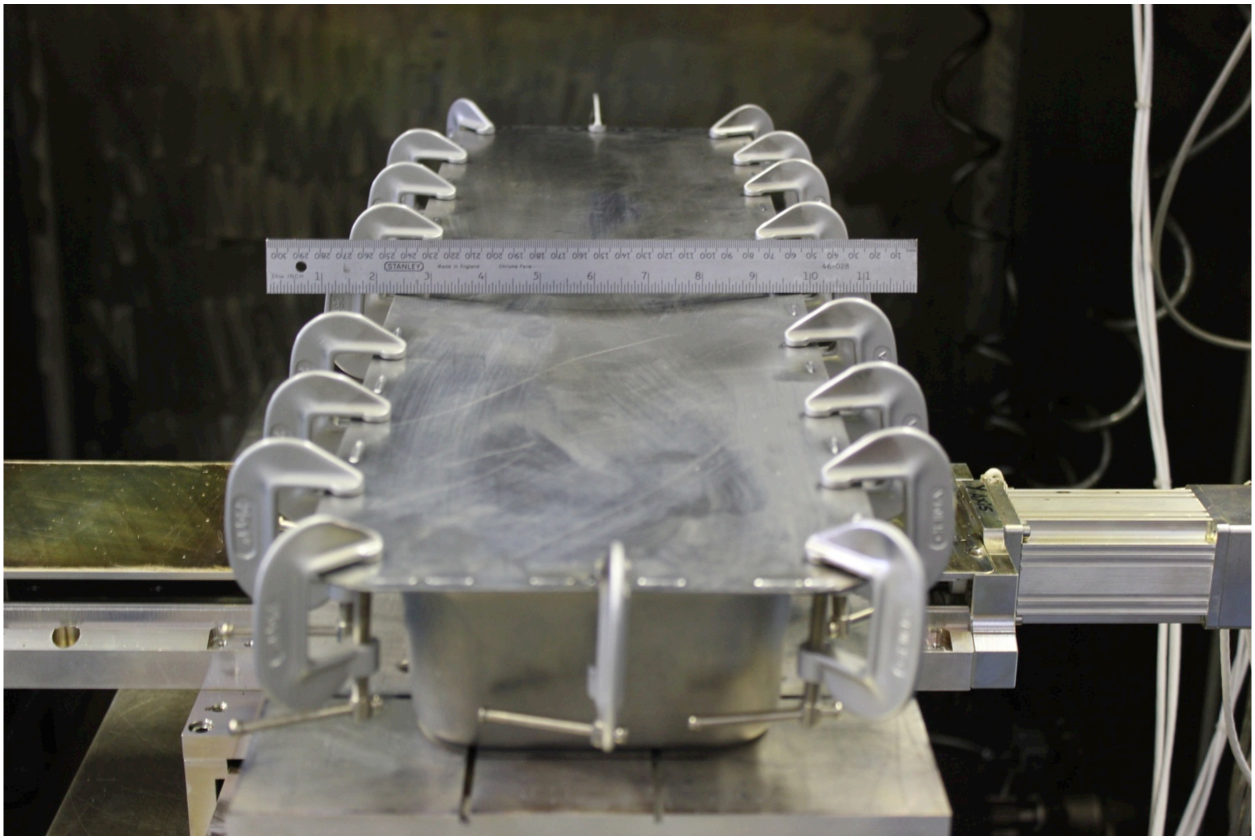

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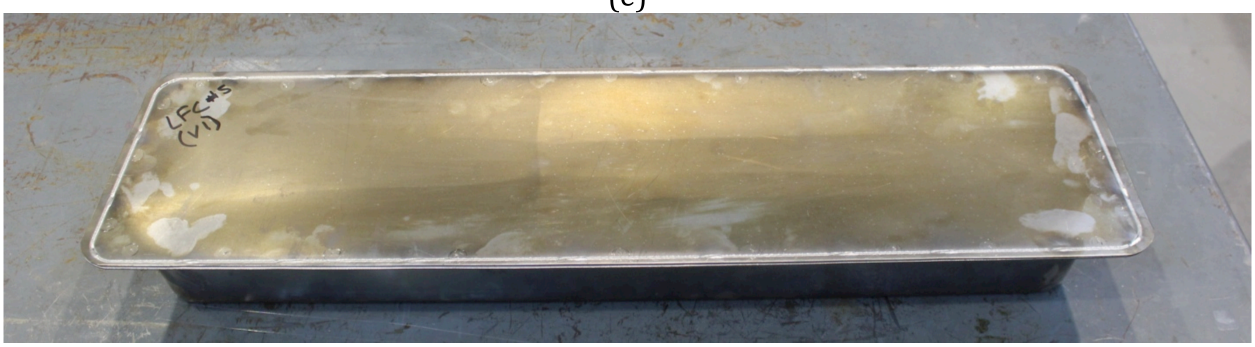

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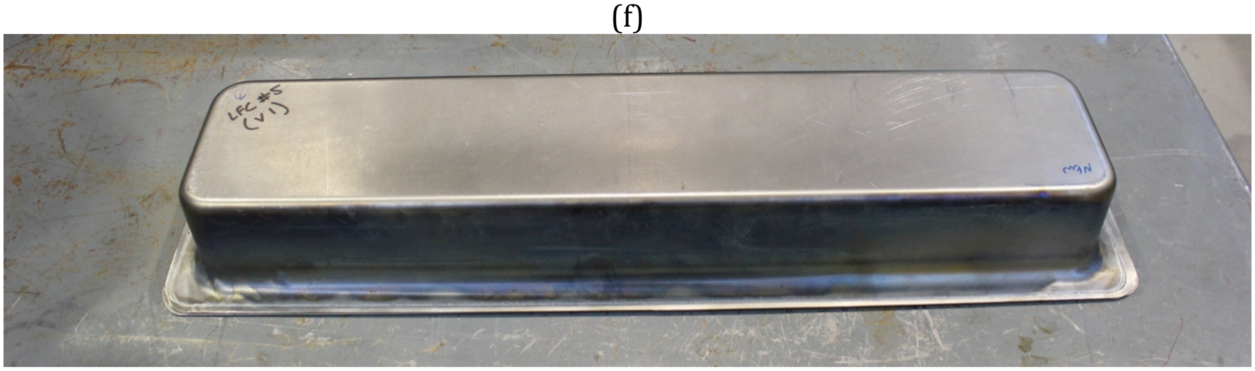

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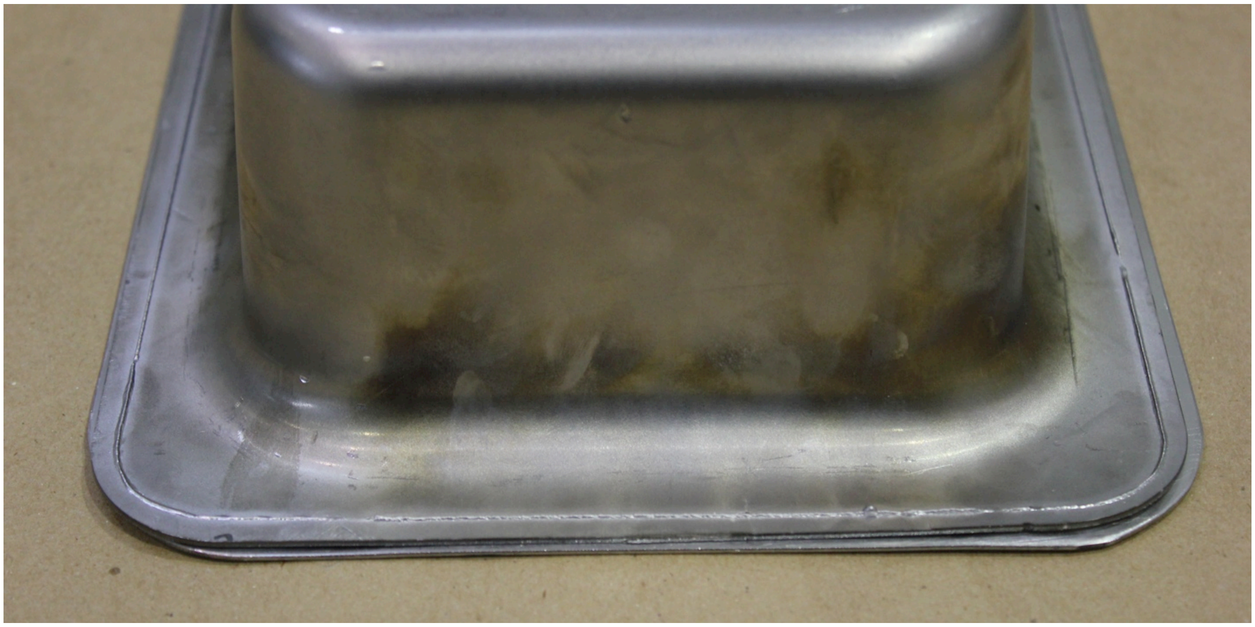

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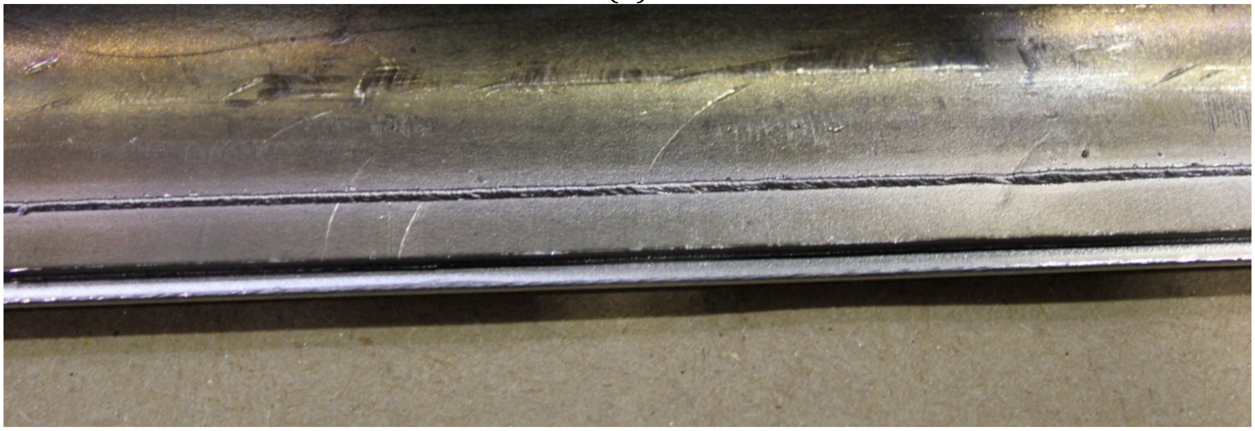


(i)

(j)

(k)

Figure 3. Images of formed HIP cans throughout the sealing process (here by electron-beam welding). (a-e) Examples of clamping and stitch-welding. (f-k) Images of the weld face and root for successful welds (i.e., welds that survived HIPing).

4. Attach Evacuation Tube, Evacuate, and Bakeout HIP cans

The bakeout configuration and procedure used at LANL is detailed below, and in-process images are shown in Figure 4. The bakeout temperature and time are dependent on the parting agent used. Details of thermo-gravimetric analysis (TGA) for several parting agents are presented in [18]. The evacuation tube can be welded on before or after electron-beam welding of the lid onto the can (step 3, above). Past practice has been to drill the hole and weld on the evacuation tube after electron-beam welding, but it may be more production-efficient to perform this task before the lid attachment, assuming the tube and valve assembly does not interfere with electron-beam (or other welding process) sealing of the can.

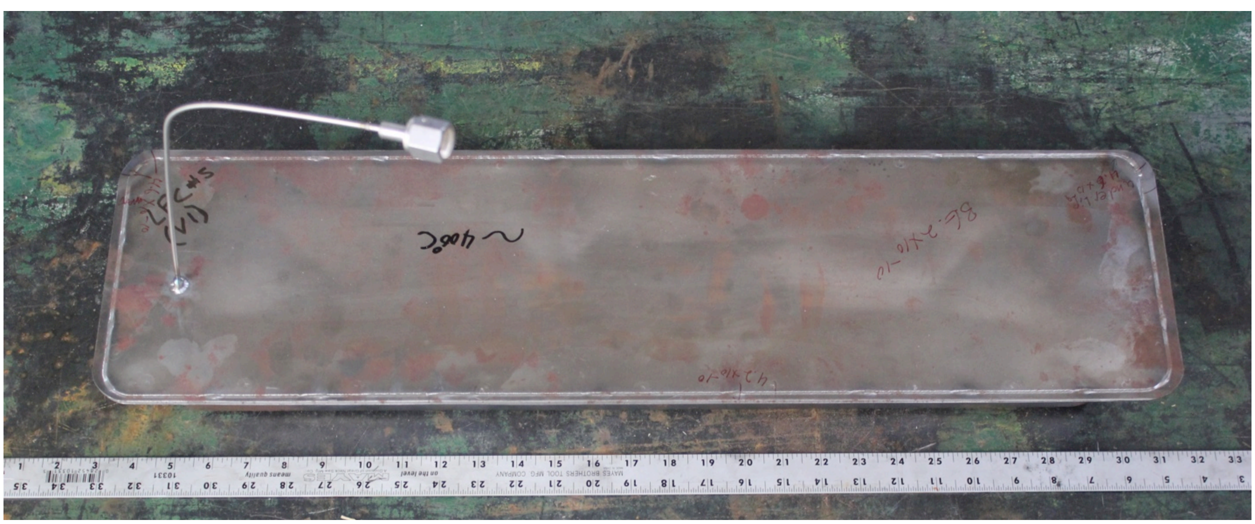
<u>Configuration of weld on vacuum tube:</u>
1/4" to 1/8" weld on fitting· Swagelok 6LV-4MW-6-2.
Weld to 1/8 x 36" SS tube
Female "B" nut - Swagelok WW-4-HVCR-ISR
Weld on VCR Fitting- Swagelok 6LV-4NCR-3-2TB7
B-nut connects to vacuum valve- Swagelok SS-4H-VCR (check valve flow direction)
Valve connects to vacuum transducer at mechanical vacuum pump.

<u>Bake Out Process</u>
1. Place HIP can in furnace and tape thermocouple to HIP can with aluminum tape. If HIP can materials are radioactive follow LANL procedures to move to the oven and before moving HIP from the oven.
2. Pass SS flex vacuum tube through side of furnace and pack hole with insulating materials.

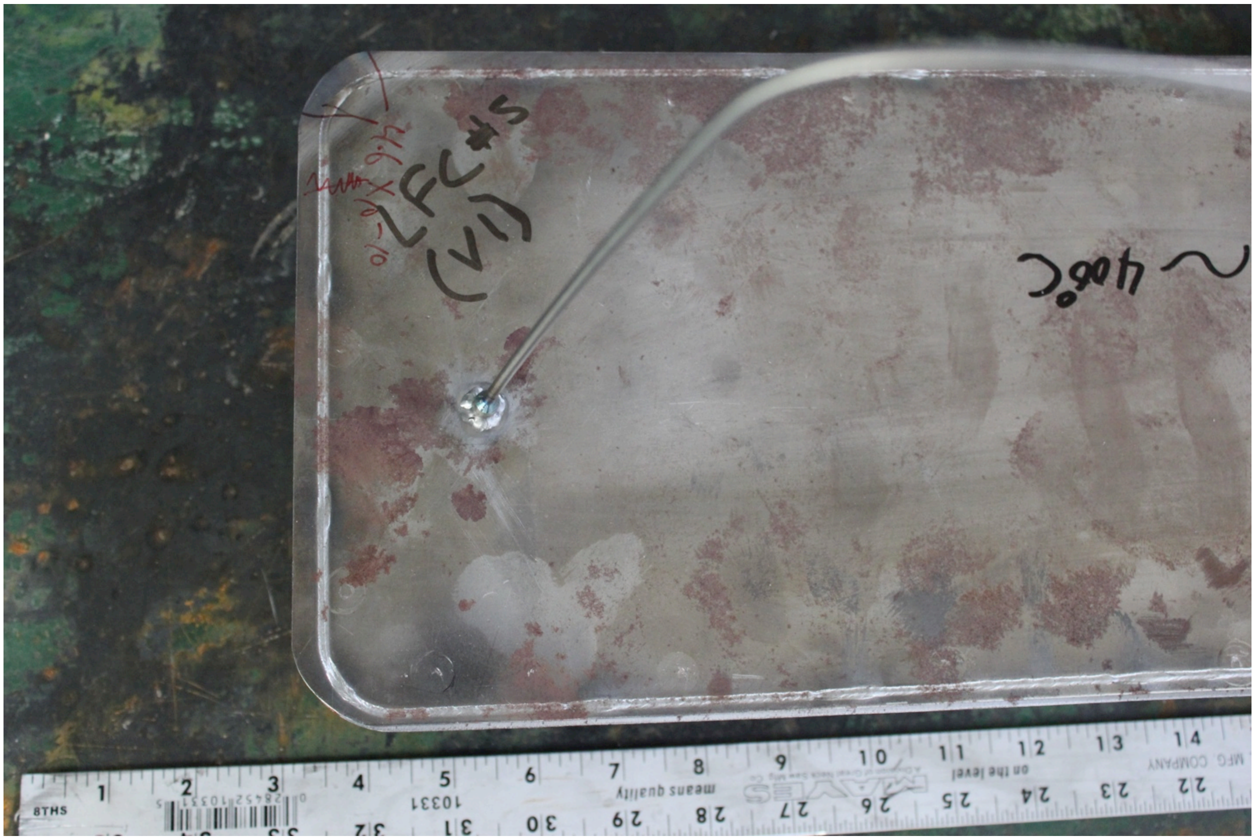
3. Connect vacuum valve to vacuum transducer at pump.
4. Start up vacuum pump. Should pump down to 100 micron or better, (this typically takes 30-60 minutes). If not, look for leaks or vacuum pump seal and rebuild.
5. Ensure that inlet and outlet vents are open on furnace.
6. Power up furnace, allow controller to boot, then set to bakeout temperature (dependent on parting agent).
7. Place placards and tapes for unattended operation and allow to bakeout for the applicable duration.
8. Keep a written log of ramp-up times and temperatures until oven reaches bakeout temperature.

Shutdown
9. Set furnace temp to room temperature and allow to ramp back down to room temp.
10. Close vacuum valve after can has cooled to room temp.
11. Disconnect HIP can from vacuum pump leaving the closed valve with the HIP can.
12. Remove from furnace.
13. Power off furnace.

After bakeout, the valve is closed to maintain vacuum within the can, and the 1/8" diameter stainless steel tube is crimp-welded to remove the valve and shorten the evacuation tube. The crimp-weld has successfully survived the HIP process, but some LANL welders prefer to TIG weld the end of the crimp-welded evacuation tube for additional robustness. Care should be taken when bending the evacuation tube to prevent damage and loss of vacuum within the can. The can is now ready for HIPing.



(a)



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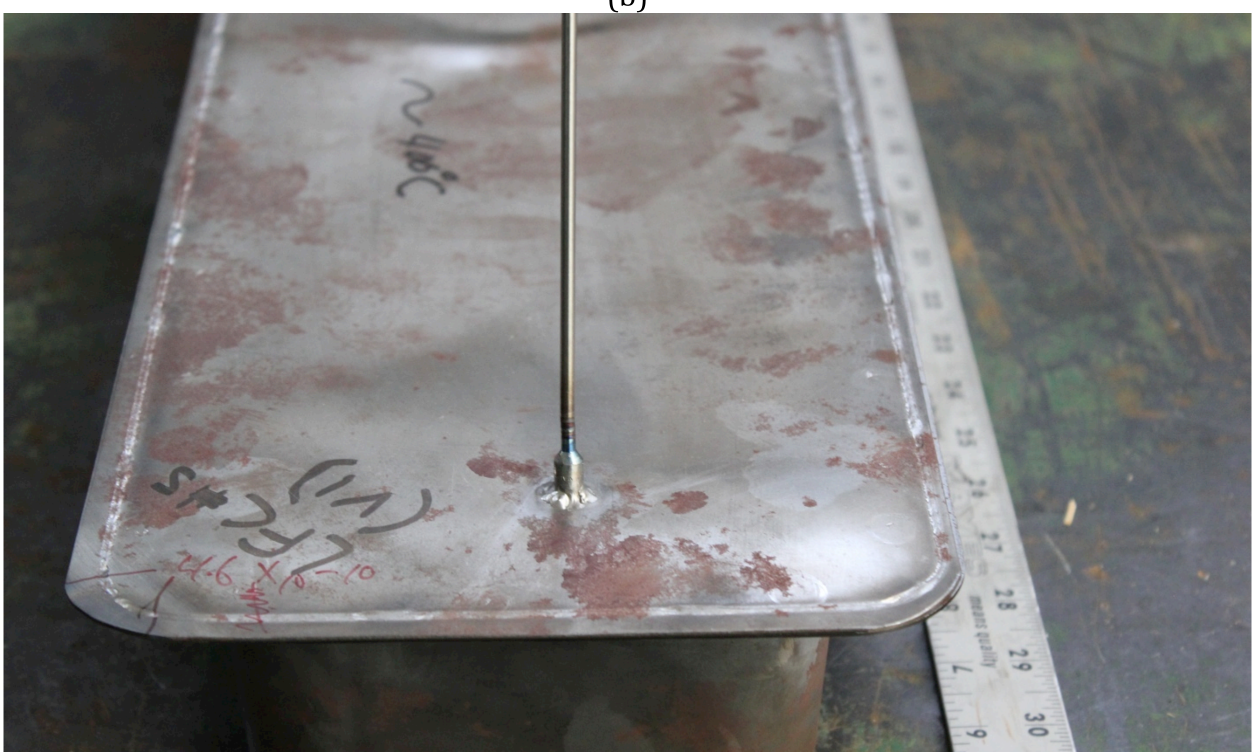

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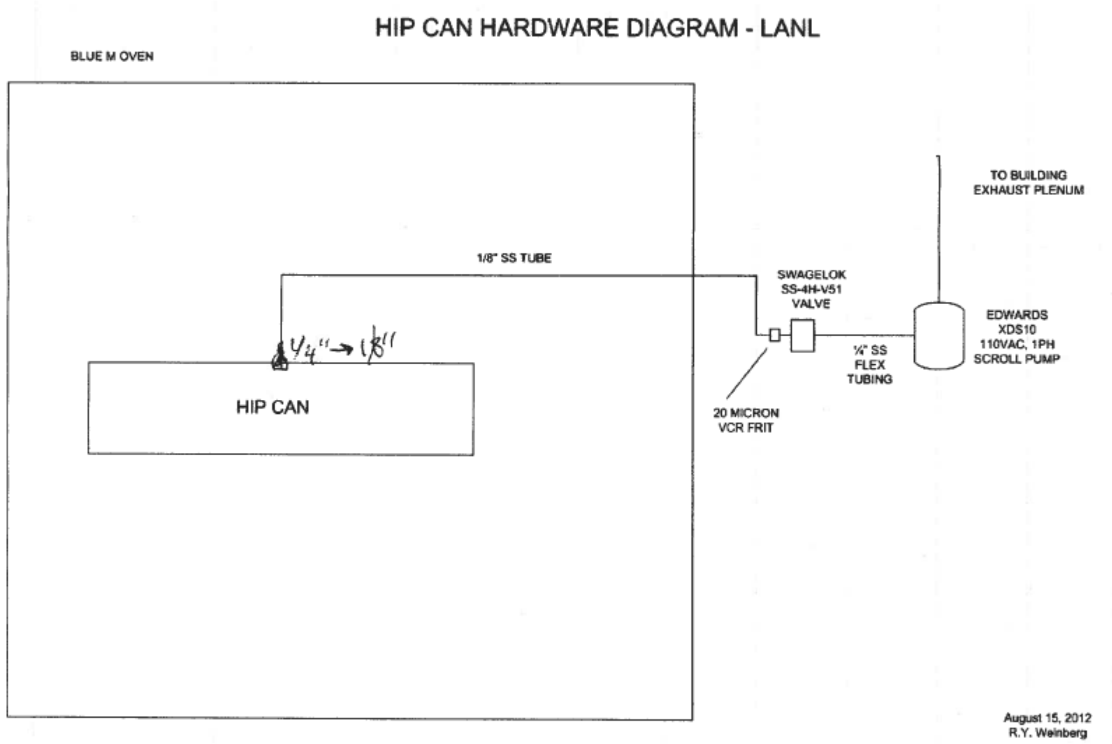

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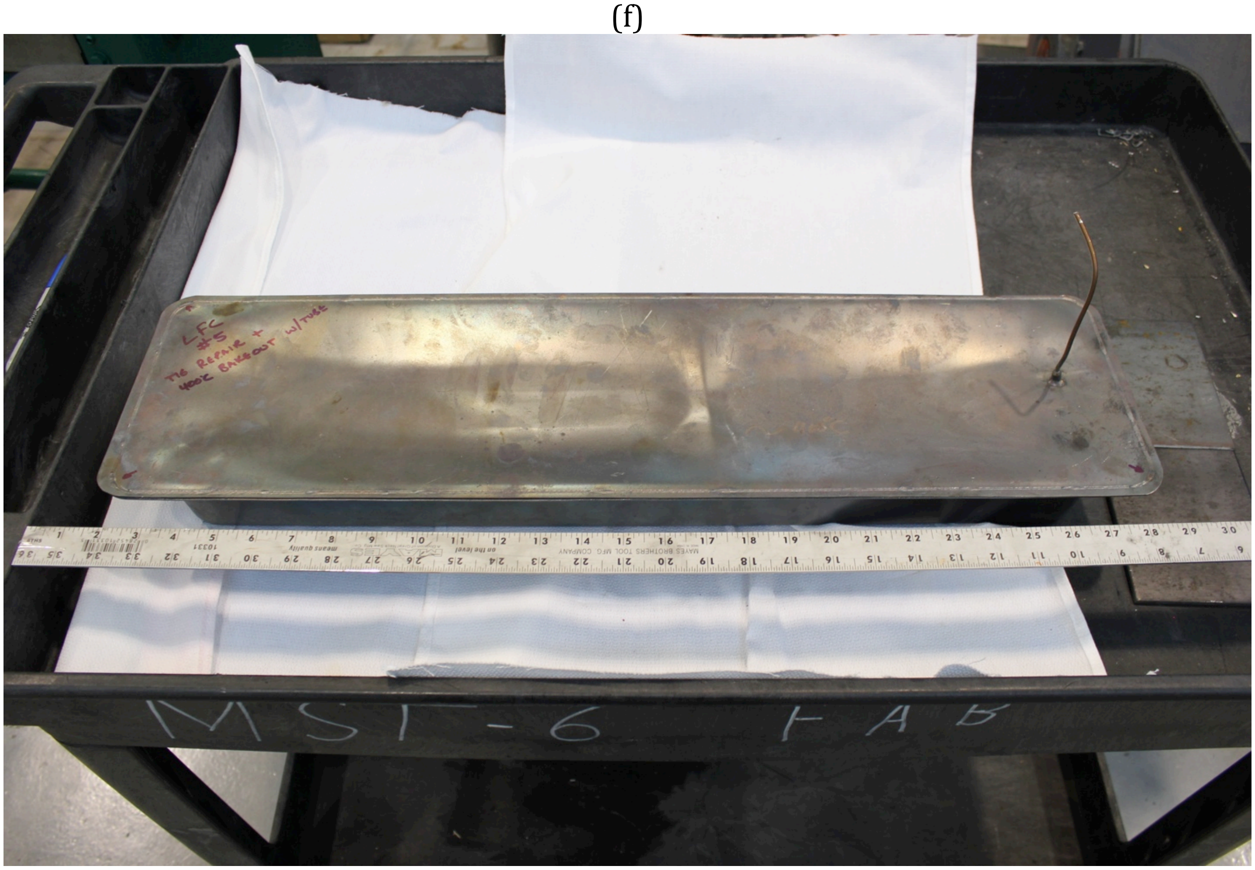


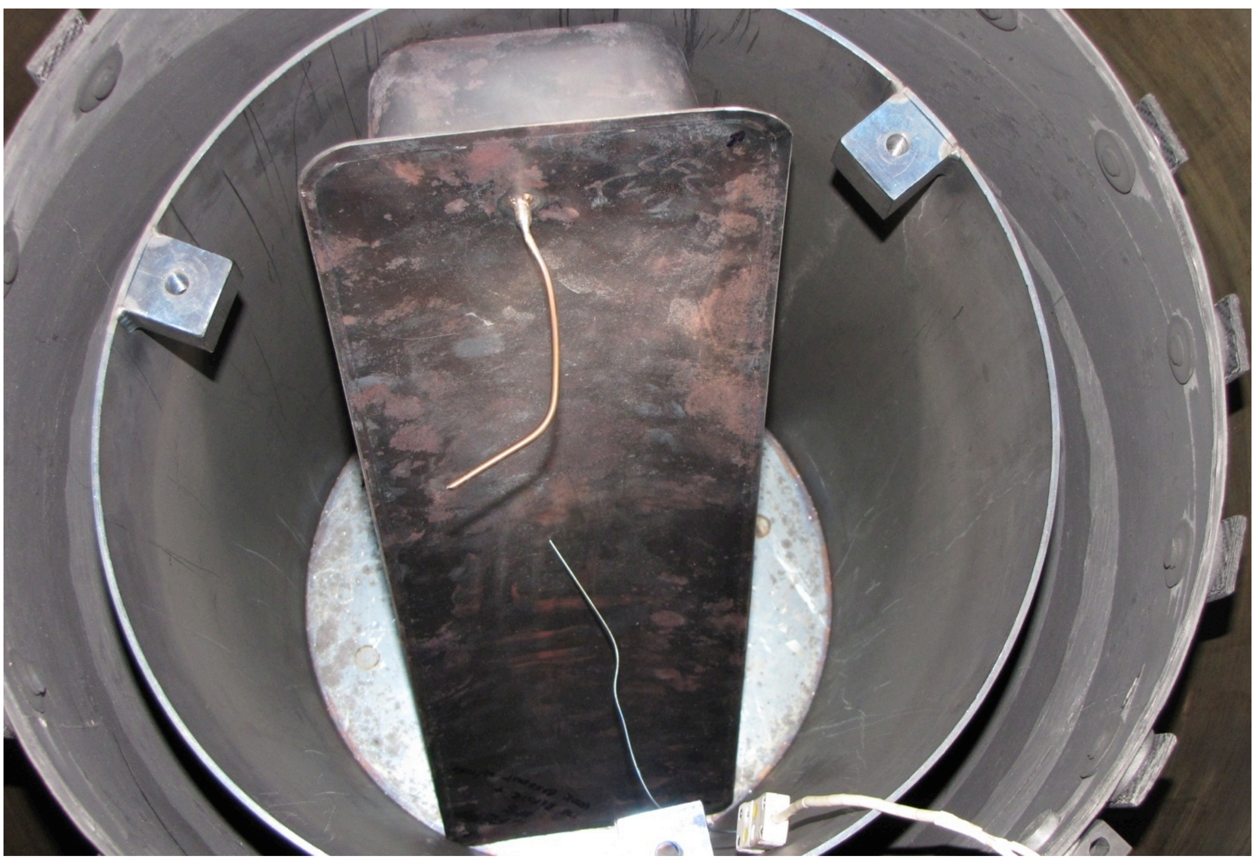
(g)

Figure 4. Images of large formed HIP can with evacuation tube attached to lid (a-c), the furnace and vacuum pump used for bakeout (d, e), a schematic diagram of the

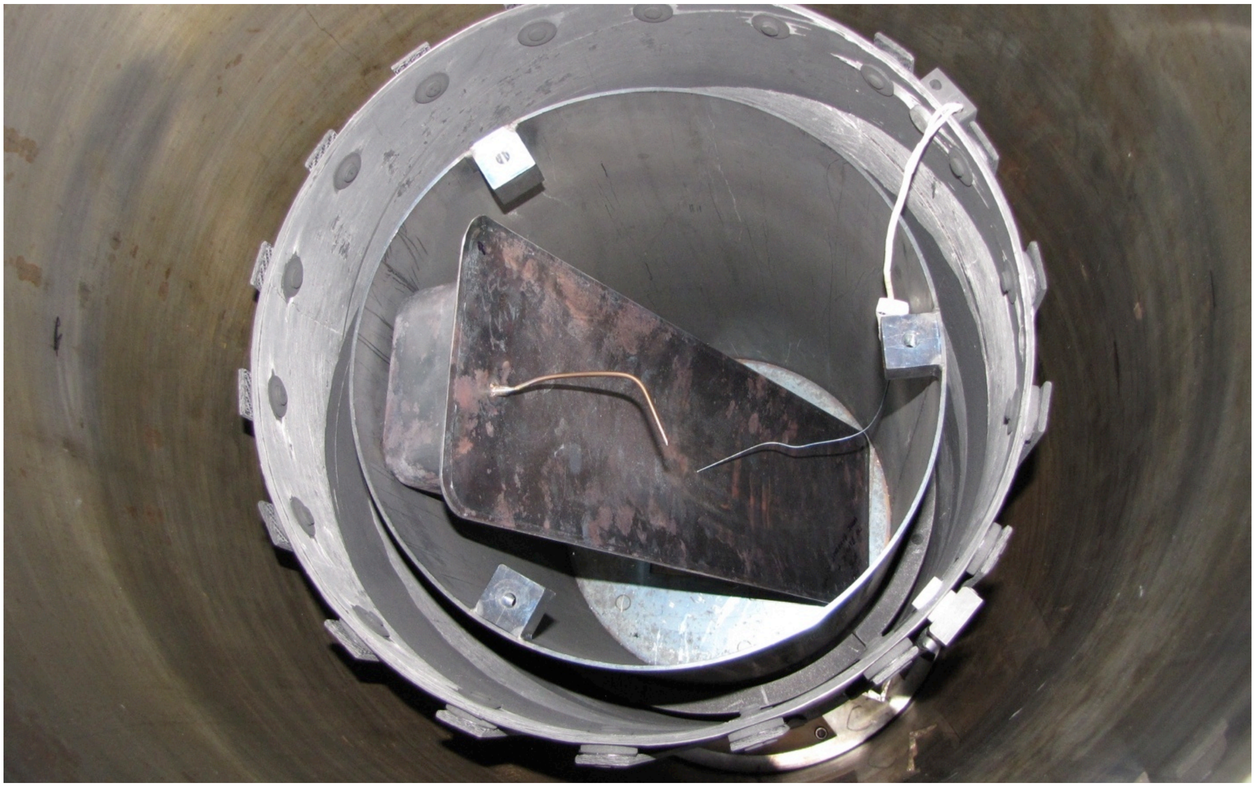
configuration of the HIP can during the bakeout (f), and a HIP can after bakeout and evacuation tube crimp-welding.

5. HIP Cycle

Figure 5 shows images of the can before and after the HIP cycle. The can is placed into a stainless steel loading bucket that can be easily loaded into the HIP. A thermocouple is placed so it touches the lid of the can (Fig. 5a and 5b). The HIP is controlled using different thermocouples, but the thermocouples attached to the can allow for direct measurement of temperature at the can surface, without relying on the control values. The standard HIP cycle is to hold for 90 minutes and 104 MPa (15 ksi) at 560°C. The heat-up/pressurize and cool-down/depressurize times are significantly dependent on individual HIP equipment. For the LANL HIP used for these experiments heating and cooling take nominally 3 hours each. Figures 5c and 5d present temperature and pressure vs. time plots for numerous HIP cycles performed at LANL, showing the variability in the experimental cycles run to date, with heating times down to 2 hours and cooling times to 100°C of as little as 1.5 hours. After HIP, the can has substantially collapsed onto the internal stackup, as shown for a successful HIP run in Figures 5e through 5h.



(a)



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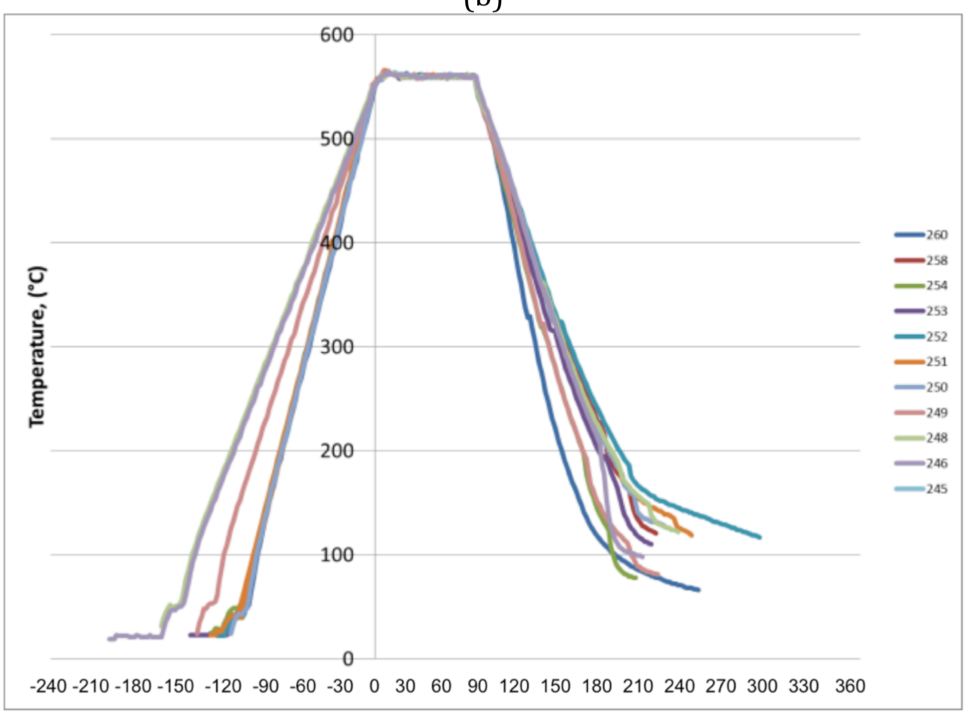
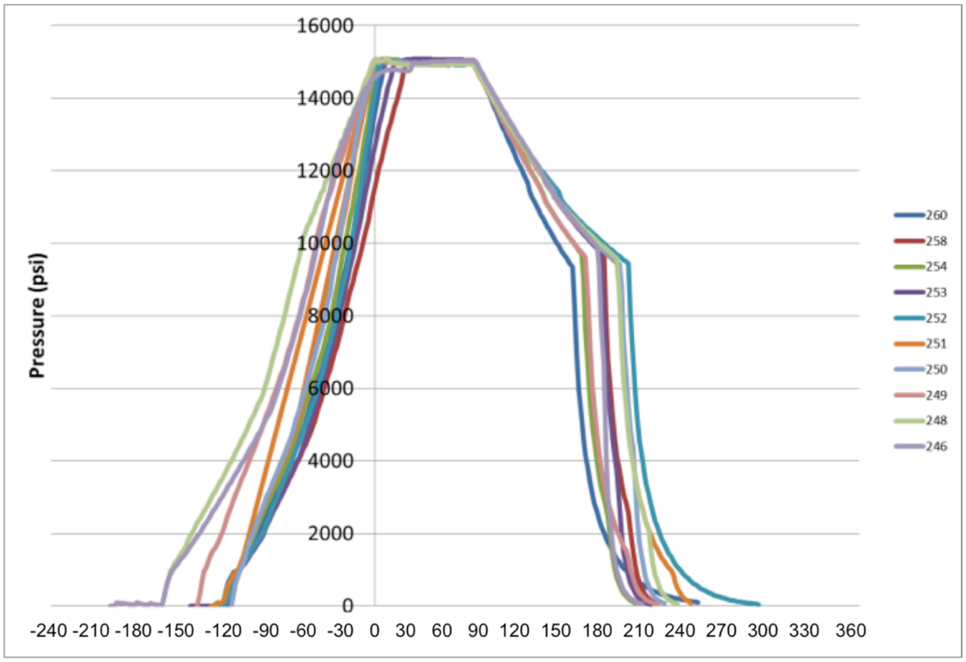


Temperature, (°C)
600
500
400
300
200
100
0
-240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300 330 360
260
258
254
253
252
251
250
249
248
246
245

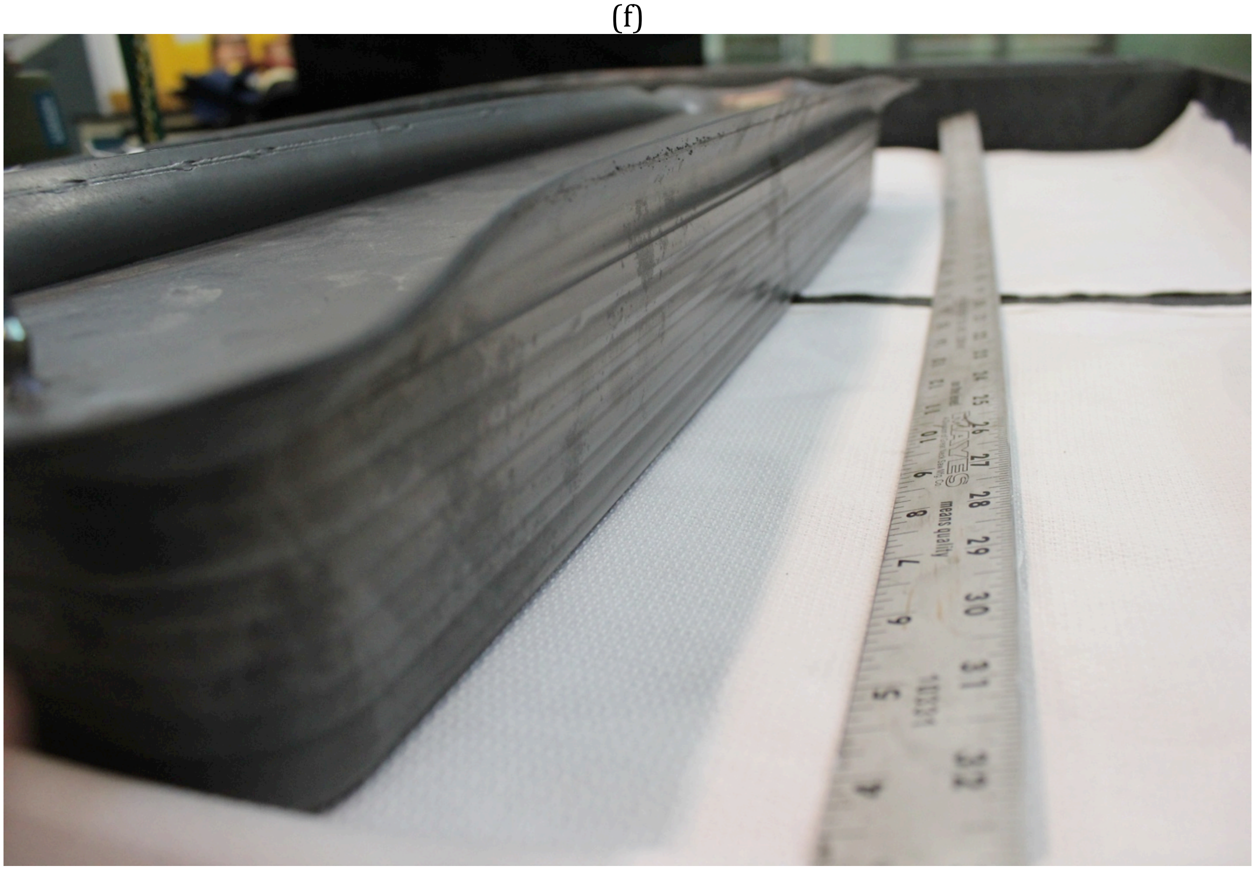
(c)


Pressure (psi)
16000
14000
12000
10000
8000
6000
4000
2000
0
-240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300 330 360
260
258
254
253
252
251
250
249
248
246

(d)

(e)

(f)



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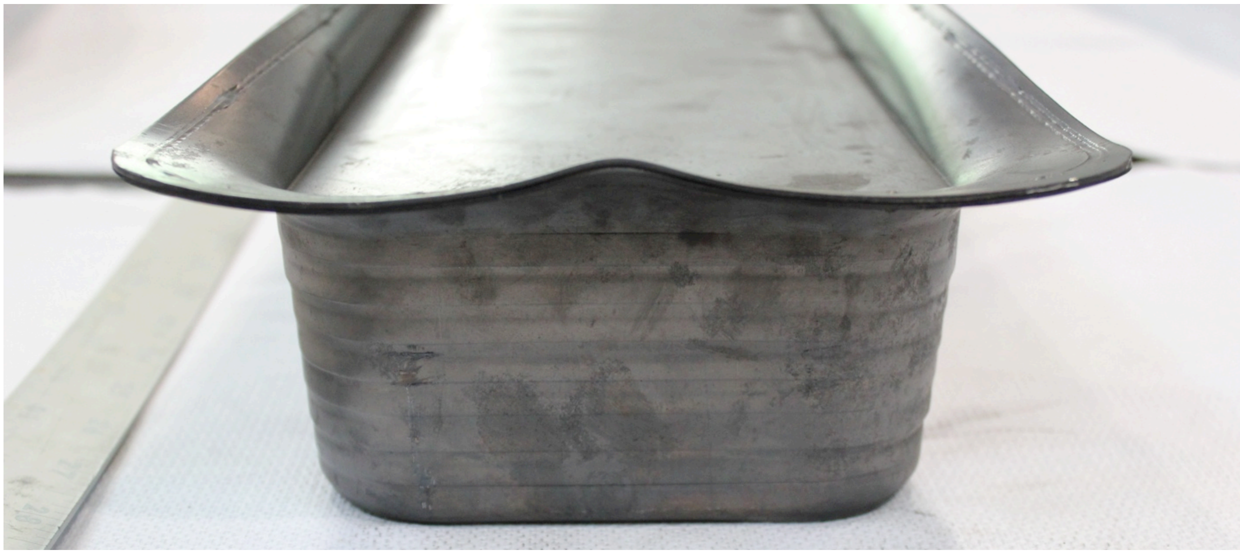
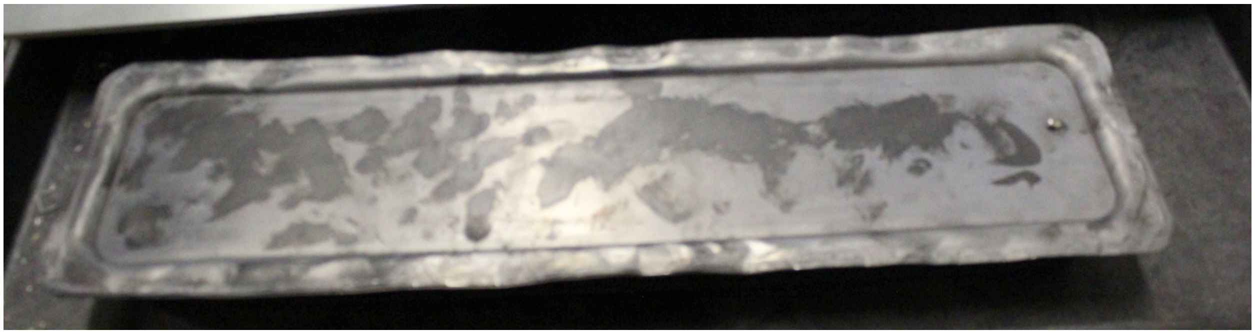


(h)
Figure 5. (a, b) Images of a large formed HIP can after bakeout and placed into the HIP chamber. (c, d) Plots of temperature and pressure versus time (mins). (e-h) Images of a successfully HIPed can. Note the substantial collapse of the can on the internal stackup and the deformation of the lid onto the top of the stackup.

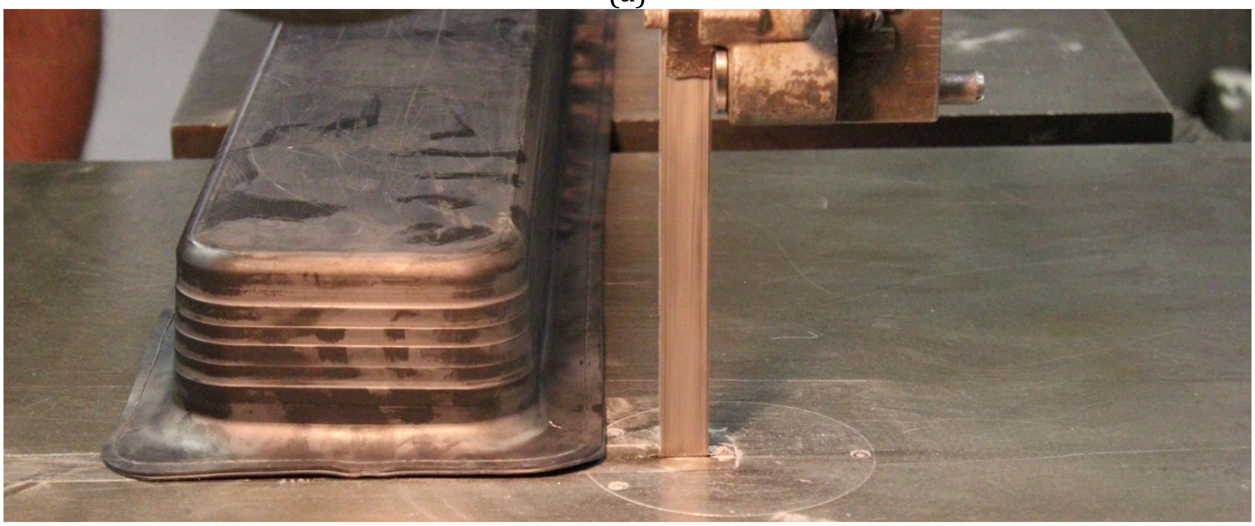
6. De-can

The large formed HIP can may be opened by simply removing the sealing welds on the flange. LANL has used a bandsaw, but other methods could be used. Figure 6a through 6d shows the flange removal process. In this case, the flange was substantially deformed during HIP (Fig. 5h), so a soft-blow hammer was used to flatten the flange to ease the sawing process. The evacuation tube was also removed prior to flange removal.

Figures 6e through 6g show that simply turning the can over leaves the internal stackup free of the can. The stackup is then taken apart layer by layer, leaving strongbacks and fuel plates separate, Figure 6h. When the fuel plates are laid out, Figures 6i and 6j, the relative flatness of each plate can be seen. In this case, it was more difficult to separate the top plate in the can (plate 7), which resulted in some bending of the plate during stackup disassembly. The difficulty in separating may be due to regions where the parting agent was applied too thin. The 6061 aluminum is now in fully annealed condition, and is quite soft, so that small amounts of bending during stackup disassembly can result in bending of the plate. If plates are difficult to separate, a thin, stiff spatula was used to aid the detachment of the fuel plates from the strongbacks.



(a)



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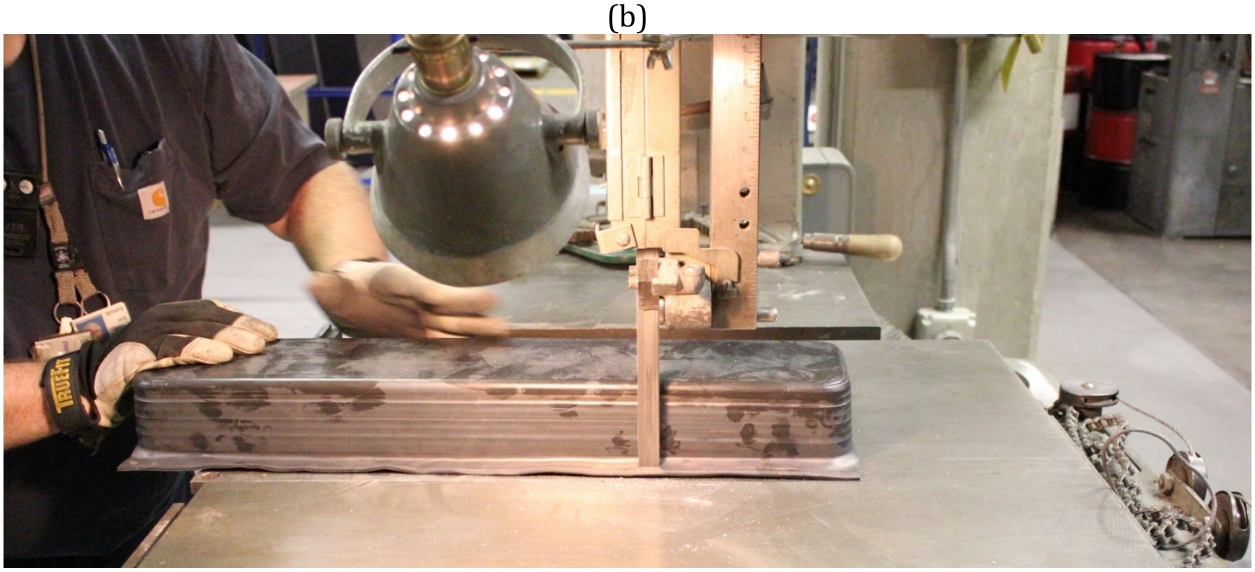

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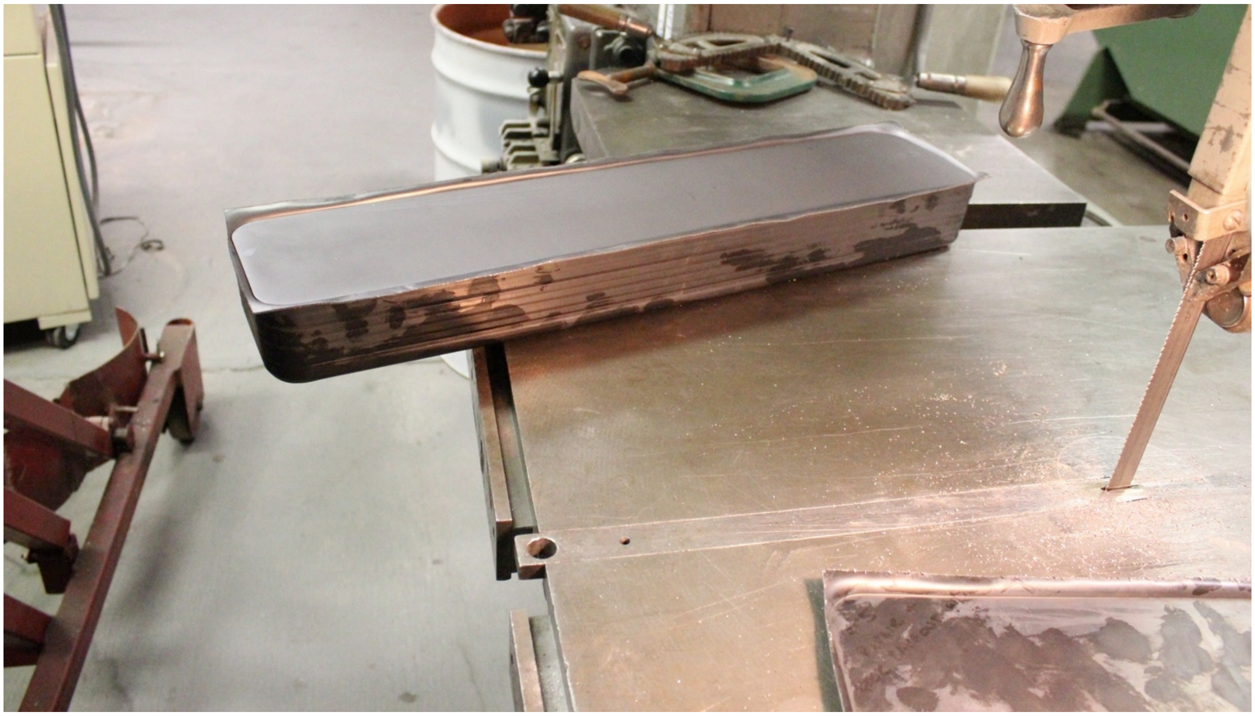

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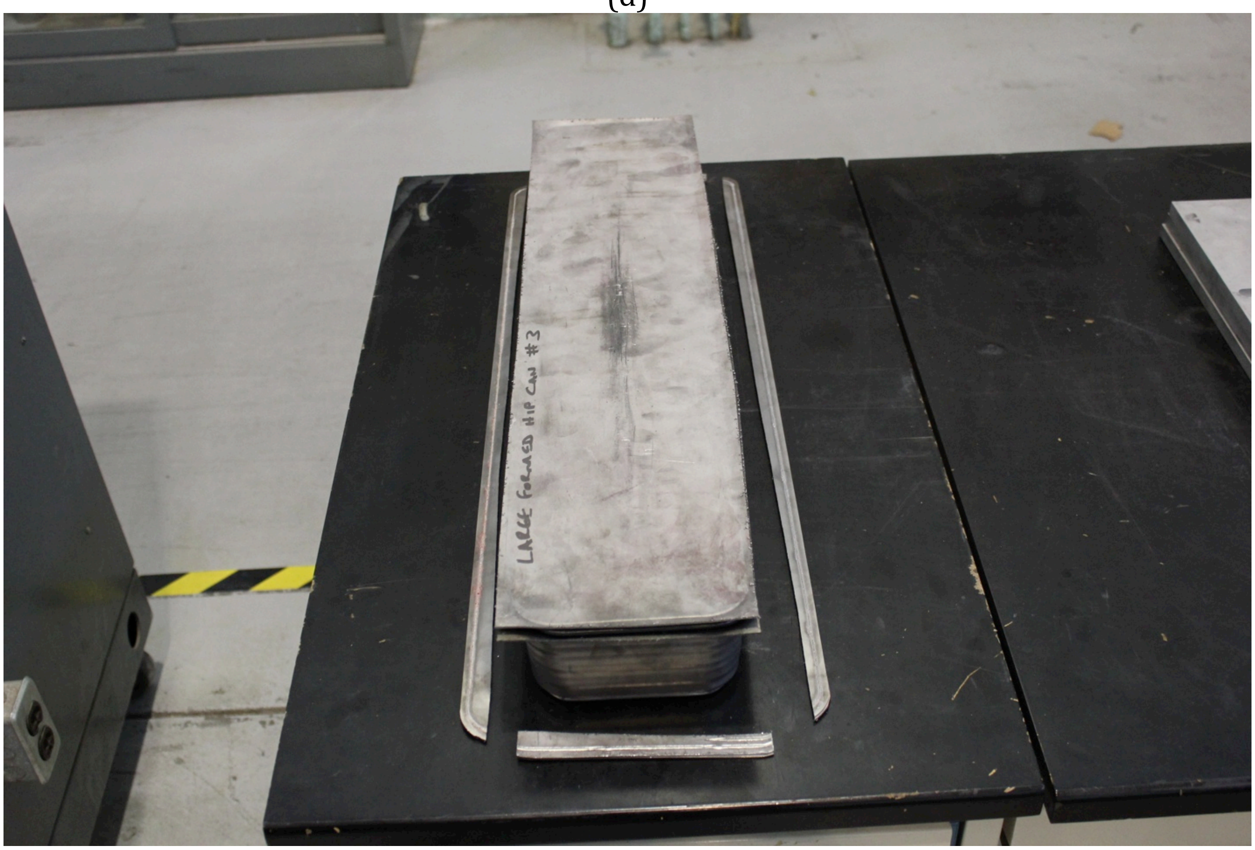

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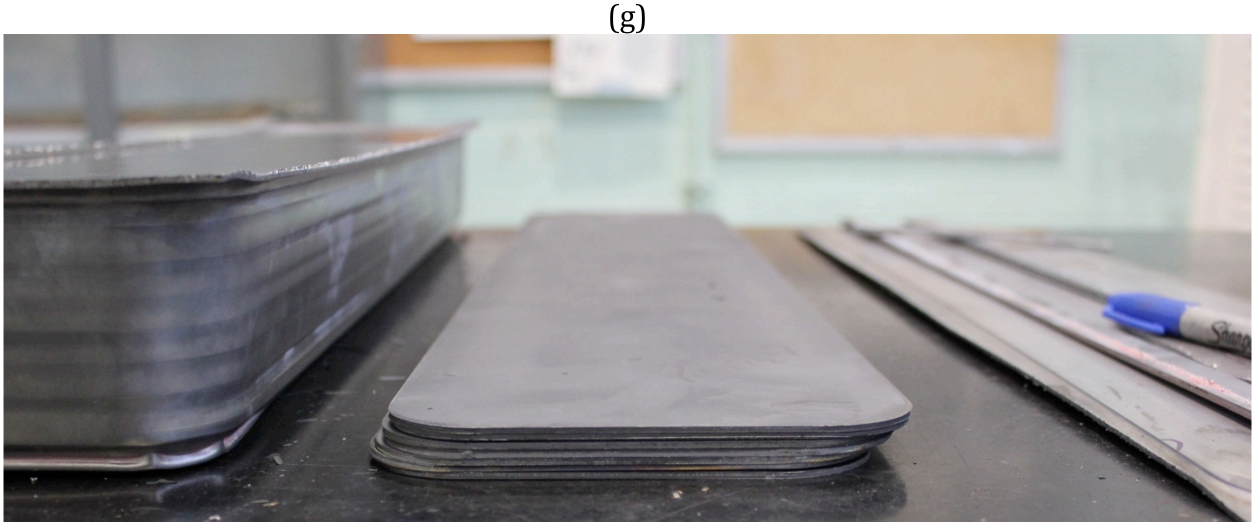

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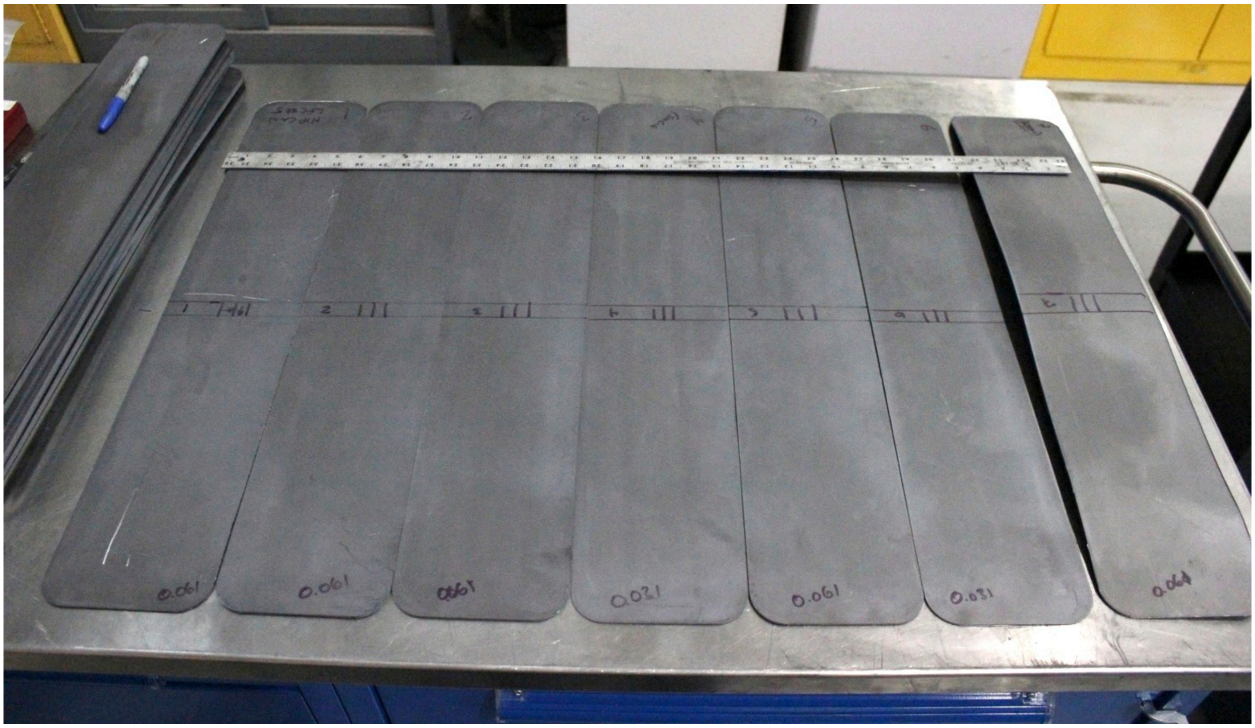
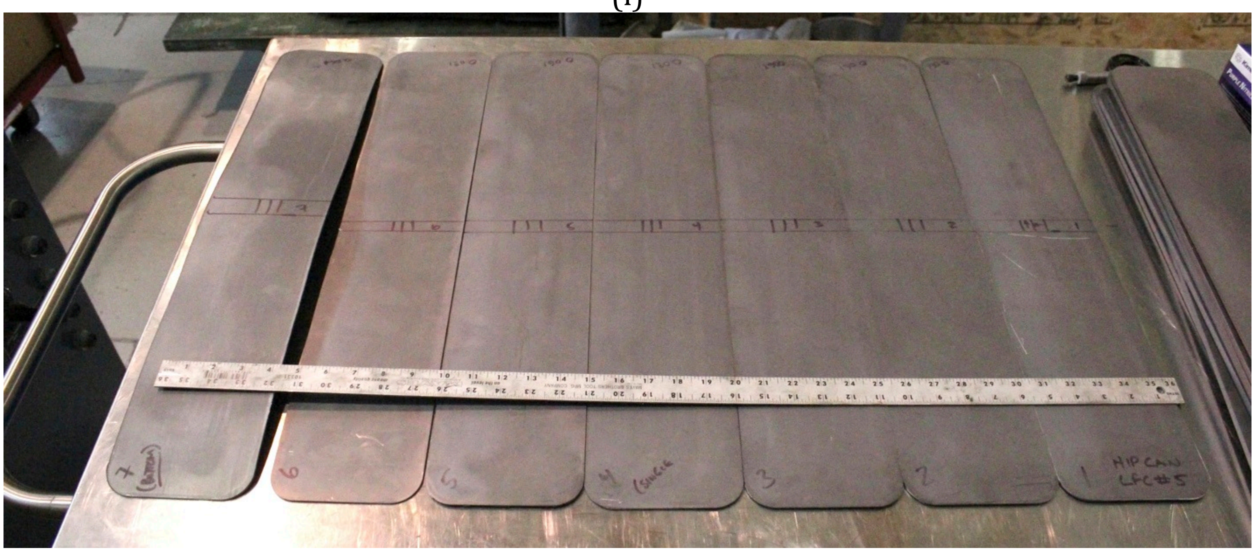


(i)



(j)

Figure 6. Images from de-canning and stackup disassembly. (a-d) Sectioning sealing welds from can to remove lid. (e-g) Removing stackup from can. (h-j) Al-Al bonded plates after HIP.

7. Cleaning/inspection and pass plates to sizing/machining

At this point, we have not done significant work to determine the cleaning and inspection needs for fuel plates. The cleaning will be dependent on parting agent used. We have done some work looking at thicknesses of formed HIP can plates, but not with DU-10Mo at this point. The Al-Al plates are nominally within 0.001" in thickness over the area of the aluminum plate.

Length and width sizing could simply be performed by electro-discharge machining (EDM), water jet, or another accurate sectioning method. Shearing is not problematic with respect to Al-Al bonding, but it does introduce some bending in the fuel plate that is sheared.

Since milling/fly-cutting is undesirable to B&W, the goal for thickness sizing would be to maintain the 0.001" thickness variation across the area of the fuel plate with DU-10Mo fuel. LANL is optimistic that this goal is achievable, but requires flat, constant thickness DU-10Mo fuel foils with straight sides and ends and 90° corners, which will allow tight tolerances when machining pockets in the aluminum cladding sheets prior to assembly in the HIP can.

<u>Notes</u>

The procedures for bonding cladding to DU-10Mo fuel foils have been described. Attempts have been made to address important details, but it is acknowledged that B&W will likely have questions that have not been answered herein or in the listed references. Thus, it is reasonable to expect this document to be revised to incorporate and clarify details.

This procedure was developed based on work at INL [1-5] and prior work by Joel Katz, Justin Crapps and others [6-10] at LANL, and the specific work shown herein was performed in collaboration with LANL colleagues Laura A. Tucker, Seth D. Imhoff, Beverly Aikin, Victor Vargas, Matthew J. Dvornak, Jeffrey E. Scott, David J. Alexander, Rick Hudson, Michael E. Mauro, and David E. Dombrowski

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