A Variable-View-Factor Two-Phase Radiator Manufactured Via Ultrasonic Welding

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In order to provide adequate cooling in the most challenging thermal environments, radiators for manned spacecraft, satellites, planetary rovers and unmanned spacecraft are typically oversized for moderate thermal environments and prone to freezing at low sink temperatures. In order to address the need for light-weight and efficient radiators capable of a significant heat rejection turndown ratio, Advanced Cooling Technologies, Inc. (ACT) has developed a novel vapor-pressure-driven variable-view-factor and deployable radiator that passively operates with variable geometry (i.e., view factor). The device utilizes two-phase heat transfer and novel geometric features that passively (and reversibly) adjust the view factor in response to internal pressure in the radiator. The focus of the current paper is to provide an update on ACT's progress manufacturing the variable view factor two phase radiator (VVFTPR). ACT in collaboration with Edison Welding Institute is developing a manufacturing process for the VVFTPR. This paper describes the ultrasonic welding technique chosen for manufacturing as well as material choices and other considerations.

I. Introduction

Radiators for heat rejection from spacecraft and satellites are typically sized for the highest power at the hottest sink conditions, and are therefore oversized most of the time and prone to freezing when the heat sink temperature and heat loads are low. There is a need to develop light-weight and efficient radiators for future spacecraft and satellites which offers the capability of significant heat rejection turndown.[1,2] The 2015 NASA Thermal Technology Roadmap says that NASA is looking for Variable Geometry Radiators,[3] "The development goal is to provide radiators with a 6:1 (with a stretch goal of 12:1) heat rejection turndown capability." ACT has developed a passive, variable-geometry radiator that has the possibility of turndown ratios greater than 40:1.[4]

For spacecraft and planetary thermal control applications, it is essential to maintain survivable operational temperatures for onboard devices and minimize temperature fluctuation when the heat load and/or the environmental temperature changes drastically. Under a Small Business Innovation Research (SBIR) project funded by NASA Marshall Space Flight Center, Advanced Cooling Technologies, Inc. (ACT) developed a novel *vapor-pressure-driven variable-view-factor and deployable radiator* that passively operates with variable geometry (i.e., view factor) and offers high heat rejection turndown ratio. The advantages of the variable-view-factor radiator over a conventional flat panel radiator include:

- *Passive temperature control*: Variable thermal resistance minimizes temperature swings despite changes in operating or environmental conditions. This feature will maintain the electronics above the minimum operating temperature even during times of low heat loads and low heat sink temperatures.
- *Survival*: In the fully closed position, heat rejection from the radiator is minimized resulting in a reduction in the required survival heater power.

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- *Deployable*: During launch the radiator is in a compact configuration allowing for simplified storage.

Previous work by Lutz et al.[4,5] and Diebold et al.[6] described the concept, experimental prototype development and testing, 2D and 3D parametric structural studies and thermal modeling. The focus of the current paper is to provide an update on ACT's progress towards manufacturing the VVFTPR. ACT has recently begun a collaboration with Edison Welding Institute (EWI), a company that specializes in advanced manufacturing techniques, in order to identify and utilize the ideal material and manufacturing methods for the VVFTPR requirements. Compared to conventional TIG welding, advanced manufacturing methods will enable the use of superior materials for the VVFTPR envelope and will eliminate manufacturing uncertainties and produce VVFTR prototypes reliably and in a repeatable manner.

II. Variable View Factor Concept

The basic concept of the variable-view-factor two-phase radiator (VVFTPR) is illustrated in Figure 1 alongside images of the Phase I SBIR prototype in operation.[4] The flexible actuator section of the VVFTPR consists of a hollow curved panel that is filled with a two-phase working fluid and sealed. An increase in fluid temperature results in a higher vapor pressure within the hollow curved panel causing the radiator to open. This opening increases the effective view factor to space of the radiator allowing more heat to be dissipated while minimizing the rise in vapor temperature.

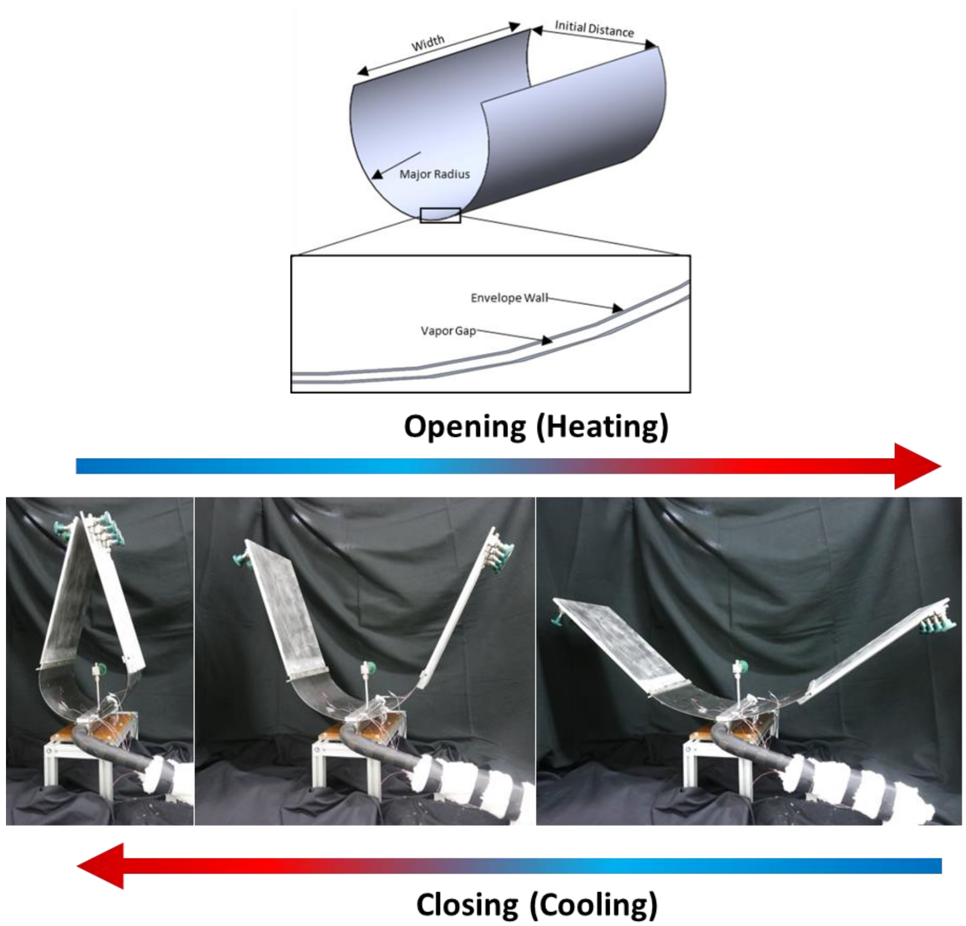


Figure 1. Schematic of VVFTPR flexible section and images of the Phase I SBIR prototype[4,5].

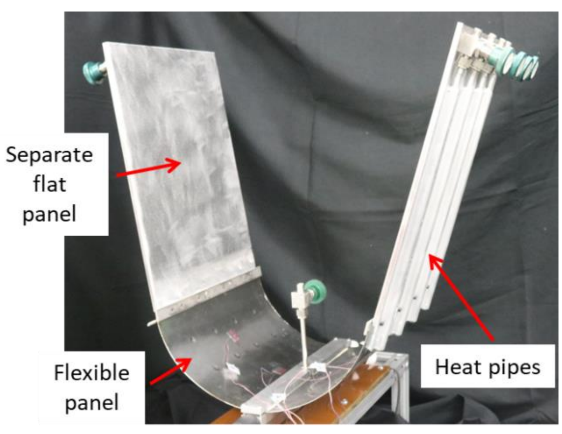
The VVFTPR developed at ACT by Lutz et al.[4, 5] demonstrated several key features:

- *High Heat Rejection Turndown Ratio:* Modeling and experimental work for the Phase I prototype, shown in Figure 1, demonstrated a heat rejection turndown ratio of 37:1.

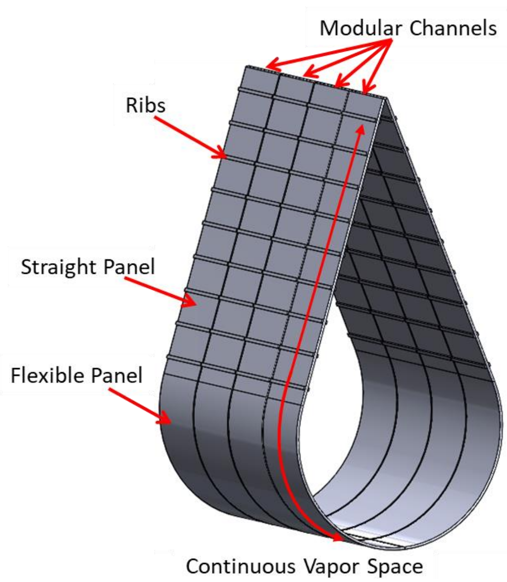
- *Passive Thermal Control*: The VVFTPR uses vapor pressure to passively change the shape of the radiator with no need for external power, equipment, or control mechanism.
- *Fast Response*: Experimental results demonstrated that the variable-view-factor radiator morphing behavior was mainly temperature dependent. The time scale of morphing due to vapor pressure changes was negligible relative to temperature changes of the wall material due to both conduction and thermal inertia.
- *Reversible and highly durable*: The radiator was designed to operate within the elastic domain of the material and was therefore reversible.
- *High radiator efficiency*: Standard heat pipe radiators rely on fins to spread the heat away from the pipe. This results in a non-uniform temperature distribution and reduces the radiator efficiency. The entire surface of the VVFTPR will be nearly isothermal resulting in an improved efficiency from 0.85 to near 1.0.

While the Phase I prototype proved successful,[4] several updates to the design concept were introduced by Diebold et al.[6] Figure 2 highlights the main features of the previous and updated design concepts. The flexible panel of the Phase I prototype was constructed from stainless steel sheets welded along the seam to form a single vapor space. Spot welds were placed periodically across the flexible section in order to prevent ballooning of the envelope. Heat was then spread to a separate flat panel via heat pipes adhered to the back of the panels as shown in Figure 2(a). The updated second-generation design includes the following improvements:

- *Envelope material:* The VVFTPR prototype will be manufactured from aluminum 7075, see Section III.
- *Modular Channels*: The vapor space is divided into several modular channels along the span of the radiator as shown in Figure 2(b). This will improve the reliability of the radiator for potential micrometeorite damage, by restricting potential leaks to a single module and not resulting in the loss of all of the working fluid.
- *Continuous Vapor Space*: The modular channels will be constructed so that the flexible panel and the straight panel contain a single continuous vapor space. This will reduce thermal resistance and result in a high efficiency radiator due to the nearly isothermal surface.
- *Structural Support*: Ribs or spot welds can be applied to the surface of the straight panel in order to contain the high internal pressure with a minimum wall thickness.



a) Previous Design



b) Updated Concept

Figure 2. Overview of the variable-view factor two-phase radiator concept evolution: (a) previous design, (b) updated second-generation design.

III. Manufacturing Method Development

This section will discuss the challenges associated with fabricating the VVFTPR and the collaboration between ACT and EWI to determine the ideal envelope material and manufacturing method.

A. Preliminary Prototypes and Testing

Preliminary prototypes fabricated in-house at ACT were constructed from aluminum 6061 and AISI 301 stainless steel in order to test manufacturing with traditional TIG welding. Figure 4 shows an example of a small-scale prototype strip constructed form aluminum 6061. The wall thickness was 0.025 in. (0.635 mm), the channel width was 2.0 in. (50.8 mm) and the radius of the curved section was 4.0 in. (101.6mm). These dimensions correspond to the simulations of Diebold et al.[6] Thinner stainless-steel prototypes were constructed with a thinner wall of 0.015 in. (0.381 mm). The prototypes were constructed by rolling individual sheets of the envelope material into the desired tear-drop shape. The two layers were then welded together forming the closed variable-view-factor strip prototype. A fill tube was included in order to pressurize the prototype. For initial testing the prototype was pressurized by pumping water into the inner space.

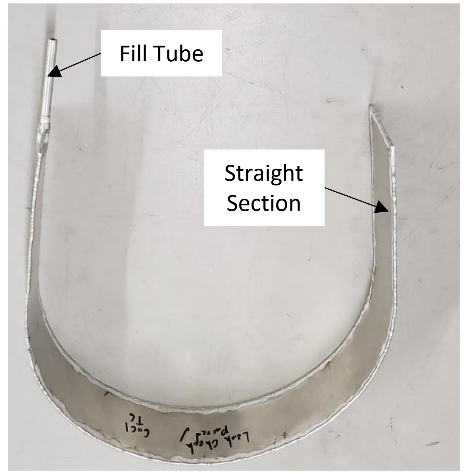


Figure 3. Small prototype strip for pressure testing. Aluminum 6061.

Experimental testing of preliminary prototypes constructed from both aluminum 6061 and 301 stainless steel proved unsatisfactory. Both materials were found to plastically deform at relatively low openings. The aluminum prototypes yielded at low openings due to the degradation of the material properties resulting from the welding process. The stainless-steel prototypes were unable to achieve satisfactory opening due to the high elastic modulus. In addition to the poor total opening of the prototypes, a lack of repeatability between nominally identical prototypes was observed. It is suspected the lack of repeatability was due to minor random variations in the weld thickness altering the stiffness. These results indicated that a more sophisticated manufacturing approach was required.

B. Material Selection

In the initial phase of the collaboration between ACT and EWI, EWI conducted a review of potential materials and welding methods. Numerous materials were investigated and evaluated based on elasticity, yield strength, weight and manufacturability. Table 1 summarizes relevant mechanical properties of three potential materials identified by EWI. Stainless steel 440 has a very high yield stress compared to the other materials but its high elastic modulus is nonideal. In addition, the high density of stainless steel is undesirable. Aluminum 7075 has one of the highest yield strengths of all the aluminum alloys, and compared to stainless steel it has a significantly lower elastic modulus. Combined with the low density of aluminum and relative ease of manufacturing using advanced welding techniques, aluminum 7075 was identified as the ideal material. EWI also identified Magnesium AZ80 as a potential candidate material due to its very low elastic modulus and low density while still possessing a moderate yield strength. While magnesium presents an interesting option due to its low stiffness, it was decided to move forward with the aluminum alloy because of concerns regarding the compatibility of magnesium with the potential working fluids as well as potential difficulties that may be faced when forming magnesium.

Table 1. Properties of candidate envelope materials based on EWI's review.

Material	Density (g/cm^3)	Elastic Modulus (GPa)	Yield Strength (MPa)
Stainless Steel 440	7.65	200	1660
Aluminum 7075	2.81	71.7	503
Magnesium AZ80	1.80	45.0	275

It should be noted that while aluminum 7075 possess favorable mechanical properties for the VVFTPR, its compatibility with potential working fluids is unknown. Many aluminum-ammonia heat pipes are constructed from aluminum 6061 but aluminum 7075 has a higher copper content which may negatively impact its compatibility with ammonia, a common working fluid for space applications. Ammonia may not be an ideal fluid choice for the VVFTPR because of the high vapor pressure requiring thicker envelope walls. ACT is also considering the use of acetone as the working fluid due its low vapor pressure. ACT began a compatibility test between aluminum 7075 and acetone. Aluminum 7075 cannot be easily welded and as a result it is not feasible to construct a typical heat pipe from this material for compatibility testing. In order to circumvent this challenge ACT constructed a standard stainless-steel heat pipe and inserted a rod of Aluminum 7075 into the pipe as illustrated in Figure 5. The stainless-steel heat pipe with internal aluminum 7075 rod has been setup to operate in thermosyphon mode at approximately 60°C. The outside of the heat pipe is outfitted with thermocouples to monitor for temperature gradients resulting from the generation of non-condensable gas (NCG). After nearly 4000 hours of operation no NCG has been detected indicating that acetone will be a suitable fluid for the VVFTPR.

The choice of acetone as the working fluid limits the operating temperature range to approximately -50°C to 100°C which is adequate for the majority of applications.

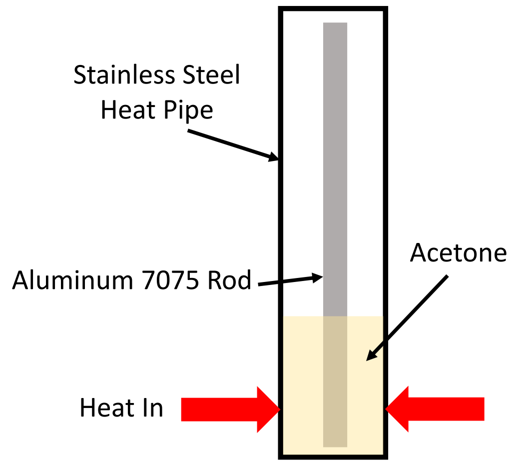


Figure 4. Illustration of compatibility test between acetone and aluminum 7075.

C. Manufacturing Method Advancement

ACT and EWI determined that aluminum 7075 was an ideal envelope material due to its high yield stress of 503 MPa compared to only 276 MPa for aluminum 6061 and low modulus of elasticity compared to stainless steel. The challenge of aluminum 7075 is that it cannot be welded using traditional fusion welding processes that require the material to undergo a phase change because it is prone to cracking under these conditions. Aluminum 6061 can be welded using traditional fusion welding but will suffer a degradation of material properties. *Ultrasonic welding* is a solid-state weld process that joins the metal without melting allowing the material to retain its mechanical properties and avoids the potential for cracking. The method is capable of welding many metals that have traditionally be considered unweldable. Figure 6 shows an illustration of the ultrasonic welding setup. The two pieces to be joined are held together under pressure and high-frequency ultrasonic vibrations are locally applied. The combination of pressure, heat and friction leads to a solid metallic bond at the weld site. The process is easily automated and well suited to the production of the VVFTPR.

The ultrasonic welding process can easily be applied to form a radiator panel made of several individual channels using the weld pattern illustrated in Figure 6. The proposed design uses two continuous top and bottom sheets of the selected envelope material and the modular channels for vapor flow are formed by welding along the length of the sheets.

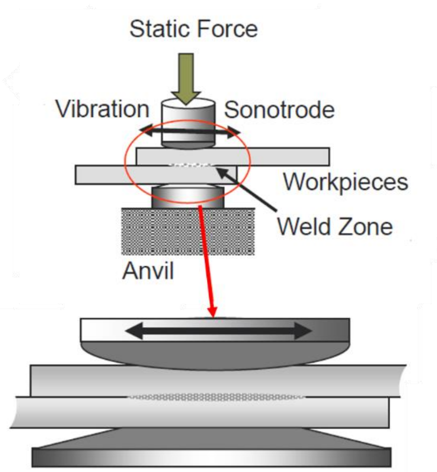


Figure 5. Illustration of the ultrasonic welding process. Source EWI.

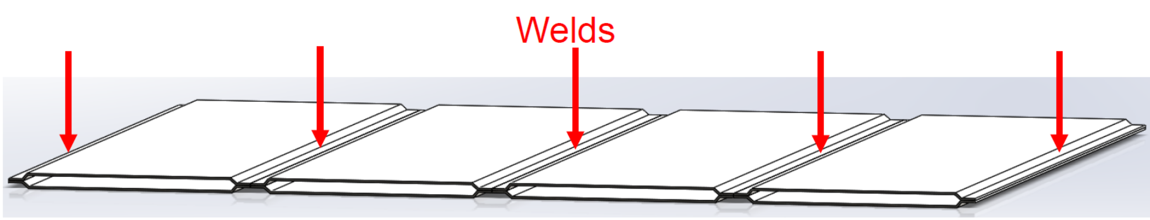


Figure 6. Welding pattern for multi-channel VVFTPR

The sheets can be laid directly on top of one another or a screen for wick can be placed in between prior to welding as shown in Figure 7. The mesh will provide capillary pumping to return liquid to the heat source in a microgravity environment. This method of fabrication will then rely on the vapor pressure to create the space shown in Figure 6 for vapor flow. This will minimize the overall thickness and therefore the stiffness of the radiator.

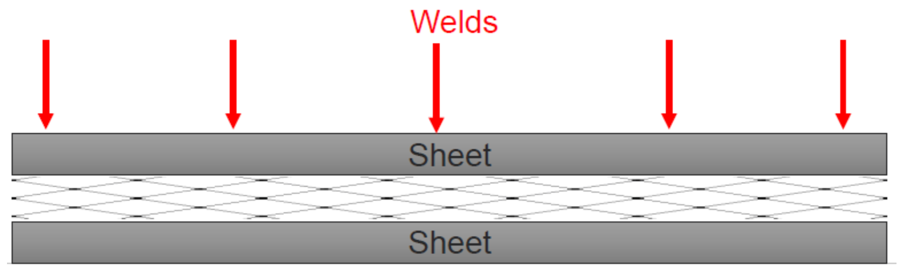


Figure 7. Setup of envelope material and screen wick for welding.

IV. Next Generation Prototype Development

After selecting aluminum 7075 for the envelope and ultrasonic welding for manufacturing ACT and EWI began work developing improved VVFTPR porotypes. This section will discuss the various prototype concepts that will be explored, the design of a single channel prototype and EWI's work adapting the ultrasonic welding process to the VVFTPR.

A. Prototype Concepts

Figure 9 illustrates the preliminary prototypes that will be fabricated. Single channel tear-drop prototypes will be used primarily to test the results of the ultrasonic welding process and to validate 3D structural modeling. The multi-channel tear-drop prototype is more representative of an actual radiator and will demonstrate the operation of multiple channels connected structurally but with separate spaces for working fluid. Note these concepts will make use of spot welds along the straight section of the channels. The three-dimensional structural simulations of Diebold et al.[6] indicated that to maximize the opening of the VVFTPR the envelope walls should be thin and the channel width should be large. This leads to significant ballooning occurring in the straight sections that can be countered with the use of spot welds.

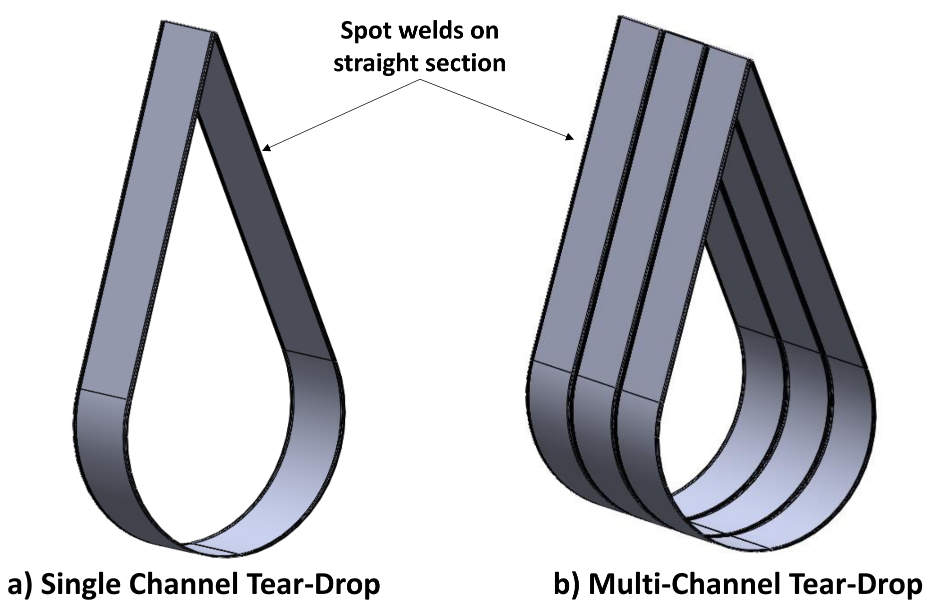


Figure 8. 3D models of preliminary VVFTPR prototype

B. Prototype Geometry

Prior to EWI developing the ultrasonic welding process it was necessary to determine the dimensions of the individual channels including wall thickness and channel width. Two wall thicknesses were selected to develop the ultrasonic welding process, a thin wall of 0.012 in. (0.305 mm) and thick wall of 0.02 in. (0.508 mm). These thicknesses were selected based on availability of aluminum 7075. The radius of the curved section was selected to be 3.0 in. (76.2 mm) and 3D structural simulations using the method described in Diebold et al.[6] were used to determine adequate channel widths. A row of spot welds spaced 1.0 in. (25.4 mm) was placed along the centerline of the straight section. Figure 11 shows the result of a simulation for the thin walled, 0.012 in. (0.305 mm), single-channel prototype with an active channel width of 1.5 in (38.1mm). The internal pressure was 11.82 psi (8.15×10^4 Pa), corresponding to the saturation pressure of acetone at 50°C. Figure 11a shows the stress distribution on the surface of the deformed channel. It can be seen that a maximum stress of approximately 60% of the yield stress occurs in the region of transition from curved to straight section. Figure 11b shows a side view to show the amount of opening predicted by the simulation. The maximum deflection was 8.8 in. The width of the thick-walled envelope (not shown) was selected to be 3.0 in. (76.2 mm.).

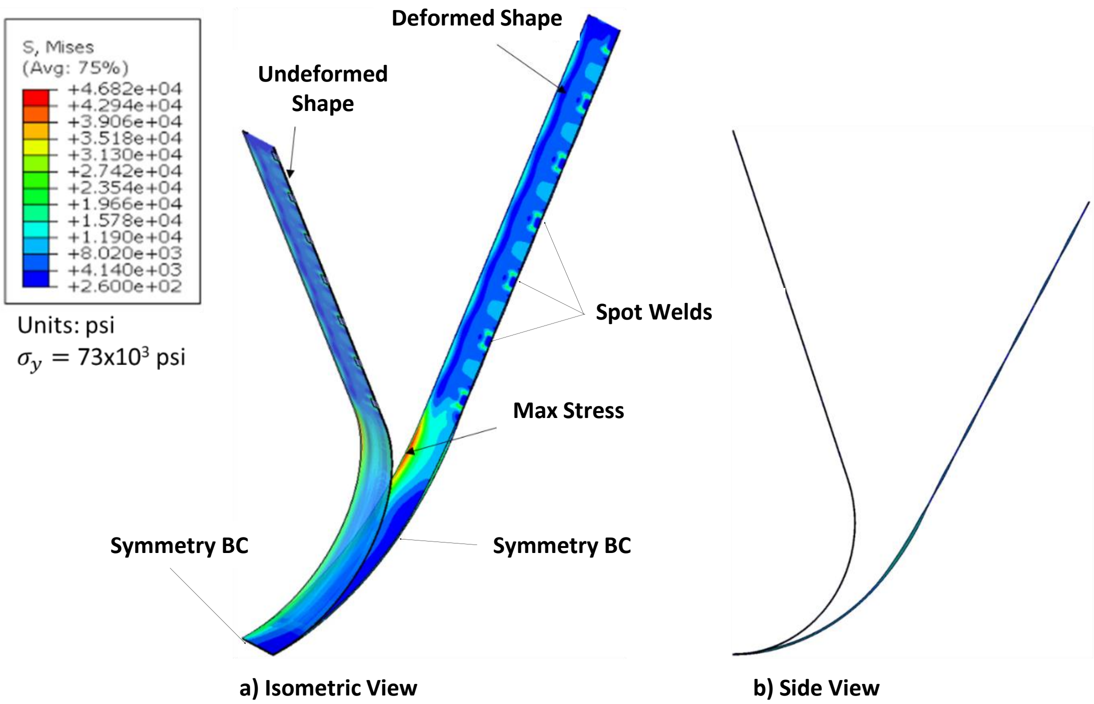
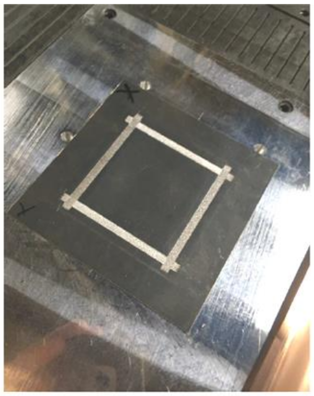
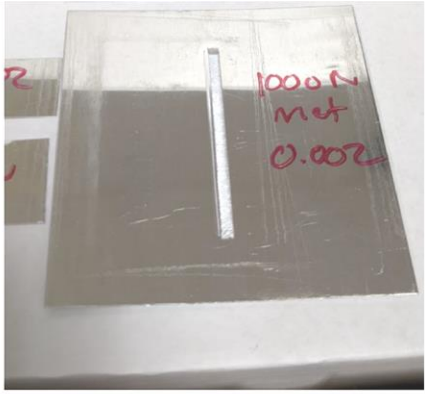


Figure 9. Simulations results of single channel prototype. Aluminum 7075. Wall thickness 0.012 in. (0.305mm), channel width 1.5 in. (38.1 mm). Internal pressure was 11.82 psi which corresponds to acetone saturation pressure at 50°C.

C. Ultrasonic Weld Development

EWI performed a series of welding trials and experiments in order to down select an acceptable set of welding parameters. Trials were carried out for both the 0.012 in. (0.305 mm) and 0.02 in. (0.508 mm) thick aluminum 7075 sheets with and without the internal mesh. Parameters investigated during the trials included the sheet thickness, interlayer material thickness, brushed or not brushed surface, single or double weld pass, ultrasonic amplitude and weld force. Figure 12 shows the two weld configurations used for testing. The pillow (square) configuration was used for helium leak checking while the lap configuration was used for tensile testing. All welds had a width of 0.15 in. (3.81mm).





a) Pillow b) Lap

Figure 10. Weld configurations used for iterative weld development testing.

Initial weld trials showed that welding two aluminum 7075 sheets directly to each other resulted in weak or inadequate bond, excessive material accumulation on the ultrasonic horn and damage to the weld foil. In order to improve the quality of the weld a single layer of aluminum 1100 foil was placed in between the sheets of aluminum 7075. Two thickness of this interlayer were tested; 0.001 in. (0.025 mm) and 0.002 in. (0.05 mm). This vastly improved weld quality for two reasons. First, an 1100 series is much easier to locally deform than the 7075, which is a requirement for a sound ultrasonic weld. Second, the 1100 insert allowed strain accumulation at the bond line, making it much easier to include dynamic recrystallization. Dynamic recrystallization is a result of high strain fields greatly reducing the needed temperature for recrystallization and is the main bonding mechanism in an ultrasonic weld. In more common terms, the 1100 series was much easier to weld and allowed the reduction of weld force. Due the force reduction, welds could be made without damage to the foils and aluminum adhesion to the ultrasonic tool was reduced.

A series of weld trials were performed varying the force, speed and ultrasonic amplitude of the ultrasonic horn and the parameters found to work best were a force of 1000 N, speed of 50 in/min, a frequency of 20-kHz, an amplitude of 36 microns and a double weld pass. Table 2 shows the results of tensile tests for the lap weld configuration. The results of the weld trials indicated that the thinner interlayer of aluminum 1100 resulted in higher tensile strength. The most consistent results were obtained for the thinner aluminum 7075 sheet with the thinner interlayer. Increasing the interlayer thickness and the envelope wall thickness resulted in more scatter in the measured the tensile strength. Metallographic examinations of the welds agree well with the tensile test results. Cross sections for each material thickness and interlayer combination are displayed in Figure 13. Please note that the joint lines are bonded but are preferentially attacked by the etch due to the very small grain size. The 0.012 in. (0.305 mm) thick 7075 with the 0.001 in. (0.025 mm) displayed a sound weld with no voids between the interlayer and either sheet of material. The 0.002

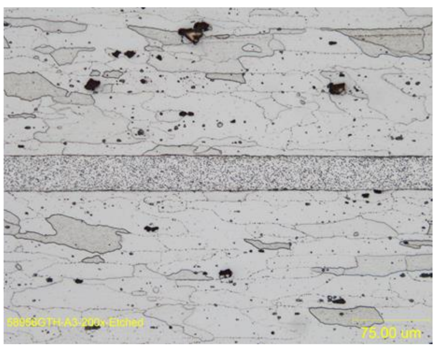
Table 2. Tensile test results of ultrasonic weld development trials.

Sample Number	Material Thickness	Interlayer thickness	Test Configuration	Weld Force (N)	Brushed surface (Y/N)	Double or Single weld	Tensile test (lbf)
A6	0.012	0.001	Lap	1000	Y	Double	728.227
A7	0.012	0.001	Lap	1000	Y	Double	766.692
A8	0.012	0.001	Lap	1000	Y	Double	785.06
A10	0.012	0.001	Lap	1000	N	Double	884.536
A11	0.012	0.001	Lap	1000	N	Double	911.054
A12	0.012	0.001	Lap	1000	N	Double	394.606
B2	0.012	0.002	Lap	1000	N	Double	647.592
B3	0.012	0.002	Lap	1000	N	Double	594.984
B10	0.012	0.002	Lap	1500	N	Double	350.964
B11	0.012	0.002	Lap	1500	N	Double	695.022
C3	0.02	0.001	Lap	1000	N	Double	313.411
C4	0.02	0.001	Lap	1000	N	Double	1025.142
C5	0.02	0.001	Lap	1000	N	Double	998.954
D2	0.02	0.002	Lap	1000	N	Double	414.12
D4	0.02	0.002	Lap	1500	N	Double	1293.301

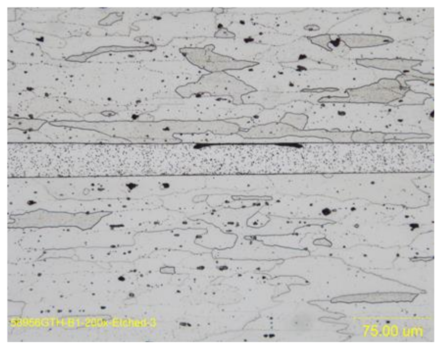
(0.05 mm) in. thick interlayer possesses volumetric voids, which would reduce both tensile performance and potentially compromise the hermetic seal. Both 0.020 in. (0.508 mm) thick 7075 materials displayed flaws near the edges of the weld. As bonding was poor at the edges, it led to cracking of the weldment at the edges. These cracks can act as stress concentrations for future tests and are likely the cause for the lower lap shear tensile tests associated with the 0.02 in. (0.508 mm) thick sheets.

Helium leak testing was performed using the pillow weld configuration shown in Figure 12a. The leak test results showed that the best seal was obtained for the thinnest envelope thickness of 0.012 in. (0.305 mm) and thinnest interlayer thickness of 0.001 in. (0.025 mm). Leaks observed for this configuration were below 1 part per million suggesting a hermetic seal. Samples with an inner layer of mesh screen formed an inadequate seal suggesting that welding over the screen may not be sufficient. Future iterations will attempt placing strips of screen mesh only in between the weld lines.

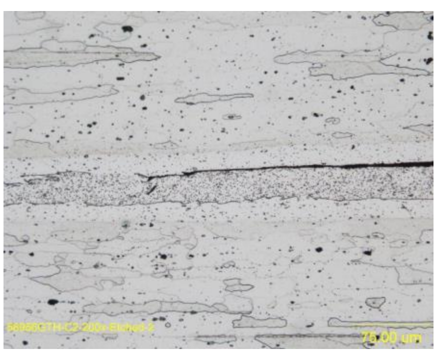
After analyzing the results of the weld trials, it was decided to move forward with the 0.012 in. (0.305 mm) thick envelope material with a 0.001 in. (0.025 mm) thick interlayer of aluminum 1100. Figure 14 shows the first single-channel prototypes manufactured with the selected weld parameters. The length of the strips is based on the selected radius of the curved section and overall height of the tear-drop shape. Spot welds were included along the centerline of the straight sections. The prototypes will be formed into the tear-drop shape by ACT and the opening as a function of internal pressure will be measured.



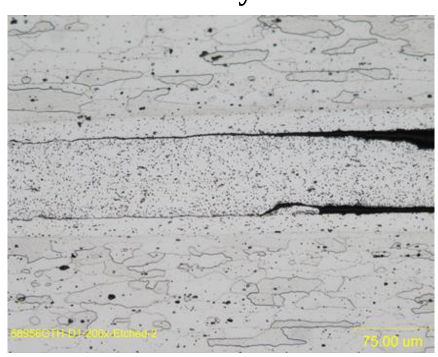
a) 0.012 in. thick with 0.001 in. thick interlayer. Defect Free Weld.



b) 0.012 in. thick with 0.002 in. thick interlayer. Gap between top sheet and interlayer.



c) 0.020 in. thick with .001 in. thick interlayer. Cracking at edge extending into weld.



c) 0.020 in. thick with .002 in. thick interlayer. Cracking at edge extending into weld.

Figure 11. Weld development cross sections.

Figure 12. Preliminary single-channel prototypes manufactured by EWI with ultrasonic welding

V. Conclusion

In previous work, ACT demonstrated an innovative variable-view-factor two-phase radiator prototype[4] and performed 3D structural trade studies and thermal analysis of the radiator design.[6] The VVFTPR allows for passive thermal control of the source temperature as the heat load and heat sink conditions change. The work presented here highlights progress made in manufacturing the VVFTPR in a reliable manner. Through in-house experimentation, ACT determined that traditional manufacturing techniques were insufficient for this application. ACT has partnered with EWI to explore the application of a superior aluminum alloy (aluminum 7075) and ultrasonic welding to the manufacturing of the VVFTPR. EWI performed a series of welding trials in order to down select to an acceptable set of welding parameters. Results of the welding trials led to the selection of 0.012 in. (0.305 mm) thick envelope of aluminum 7075 with a 0.001 in. (0.025 mm) thick interlayer of aluminum 1100. Several prototype configurations were introduced and initial single channel prototype strips have been fabricated. Next steps in the development of the manufacturing process include:

- Forming single channel strips into the single-channel tear-drop prototypes.
- Experimentally measuring the opening of the single-channel prototypes as a function of internal pressure.
- Manufacturing and testing of the multi-channel tear-drop prototypes.

After finalizing and successfully demonstrating the manufacturing process, future work will include:

- Fatigue testing of VVFTPR prototypes.
- Design and demonstration of a thermal bus to interface the VVFTPR to the heat sources.

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