

***Robotic Manufacturing of 18ft (5.5m) Diameter Cryogenic Fuel Tank Dome
Assemblies for the NASA Ares I Rocket***

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Abstract

The Ares I rocket was the first launch vehicle scheduled for manufacture under the National Aeronautic and Space Administration's Constellation program. A series of full-scale Ares I development articles were constructed on the Robotic Weld Tool at the NASA George C. Marshall Space Flight Center in Huntsville, Alabama. The Robotic Weld Tool is a 100 ton, 7-axis, robotic manufacturing system capable of machining and friction stir welding large-scale space hardware. This paper will focus on the friction stir welding of 18ft (5.5m) diameter cryogenic fuel tank components; specifically, the liquid hydrogen forward dome and two common bulkhead manufacturing development articles.

1.0 Objective

The objectives of this paper are to:

1. Present an overview of the manufacturing and welding processes used to assemble Ares I rocket components on the Robotic Weld Tool at the NASA George C. Marshall Space Flight Center
2. Present tooling solutions used to overcome manufacturing and welding issues.

2.0 Introduction

The Ares I was the first launch vehicles scheduled for manufacture under the National Aeronautic and Space Administration's (NASA) Constellation program. It consisted of two stages. The second stage, or Upper Stage, was composed of a liquid oxygen oxidizer tank and a liquid hydrogen (LH2) fuel tank as well as an engine and an instrumentation unit. Before flight hardware would be produced, a series of Upper Stage test and development articles would be constructed on the Robotic Weld Tool (RWT) at the NASA – Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

The Robotic Weld Tool is a 100 ton, 7-axis, robotic manufacturing system capable of machining and friction stir welding (FSW) large-scale space hardware. The RWT has a 3-axis horizontal traveling column with retractable boom and a 2-axis roll and pitch assembly positioned on the end of the boom. It has a 30ft (9.1m) rotary turntable that can both slew and slide. The robot has the ability to control the position of the tool tip by coordinating motion around all 7 axes. It can perform self reacting (SRFSW), conventional (CFSW) and retractable pin tool friction stir welding within its roughly 2000 ft³ (56 m³) working volume. Figure 1 is a picture of the RWT.



Figure 1 - Robotic Weld Tool

The LH2 Manufacturing Development Article (LH2 MDA) was the first Ares I article produced on the RWT. Gores, y-rings and fittings were trimmed, welded, and non-destructively evaluated. A “fixtureless” tooling approach was implemented on the fitting-to-dome weld to replace complex and expensive external tooling.

The Aft Confidence Common Bulkhead Manufacturing Development Article (CBMDA #1) and the Aft Common Bulkhead Manufacturing Development Article (CBMDA #2) were the next two articles produced. Spun-formed domes were trimmed and welded to y-ring stiffeners. Tack anvils were employed for CBMDA #2 in an effort to better support the weld joint and ultimately eliminate PAUT indications.

3.0 LH2 Manufacturing Development Article

The LH2 MDA was the first full-scale, flight-like Ares I hardware produced on the RWT. It was an 18 ft (5.5 m) diameter LH2 fuel tank dome assembly. The assembly consisted of eight gore panels, a y-ring stiffener and a manhole fitting. Figure 2 shows a CAD model of the LH2 MDA dome assembly. All components were made from aluminum lithium alloy 2195. The gore panels were stretch formed then chemically milled. The weld lands were 0.250” (6.35mm) with an additional 6” (152.4mm) of excess material at top and bottom. The y-rings were machined from ring forgings and were delivered dimensionally net. The manhole was machined from plate. All welding fixtures were

designed and manufactured at MSFC. The gore welding fixture is shown in Figure 3. The dome-to-y-ring fixture is shown in Figure 4.

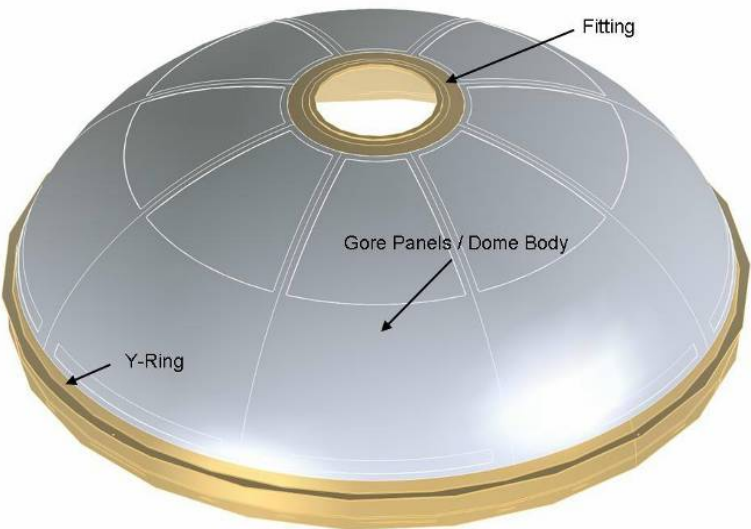


Figure 2 - LH2 MDA Dome Assembly

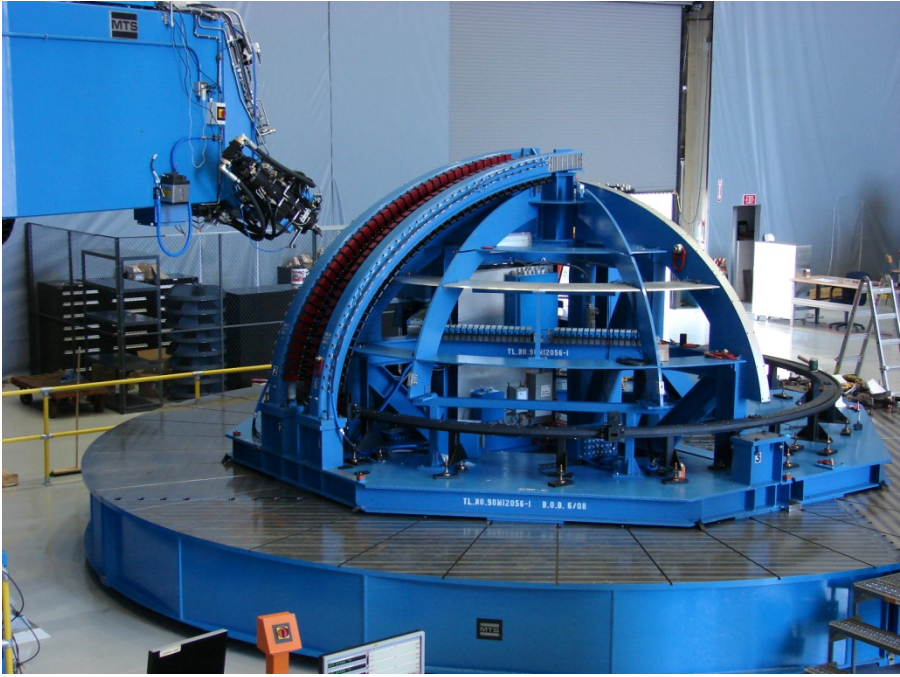


Figure 3 - Gore Welding Fixture

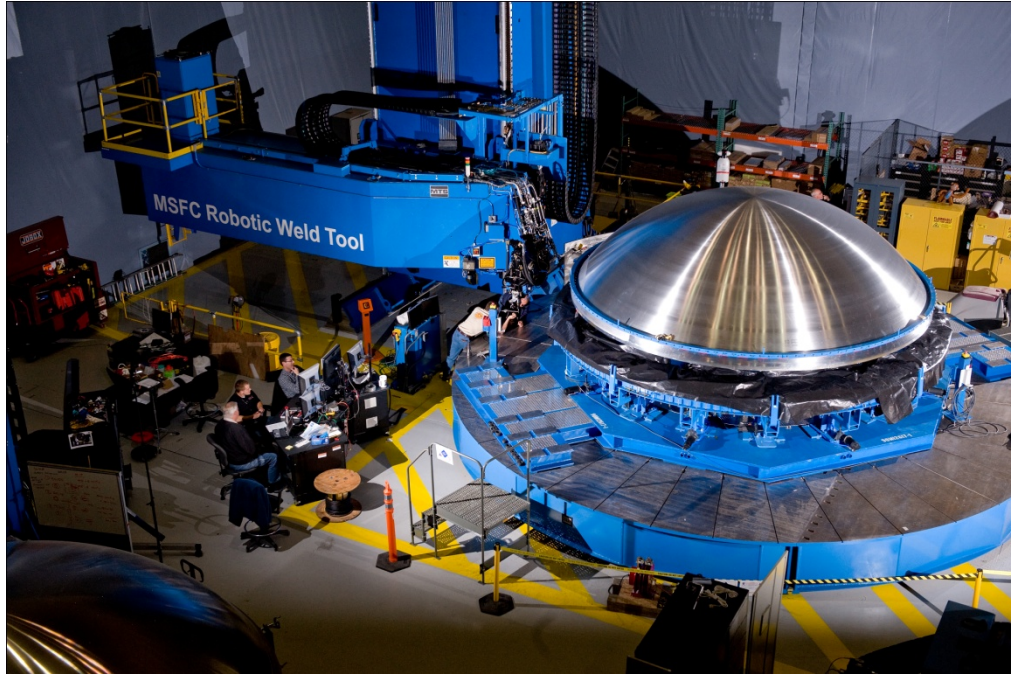


Figure 4 - Dome-to-Y-ring Welding Fixture

The gore welding process involved trimming, CFSW, and Non-Destructive Evaluation (NDE). The process was as follows: A single gore panel was positioned under the curved clamp beams. Seventy-two Destaco “cam-over” clamps were activated. The gore was trimmed to the nominal trim line. The gore was then rotated out of the way and another gore was trimmed in the same manner but on the opposite edge. Both gore panel faying surfaces were prepared for welding. The panels were mated and clamped into position. The gore panels were then tack welded using CFSW with a monolithic, H13, tapered pin tool with a single-scrolled shoulder. After tack welding, the full penetration weld was performed with CFSW using an MP159 super alloy, left-hand threaded, straight pin with a convex shoulder. This procedure was repeated until three “quarter domes” were produced. The quarter domes were then welded together. The seventh gore panel was welded to the assembly followed by the eighth and final “keystone” gore. A Phased Array Ultra-sonic (PAUT) transducer was mounted to the RWT weld head, and NDE was performed on each weld immediately after the weld was performed. No indications were reported for any of the eight gore welds. The LH2 MDA gore dome was the first known, fully friction stir welded dome ever produced.

The dome-to-y-ring assembly process involved trimming, gas tungsten arc welded (GTAW) tack welds, SRFWS and NDE. The y-ring loading and clamping process was as follows: The y-ring was loaded onto the fixture to come to rest on 72 lower mandrel shoes assembled on a circular support beam. The lower mandrel shoes were pre-positioned to the correct radii so that when the y-ring was lowered onto them, the ring was automatically rounded and set to the correct elevation. Seventy-two external

clamps were then installed and tightened. Each external clamp shoe aligned with an internal lower mandrel shoe. The clamps were tightened and the y-ring was covered and lowered out of the way via a motorized axis.

The previously welded gore dome was loaded and clamped. The dome was lowered onto a set of 72 upper mandrel shoes that were mounted and pre-positioned on a circular support structure. A “halo” ring was then loaded onto the outer mold line (OML) of the dome. The intent of the halo ring was to act as an external clamping mechanism. The halo ring also had 72 mandrel shoes that were pre-positioned and aligned with the internal upper mandrel shoes. Figure 5 shows a cross sectional view of the dome-to-y-ring clamp interfaces and Figure 6 depicts the weld head positioned at the dome / y-ring weld line.

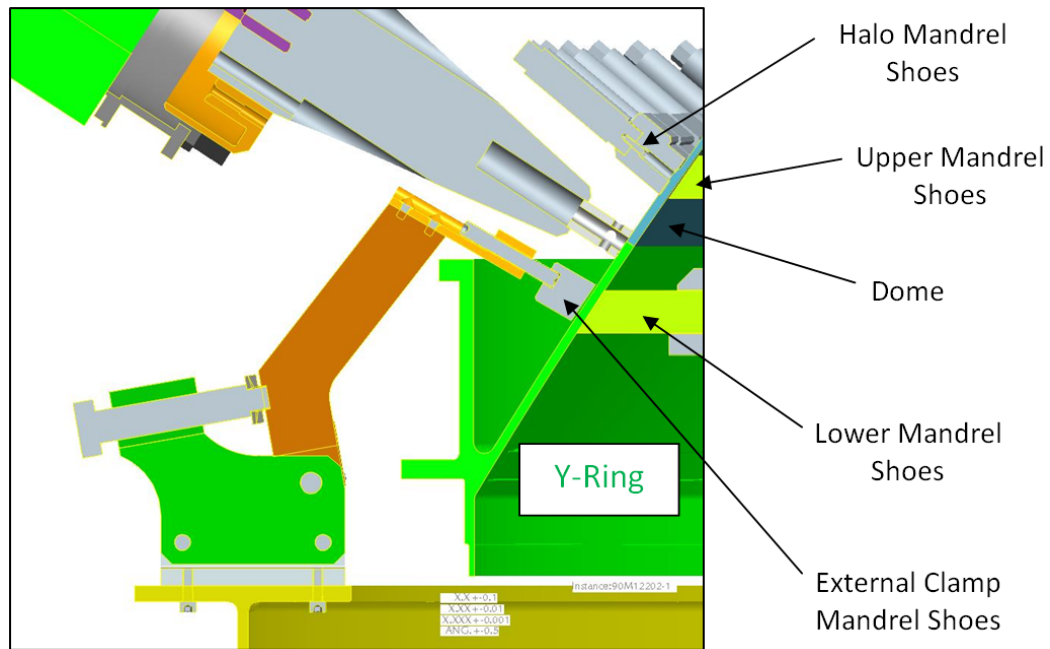


Figure 5 - Cross Section of Dome-to-Y-ring Clamp Interfaces

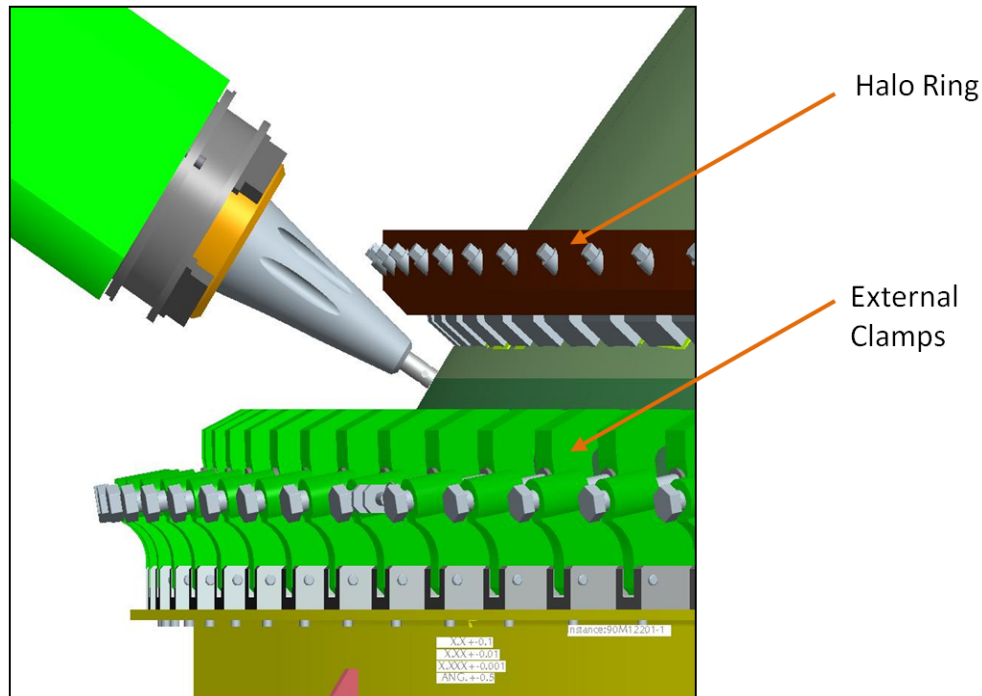


Figure 6 - Weld Head at Dome / Y-ring Weld Line

The dome was trimmed to fit the y-ring. The gore dome was designed to have excess material along the bottom edge. The y-ring was delivered to MSFC dimensionally net. In order for the two components to fit together, the bottom edge of the dome had to be machined. The machining operation was performed with the RWT. The bottom edge of the dome was trimmed to within 0.100" (2.54mm) of the nominal circumference. The dome was intentionally left 0.100" (2.54mm) "fat" to verify that the robots programmed trim path was indeed correct. The y-ring was then raised and fit-checked with the dome. The amount of additional trim was determined and the dome was trimmed to meet the y-ring.

The dome was welded to the y-ring. After checking the final fit with the dome, the y-ring was lowered and both the dome and y-ring faying edges were prepped for welding. Sixty-four, 4" (102mm) long, partial penetration GTAW tack welds were performed on 10 inch centers. The self-reacting start hole was drilled. A 0.500" (12.7mm), left-hand / right-hand threaded (LH/RH) pin tool was assembled with a 1.2" (30.5mm) scrolled shoulder. The SR weld was successfully performed. Peaking, mismatch and joint gap measurements were taken pre tack, post tack and post weld. PAUT NDE was performed. No indications were reported.

Complex and expensive dedicated tooling would typically be utilized for the fitting-to-dome weld. An alternative “fixtureless” welding approach was taken. After the dome was trimmed and the faying edges prepared, off-the-shelf “c” clamps were positioned around the fitting to secure it to the dome. Smaller c-clamps were used to work out localized joint mismatch, and GTAW tack welds were performed. CFSW tack welds were not used since no backing anvil was available to support the axial tool loads. The c-clamps were removed after tacking and the self-reacting start hole was drilled with the RWT. A 0.375” (9.5 mm), left-hand / right-hand threaded pin tool was assembled with a 0.9” (22.8 mm) diameter scrolled shoulder. The self reacting (SR) weld was successfully performed with no localized internal or external tooling in place to secure the joint. Peaking, mismatch and joint gap measurements were taken pre tack, post tack and post weld. PAUT NDE was performed. No indications were reported. Figure 7 shows an inner mold line (IML) view of the welded fitting. Figure 8 shows the completed dome assembly on the RWT



Figure 7 - Welded Manhole Fitting

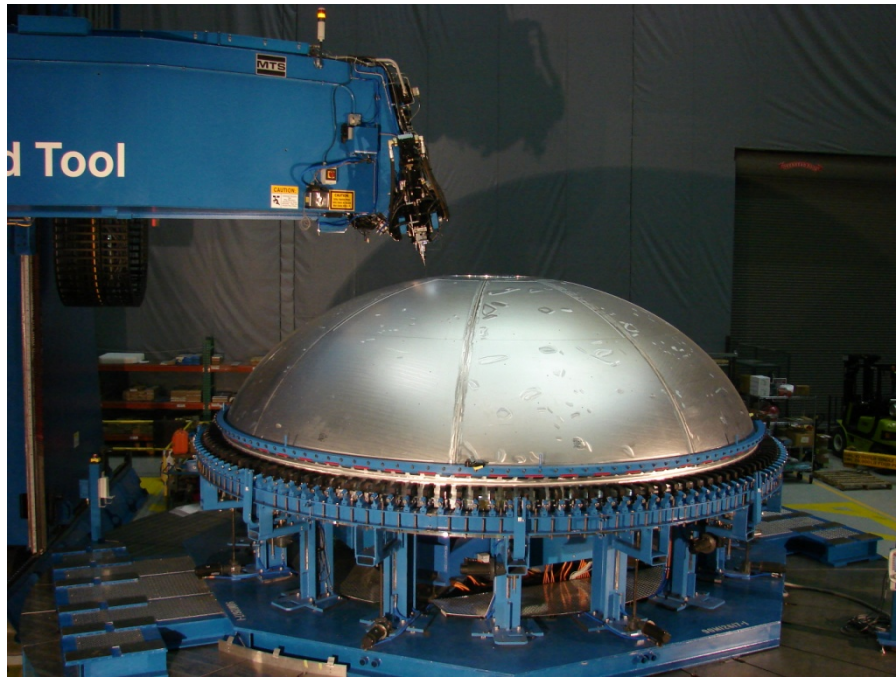


Figure 8 - Completed Dome Assembly

4.0 Common Bulkhead Manufacturing Development Articles

The Common Bulkhead Manufacturing Development Articles, CBMDA #1 and CBMDA #2, consisted of 18 ft (5.5m) diameter domes and y-ring stiffeners. The domes were spun formed from aluminum alloy 2014. The weld lands were 0.208" (5.3mm) thick and transitioned to an approximate 0.050" (1.27mm) dome membrane. The domes had approximately 6" (152mm) of excess material on the bottom edge. The y-rings were machined from single, aluminum alloy 2219, rolled, ring forgings. The y-ring weld lands were 0.208" (5.3mm) thick in order to mate with the domes. The y-rings were delivered dimensionally net.

The dome-to-y-ring assembly involved trimming, conventional friction stir tack welding, SRFSW and NDE. The domes were tack welded to the y-rings using CFSW. A 0.625" (15.9mm) diameter, single-scrolled shoulder tool was used. The tool had a 0.038" (0.96mm) tapered pin. The tack welding parameters are shown in Table 1. Sixty-four, 4" (102mm) long CFSW tack welds were performed on 10" (254mm) centers. All operations were performed on the dome-to-y-ring fixture as shown in Figures 4 and 8. No backing anvils were used to support the CFSW tack process for CBMDA #1. Backing anvils were used during the tack welding of CBMDA#2. The y-ring and dome loading, the dome trimming, and the SRFSW processes for both CBMDA #1 and CBMDA #2 were similar to those outlined in Section 3.0 and will not be detailed further.

Table 1 - CBMDA Tack Welding Parameters

Spindle Speed (rpm)	1400
Load (lbf/N)	850/3781
Travel (ipm /mm/m)	7/178

4.1 CBMDA #1

The CBMDA #1 hardware was loaded and clamped. The joints were prepared and tack welding was performed with CFSW. Tack welding induced peaking and mismatch in the weld joint. Heat from the tack weld caused the advancing side dome to move inward, away from the OML, causing a mismatch condition. During tacking, the movement was observed as far as 2ft (0.61m) ahead of the tack weld where the dome would move inward as much as 0.150" (3.81mm). After tacking, the dome would cool and move back to its nominal position ahead of the tack, but the mismatch would be locked in locally along the tack. The movement of the dome was attributed to the relatively thin membrane thickness of 0.050" (1.27mm). The movement of the advancing side during tack welding was not observed during test panel development. The test panels were a constant 0.208" (5.3mm) thickness.

Peaking and mismatch measurements were taken along the weld joint after tack welding. The general trend of peaking and mismatch severity in relation to the tack distance is shown in Figure 9. Crown side mismatch measurements along a tack weld are shown in Figure 10. The sign convention for mismatch is such that a negative value indicates the advancing crown-side (dome) is lower than the retreating crown-side (y-ring) as viewed from the OML. The measured mismatch does not account for the additional mismatch incurred from differences in material thickness. The dome weld land was an average 0.008" (0.2mm) thicker than the y-ring weld land. This meant that with no mismatch on the crown surface, there was an average 0.008" (0.2mm) mismatch on the advancing root. The mismatch induced by the tack welding exacerbated the already existing advancing root mismatch. The thickness difference mismatch added to the measured post tack mismatch is referred to as the "effective mismatch". The post- tack, effective mismatch from CBMDA #1 is shown in Table 2. The sign convention for effective mismatch is such that a negative indicates the advancing root is "lower" than the retreating root. The maximum value of effective mismatch is -0.041" (1.04mm) which is approximately 20% of the weld land thickness.

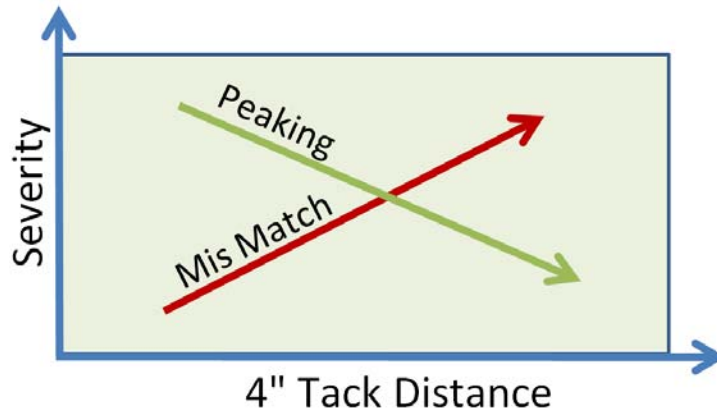


Figure 9- Trend of Joint Fit-up Severity along Tack Welds

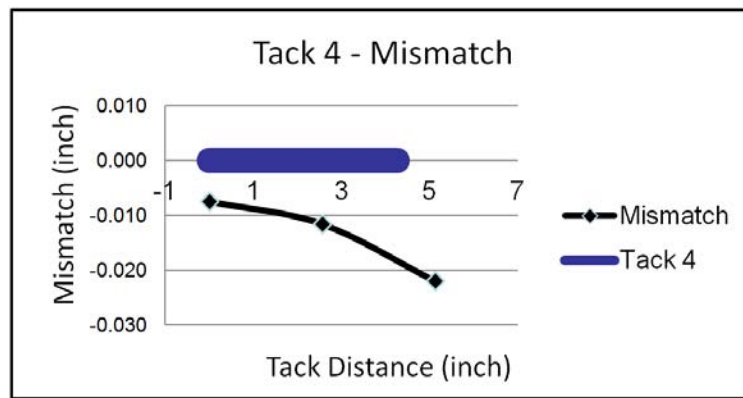


Figure 10 - Mismatch along a Tack Weld

Table 2 - CBMDA #1 Effective Mismatch

Average (in/mm)	-0.021 / -0.53
Minimum (in/mm)	-0.004 / -0.10
Maximum (in/mm)	-0.041 / -1.04

PAUT NDE indications were reported from the full penetration self-reacting weld. The weld was scanned after the full penetration weld and approximately 100 PAUT indications were reported. The locations of the indications from the transverse, cross-sectional view were categorized as crown, root or volume. The crown was defined as the upper one-third area of the cross section, the volume as the middle one-third, and the root as the lower one-third. Figure 11 shows a screen capture from a transverse, cross-sectional view of the PAUT scan. A PAUT indication is identified in the weld nugget volume. The shape of a typical SRFSW weld nugget was sketched and overlaid on the scan data as a visual aid. The PAUT indications were also presented in the c-

scan or “plan” view. The lengths and locations along the weld were determined. The lengths ranged from 0.15” (3.81mm) to 9.7” (246.4mm) and occurred intermittently along the entire circumference.

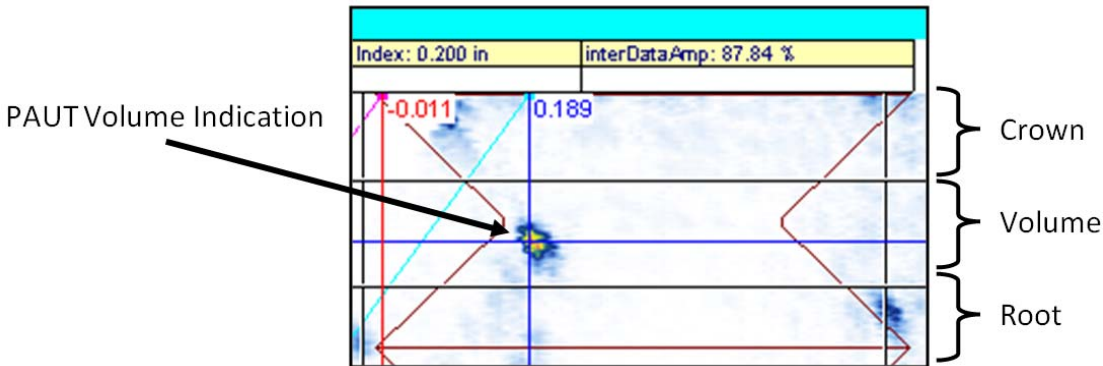


Figure 11 – Cross-sectional View of PAUT Scan with Volume Indication

The PAUT indications aligned with the tack welding locations. The tack weld locations were shown graphically. The locations of all the PAUT indications were plotted on the same chart. The chart was a simple observational tool that revealed a positive relationship between the locations of PAUT indications to the locations of tack welds. Figure 12 shows a sample chart with the tack welds and PAUT indications overlaid.

Tack anvils were employed to remediate joint fit-up issues. The prevailing theory was that the weld discontinuities identified by PAUT were a result of poor joint fit-up during the self reacting friction stir. The poor joint fit up was known to be caused by the tack welding process. Tack anvils were intentionally not used on CDMDA #1 in order to determine the effects. The rationale was that if tack anvils proved unnecessary, tooling and operational cost savings would be realized. The decision was made to use supporting tack anvils on the next article and compare the results.

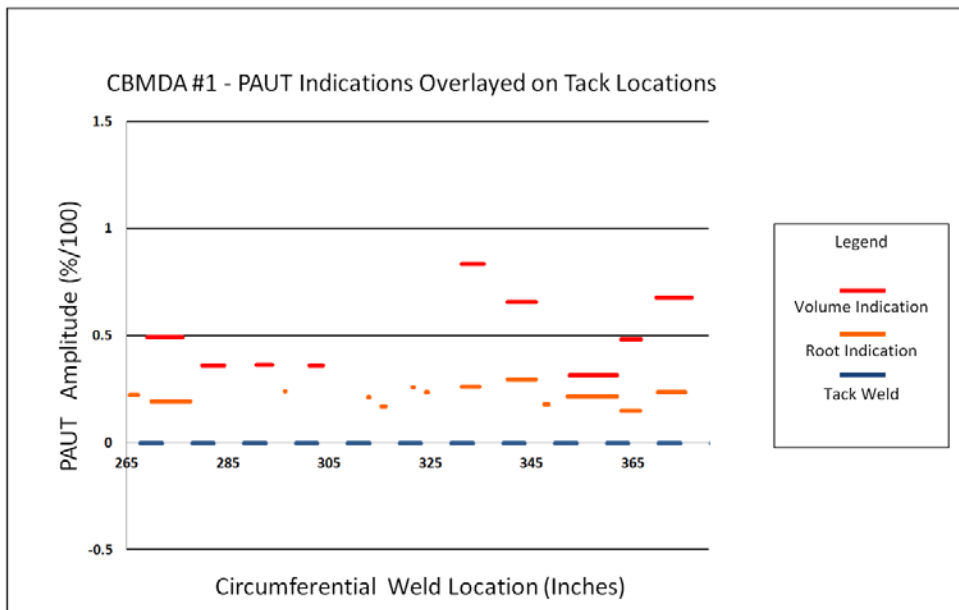


Figure 12 - PAUT Indications Plotted with Tack Weld Locations

4.2 CBMDA #2

PAUT indications were eliminated from CBMDA #2. The manufacturing and welding processes used to fabricate CBMDA #1 and #2 were consistent except for the use of tack anvils. Tack anvils were used on CBMDA #2. The dome and y-ring weld land thicknesses were measured before tack welding. The peaking and mismatch was measured after tack welding. Table 3 shows the effective mismatch statistics. The average effective mismatch was reduced from -0.021" on CBMDA #1 to -0.003" on CBMDA #2. The maximum effective post tack mismatch was improved to 0.015" (0.381mm). The positive value indicated that the dome was now slightly higher than the y-ring. The tack anvils in some locations slightly over compensated and pushed the dome out. The full penetration SR weld was executed. The weld joint was scanned with PAUT. Only two indications were reported. Both reported indications were shallow, root type. The indications were removed by sanding and blending the root surface. The indication areas were rescanned with PAUT. The CBMDA #2 self reacting friction stir weld was reported as defect free.

Table 3 - CBMDA #2 Effective Mismatch

Average (in/mm)	-0.003 / 0.076
Minimum (in/mm)	-0.002 / 0.051
Maximum (in/mm)	0.015 / 0.381

5.0 Conclusion

The successful completion of the LH2 MDA, the CBMDA #1 and the CBMDA #2 was considered an Ares I program milestone. A low cost “fixtureless” tooling approach was implemented on the LH2 MDA to replace complex and expensive fitting-to-dome weld external tooling. Tacking anvils were employed on the CBMDA #2 to ultimately eliminate weld discontinuities. Welding and manufacturing lessons learned from these development articles were translated to schedule and cost savings for the production contractor and to the National Aeronautic and Space Administration as a whole.



Robotic Manufacturing of 18ft (5.5m) Diameter Cryogenic Fuel Tank Dome Assemblies for the NASA Ares I Rocket

Robert Carter – NASA

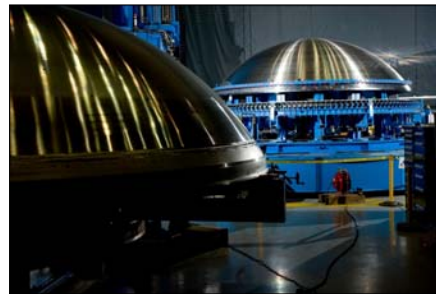
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Presentation Objective

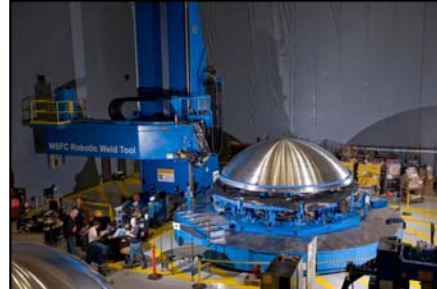


- ◆ Present an overview of the manufacturing and welding processes used to assemble Ares I upper stage rocket components on the Robotic Weld Tool at the NASA George C. Marshall Space Flight Center





Robotic Weld Tool



◆ Robotic Weld Tool (RWT)

- Marshall Space Flight Center
- Conventional FSW
- Self-reacting FSW
- Retractable pin FSW
- OEM is MTS Systems Corporation
- 7-axis
- Applied axial load >10,000 lbf
- Positional accuracy <0.010"

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Facility




Bldg 4755 Advanced Manufacturing Facility


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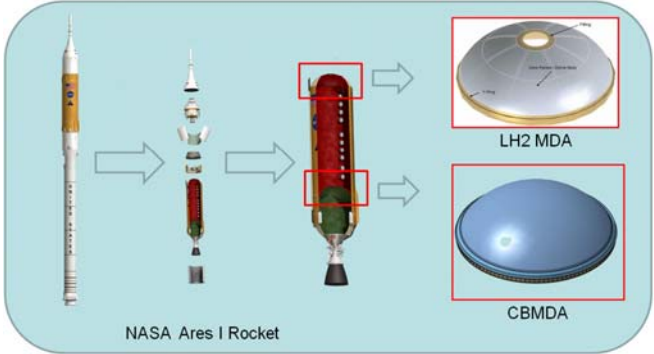
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Development Articles







NASA Ares I Rocket

- ◆ **Liquid Hydrogen Manufacturing Development Article (LH2 MDA)**
 - Represents the forward end of the upper stage LH2 tank
- ◆ **Common Bulkhead Manufacturing Development Article (CBMDA)**
 - Represents the forward LOX and aft LH2 tank domes


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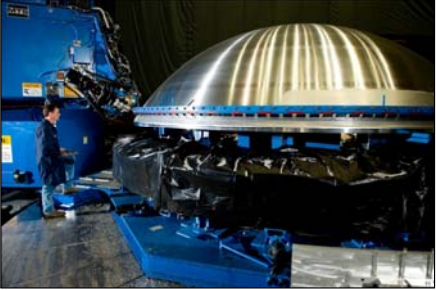




Components








- ◆ **Gore Panels**
 - Al 2195
 - Stretch formed
 - 0.250" (6.35mm) weld land

- ◆ **Formed Domes**
 - Al 2014
 - Spun formed
 - 0.208" (5.3mm) weld land

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Components



◆ Y-ring Stiffeners

- Al 2219
- Machined from forging
- 0.208" (5.3mm) weld land



◆ Barrel "Skirt" Section

- Al 2195
- Bumped formed
- 0.327" (8.3mm) weld land

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Components



◆ "Manhole" fitting

- Al 2195
- Machined from forging
- 0.250" (6.35mm) weld land



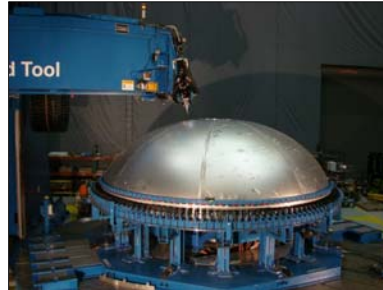
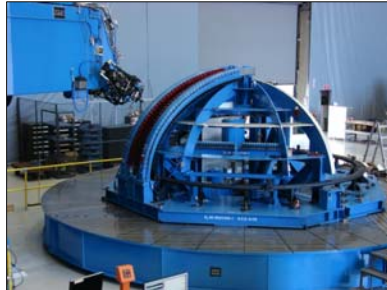
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LH2 MDA



Liquid Hydrogen (LH2) Manufacturing Development Article (MDA)

◆ Dome Fabrication

- 8 gore panels welded together
- Conventional FSW
- ET style left-hand threaded pin
- Convex shoulder
- Panels trimmed on RWT
- Quarter domes constructed
- Final 'keystone' gore custom fit

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LH2 MDA



Liquid Hydrogen (LH2) Manufacturing Development Article (MDA)

◆ Y-ring to Dome

- Self reacting FSW
- LH / RH pin tool
- Scrolled shoulder
- Dome trimmed to fit y-ring

◆ Fitting to Dome

- Self reacting FSW
- LH / RH pin tool
- Scrolled shoulder
- Dome trimmed to fit fitting

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Common Bulkhead

Hydrogen Tank (LH2)

Oxygen Tank (LOX)

CB Fwd Dome Assembly

Honeycomb Core

CB Aft Dome Assembly

Bolting Ring

Seal Plate

◆ **What is a common bulkhead?**

- Common bulkhead separates LH2 and LOX tanks
- Composed of 2 separate dome assemblies
- LH2 dome stacked on LOX dome
- Separated by honeycomb core
- Honeycomb acts as thermal barrier

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CBMDA

Common Bulkhead Manufacturing Development Article (CBMDA)

◆ **Dome to Y-ring Weld**

- Self reacting FSF
- LH / RH pin tool
- Scrolled shoulder
- Spun formed dome
- Dome trimmed to fit y-ring
- Welded (2) forward LH2 articles
- Welded (2) aft LOX articles

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TPS Dome

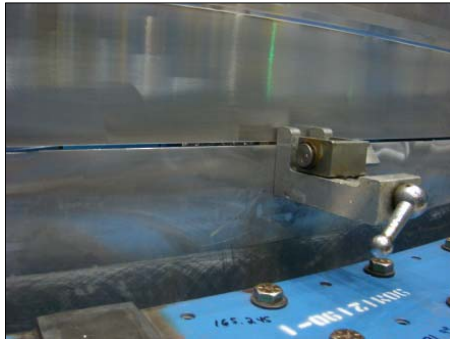


Thermal Protection System Dome (TPS)

- ◆ **Barrel Skirt to Y-ring / Dome Assembly**
 - Ares follow-on work
 - Self reacting FSW
 - LH / RH pin tool
 - Scrolled shoulder
 - Improved tooling
 - 0.327" (8.3mm) weld land



TPS Dome



Hawthorne clamps squeeze out mismatch



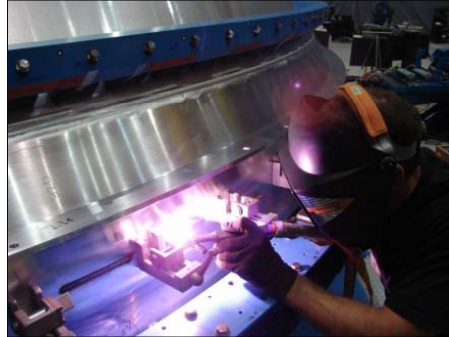
Bottle jacks position skirt



TPS Dome



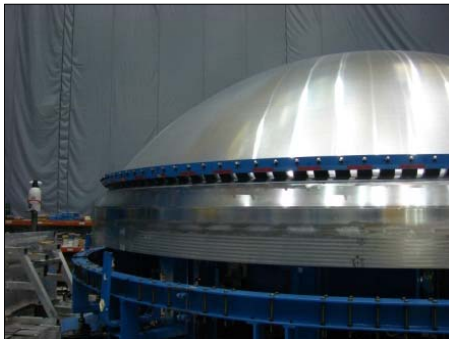
Interior view of Hawthorne Clamps



GTAW tack welding



TPS Dome



Skirt assembled, tack welded and cleaned



Start hole for self-reacting FSW



TPS Dome



Welded skirt



RWT drilling tooling attachment holes

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Robotic Weld Tool Team



- Ronnie Renfroe – Lead Technician, NASA
- Sam Smith – Technician, APL
- Larry Holt – Senior Technician, Boeing
- Curtis Bahr – Senior Technician, Qualis
- Todd Renz – Engineer, Boeing
- Ron Jones – Engineer, JTI

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Thank you!



Questions?