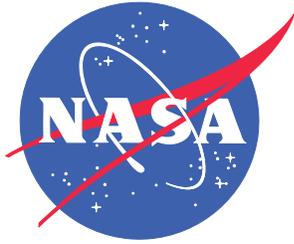


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# Spin Forming Aluminum Crew Module (CM) Metallic Aft Pressure Vessel Bulkhead (APVBH) – Phase II

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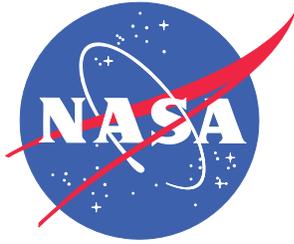
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Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 1 of 223

**Spin Forming Aluminum Crew Module (CM) Metallic  
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**November 20, 2014**

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:		Page #:	
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>		<b>2 of 223</b>	

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>3 of 223</b>

## Table of Contents

<b>1.0</b>	<b>Notification and Authorization</b> .....	<b>11</b>
<b>2.0</b>	<b>Signature Page</b> .....	<b>12</b>
<b>3.0</b>	<b>Team List</b> .....	<b>13</b>
3.1	Acknowledgements.....	13
<b>4.0</b>	<b>Executive Summary</b> .....	<b>15</b>
<b>5.0</b>	<b>Background</b> .....	<b>19</b>
5.1	Goals and Objectives.....	22
5.2	Spin Formed Aft-Bulkhead Pathfinder.....	22
<b>6.0</b>	<b>Aft-Bulkhead Spin Forming Pathfinder:</b> .....	<b>22</b>
6.1	Requirements and Specifications.....	22
6.2	Material Specifications.....	24
<b>7.0</b>	<b>Spin Forming Manufacturing Process</b> .....	<b>25</b>
7.1	Manufacturing of Aft Bulkhead.....	25
7.2	Material Procurement.....	25
7.3	Inspection of Raw Plate.....	26
7.4	Machining and Preparation of Forming Blank.....	26
7.5	Annealing of Spin Forming Blank.....	26
7.6	Spin Form Process.....	26
7.7	Post Spin Forming Inspection.....	27
7.8	Heat Treatment to the T62 Temper.....	30
7.9	Final Product Inspection.....	31
7.10	Coupon Blank Machining.....	34
<b>8.0</b>	<b>Aft Bulkhead Test and Analysis</b> .....	<b>38</b>
8.1	Test and Analysis Procedures.....	39
8.2	Metallurgical Analysis.....	39
8.3	Tensile Test Procedures.....	41
8.4	Fracture Toughness Test Procedures.....	47
8.5	Stress Corrosion Test Procedures.....	53
8.6	Seacoast Exposure SCC Test Plan.....	64
<b>9.0</b>	<b>LM Test Plan</b> .....	<b>66</b>
9.1	Self-Reacting FSW and FPPW Development.....	66
9.2	Mechanical Property and Structural Subcomponent Testing.....	68
<b>10.0</b>	<b>Results and Discussion</b> .....	<b>70</b>
10.1	Metallurgical Analysis.....	70
10.1.1	Thickness Measurements.....	70
10.1.2	Microstructural Analysis.....	72
10.2	Tensile Test Results.....	88
10.2.1	Uniformity of Tensile Properties.....	90
10.2.2	Comparison with Handbook Data and Other T6 and T8 Products.....	116
10.2.3	Tensile Fractography.....	124
10.3	Fracture Toughness Test Results.....	128
10.3.1	Uniformity of Fracture Properties.....	129

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>4 of 223</b>

10.3.2	Fractography .....	140
10.3.3	Comparison with Handbook Data and Other T6 and T8 Products .....	142
10.4	SCC Test Results .....	145
10.4.1	Alternate Immersion Test Results.....	146
10.4.1.1	30-day Alternate Immersion Exposure Test Results .....	146
10.4.1.2	90-day Alternate Immersion Exposure Test Results .....	148
10.4.1.3	Discussion of Alternate Immersion Exposure Test Results.....	148
10.4.2	Salt Spray Test Results .....	149
10.4.2.1	30-day Salt Spray Exposure Test Results.....	149
10.4.2.2	90-day Salt Spray Exposure Test Results.....	150
10.4.3	Comparison with Handbook Data and Other T6 and T8 Products .....	150
10.4.4	Discussion of Stress Corrosion Results .....	152
<b>11.0</b>	<b>Supplemental Mechanical Test Program.....</b>	<b>170</b>
11.1	Tensile .....	171
11.2	Fracture Toughness.....	172
11.3	Stress Corrosion.....	173
<b>12.0</b>	<b>Findings, Observations, and NESC Recommendations.....</b>	<b>175</b>
12.1	Findings .....	175
12.2	Observations .....	177
12.3	NESC Recommendations .....	178
<b>13.0</b>	<b>Alternate Viewpoint.....</b>	<b>179</b>
<b>14.0</b>	<b>Other Deliverables .....</b>	<b>179</b>
<b>15.0</b>	<b>Lessons Learned.....</b>	<b>179</b>
<b>16.0</b>	<b>Recommendations for NASA Standards and Specifications.....</b>	<b>179</b>
<b>17.0</b>	<b>Definition of Terms.....</b>	<b>179</b>
<b>18.0</b>	<b>Acronyms List .....</b>	<b>180</b>
<b>19.0</b>	<b>References.....</b>	<b>182</b>
<b>20.0</b>	<b>Appendices.....</b>	<b>185</b>
20.1	Appendix A: Temper Designations .....	185
20.2	Appendix B: Material Certification .....	185
20.3	Appendix C: Fracture Toughness Data.....	187

### List of Figures

Figure 5.0-1.	Welded MPCV CM Configuration .....	19
Figure 5.0-2.	Schematic of the Metal Spinning Process.....	20
Figure 6.1-1.	Proposed Aft Bulkhead Pathfinder Configuration.....	23
Figure 7.6-1.	Convex Spin Forming Of The Aft Bulkhead.....	27
Figure 7.7-1.	Schematic of Forming Inspection Template showing Numbered Locations of Ultrasonic Thickness Measurements .....	28
Figure 7.7-2.	Thickness Profile of the Aft Bulkhead based on Ultrasonic Thickness Measurements at the Locations shown in Figure 7.7-1.....	30
Figure 7.8-1.	Aft Bulkhead Following Heat Treatment.....	31

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>5 of 223</b>

Figure 7.9-1.	Section of Laser Scan showing the Locations of Thickness Determinations .....	32
Figure 7.9-2.	Thickness Measurements of the Aft Bulkhead determined from the Laser Scan Data compared with the UT Measurements.....	34
Figure 7.10-1.	Aft Bulkhead Coupon Cut Plan .....	35
Figure 7.10-2.	Aft Bulkhead following Extraction of Coupon Blanks for Test and Analysis .....	35
Figure 7.10-3.	Coupon Blank Marking Scheme .....	36
Figure 8.2-1.	Aft Bulkhead Cut Plan showing the Location of the Metallurgical Analysis Strip Highlighted in Yellow. ....	40
Figure 8.2-2.	Metallurgical Analysis Blank showing the Locations of Specimens L7-1 through L7-5.....	41
Figure 8.2-3.	Thermally Processed Test Blocks.....	41
Figure 8.3-1.	Aft Bulkhead Cut Plan showing the Location of the Tensile Coupon Blanks highlighted in Yellow .....	42
Figure 8.3-2.	Round Subsize Tensile Specimen Design used for Testing in the L and LT Orientations.....	43
Figure 8.3-3.	Round Subsize Tensile Specimen Design used for Testing in the ST and ST45 Orientations.....	44
Figure 8.3-4.	Tensile Test Load Stand, Specimen, and Instrumentation.....	46
Figure 8.3-5.	Typical Stress-Strain Curve for the Spin Formed Al 2219-T62 Aft Bulkhead Material in the L Orientation; Coupon Blank L2, Specimen T-L2-L-13.....	47
Figure 8.4-1.	Aft Bulkhead Cut Plan showing the Location of the Fracture Toughness Coupon Blanks highlighted in Yellow.....	48
Figure 8.4-2.	J <sub>IC</sub> Fracture Toughness Specimen Design; L-T and T-L Orientations.....	49
Figure 8.4-3.	J <sub>IC</sub> Fracture Toughness Specimen Design; S-T Orientation .....	49
Figure 8.4-4.	J <sub>IC</sub> fracture Toughness Specimen and Test Apparatus.....	51
Figure 8.4-5.	J <sub>IC</sub> Fracture Toughness R-Curve Plot.....	52
Figure 8.4-6.	Typical J <sub>IC</sub> Fracture Toughness R-Curve Plot .....	52
Figure 8.4-7.	Typical Cross-Sectional Fracture Surface of a J <sub>IC</sub> Fracture Toughness Specimen .....	53
Figure 8.5-1.	Aft Bulkhead Cut Plan showing the Location of the SCC Coupon Blanks highlighted in Yellow .....	54
Figure 8.5-2.	Round Sub-Size Tensile Specimen Design used for SCC Testing .....	55
Figure 8.5-3.	Cut Plan for Machining SCC Specimens from Coupon Blank M7 (specimens CP-406-1 through CP-406-42).....	56
Figure 8.5-4.	Cut Plan for Machining SCC Specimens from Coupon Blank M8 (specimens CP-406-43 through CP-406-84).....	57
Figure 8.5-5.	Cut Plan for Machining SCC Specimens from Coupon Blank M9 (specimens CP-406-85 through CP-406-126).....	58
Figure 8.5-6.	Cut Plan for Machining SCC Specimens from Coupon Blank M10 (specimens CP-406-127 through CP-406-189).....	59
Figure 8.5-7.	(a) Stressing Device and (b) Representative Stressed Specimens and Stressing Frames.....	62
Figure 8.5-8.	(a) Alternate Immersion Test Apparatus and (b) Salt Spray Chamber .....	62
Figure 8.6-1.	Aft Bulkhead Cut Plan showing the Location of the Seacoast Exposure SCC Coupon Blanks highlighted in Yellow.....	65
Figure 9.1-1.	Aft Bulkhead Cut Plan showing the Location of the FSW and FPPW Schedule Development Coupon Blanks .....	67

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP-13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 6 of 223	

Figure 9.2-1.	Aft Bulkhead Cut Plan showing the Location of the Supplemental Mechanical Property Test Coupon Blanks highlighted in Yellow .....	69
Figure 9.2-2.	Schematic showing the Simulated Location for Backbone Panel 6 Connection to Aft Bulkhead Joint .....	70
Figure 10.1-1.	Thickness Profile of Coupon Blank L7 compared with the UT and Laser Scan Data.....	72
Figure 10.1-2.	Through-Thickness Microstructures of the Aft Bulkhead at Locations along the 0° Meridian.....	73
Figure 10.1-3.	Microstructure at the IML, t/8, t/4, 3t/8, t/2, 5t/8, 3t/4, 7t/8, and OML Through-thickness Positions for (a) L7-1, (b) L7-2, (c) L7-3, (d) L7-4, and (e) L7-5 Locations along the 0° Meridian.....	76
Figure 10.1-4.	Through-thickness Microstructures of the Thermally Processed Test Blocks.....	78
Figure 10.1-5.	Microstructure at the IML, t/2, 5t/8, 3t/4, 7t/8, and OML Through-thickness Positions for the (a) T4 and (b) T6 Thermally Processed Test Blocks.....	80
Figure 10.1-6.	Microstructure of Aft Bulkhead Locations L7-1 through L7-5 compared with the T6 Thermally Processed Test Blocks at Through-thickness Positions (a) IML, (b) t/2, (c) 5t/8, (d) 3t/4, (e) 7t/8, and (f) OML.....	87
Figure 10.2-1.	Aft Bulkhead Cut Plan showing the Location of the Tensile Coupon Blanks highlighted in Yellow .....	89
Figure 10.2-2.	Average Longitudinal (L) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan.....	101
Figure 10.2-3.	Average Long Transverse (LT) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan .....	102
Figure 10.2-4.	Average Short Transverse (ST) Tensile Properties Superimposed on the Aft Bulkhead Cut plan .....	103
Figure 10.2-5.	Average Short Transverse 45° (ST45) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan .....	104
Figure 10.2-6.	Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle.....	105
Figure 10.2-7.	Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle .....	106
Figure 10.2-8.	Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole Along the 90° to 270° Meridian Angle.....	107
Figure 10.2-9.	Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle.....	108
Figure 10.2-10.	Short Transverse (ST) Tensile Properties Of The Spin Formed Al 2219-T62 Aft Bulkhead Material As A Function Of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle.....	109
Figure 10.2-11.	Short Transverse 45° (ST45) tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle.....	110

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP-13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 7 of 223	

Figure 10.2-12. Short Transverse (ST) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle.....	111
Figure 10.2-13. Short Transverse 45° (ST45) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle.....	112
Figure 10.2-14. Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc Length .....	113
Figure 10.2-15. Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc Length .....	114
Figure 10.2-16. Short Transverse (ST) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a function of Meridian Angle along the R35 Circumferential Arc Length .....	115
Figure 10.2-17. Short Transverse 45° (ST45) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a function of Meridian Angle along the R35 Circumferential Arc Length.....	116
Figure 10.2-18. Representative Macroscopic view of the Fracture Surfaces from the top and side views for Tensile Specimens L1-L-3 (left), L2-L-14 (middle), and L2-LT-16 (right) .....	125
Figure 10.2-19. SEM Images of the Fracture Surface of Tensile Specimen L2-L-14 at a) 14x; b) 50x; c) 500x and d) 2,000x Magnifications.....	126
Figure 10.2-20. SEM Images of the Fracture Surface of Tensile Specimen ST-43 at (a) 25x; (b) 50x; (c) 500x and (d) 2,000x Magnifications.....	127
Figure 10.2-21. SEM Images of the Fracture Surface of Tensile Specimen ST45-12 at (a) 25x; (b) 50x; (c) 500x and (d) 2,000x Magnifications.....	128
Figure 10.3-1. Aft Bulkhead Cut Plan showing the Location of the fracture Coupon Blanks highlighted in Yellow .....	129
Figure 10.3-2. Fracture Toughness Data as a Function of Orientation.....	131
Figure 10.3-3. Fracture Toughness Data as a Function of Coupon Blank Location and Grain Orientation .....	133
Figure 10.3-4. Fracture Toughness Data as a Function of Arc Length Distance from Pole for the 0° to 180° Meridian .....	134
Figure 10.3-5. Fracture Toughness Data as a Function of Arc Length Distance from Pole for the 90° to 270° Meridian. ....	135
Figure 10.3-6. Fracture Toughness Data as a Function of Meridian Angle for Arc Length Distance of 36 inches.....	136
Figure 10.3-7. Fracture Toughness Data as a Function of Meridian Angle for Arc Length Distance of 55 inches.....	137
Figure 10.3-8. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the L-T Orientation; Coupon Blank M3, Specimen CP-406-223. ....	138
Figure 10.3-9. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the T-L Orientation; Coupon Blank M3, Specimen CP-406-228. ....	139
Figure 10.3-10. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the S-T Orientation; Coupon Blank M3, Specimen CP-406-233 .....	140

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>8 of 223</b>

Figure 10.3-11. Photomicrograph of Fracture Surface of T-L Fracture Specimen from Coupon Blank M2 .....	141
Figure 10.3-12. Photomicrograph of Fracture Surface of L-T Fracture Specimen from Coupon Blank M2 .....	141
Figure 10.3-13. Photomicrograph of Fracture Surface of S-T Fracture Specimen from Coupon Blank M2 .....	142
Figure 10.3-14. Fracture Toughness Comparison between Spin Formed Al 2219-T62 Aft Bulkhead Material and Al 2219-T87 Plate .....	144
Figure 10.3-15. Fracture Toughness Comparison between Spin Formed Al 2219-T62 Aft Bulkhead Material and other Al 2219 Tempers in the T-L Orientation.....	145
Figure 10.4-1. Aft Bulkhead Cut Plan showing the location of the SCC Coupon Blanks highlighted in Yellow.....	146
Figure 10.4-2. Photomicrographs of Representative SCC Specimens obtained from Coupon blank M7 following 3.5% NaCl Alternate Immersion Exposure (30-day test) .....	157
Figure 10.4-3. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M8 following 3.5% NaCl Alternate Immersion Exposure (30-day test) .....	158
Figure 10.4-4. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M9 following 3.5% NaCl Alternate Immersion Exposure (30-day test) .....	159
Figure 10.4-5. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M10 following 3.5% NaCl Alternate Immersion Exposure (30-day test) .....	160
Figure 10.4-6. Photomicrographs of Representative SCC Specimens obtained from Various Coupon Blanks following 3.5% NaCl Alternate Immersion Exposure (90-day test).....	168
Figure 20.2-1. Material Certification Report for the 2219-F Plate.....	186

### List of Tables

Table 7.2-1. Chemical Composition, wt % .....	25
Table 7.7-1. Ultrasonic Thickness Measurements of the Aft Bulkhead corresponding to Locations 5 through 20 shown in Figure 7.7-1. ....	29
Table 7.9-1. Thickness Measurements of the Aft Bulkhead based on Laser Tracking Scans of the IML and OML. ....	33
Table 7.10-1. Location and Orientation of Coupon Blanks. ....	37
Table 7.10-2. Coupon Blank Designation, Test Center, and Test Type.....	38
Table 8.3-1. Tensile Coupon Blank Size, Locations, and Orientations .....	42
Table 8.3-2. Tensile Test Matrix for the Aft Bulkhead.....	45
Table 8.4-1. Fracture Toughness Coupon Blank Locations and Orientations.....	48
Table 8.4-2. Fracture Test Matrix for the Aft Bulkhead. ....	50
Table 8.5-1. SCC Coupon Blank Locations and Orientations.....	54
Table 8.5-2. 30-day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material .....	60
Table 8.5-3. 90-day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material .....	61
Table 8.5-4. 30-day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material .....	61
Table 8.5-5. 90-day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material .....	61
Table 8.6-1. Seacoast Exposure SCC Coupon Blank Locations and Orientations.....	65
Table 8.6-2. Test Matrix for the Seacoast Exposure SCC Tests. ....	66
Table 9.1-1. FSW and FPPW Schedule Development Coupon Blank Locations and Orientations .....	67



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
9 of 223

Table 9.2-1.	LM Mechanical Property Test Coupon Blank Locations and Orientations.....	69
Table 10.1-1.	Thickness Measurements of Coupon Blank L7 at Distances from the Pole.....	71
Table 10.2-1.	Tensile Coupon Blank Locations and Orientations.....	90
Table 10.2-2.	Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Longitudinal (L) Orientation.....	91
Table 10.2-3.	Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Long- Transverse (LT) Orientation.....	92
Table 10.2-4.	Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse (ST) Orientation.....	93
Table 10.2-5.	Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse 45° (ST45) Orientation.....	94
Table 10.2-6.	Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Longitudinal (L) Orientation.....	95
Table 10.2-7.	Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Long Transverse (LT) Orientation.....	96
Table 10.2-8.	Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse (ST) Orientation.....	97
Table 10.2-9.	Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse 45° (ST45) Orientation.....	98
Table 10.2-10.	Average Tensile Properties and standard Deviation Values for the Spin Formed Al 2219-T62 Aft Bulkhead Material.....	98
Table 10.2-11.	Design Tensile Properties of Al 2219-T62, T851 and T87 Sheet and Plate.....	120
Table 10.2-12.	Typical tensile Properties of Al 2219-T62, T851, and T87 sheet and plate.....	120
Table 10.2-13.	Average Tensile Properties for the Spin Formed Al 2219-T62 FPVBH Material.....	121
Table 10.2-14.	Tensile Properties of Spin Formed Al 2219-T62 Domes for the Cryogenic Propellant Storage and Transfer (CPST) Program.....	122
Table 10.2-15.	Typical Tensile Properties of Spin Formed Al 2219-T62 Domes Commercially Produced by Spincraft.....	123
Table 10.2-16.	Minimum Tensile Properties for Al 2219-T6 Forgings and Rolled or Forged Rings.....	124
Table 10.3-1.	Fracture Toughness Coupon Blank Locations and Orientations.....	129
Table 10.3-2.	Summary of Fracture Data for the Spin Formed Al 2219-T62 Aft Bulkhead Material.....	130
Table 10.4-1.	SCC Coupon Blank Locations and Orientations.....	146
Table 10.4-2.	30-day SCC Test Results for Spin Formed Al 2219-T62 Aft Bulkhead Material.....	155
Table 10.4-3.	Baseline Tensile Properties of Spin Formed Al 2219-T62 Aft Bulkhead Material.....	156
Table 10.4-4.	Residual tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44.....	161
Table 10.4-5.	Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44.....	162
Table 10.4-6.	Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44.....	163

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 10 of 223	

Table 10.4-7.	Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44. ....	164
Table 10.4-8.	Rating of Spin Formed Al 2219-T62 Aft Bulkhead Material per MSFC-STD-3029 .....	165
Table 10.4-9.	90-day SCC Test Results for Spin Formed Al 2219-T62 Aft Bulkhead Material .....	166
Table 10.4-10.	Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 90-day exposure to 3.5% NaCl alternate immersion per ASTM G44. ....	167
Table 10.4-11.	30-day SCC Test Results for Spin Formed Al 2219-T62 Aft Bulkhead Material .....	169
Table 10.4-12.	90-day SCC Test Results for Spin Formed Al 2219-T62 Aft Bulkhead Material. ....	169
Table 10.4-13.	Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following Exposure to 5% Salt Spray per ASTM B117. ....	169
Table 10.4-14.	SCC Test Data for other 2xxx series Al Alloys for Comparison. ....	170
Table 10.4-15.	Rating of Al 2195-T8 and Al 2219-T87 per MSFC-STD-3029. ....	170
Table 11.1-1.	Supplemental Tensile Test Matrix .....	171
Table 11.2-1.	Supplemental Fracture Toughness Test Matrix .....	172
Table 11.3-1.	Supplemental SCC Test Matrix .....	174

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 11 of 223	

## Technical Assessment Report

### 1.0 Notification and Authorization

The principal focus of this project was to assist the Multi-Purpose Crew Vehicle (MPCV) program in developing a spin forming fabrication process for manufacture of the Orion crew module (CM) aft pressure vessel bulkhead. The spin forming process will enable a single piece aluminum (Al) alloy 2219 aft bulkhead resulting in the elimination of the current multiple piece welded construction, simplify CM fabrication, and lead to an enhanced design. Phase I (NASA TM-2014-218163, (1)) of this assessment explored spin forming the single-piece CM forward pressure vessel bulkhead.

The MPCV Program and Lockheed Martin (LM) recently made two critical decisions relative to the NESC Phase I work scope: (1) LM selected the spin forming process to manufacture a single-piece aft bulkhead for the Orion CM, and (2) the aft bulkhead will be manufactured from Al 2219.

Based on the Program's new emphasis related to the spin forming process, the NESC was asked to conduct a Phase II assessment to assist in the LM manufacture of the aft bulkhead and to conduct a feasibility study into spin forming the Orion CM cone.

This activity was approved on June 19, 2013. Dr. Robert Piascik, NASA Technical Fellow for Materials at the Langley Research Center (LaRC), was selected to lead this assessment. The project plan was approved by the NASA Engineering and Safety Center (NESC) Review Board (NRB) on July 18, 2013.

The primary stakeholders for this assessment are the NASA and LM MPCV Program offices. Additional benefactors are commercial launch providers developing CM concepts.



	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>13 of 223</b>

### 3.0 Team List

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### 3.1 Acknowledgements

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 14 of 223	

DeWeese (MSFC) for their dedicated support for tensile, stress corrosion cracking (SCC), fracture testing, and metallurgical analysis support. The team appreciates the dedicated support of Ayman Girgis (ESSSA/Jacobs) for his tensile and fracture toughness assessment and PoShou Chen (ESSSA/Jacobs) for his microstructural and failure analysis assessment.

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			15 of 223

## 4.0 Executive Summary

The objective of this project was to assist the Multi-Purpose Crew Vehicle (MPCV) Program in developing a spin forming fabrication process for the manufacture of the Orion crew module (CM) aft pressure vessel bulkhead (APVBH) and evaluate the feasibility for manufacture of a single-piece cone. The spin forming process would enable a single-piece aluminum (Al) alloy 2219 aft bulkhead and single-piece cone resulting in the elimination of the current multiple piece welded construction, simplify CM fabrication, and lead to an enhanced design. The objectives of this two-part study were to: (1) spin form a full scale generic aft bulkhead component and characterize its properties as a pathfinder for the Lockheed-Martin (LM) Orion CM, and (2) develop a first-of-a-kind thick-component (6 inches thick) spin forming process for the manufacture of a single piece integrally-machined CM cone that would accommodate all design features (i.e., integral stiffeners, window frames, etc.). This report will focus on the aft bulkhead portion of this study only. The cone feasibility study determined that the benefits of a single-piece cone fabricated using spin forming were not sufficient to warrant proceeding with fabrication and testing. The single-piece cone feasibility study will be described in a supplement to this report.

The NESC Phase I activity, Spin Forming Aluminum Crew Module (CM) Forward Pressure Vessel Bulkhead (FPVBH) (1), demonstrated the feasibility of spin forming a single-piece FPVBH using either Al alloys 2219 or 2195. Based on the Phase I feasibility results, the MPCV Program requested that a Phase II spin forming activity be conducted to address specific objectives (processing and preliminary properties) associated with spin forming the aft bulkhead.

The MPCV Program and LM recently made two critical decisions relative to the NESC Phase I work scope: (1) LM selected the spin forming process to manufacture a single-piece aft bulkhead for the Orion CM, and (2) the aft bulkhead will be manufactured from Al 2219. The motivation for the change in manufacturing method included eliminating weld lands, lowering overall weight, simplifying the design, and improving design analysis and fidelity. The change in material was driven by the single-piece aft bulkhead design, which requires a preform thicker than 2 inches in order to accommodate all design features. Al-Li 2195 is limited in thickness to 2 inches or less due to quench rate sensitivity, which results in in-plane and through-thickness mechanical property anisotropy. As a result, the spin formed single-piece aft bulkhead design requires a corresponding change in material to thicker gage Al 2219.

The following tasks were defined to validate the spin forming process feasibility and demonstrate that acceptable material properties are achieved in a fully processed aft bulkhead:

1. Develop process parameters and spin form a pathfinder aft bulkhead representative of the Orion CM geometry using Al alloy 2219.
2. Develop a preliminary properties data base using material from the fully processed Al 2219-T62 pathfinder aft bulkhead regarding:
  - a. Microstructure
  - b. Mechanical properties (tensile and fracture toughness)
  - c. Stress corrosion cracking (SCC)

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			16 of 223

3. Develop circumferential (aft bulkhead to barrel) friction stir welding (FSW) parameters using material from the pathfinder aft bulkhead (LM activity).

A pathfinder aft bulkhead was successfully fabricated at a spin forming vendor using standard commercial spin forming and heat treatment practices. The curvature and thickness of the pathfinder were representative of and scalable to the Orion CM geometry. The aft bulkhead was fabricated using a single plate of Al 2219 and was fully processed to the T62 temper. Material was provided for metallurgical examination, tensile, fracture toughness, and stress corrosion testing by NASA. Additional material was provided to LM for additional mechanical property testing, self-reacting friction stir weld (SR-FSW) development for the aft bulkhead-to-CM barrel section joint, and structural sub element testing. The goal of these tasks was to address specific MPCV Program needs related to spin forming the Orion CM APVBH. The overall goal was to reduce risk by assessing a new manufacturing method prior to program deployment, provide information to guide first article test and analysis, develop an initial property database, identify preliminary issues or “show stoppers,” and accelerate program implementation.

This NESC assessment included microstructure evaluation, tensile and fracture toughness property testing, and SCC characterization to develop an initial property database for spin formed and heat treated Al 2219. Selected pathfinder regions (acreage locations) were tested to assess property uniformity. The resulting properties were compared to existing databases, such as Metallic Materials Properties Development and Standardization (MMPDS) to determine relative ranking. This study concluded that there were no insurmountable technical issues that precluded spin forming an aft bulkhead. Major findings are as follows:

The microstructure of the aft bulkhead varied both through-thickness and with meridian distance from the pole. The primary differences were grain size, extent of recrystallization, and residual deformation bands. Strain-induced recrystallized microstructures occurred toward the outer mold line (OML) of the aft bulkhead and reflect deformation imparted by the spin forming rollers. The recrystallized region extended through more of the section thickness in regions of greater deformation, specifically farther from the pole. These variations in grain size in the aft bulkhead are indicative of the complex and varied deformation levels associated with the spin forming process, particularly when combined with the plate rolling history and post-forming heat treatment. Material property tests were performed for in-plane orientations (longitudinal (L) and long transverse (LT)) only at the mid-plane ( $t/2$  where  $t$  = thickness) location. Depending on the microstructure developed in a first article produced by LM for Orion, testing may be warranted at other through-thickness positions, particularly those biased toward the OML.

Tensile properties of the spin formed Al 2219-T62 aft bulkhead material were comparable to the MMPDS design properties for T62 wrought plate and other fabricated products in the T6 temper, such as spin formed domes, forgings and rolled rings. Tensile strength increased slightly, but measurably with distance from the pole and was uniform about the circumference. The short transverse (ST) tensile properties were notably greater than those for the other orientations L, LT, and 45° to the ST (ST45)), but elongations were about half. The tensile properties were lower than for Al 2219-T851 and T87 plate, as expected due to the increased precipitation

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 17 of 223	

strengthening in T8 temper wrought products that is imparted by the cold work prior to artificial aging.

Fracture toughness values were in-family with conventional Al 2219 tempers and product forms, and the typical variation with orientation was observed. Toughness values were higher for the spin formed material compared with Al 2219–T87 plate, which is expected for the strength levels measured). For 2xxx series Al alloys, strength and toughness are inversely proportional (i.e., T8 tempers achieve higher strength, but lower toughness. In-plane (L-T and T-L) toughness values were relatively constant for a given orientation and did not vary significantly across the aft bulkhead acreage. Toughness in the T-L orientation did decrease slightly with distance from the pole, which is in agreement with the trend noted for tensile strength. The test results showed high toughness values, high toughness-to-yield strength (YS) ratios, and rising R-curve behavior, which suggests excellent damage tolerance capability of the aft bulkhead material. In order to more fully characterize the damage tolerance capability of the material, the NESC team recommends conducting fatigue crack growth rate and surface crack tension testing on the aft bulkhead material.

Stress corrosion resistance varied with location and orientation, ranging from the equivalent of Table I to Table III ratings as per MSFC-STD-3029. The L and LT orientations were significantly more resistant to SCC than the ST orientation. The primary data of interest is the 30-day alternate immersion exposure. Results from this test method and test duration are typically the basis for handbook and table ratings for SCC resistance. No failures occurred for the LT orientation, even at the highest stress levels, and all specimens had passing post-exposure residual strength levels. Susceptibility to SCC in the ST orientation varied with location in the aft bulkhead with the highest SCC resistance occurring at the rim. Regions near the pole and some in the membrane had moderate SCC resistance. One SCC failure of an ST specimen from a membrane location occurred at a low enough exposure stress level to warrant concern, and if validated would result in a Table III rating for the spin formed aft bulkhead material. More importantly, the allowable design stress may need to be reduced.

However, some important points must be noted regarding this data. The aft bulkhead tests followed MSFC test standard MSFC-STD-3029 in which the exposure stress levels are based on the measured strength of the material. Handbook values are based on standards that use MMPDS A-basis allowables to determine exposure stress levels. Actual strength is always higher than the allowables due to statistical knockdown; consequently, the aft bulkhead specimens were exposed to higher stress levels than handbook data being used for comparison. Al 2219 is considered an isotropic material with properties in the L, LT, and ST orientations generally agreeing within less than 5%. The ST YS in the aft bulkhead was 10% greater than that for L and LT. While it is unclear whether the high ST YS is inherent in the plate used in fabrication of the spin forming blank or is related to the spin forming process, the high ST YS of the aft bulkhead material further increased the exposure stress levels. The MSFC standard is realistic in that actual material strength will govern the performance of fabricated hardware. However, the difference in exposure stress levels makes interpretation of the aft bulkhead data more difficult.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 18 of 223	

The test duration specified by MSFC-STD-3029 is an additional deviation from recommended practice. One disadvantage of the 3.5% NaCl alternate immersion test is that severe pitting may develop in the test specimens. As per ASTM G47, such pitting in tensile specimens with relatively small cross-sections can markedly reduce the effective cross-sectional area and result in net sectional stresses greater than nominal gross section stress. This end result is that the pitting may interfere with the valid evaluation of the SCC resistance of the material. For this reason, ASTM G47 and G64 recommend a 10-day alternate immersion exposure period for 2xxx series Al alloys when tested in the ST orientation and a 40-day exposure period when tested in the L and LT orientations. These exposure periods are believed to be long enough to detect susceptibility to intergranular SCC yet short enough to avoid excessive pitting that can lead to failure by another mechanism. General pitting, which served as initiation sites for SCC, was noted in the aft bulkhead material following 30-day alternate immersion exposure. The NESC team recommends that further evaluation of the aft bulkhead material be evaluated at shorter exposure times.

For alloys requiring microstructural control to avoid susceptibility to SCC, resistance is obtained by using heat treatments that produce uniform precipitation throughout the microstructure. The susceptibility of the Al 2219 aft bulkhead material to SCC is further exacerbated by the T62 temper, which results in a non-uniform distribution of precipitates. Because of the pitting potential and a susceptible heat treat temper to SCC, deployment of this material for the aft bulkhead may require a materials usage agreement (MUA) prior to acceptance for service.

Interpreting the significance of the SCC results was difficult due to the small data sets generated and the limited SCC data available in handbooks and open literature publications for Al 2219-T6. While the SCC results provide insight about the performance of spin formed Al 2219-T62 material, the data sets were insufficient to establish a threshold stress level for SCC, information that is of high importance to the LM Orion design team. The NESC team recommends that additional SCC testing be performed on serial aft bulkheads to define the SCC threshold. Additionally, SCC testing of Al 2219-T6 wrought products should be performed to generate sufficient data to substantiate handbook and table ratings of the SCC resistance of Al 2219. Finally, in order to understand the impact of the SCC susceptibility of the material on fracture toughness and fatigue, the NESC team recommends evaluating environmentally assisted cracking fracture toughness (KEAC) and fatigue  $((da/dN)_{SCC})$  in the S-T orientation in a 3.5% NaCl solution.

Based upon the findings and observations, recommendations for follow-on testing to be conducted by Orion are made. A supplemental mechanical property test program designed to address key findings and observations is also presented. These supplemental mechanical property test results will be issued as an addendum report to be published at a later date.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
19 of 223

## 5.0 Background

The primary structural elements of the Orion welded crew module (WCM), shown in Figure 5.0-1, consist of a single piece forged barrel, a multi-piece cone section, a single piece forward bulkhead, a single piece forward tunnel, integrated forward gussets, and a multi-piece welded aft bulkhead. The aft bulkhead configuration shown is assembled from Al-Li 2195 using one circular and two latitudinal welds. Fabrication of a Al 2219 single-piece aft bulkhead by spin forming, as is now planned by the Orion Program, will eliminate these welds, improving manufacturing efficiency and reducing the risk associated with welded structure.

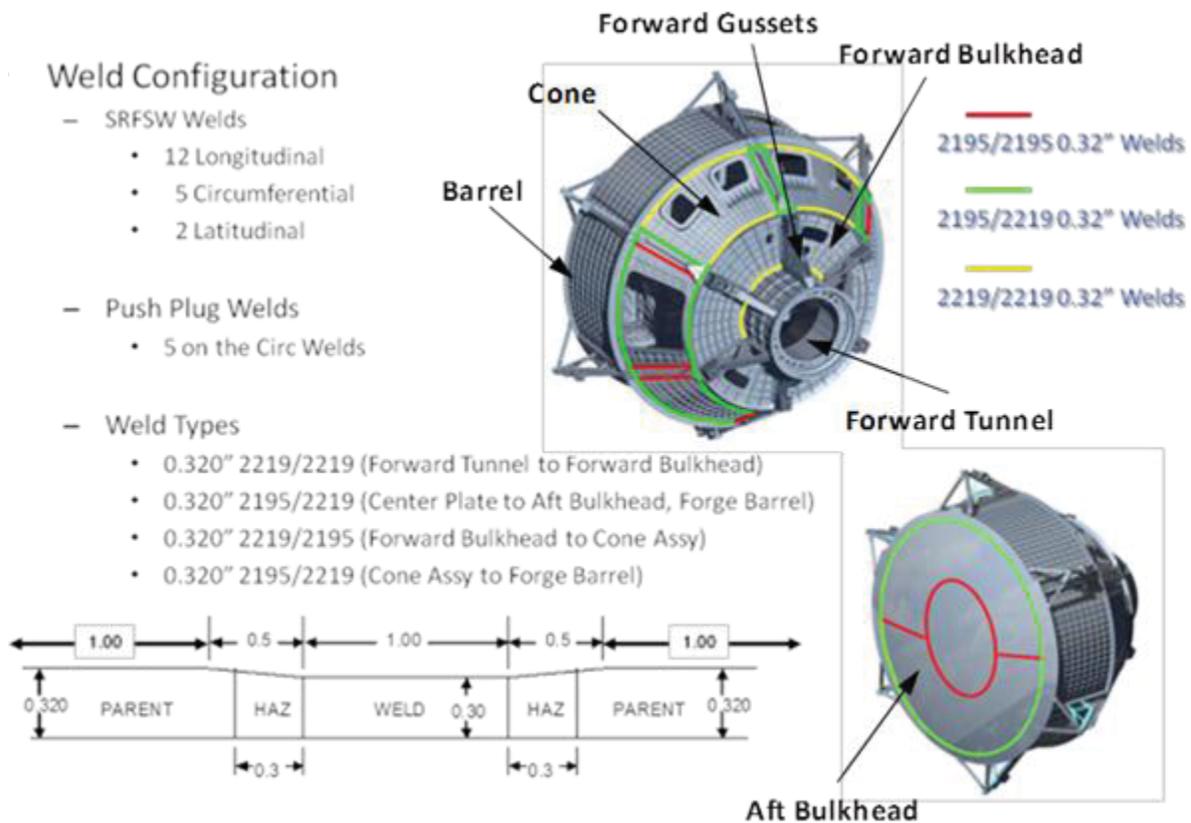


Figure 5.0-1. Welded MPCV CM Configuration

Spin forming is an established commercial metalworking process used in many industries, including fabrication of cryogenic tank domes. In convex spin forming, a circular disc of metal, called the forming blank, and a mandrel, whose shape corresponds to the internal contour of the part to be produced, are mounted in a spinning lathe (Figure 5.0-2). The blank is clamped between mandrel and a follower on the tailstock spindle of the lathe. The mandrel, blank, and follower are then set in rotation. During rotation, a forming roller is used to apply localized pressure to the blank to gradually form it over the mandrel. The size of the part and the thickness and alloy of the forming blank will determine the force required to deform the metal blank to the



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

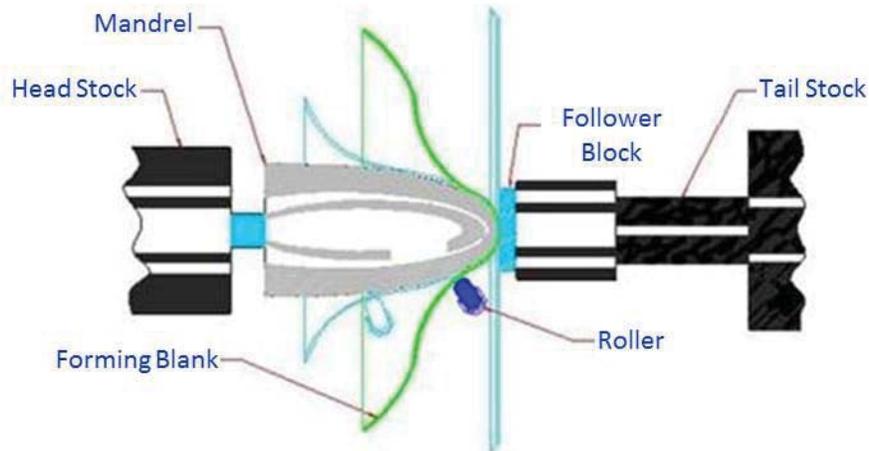
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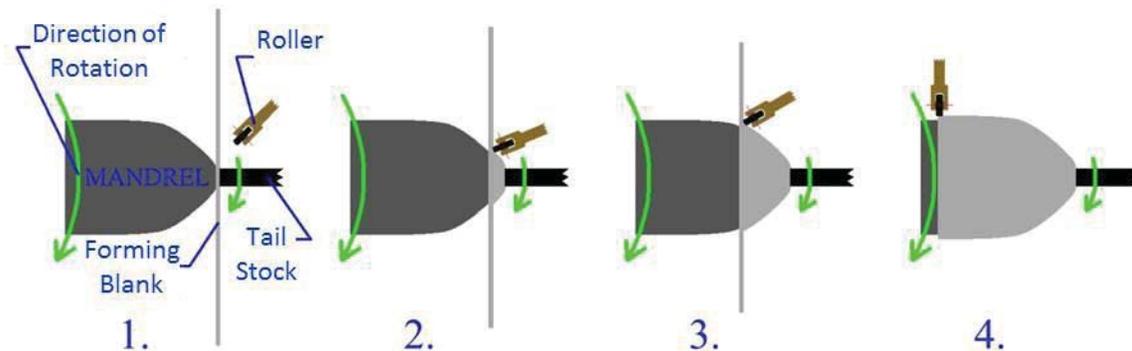
**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
20 of 223

shape (contour) of the mandrel. Heating of the part during spinning (hot forming) is determined to meet the force requirements and/or the ductility requirements during forming.



*[Credit: Spincraft]*



**Figure 5.0-2. Schematic of the Metal Spinning Process**

*[Credit: The Library of Manufacturing – Metal Spinning]*

Spin forming is applicable to most malleable metals and can produce a wide range of part sizes; parts can be spun up to 26 feet in diameter and thicknesses of up to 4.5 inches for Al and 1.5 inches in ferrous alloys. Spin forming is particularly adaptable to rotationally symmetric hollow shapes, such as cylinders, cones, and hemispheres and can enable considerable savings in both materials and manufacturing costs compared with other fabrication methods. Benefits include simple and low cost tooling requirements, involving primarily a contoured spinning mandrel, reduced lead times, and increased material yields compared to other forming methods.

The deformation induced during spin forming is complex and non-uniform. During convex spin forming there is generally no deliberate reduction in wall thickness as the material is shaped over the mandrel (2). Through-thickness compressive stresses are generated as a result of pressure from the forming tool as well as the strains induced during forming of the contour. During

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 21 of 223	

forming the blank diameter is reduced as material is pushed onto the mandrel, particularly near the rim, consequently the material experiences circumferential compressive stress superimposed on radial tensile stress, which combine to result in nearly constant wall thickness. The tool pressure is fairly uniform from the pole to the rim, but the imposed strain levels likely increase due to the superimposed forming stresses (tangential compressive and radial tensile and compressive) acting on the material, particularly towards the edge of the forming blank. So many process parameters affect material response during spin forming that modeling the process has been unsuccessful. The industrial success of spin forming is based on extensive experience at the vendors.

Producing a single-piece aft bulkhead by spin forming is consistent with design for manufacturing principles that enable lower manufacturing costs by reducing the number of parts and manufacturing steps. Eliminating welds reduces mass by eliminating weld lands and cost because post-weld NDE is no longer required. Spin forming has potential weight and production cost advantages over the current MPCV welded CM design and provides opportunities for improved performance and design margins as a result of design changes made possible using spin forming. A single-piece aft bulkhead also enables a simplified design analysis, which improves the fidelity of analysis and reduces the risk of analysis errors.

The components of the CM are constructed from high strength, heat treatable Al alloys such as Al 2219 and Al-Li 2195 because they offer high strength-to-weight ratios, good fracture and SCC resistance properties, and are weldable via FSW. These alloys are typically used in the T8 heat treat temper, which involves a solution heat treatment, water quench, and cold work to promote precipitation strengthening during subsequent artificial aging heat treatments. The thickness of the aft bulkhead is large enough that uniform cold stretch/work cannot be introduced after solution heat treatment. Consequently, the final heat treat temper for the aft bulkhead is T6 (solution heat treat, water quench, and age), which can result in lower strength, greater potential for pitting corrosion, and greater susceptibility to SCC compared to T8 temper products. In addition, very little data exist in open literature sources on mechanical properties of spin formed products. The spin formed aft bulkhead mechanical properties were compared to existing databases and standards for both T6 and T8 wrought plate and fabricated product forms to assist designers in determining any property knockdowns associated with the spin forming process and to provide fundamental material property data sets for manufacturing trade studies.

Throughout this report the temper designations will follow the Aluminum Association's definitions of T6 being solution heat treated and then artificially aged by the material producer and T62 being solution heat treated and then artificially aged by the user. Furthermore, the aft bulkhead material was also compared to both wrought plate and fabricated products forms in the T851 and T87 temper. T851 temper is solution heat treated, stress-relieved by controlled stretching (permanent set 1.5% to 3% for plate) and then artificially aged while T87 temper is solution heat treated, cold worked approximately 7% and then artificially aged.

See Appendix, Section 20.1 for a full description of the temper designations used in this report.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>22 of 223</b>

## 5.1 Goals and Objectives

The proposed scope of this Phase II project was to spin form an aft bulkhead test article to assess the mechanical properties (e.g., tensile, fracture, and SCC) and to provide representative spin formed material for LM circumferential FSW development. A second objective was to conduct a feasibility study to spin form a 6-inch thick single-piece cone to accommodate integral machining of all required structural elements (i.e., window frames, door hatches, etc.). A closer investigation of the cone region showed that the thickness requirements were approximately 8 inches and spin forming using current capabilities was not feasible; therefore, this objective was cancelled. A summary of the cone feasibility study will be provided in a supplement to this report.

## 5.2 Spin Formed Aft-Bulkhead Pathfinder

This task included spin forming and heat treating a pathfinder article from a single plate of Al 2219 (1.5 to 2.5-inch thick) with a diameter and curvature similar to the Orion CM aft bulkhead. After fabrication, the pathfinder was sectioned to supply spin formed material to support the two following studies that were conducted in parallel.

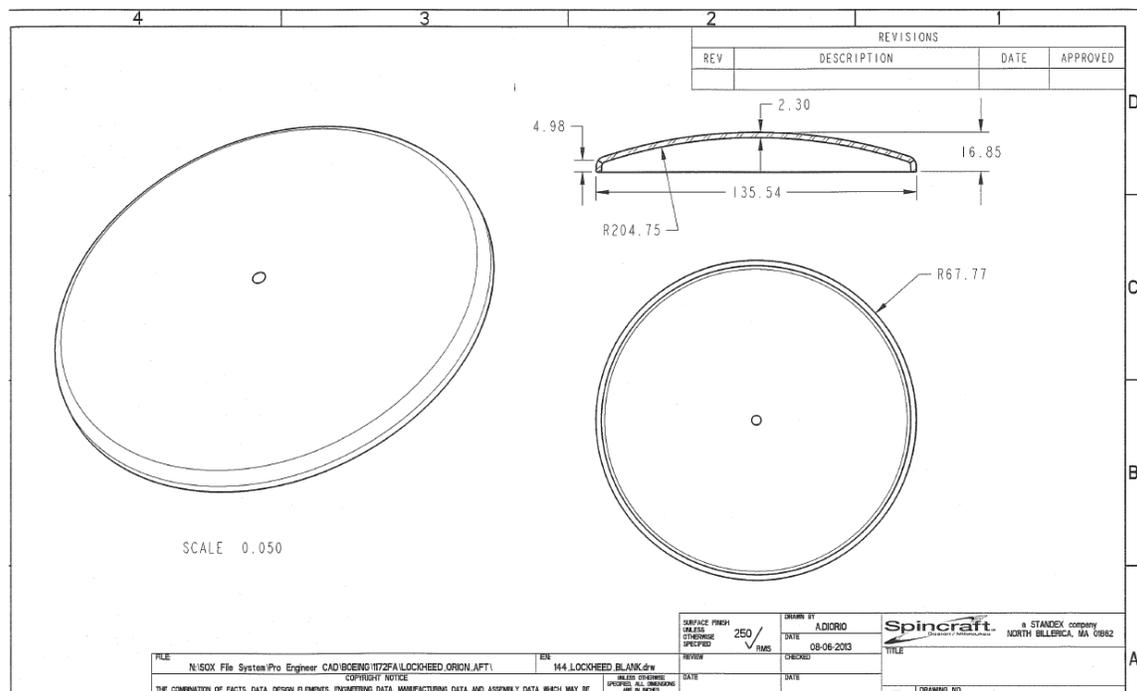
- i. **Material Property Testing:** The NESC team conducted a microstructure (grain size) evaluation, tensile and fracture toughness property testing, and SCC characterization to develop an initial property database for spin formed and heat treated Al 2219. Selected pathfinder regions (acreage locations) were tested to assess uniformity.
- ii. **FSW Development:** The NESC team supplied LM with sufficient spin formed pathfinder material for an initial FSW development study required to optimize the final aft bulkhead pressure vessel circumferential weld. Additional material was supplied to support mechanical property and structural subcomponent testing by the Orion structural design group.

## 6.0 Aft-Bulkhead Spin Forming Pathfinder:

### 6.1 Requirements and Specifications

The preliminary design for the Al 2219 Orion aft bulkhead has a 148.8-inch diameter, a 229.3-inch radius of curvature, and a 2.6-inch wall thickness. To meet the assessment objectives, the NESC team conducted a preliminary engineering analysis to assess manufacturing capabilities, tooling requirements, production schedule, and material availability for fabricating an aft bulkhead pathfinder component using spin forming technologies currently employed for the manufacture of Al alloy cryogenic tank dome structures. The funding level and schedule did not support fabrication of tooling (mandrel) required to produce the current Orion design nor could it afford long lead times for material delivery and production schedule openings. Based on this engineering assessment, Spincraft, a division of the Standex International Corporation, of North Billerica, MA, was chosen as the contractor to produce the aft bulkhead pathfinder. Among the large-scale spin forming vendors, it was determined that only Spincraft had both the

capability to produce components with the combined thickness and diameter needed to produce a pathfinder component representative of the Orion CM aft bulkhead and had production schedule openings to meet the project schedule. To support the aft bulkhead fabrication, Spincraft used an existing mandrel designed for a commercial customer that had similar size and geometry to the Orion aft bulkhead design. Figure 6.1-1 shows the aft bulkhead pathfinder component that was spin formed at Spincraft with dimensions of 135.5-inch diameter, 204.75-inch radius of curvature, and a wall thickness of 2.3 inches. Due to long material production lead times from Al producers, Spincraft was able to provide a suitably sized Al 2219 plate by diverting a plate from an existing production contract.



**Figure 6.1-1. Proposed aft bulkhead pathfinder configuration. Dimensions are based on existing mandrel at Spincraft.**

To support Orion in determining the suitability of the spin forming process for fabricating the aft bulkhead for the Orion CM, a spin formed pathfinder component was fabricated using standard spin forming technologies and practices. The spin formed component was fabricated on a best effort basis using existing commercial tooling and commercially-available materials, and was subjected to standard industry inspections, company proprietary spin forming processing, and post-forming thermal treatments.

Specifically, Spincraft was tasked with fabricating a pathfinder component through the following tasks outlined in the statement of work:

1. Perform a preliminary engineering analysis to assess the tooling requirements for fabricating the pathfinder component using spin forming technologies currently employed for manufacture of launch vehicle upper stage Al alloy cryogenic tank

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>24 of 223</b>

dome structures. Based on preliminary designs, the component shall have approximate dimensions ranging from 100 to 150 inches diameter at the rim, 200 to 250 inches radius of curvature, and 1.5 to 2.5 inches thick.

2. Identify existing tooling necessary to support spin forming, heat treatment, and machining. Identify and procure Al 2219 plate suitable for manufacturing the pathfinder component.
3. Fabricate the pathfinder component including all preparation of the spin forming blank, spin forming operations, inspections, subsequent heat treatment and machining.
4. After all spin forming and post-fabrication processing is complete, section the pathfinder component and corner drops from the forming blank per NASA-supplied cut plan and ship pieces to NASA LaRC, MSFC, JSC, and LM-MAF.
5. Prepare a final report on the spin formed pathfinder component fabrication to include a detailed description of the tooling and fabrication process and recommendations for further process development.

## 6.2 Material Specifications

For the commercial production of Al 2219 spin formed components, Spincraft starts with Al 2219-F temper plate that meets material certification specifications in accordance with AMS QQ-A-250/30 (3). For domes of the size required in the aft bulkhead pathfinder, the minimum dimensions required were 2.3 inches thick x 141 inches x 141 inches. The following notes are the material specification standards utilized by Spincraft:

General notes:

1. Chemical composition shall conform to the specified standard.
2. Heat treatment response testing is required to demonstrate compliance to the T62 temper.
3. Plate shall be ultrasonically inspected for internal defects in accordance with AMS-STD-2154, Class A.
4. Plate shall be stretched to an amount necessary to achieve flatness of 1.00 inch in any 72-inch direction.
5. Provide material certification standards confirming the chemical analyses, mechanical property testing after heat treatment, and nondestructive inspection for defects are in compliance with AMS QQ-A-250/30.
6. Heat Lot Number to be marked on the plate surface using black permanent ink (STM0257A37038 or equivalent) in accordance with FED-STD-595.
7. The grain direction is to be identified on each plate by an ink arrow.
8. Water jet cut plate to form a circular blank of approximately 140-inch diameter.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>25 of 223</b>

9. Plate will be packaged for shipment in accordance with AMS-QQ-A-250 Level “C”.
10. Shipment will include plate corners remaining after cutting circular blank.

## 7.0 Spin Forming Manufacturing Process

### 7.1 Manufacturing of Aft Bulkhead

The aft bulkhead was fabricated in accordance with Spincraft’s standard practice for Al spin formed domes, process plan 2009FA, and was documented in the final report (4). The processing steps used in the production of the aft bulkhead are as follows:

1. Material procurement
2. Inspection of raw plate
3. Machining and preparation of forming blank
4. Annealing of spin forming blank
5. Spin form process
6. Post-spin forming inspection
7. Heat treatment to the T62 temper
8. Final product inspection
9. Coupon blank machining

### 7.2 Material Procurement

The Al 2219-F plate material used by Spincraft to spin form the aft bulkhead measured 2.3 inches x 141 inches x 141 inches and was supplied by Alcoa North American Rolled Products – Davenport Works, Davenport, IA. Chemical analysis was performed to determine the composition relative to AMS QQ-A-250/30 specification standards (Table 7.2-1). The plate stock was found to be in compliance with material certification AMS QQ-A-250/30 and of the proper thickness and size. The material certification supplied with the plate is shown in the Appendix (see Section 20.2, Figure 20.2-1).

**Table 7.2-1. Chemical Composition, wt %**

Heat No. H9134063; Lot No. 446391

Actuals	Si	Fe	Cu	Mn	Mg	V	Zn	Ti	Zr	Each	Total	Aluminum Balance
	0.06	0.14	6.3	0.25	0.01	0.09	0.02	0.04	0.13			

Specification AMS-QQ\_A-250/30

Max	Si	Fe	Cu	Mn	Mg	V	Zn	Ti	Zr	Each	Total	Aluminum
	0.20	0.30	6.8	0.40	0.02	0.15	0.10	0.10	0.25	0.05	0.15	
Min			5.8	0.20		0.05		0.02	0.10			Balance

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 26 of 223	

### 7.3 Inspection of Raw Plate

The incoming inspection of the raw plate consisted of verifying material certification specifications, visual inspection for defects, and measurement of plate size and thickness using an ultrasonic transmission (UT) inspection and pull tape. The incoming plate stock was found to be in compliance to the material certifications and of the proper size and thickness. Thickness of the plate was measured at numerous locations using ultrasonic methods and varied from 2.326 to 2.316 inches. Following inspection, the plate was stamped with the Alcoa plate lot number, Spincraft identification number, and plate rolling direction.

### 7.4 Machining and Preparation of Forming Blank

Following inspection, the plate was shipped to a waterjet vendor where it was cut into a circular forming blank measuring 140-inch in diameter. It was then re-inspected following return to Spincraft and found to be in compliance.

As per Spincraft's standard practice for spin forming domes without center holes or manways, two central pins were installed in the forming blank to support the blank during spin forming operations.

### 7.5 Annealing of Spin Forming Blank

The forming blank was given a full anneal in an air furnace to ensure maximum formability and ductility during spin forming operations. This annealing treatment was conducted in accordance with AMS 2770 (5) and consisted of a thermal soak at  $775^{\circ}\text{F} \pm 25^{\circ}\text{F}$  for a soak time of 3 hours followed by a furnace cool at  $50^{\circ}\text{F}$  per hour to  $500^{\circ}\text{F}$ , and an air cool to room temperature. The annealing treatment used is the standard practice at Spincraft for spin formed Al 2219 domes.

### 7.6 Spin Form Process

Spincraft uses the convex spin forming process to manufacture domes and bulkheads (Figure 7.6-1). The sequence for forming a dome from flat plate consists of a series of sequential forming operations, beginning with break forming over a dome-shaped mandrel and then final spinning over the mandrel. In this process, a thick circular blank is rigidly clamped at the pole between a head stock/mandrel assembly and a tail stock, and the assembly is rotated about its central axis. A roller forming tool is used to force the forming blank against the mandrel as it translates from the pole to rim along the outer mold line surface (OML or convex side) of the rotating blank in multiple forming steps. The force of the roller forming tool against the forming blank causes the metal to plastically deform and flow against the mandrel. In the final spin forming operation, the dome or bulkhead is spun against the male tool until the desired surface contour is achieved to create the final dome configuration.

The forming blank was installed on the convex spin forming lathe and spin formed to the contour of the mandrel as per Spincraft's standard production practice. Torches were used to heat the mandrel and forming blank to the forming temperature of 500 to  $700^{\circ}\text{F}$ . Temperatures were monitored with temperature indicating sticks and recorded throughout the spin forming process.



# NASA Engineering and Safety Center Technical Assessment Report

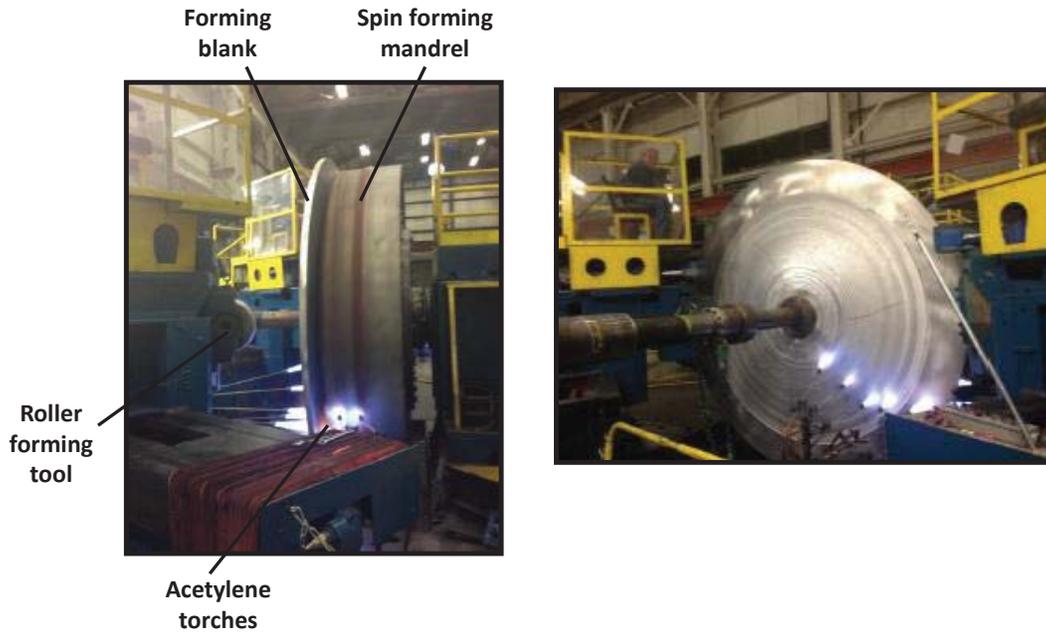
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
27 of 223



*Figure 7.6-1. Convex Spin Forming of the Aft Bulkhead*

## 7.7 Post Spin Forming Inspection

Following spin forming, the aft bulkhead was removed from the tooling and visually inspected for defects. The inner mold line (IML) surface of the aft bulkhead was inspected with forming inspection templates with the same contour shape as the mandrel while the circumference of the aft bulkhead was measured with pi tape to verify that the aft bulkhead was in compliance with the final part contour and diametric specifications. No visible damage or contour deviations were noted.

The thickness of the aft bulkhead was measured using ultrasonic methods at locations along the inspection template noted numerically in Figure 7.7-1. Measurements were made at locations 5 through 20, spaced 4 inches apart along the meridian line, spanning from 4 to 64 inches from the pole. Measurements 12 and 13 were separated by 8 inches. Measurements were made along four meridian lines at 90 degree intervals and results for each meridian and the average are provided in Table 7.7-1 and shown graphically in Figure 7.7-2. The OML surface of the aft bulkhead exhibited a scalloped pattern due to the advance of the forming roller and this is reflected in the fluctuation observed in the plotted data in Figure 7.7-2. Despite the fluctuation in the curve, overall the thickness decreased from pole to rim. The thickness was a maximum within 12 inches of the pole, a minimum at about 54 inches from the pole, and increased again at the rim. The maximum change in thickness was approximately 0.089 inches, which corresponds to a reduction in thickness of less than 4% during spin forming.



# NASA Engineering and Safety Center Technical Assessment Report

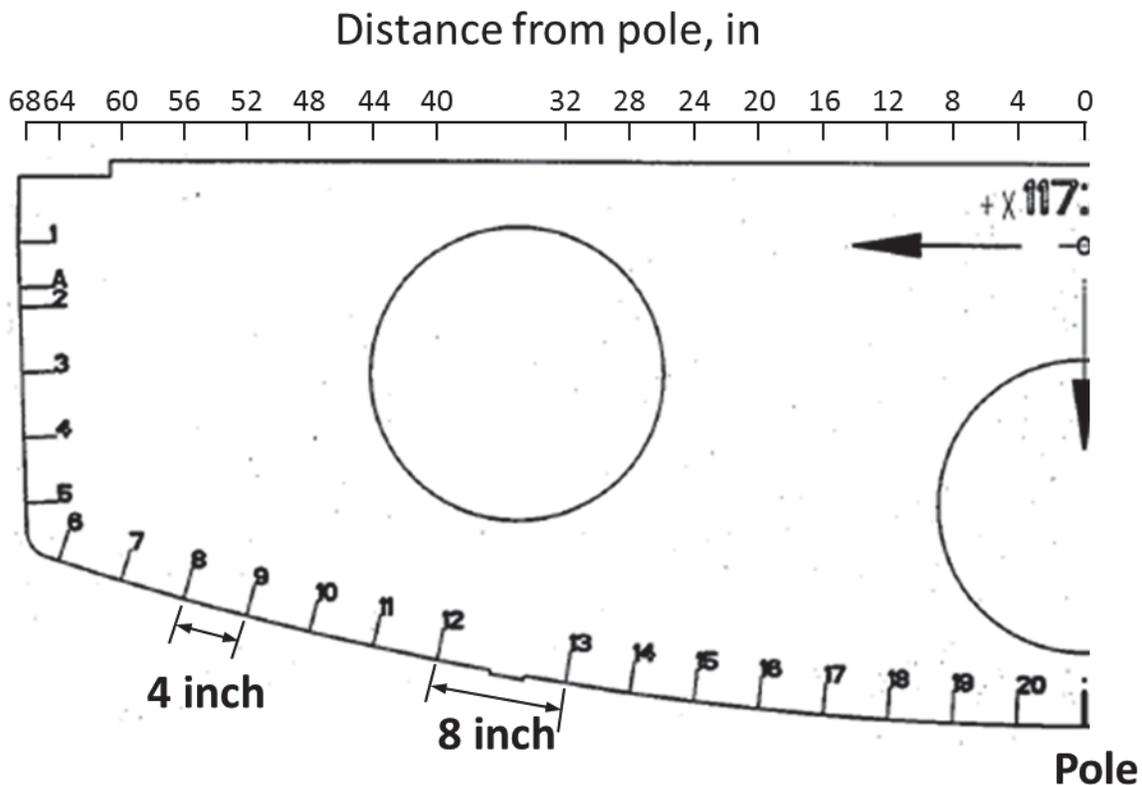
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
28 of 223



**Figure 7.7-1. Schematic of forming inspection template showing numbered locations of ultrasonic thickness measurements. The aft bulkhead was measured at locations 5 through 20, with measurements made every 4 inches along a meridian line.**

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>29 of 223</b>

**Table 7.7-1. Ultrasonic Thickness Measurements of the Aft Bulkhead corresponding to Locations 5 through 20 shown in Figure 7.7-1**

Template Point	Distance from Pole (in)	UT Thickness Measurements (in)				
		0 deg	180 deg	90 deg	270 deg	Average
20	4	2.311	2.319	2.311	2.310	2.313
19	8	2.310	2.313	2.314	2.309	2.312
18	12	2.315	2.314	2.316	2.318	2.316
17	16	2.294	2.288	2.289	2.286	2.289
16	20	2.291	2.293	2.295	2.295	2.294
15	24	2.303	2.307	2.309	2.308	2.307
14	28	2.275	2.275	2.279	2.275	2.276
13	32	2.272	2.273	2.264	2.270	2.270
12	40	2.239	2.251	2.246	2.236	2.243
11	44	2.272	2.287	2.293	2.282	2.284
10	48	2.262	2.258	2.259	2.244	2.256
9	52	2.224	2.241	2.226	2.238	2.232
8	56	2.245	2.207	2.243	2.212	2.227
7	60	2.274	2.283	2.290	2.277	2.281
6	64	2.276	2.284	2.286	2.273	2.280
5	68	1.965	1.941	1.995	1.948	1.962



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
30 of 223

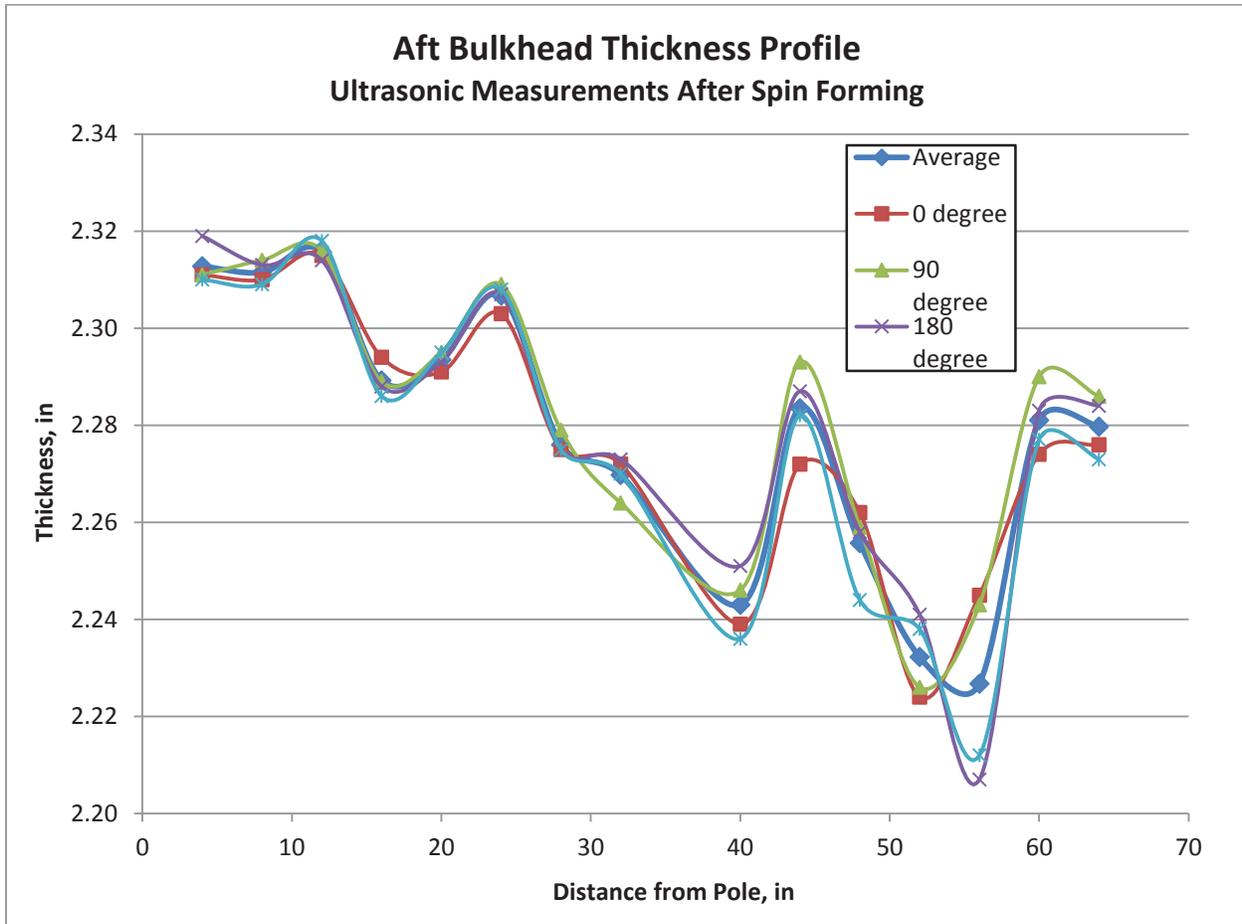


Figure 7.7-2. Thickness Profile of the Aft Bulkhead based on Ultrasonic Thickness Measurements at the Locations shown in Figure 7.7-1

## 7.8 Heat Treatment to the T62 Temper

Following final spinning, the Al 2219 aft bulkhead pathfinder was solution heat treated, quenched and artificially aged to the T62 temper (Figure 7.8-1). Due to the thickness of the aft bulkhead, uniform cold deformation after solution heat treatment, typically used to produce T8 temper, is not feasible. Therefore, for parts of this size and thickness, Spincraft’s manufacturing process can only produce Al spin formed articles in the T62 temper. Thinner spin formed products can be produced in a T8 temper, such as the 0.5-inch-thick Shuttle External tank dome caps, which were spin formed at room temperature in the T37 condition and heat treated to T87. Solution heat treatment, quenching, and artificial aging processes for the aft bulkhead were performed per AMS 2770 specifications. This heat treatment consists of solutionizing at 995°F ± 10°F for a soak time of 3 hours, followed by a quench in 15 to 17% polymer solution type 1/water quench medium (glycol quench). This quench medium provides uniform wetting of the

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 31 of 223	

surface and fast, uniform heat transfer thereby reducing distortion problems normally associated with water quenched Al. Normally, following solution heat treatment to the T42 temper, spin formed Al components are installed on a hydraulic straightener and any out-of-round deviations and distortions resulting from the quenching operation are corrected. However, since this spin formed aft bulkhead did not have any finished machining sizing or contour requirements, this processing step was omitted. The aft bulkhead was then artificially aged at  $375^{\circ}\text{F} \pm 10^{\circ}\text{F}$  for 36 hours to the T62 temper.



*Figure 7.8-1. Aft bulkhead following heat treatment.*

## 7.9 Final Product Inspection

Following final heat treatment, hardness and electrical conductivity inspections were performed per AMS 2658 (6) to verify proper temper. All inspections were compliant to a T62 temper. An outside vendor conducted a laser tracking assessment of both the OML and IML surfaces of the aft bulkhead to confirm that the bulkhead meets the specified contour forming profile. Measurements were made from the pole to the rim at approximately 0.25 inch increments at 5-degree intervals and the results were provided electronically. The laser scan data was analyzed to determine thickness along one meridian line at the same locations as the UT measurements, as illustrated in Figure 7.9-1. The resulting thickness values are shown in Table 7.9-1 and compared with the UT data in Figure 7.9-2. Maximum thickness was at a location of approximately 8 inches from the pole, minimum thickness was at 40 inches, and the overall reduction in thickness was 0.086 inches, values, which agree well with the ultrasonic thickness measurements shown in Table 7.7-1. Figure 7.9-2 illustrates that the laser scan data also exhibits fluctuations related to the surface scalloping.



# NASA Engineering and Safety Center Technical Assessment Report

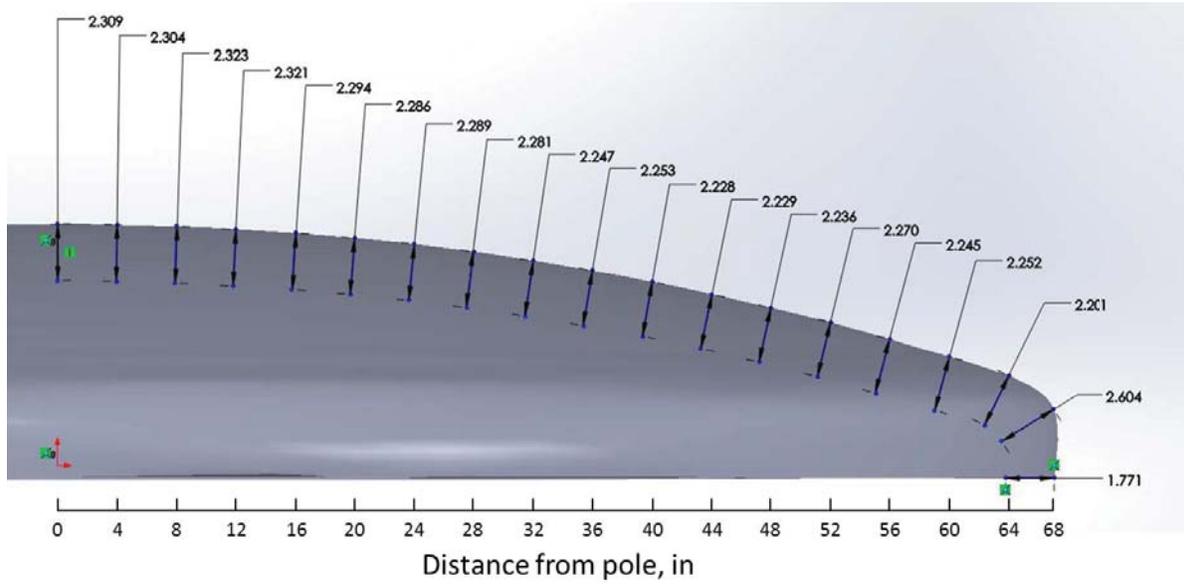
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
32 of 223



*Figure 7.9-1. Section of Laser Scan showing the Locations of Thickness Determinations*



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
33 of 223

**Table 7.9-1. Thickness Measurements of the Aft Bulkhead Based on Laser Tracking Scans of the IML and OML**

Laser Scan	
Thickness (in)	Distance from Pole (in)
2.309	0
2.304	4
2.323	8
2.321	12
2.294	16
2.286	20
2.289	24
2.281	28
2.247	32
2.253	36
2.228	40
2.229	44
2.236	48
2.270	52
2.245	56
2.252	60
2.201	64
2.604	68



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
34 of 223

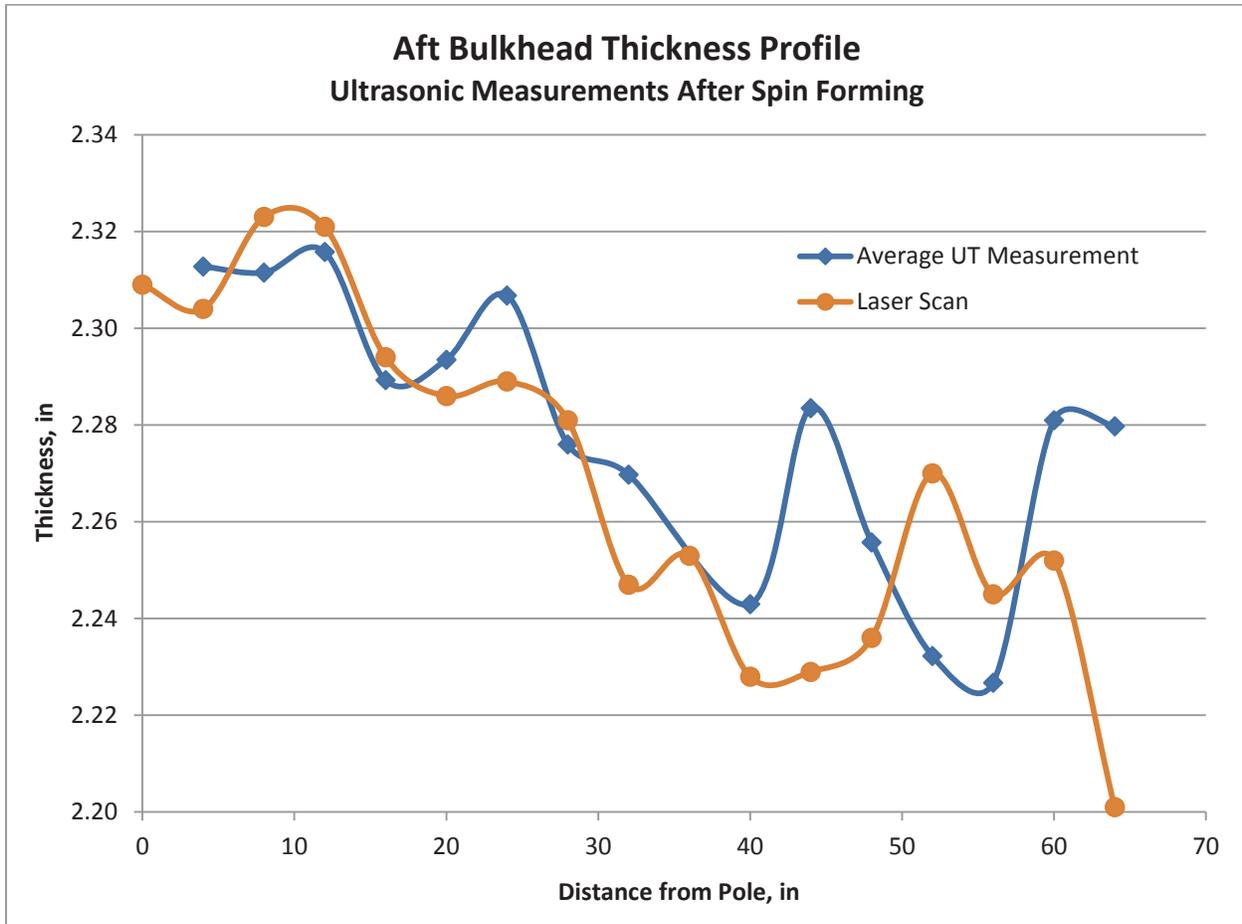


Figure 7.9-2. Thickness Measurements of the Aft Bulkhead determined from the Laser Scan Data compared with the UT Measurements

### 7.10 Coupon Blank Machining

A coupon cut plan was created prior to spinning the bulkhead and was used as a basis for locating the coupons to be cut for mechanical property testing, metallurgical analysis, and FSW schedule development (Figure 7.10-1). An outside vendor waterjet-machined coupon blanks from representative areas from the pole, membrane, and rim regions, as depicted in the cut plan and Figure 7.10-2.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
35 of 223

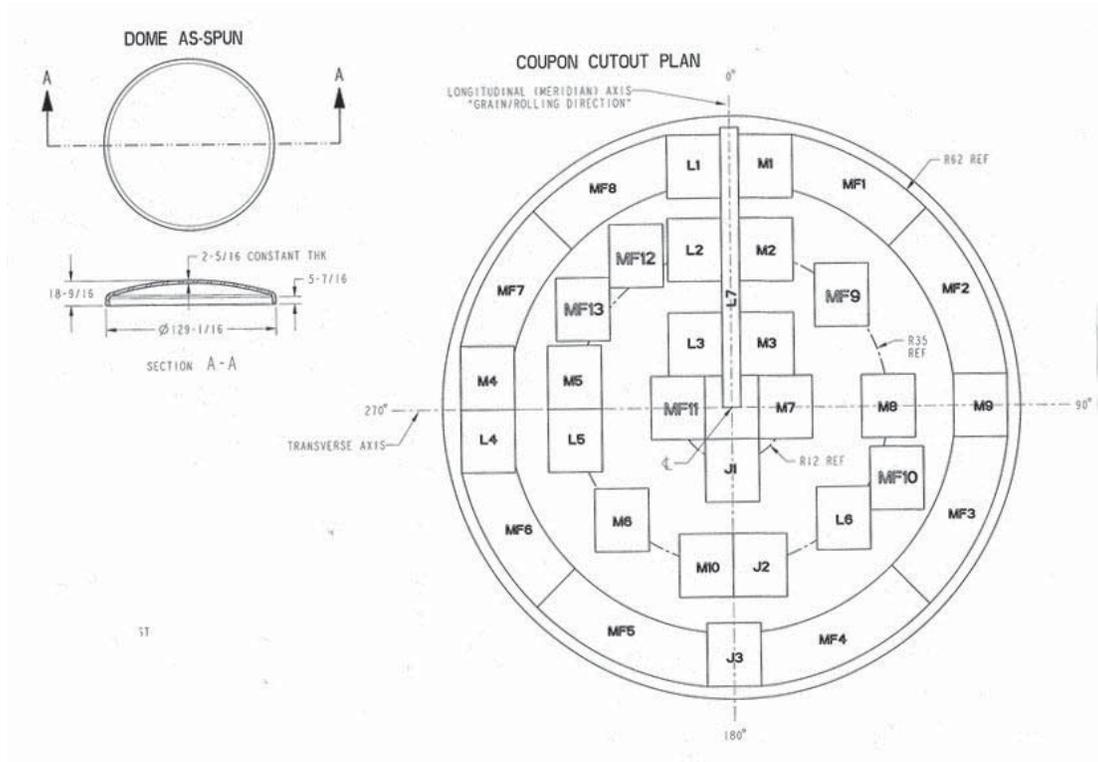


Figure 7.10-1. Aft Bulkhead Coupon Cut Plan



Figure 7.10-2. Aft Bulkhead following Extraction of Coupon Blanks for Test and Analysis



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

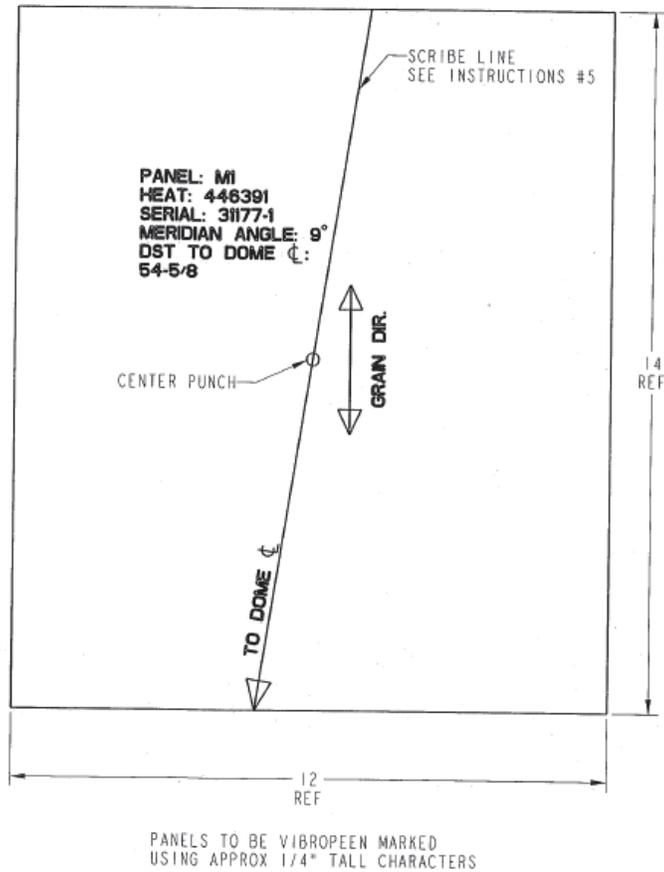
Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
36 of 223

To maintain coupon blank location and orientation reference, every coupon blank was stamped with the identifying blank number, plate rolling direction (within 5 degrees), meridian arc length distance from the central pole, and meridian angle with respect to the original plate rolling direction as depicted in Figure 7.10-3 and Table 7.10-1.



**Figure 7.10-3. Coupon Blank Marking Scheme**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
37 of 223

*Table 7.10-1. Location and Orientation of Coupon Blanks*

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
M1	14	12	9°	54-5/8
M2	14	12	13°	36
M3	14	12	30°	16-1/8
M4	14	12	277°	55-1/2
M5	14	12	281°	35-7/8
M6	14	12	225°	35-1/8
M7	14	12	90°	12
M8	14	12	90°	35-1/8
M9	14	12	90°	56-1/4
M10	14	12	190°	35-5/8
J1	14	12	180°	12
J2	14	12	170°	35-5/8
J3	14	12	180°	55-5/8
MF9	14	12	45°	35-1/8
MF10	14	12	114°	40-3/8
MF11	14	12	270°	12
MF12	14	12	328°	40
MF13	14	12	304°	39-7/8
L1	14	12	351°	54-5/8
L2	14	12	347°	36
L3	14	12	330°	16-1/8
L4	14	12	259°	55-1/2
L5	14	12	263°	35-7/8
L6	14	12	135°	35-1/8
L7	CL to R62	4	0°	N/A
MF1	N/A	N/A	31°	56-3/4
MF2	N/A	N/A	64°	56-3/4
MF3	N/A	N/A	116°	56-3/4
MF4	N/A	N/A	154°	56-3/4
MF5	N/A	N/A	206°	56-3/4
MF6	N/A	N/A	240°	56-3/4
MF7	N/A	N/A	296°	56-3/4
MF8	N/A	N/A	329°	56-3/4

Additional coupon blanks were waterjet cut from the remnant plate corners remaining after machining of the circular forming blank. To assist in characterizing the effects of spin forming processing on the plate microstructure, test blocks from the remnant plate corners were thermally processed for the same temperature-time combination associated with the various thermal

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>38 of 223</b>

processing steps used in the production of the aft bulkhead (but without any spin form deformation). These thermal processing steps include the starting plate condition (F temper), pre - spin forming full anneal condition (O temper); solution heat treat condition (T4 temper), and the precipitation aged condition (T6 temper). The coupon blanks from the aft bulkhead, remnant plate corner material, and thermally processed test blocks were then shipped to the respective centers for test and analysis as shown in Table 7.10-2.

**Table 7.10-2. Coupon Blank Designation, Test Center, and Test Type**

Coupon Blank Designation	Test Center	Test Type
L1, L2, L3, L4, L5, L6	LaRC	Tensile
L7, F, O, T4, T6 test blocks	LaRC	Metallurgical analysis
M1, M2, M3, M4, M5, M6	MSFC	Fracture toughness
M7, M8, M9, M10	MSFC	SCC
J1, J2, J3	JSC/KSC	Seacoast exposure SCC <sup>1</sup>
MF1, MF2, MF3, MF4, MF5, MF6 MF7, MF8	MAF	FSW development
MF9, MF10, MF11, MF12, MF13	MAF	Mechanical property and structural subcomponent testing

<sup>1</sup> Specimens for seacoast exposure were diverted to laboratory alternate immersion SCC testing at MSFC.

## 8.0 Aft Bulkhead Test and Analysis

The overall goal of testing and analysis was to examine property uniformity throughout the aft bulkhead and to determine how the properties compared with Al 2219 plate and other formed components. The Spincraft spin forming process cannot impart cold stretch prior to aging, consequently the aft bulkhead was heat treated to the T62 condition. The aft bulkhead mechanical properties were evaluated to determine whether results were comparable (in family) with T6 products. Comparison with Al 2219-T851 plate was made since this is the condition used for elements of the Orion CM that are machined from thick plate and would likely be the condition used if a multi-piece welded Al 2219 aft bulkhead were produced. For cases in which little or no data were available for T851 plate, comparisons were made with T87 plate. Metallurgical analysis and mechanical property (tensile, fracture toughness, stress corrosion) evaluation of the fully processed spin formed Al 2219 aft bulkhead pathfinder component was performed to screen property levels and to provide recommendations to the Orion Program Office regarding implementation of the spin forming fabrication method.

The aft bulkhead was successfully spin formed, heat treated and sectioned for coupon testing. Dimensional analysis was conducted on the completed bulkhead and confirmed that final shape conformed to the manufacturing mandrel and any warping from solution heat treat, quench, or artificial aging was within acceptable manufacturing tolerances. An aft bulkhead coupon cut plan was created prior to spinning the bulkhead and was used as a basis for locating the coupons to be sectioned. Additional metallurgical and fractographic analyses were conducted to gain further insight into the effects of the processing and heat treat practice on the Al 2219 microstructure and resultant mechanical properties.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 39 of 223

## 8.1 Test and Analysis Procedures

The spin formed aft bulkhead dome coupon testing was conducted by NASA LaRC, NASA MSFC, and NASA JSC. Qualifying tests were also conducted by LM-MAF, but are not included in this report due to schedule and mission requirements. Table 7.10-2 shows the test center and test type based upon coupon blank letter and number designations. Further details on the test and analysis procedures are presented in Sections 8.2 through 8.6.

## 8.2 Metallurgical Analysis

A strip-shaped blank was cut from the fully processed aft bulkhead for metallurgical analysis, spanning from the center of the aft bulkhead to near the rim along the 0° meridian line, noted as L7 in Figure 8.2-1. The blank dimensions were 4 inches in the transverse plate direction and 62 inches along the meridian. Metallurgical samples were extracted at five locations along the strip as shown in Figure 8.2-2. Samples L7-1 through L7-5 were located at arc length distances from the pole that corresponded approximately to L/8 (8 inches), L/4 (16 inches), L/2 (27 inches), 3L/4 (43 inches), and L (61 inches). Samples were examined using optical microscopy to evaluate variability in grain morphology and degree of recrystallization with distance from the pole and uniformity through the thickness at each location.

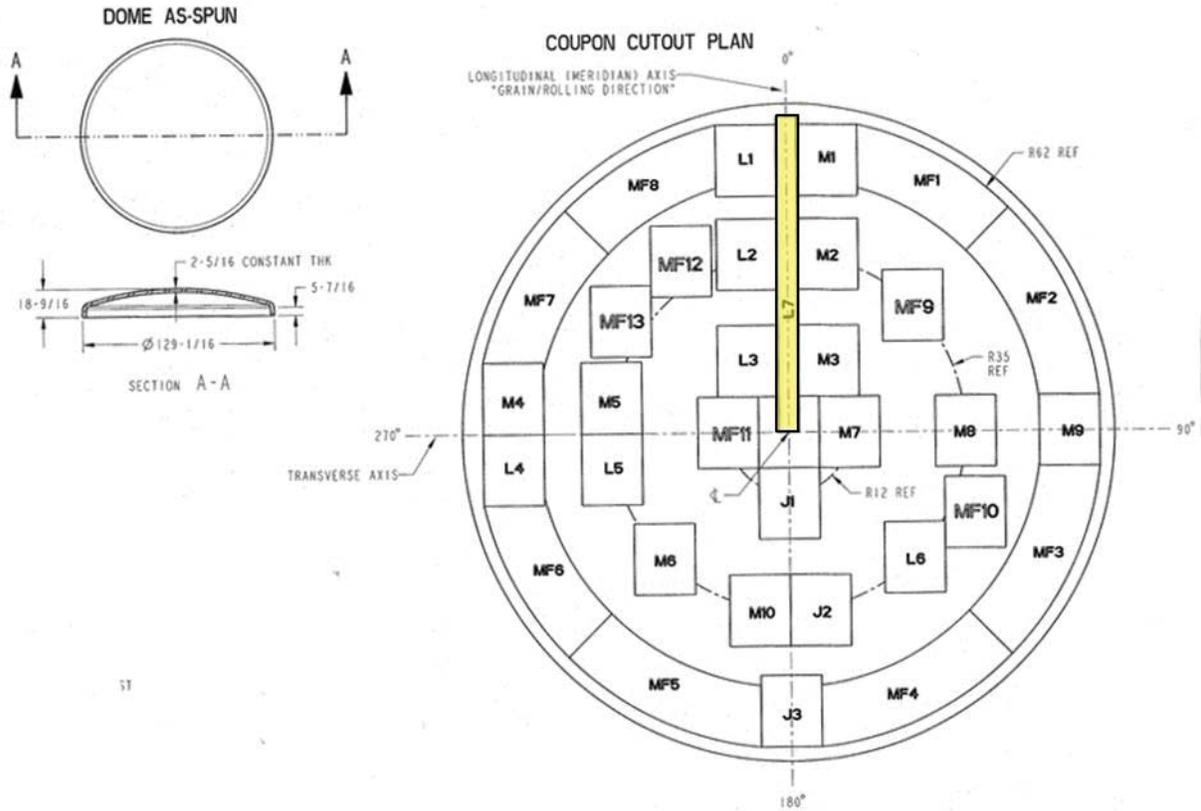
The thickness of the L7 strip was measured at locations along the meridian line that corresponded to the locations of the UT measurements and laser scan analysis. Changes in thickness relative to the starting plate thickness were used to estimate the variation in deformation level throughout the aft bulkhead. Vernier calipers with ball end caps were used for these measurements.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
40 of 223



**Figure 8.2-1. Aft Bulkhead Cut Plan showing the Location of the Metallurgical Analysis Strip highlighted in Yellow**

Additional samples from the supplied starting plate were thermally processed at the time-temperature profiles associated with the various processing steps used in the production of the aft bulkhead (but without any spin forming deformation). Thermal exposures were performed during processing of the aft bulkhead in order to evaluate grain morphology evolution due to thermal processing alone. Samples were examined of the as-received plate (F temper), after the pre-spin forming anneal (O), after solution heat treat and water quench (T4), and after artificial aging (T6). The samples, shown in Figure 8.2-3, were examined using optical microscopy and compared with the aft bulkhead samples.

Samples of the LT-S plane were polished through various grades of SiC paper and then colloidal diamond paste. Following polishing, the samples were etched with Keller's reagent.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
 41 of 223

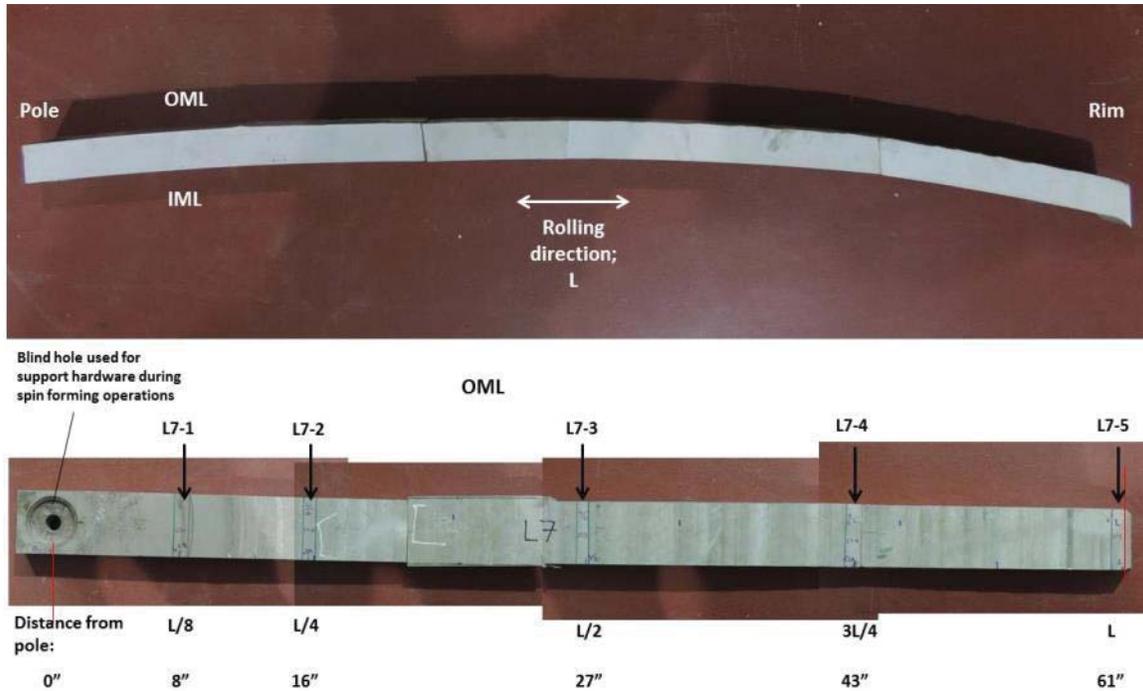


Figure 8.2-2. Metallurgical Analysis Blank showing the Locations of Specimens L7-1 through L7-5

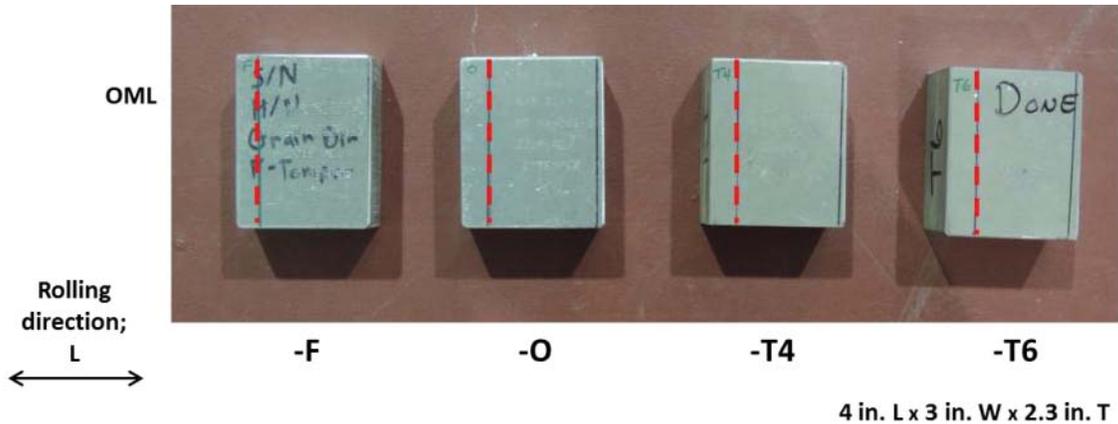


Figure 8.2-3. Thermally Processed Test Blocks

### 8.3 Tensile Test Procedures

Coupon blanks L1-L6 from the aft bulkhead were provided to NASA LaRC for tensile testing. These blanks were obtained from the locations highlighted in yellow in the aft bulkhead cut plan (Figure 8.3-1) and coupon blank matrix (Table 8.3-1). Additional tensile tests were conducted on coupon blanks M1-M10 provided to NASA MSFC in support of SCC and fracture testing. These coupon blanks are also shown in the accompanying figure and table.



# NASA Engineering and Safety Center Technical Assessment Report

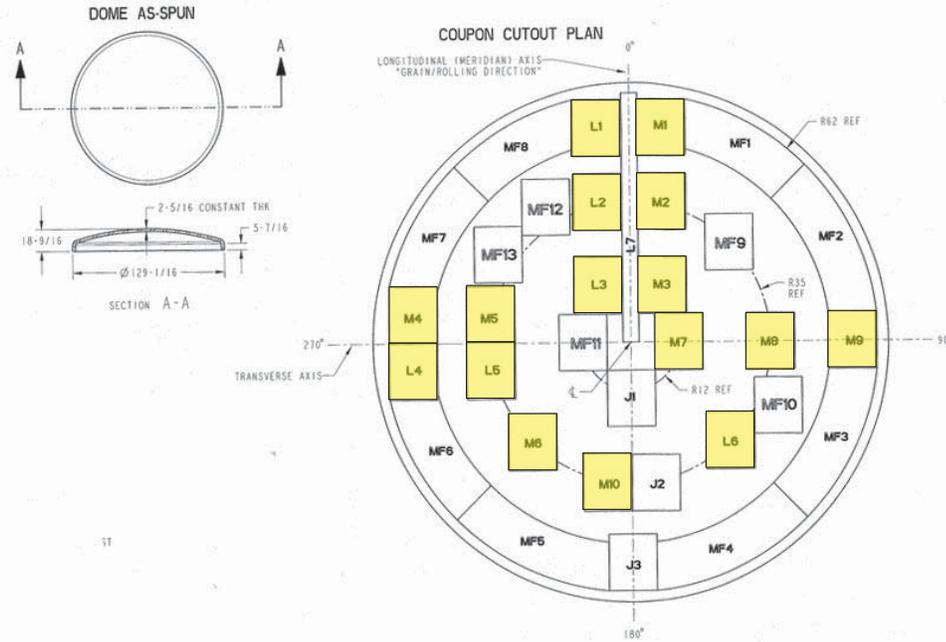
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
42 of 223



**Figure 8.3-1. Aft Bulkhead Cut Plan Showing the Location of the Tensile Coupon Blanks highlighted in Yellow**

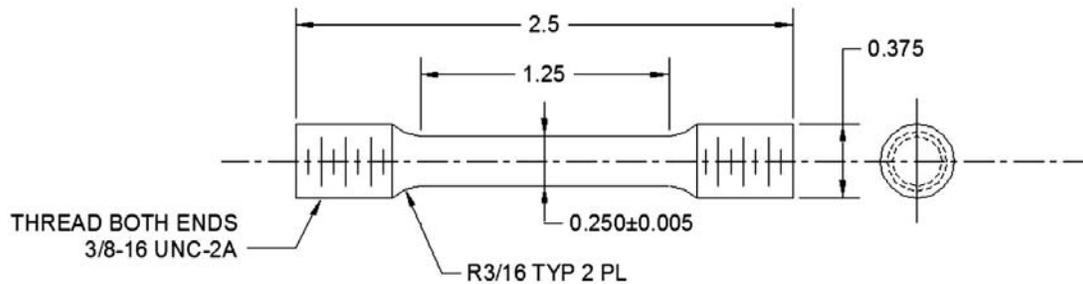
**Table 8.3-1. Tensile Coupon Blank Size, Locations, and Orientations**

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Long. Dimension, in.	Transv. Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
L1	14	12	351	54.63
L2	14	12	347	36.00
L3	14	12	330	16.13
L4	14	12	259	55.50
L5	14	12	263	35.88
L6	14	12	135	35.13
M1	14	12	9	54.63
M2	14	12	13	36.00
M3	14	12	30	16.13
M4	14	12	277	55.50
M5	14	12	281	35.88
M6	14	12	225	35.13
M7	14	12	90	12.00
M8	14	12	90	35.13
M9	14	12	90	56.25
M10	14	12	190	35.63

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>43 of 223</b>

Tensile testing of the spin formed aft bulkhead material was conducted in accordance with ASTM E8 (7). Room temperature tensile characterization was conducted in four grain orientations; L, LT, ST, and 45° to the ST (ST45). These grain orientations were with respect to the original plate rolling direction prior to spin forming. The ST45 orientation is not a typical test orientation for Al alloy plate, but was included for two reasons: (1) there may be regions of the aft bulkhead where service loads are aligned with the ST45 orientation, and (2) metallurgical theory suggests that for some alloys this may be the minimum strength orientation for plate. Two specimen designs were used; one for the L and LT orientations (Figure 8.3-2) and one for the ST and ST45 orientations (Figure 8.3-3). All specimens were machined from the coupon blanks such that the test section was located at the mid-plane thickness ( $t/2$ ) of the coupon blank. Three replicate tests were conducted for each grain orientation as per the test matrix shown in Table 8.3-2.

Tensile tests were conducted in a servo-hydraulic test machine at a displacement rate of 0.01 in/min (ipm) to specimen failure using the test setup shown in Figure 8.3-4. Back-to-back extensometers with either a 1.000 in (L and LT specimens) or 0.500 in (ST and ST45 specimens) gauge length were used to measure specimen strain response. For tensile tests conducted at NASA MSFC, the displacement rate was 0.05 ipm and only a single 1.000/0.500 in extensometer was used. Ultimate tensile strength (UTS), 0.2% YS, and percent elongation (e) were determined for each test condition. The modulus of elasticity (E) was also calculated from the stress-strain plot and is shown in the results section as a reference value. Figure 8.3-5 shows a typical stress-strain curve for a tensile test.



**Figure 8.3-2. Round Subsize Tensile Specimen Design used for Testing in the L and LT Orientations**



# NASA Engineering and Safety Center Technical Assessment Report

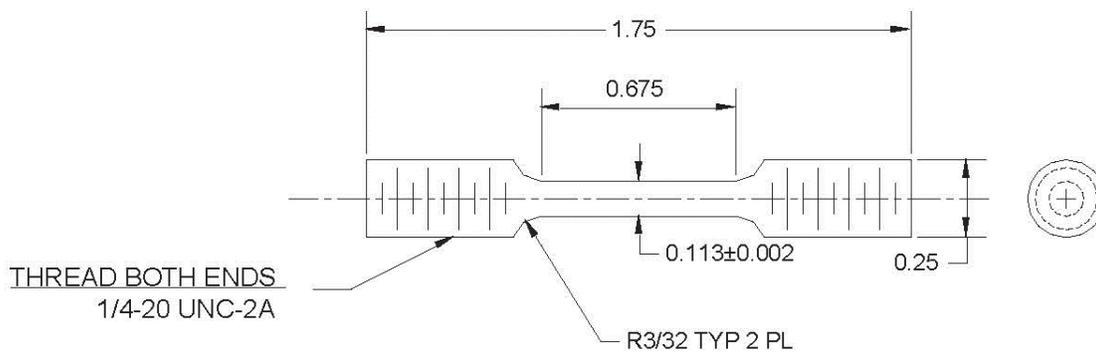
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
44 of 223



***Figure 8.3-3. Round Subsize Tensile Specimen Design used for Testing in the ST and ST45 Orientations***



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
45 of 223

**Table 8.3-2. Tensile Test Matrix for the Aft Bulkhead**

Coupon Blank	Meridian Angle, degrees	Arc Length from dome CL, in.	Orient.	Specimen Number		
L1	351	54.63	L	T-L1-L-01	T-L1-L-02	T-L1-L-03
			LT	T-L1-LT-04	T-L1-LT-05	T-L1-LT-06
			ST	T-L1-ST-07	T-L1-ST-08	T-L1-ST-09
			ST45	T-L1-ST45-10	T-L1-ST45-11	T-L1-ST45-12
L2	347	36.00	L	T-L2-L-13	T-L2-L-14	T-L2-L-15
			LT	T-L2-LT-16	T-L2-LT-17	T-L2-LT-18
			ST	T-L2-ST-19	T-L2-ST-20	T-L2-ST-21
			ST45	T-L2-ST45-22	T-L2-ST45-23	T-L2-ST45-24
L3	330	16.13	L	T-L3-L-25	T-L3-L-26	T-L3-L-27
			LT	T-L3-LT-28	T-L3-LT-29	T-L3-LT-30
			ST	T-L3-ST-31	T-L3-ST-32	T-L3-ST-33
			ST45	T-L3-ST45-34	T-L3-ST45-35	T-L3-ST45-36
L4	259	55.50	L	T-L4-L-37	T-L4-L-38	T-L4-L-39
			LT	T-L4-LT-40	T-L4-LT-41	T-L4-LT-42
			ST	T-L4-ST-43	T-L4-ST-44	T-L4-ST-45
			ST45	T-L4-ST45-46	T-L4-ST45-47	T-L4-ST45-48
L5	263	35.88	L	T-L5-L-49	T-L5-L-50	T-L5-L-51
			LT	T-L5-LT-52	T-L5-LT-53	T-L5-LT-54
			ST	T-L5-ST-55	T-L5-ST-56	T-L5-ST-57
			ST45	T-L5-ST45-58	T-L5-ST45-59	T-L5-ST45-60
L6	135	35.13	L	T-L6-L-61	T-L6-L-62	T-L6-L-63
			LT	T-L6-LT-64	T-L6-LT-65	T-L6-LT-66
			ST	T-L6-ST-67	T-L6-ST-68	T-L6-ST-69
			ST45	T-L6-ST45-70	T-L6-ST45-71	T-L6-ST45-72
M1	9	54.63	L	CP-406-190	CP-406-192	CP-406-194
			LT	CP-406-195	CP-406-197	CP-406-199
			ST	CP-406-200	CP-406-202	CP-406-204
			ST45	----	----	----
M2	13	36.00	L	CP-406-205	CP-406-207	CP-406-209
			LT	CP-406-210	CP-406-212	CP-406-214
			ST	CP-406-215	CP-406-217	CP-406-219
			ST45	----	----	----
M3	30	16.13	L	CP-406-220	CP-406-222	CP-406-224
			LT	CP-406-225	CP-406-227	CP-406-229
			ST	CP-406-230	CP-406-232	CP-406-234
			ST45	----	----	----
M4	277	55.50	L	CP-406-235	CP-406-237	CP-406-239
			LT	CP-406-240	CP-406-242	CP-406-244
			ST	CP-406-245	CP-406-247	CP-406-249
			ST45	----	----	----
M5	281	35.88	L	CP-406-250	CP-406-252	CP-406-254
			LT	CP-406-255	CP-406-257	CP-406-259
			ST	CP-406-260	CP-406-262	CP-406-264
			ST45	----	----	----
M6	225	35.13	L	CP-406-265	CP-406-267	CP-406-269
			LT	CP-406-270	CP-406-272	CP-406-274
			ST	CP-406-275	CP-406-277	CP-406-279
			ST45	----	----	----
M7	90	12.00	L	----	----	----
			LT	CP-406-1	CP-406-11	CP-406-21
			ST	CP-406-22	CP-406-32	CP-406-42
			ST45	----	----	----
M8	90	35.13	L	----	----	----
			LT	CP-406-43	CP-406-53	CP-406-63
			ST	CP-406-64	CP-406-74	CP-406-84
			ST45	----	----	----
M9	90	56.25	L	----	----	----
			LT	CP-406-85	CP-406-95	CP-406-105
			ST	CP-406-106	CP-406-116	CP-406-126
			ST45	----	----	----
M10	190	35.63	L	CP-406-127	CP-406-137	CP-406-147
			LT	CP-406-169	CP-406-179	CP-406-189
			ST	CP-406-148	CP-406-158	CP-406-168
			ST45	----	----	----



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
46 of 223



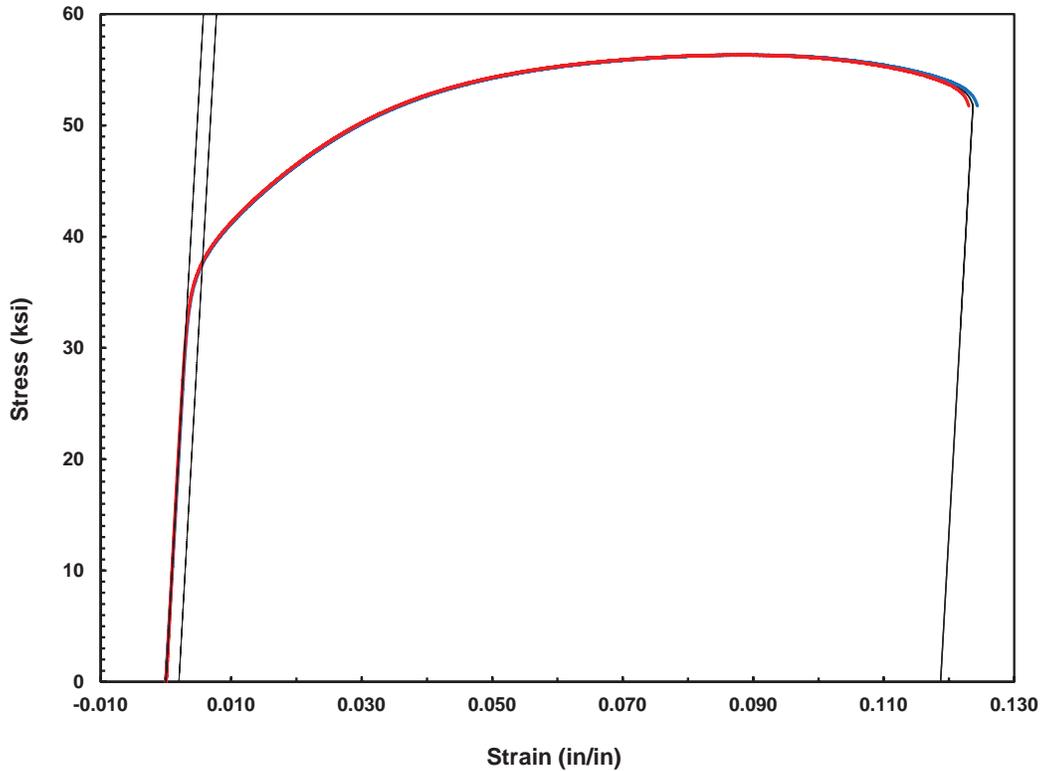
*Figure 8.3-4. Tensile Test Load Stand, Specimen, and Instrumentation*



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
47 of 223



*Figure 8.3-5. Typical Stress-Strain Curve for the Spin Formed Al 2219-T62 Aft Bulkhead Material in the L Orientation; Coupon Blank L2, Specimen T-L2-L-13*

## 8.4 Fracture Toughness Test Procedures

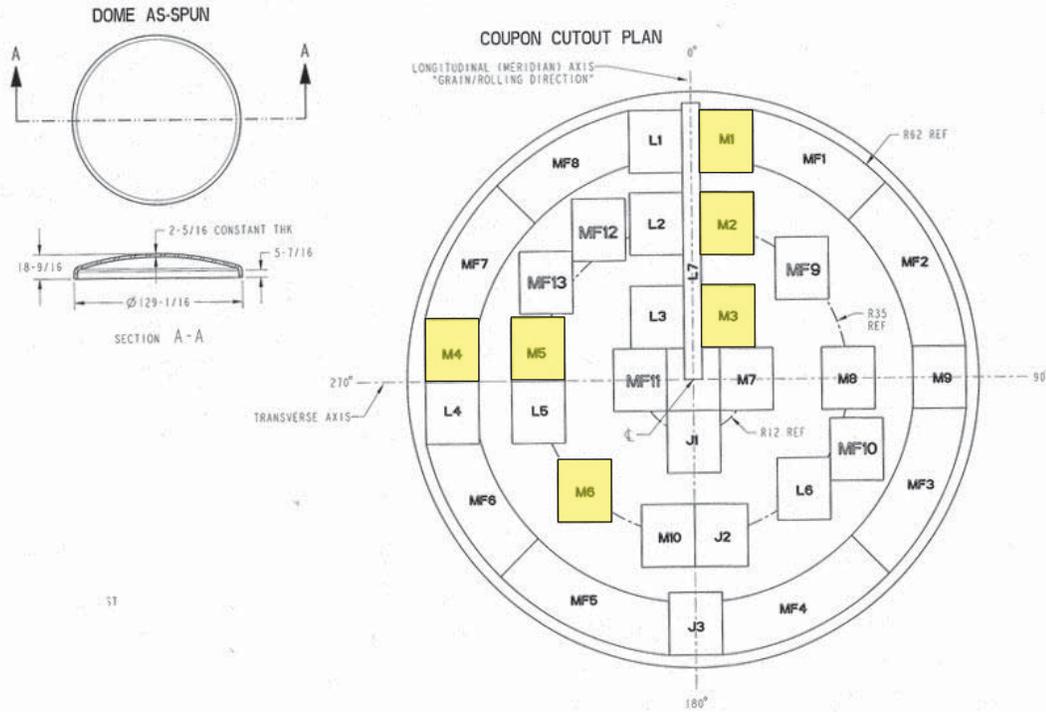
Coupon blanks from the aft bulkhead were provided to NASA MSFC for fracture toughness testing. These blanks were identified as M1, M2, M3, M4, M5, and M6 and were obtained from the locations highlighted in yellow in the aft bulkhead cut plan (Figure 8.4-1) and coupon blank matrix (Table 8.4-1).



Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
 48 of 223



**Figure 8.4-1. Aft Bulkhead Cut Plan showing the Location of the Fracture Toughness Coupon Blanks highlighted in Yellow**

**Table 8.4-1. Fracture toughness Coupon Blank Locations and Orientations**

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
M1	14	12	9°	54-5/8
M2	14	12	13°	36
M3	14	12	30°	16-1/8
M4	14	12	277°	55-1/2
M5	14	12	281°	35-7/8
M6	14	12	225°	35-1/8

Fracture toughness testing of the spin formed aft bulkhead material was conducted in accordance with ASTM E1820 (8). Per this test method, the fracture toughness is quantified in terms of  $J_{IC}$ , which is a measure of the fracture toughness of the material at the onset of stable crack extension. Fracture toughness characterization was conducted in three grain orientations, L-T, T-L, and S-T. The test orientation designation first identifies the loading direction and is followed by the crack growth orientation as they relate to the grain orientation of the material. The grain orientations are relative to the original grain orientation of the rolled plate prior to spin forming. Fracture toughness was measured using a compact tension (C(T)) specimen configuration.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

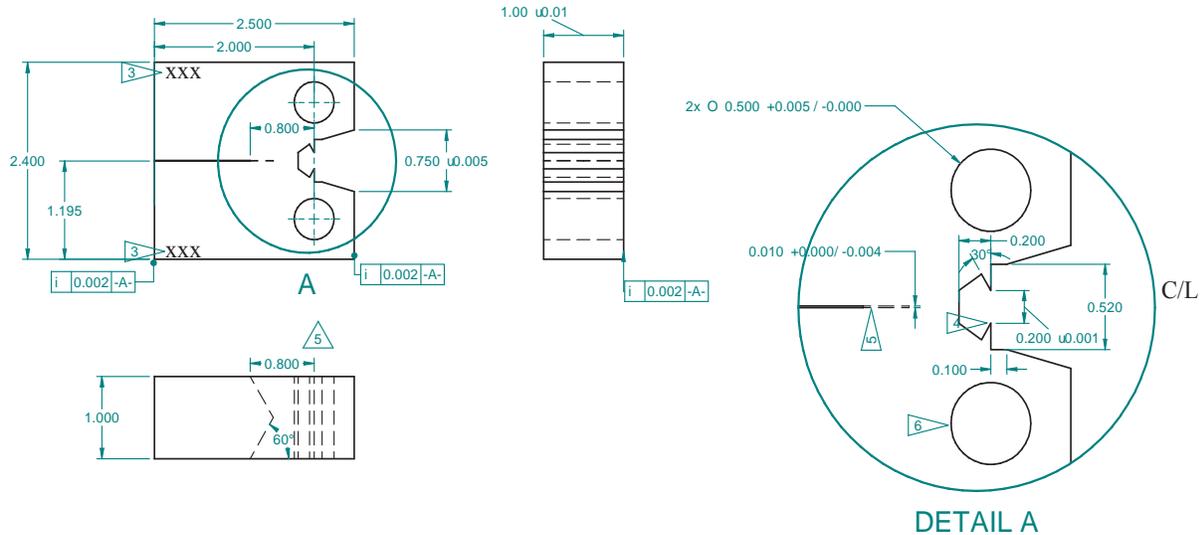
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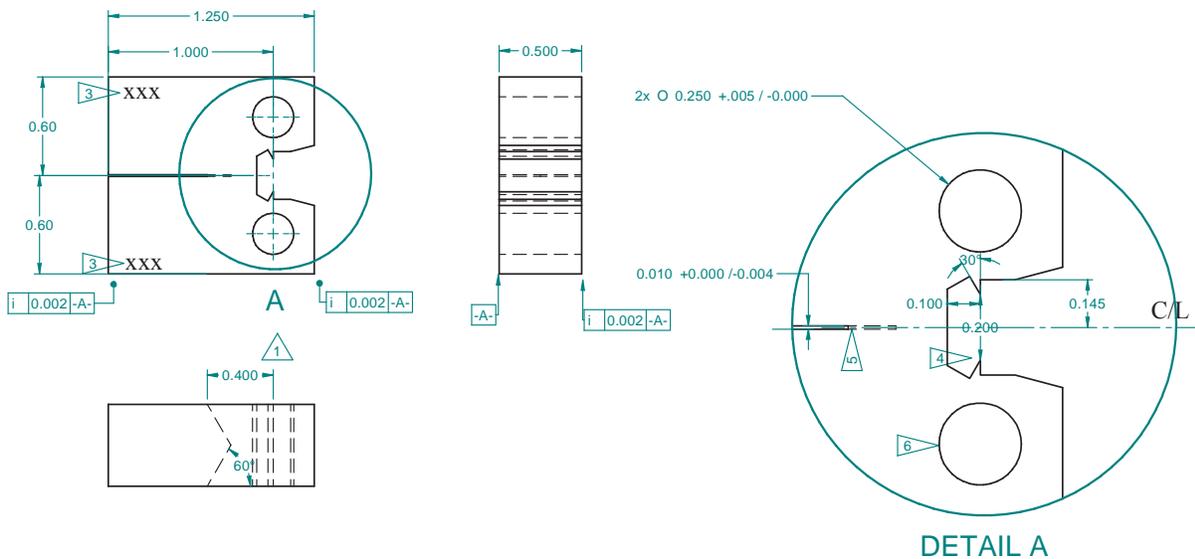
## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
49 of 223

Two specimen designs were used; one for the L-T and T-L orientations (Figure 8.4-2) and one for the S-T orientation (Figure 8.4-3). All specimens were machined from the coupon blanks such that the test section was located at the mid-plane thickness ( $t/2$ ) of the coupon blank. Two replicate tests were conducted for each grain orientation as per the test matrix shown in Table 8.4-2. The test apparatus used for fracture toughness testing is shown in Figure 8.4-4.



**Figure 8.4-2.  $J_{IC}$  Fracture Toughness Specimen Design; L-T and T-L Orientations. Drawing No. S-295. All dimensions are in inches.**



**Figure 8.4-3.  $J_{IC}$  Fracture Toughness Specimen Design; S-T Orientation. Drawing No. S-294. All dimensions are in inches.**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

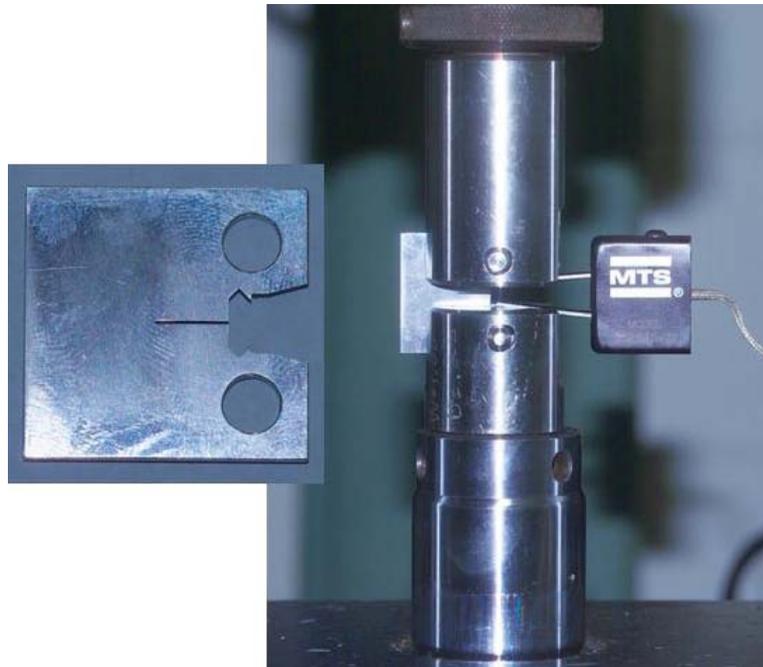
**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
50 of 223

*Table 8.4-2. Fracture Test Matrix for the Aft Bulkhead*

<b>Specimen ID</b>	<b>Coupon Blank</b>	<b>Orient.</b>
CP-406-191	M1	L-T
CP-406-193	M1	L-T
CP-406-196	M1	T-L
CP-406-198	M1	T-L
CP-406-201	M1	S-T
CP-406-203	M1	S-T
CP-406-206	M2	L-T
CP-406-208	M2	L-T
CP-406-211	M2	T-L
CP-406-213	M2	T-L
CP-406-216	M2	S-T
CP-406-218	M2	S-T
CP-406-221	M3	L-T
CP-406-223	M3	L-T
CP-406-226	M3	T-L
CP-406-228	M3	T-L
CP-406-231	M3	S-T
CP-406-233	M3	S-T
CP-406-236	M4	L-T
CP-406-238	M4	L-T
CP-406-241	M4	T-L
CP-406-243	M4	T-L
CP-406-246	M4	S-T
CP-406-248	M4	S-T
CP-406-251	M5	L-T
CP-406-253	M5	L-T
CP-406-256	M5	T-L
CP-406-258	M5	T-L
CP-406-261	M5	S-T
CP-406-263	M5	S-T
CP-406-266	M6	L-T
CP-406-268	M6	L-T
CP-406-271	M6	T-L
CP-406-273	M6	T-L
CP-406-276	M6	S-T
CP-406-278	M6	S-T

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP-13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 51 of 223	



***Figure 8.4-4.  $J_{IC}$  Fracture Toughness Specimen and Test Apparatus***

Following machining, the C(T) specimen was cyclically loaded in tension to generate a fatigue precrack. The specimen was then tested per ASTM E1820 using the unloading compliance method for calculating crack length. A crack-mouth opening displacement gauge (COD) was used for measuring load-line displacement. The load and COD data was then used to generate a resistance curve, or R-curve, for each specimen that describes  $J$  (in-lbf/in<sup>2</sup>) versus crack extension. An illustrative R-curve is shown in Figure 8.4-5. The critical  $J$  value, or  $J_{IC}$ , is taken where the crack extension reaches 0.008 inches. This is considered the onset of tearing. Data beyond the critical value provides insight into the ability of the material to tear (crack extension) in a stable manner. Critical  $J$  values can be converted to  $K$  values (crack tip stress intensity, ksi $\sqrt{\text{in}}$ ) to support linear elastic fracture analysis. In the event the material displays unstable fracture, data from the ASTM E1820 test can be used to evaluate the critical crack tip stress intensity value ( $K_{IC}$ ). A typical R-curve for the spin formed aft bulkhead material is shown in Figure 8.4-6. Also, a typical post-test specimen fracture surface is shown in Figure 8.4-7. Significant features along the fracture surface are noted in Figure 8.4-7.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
52 of 223

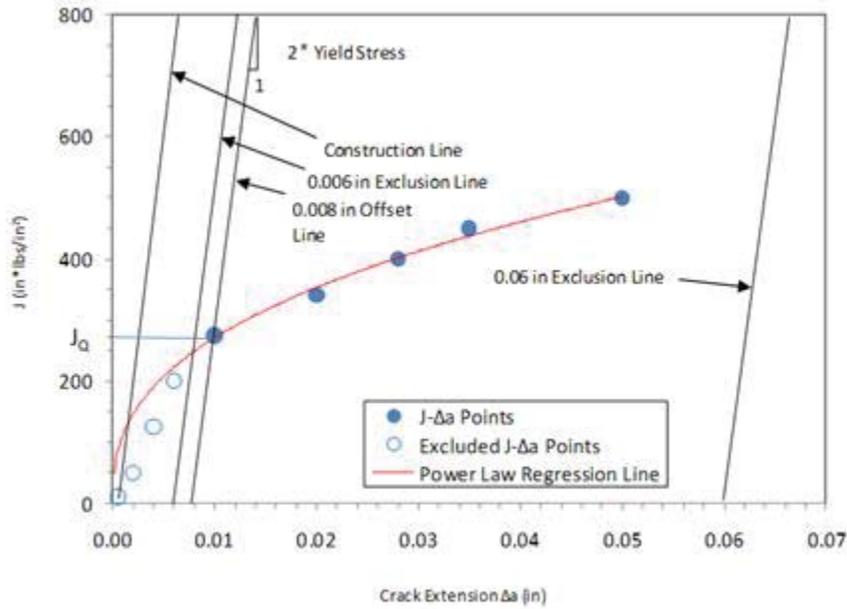


Figure 8.4-5.  $J_c$  Fracture Toughness R-Curve Plot

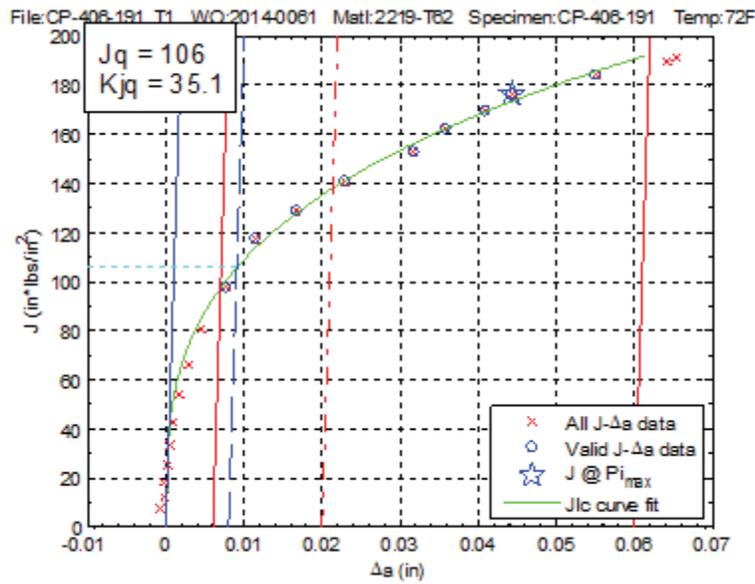
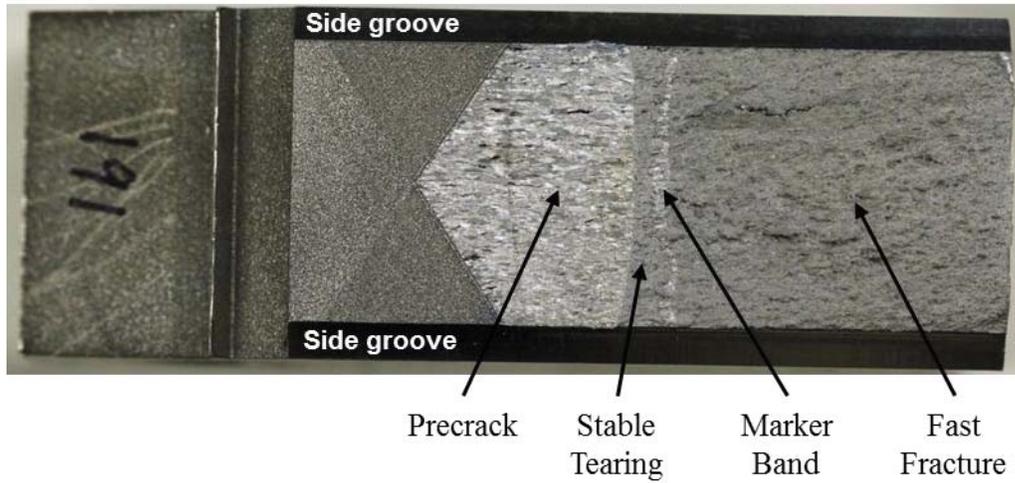


Figure 8.4-6. Typical  $J_c$  Fracture Toughness R-Curve Plot

Plot shown is for specimen CP-406-191 from coupon blank M1 in the L-T orientation.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>53 of 223</b>



**Figure 8.4-7. Typical Cross-Sectional Fracture Surface of a  $J_{1C}$  Fracture Toughness Specimen (specimen shown is CP-406-191 from coupon blank M1 in the L-T orientation)**

### 8.5 Stress Corrosion Test Procedures

Coupon blanks M7, M8, M9, and M10 from the aft bulkhead were provided to NASA MSFC for SCC testing. These blanks were obtained from the locations highlighted in yellow in the aft bulkhead cut plan (Figure 8.5-1) and coupon blank matrix (Table 8.5-1). For each coupon blank, 21 LT and 21 ST tension specimens were machined per the ASTM E8 small-size round tension test specimen design shown in Figure 8.5-2. In addition, 21 L tension specimens were machined from coupon blank M10. These specimen orientations were with respect to the original plate rolling direction. The coupon blank cut plans for these tension specimens are shown in Figures 8.5-3 through 8.5-6. Three specimens from each set of 21 were used to obtain baseline tensile data to establish applied stress levels for SCC testing; the remaining 18 were used for SCC testing. Specimen design and test procedures for these baseline tensile tests are discussed in Section 8.3.



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
 54 of 223

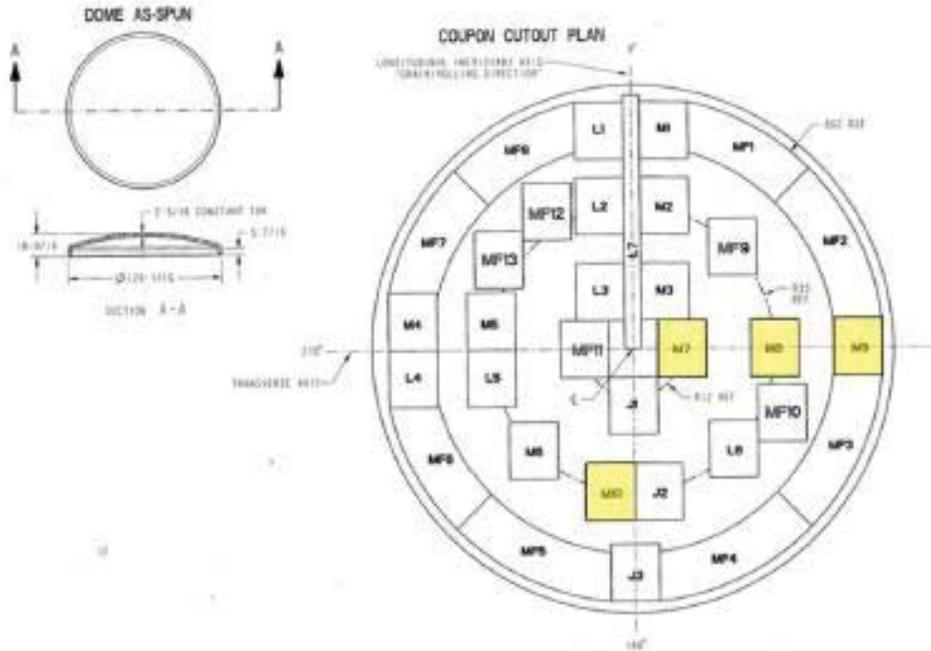


Figure 8.5-1. Aft Bulkhead Cut Plan showing the Location of the SCC Coupon Blanks highlighted in Yellow

Table 8.5-1. SCC Coupon Blank Locations and Orientations

Coupon Blank	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Center Point Arc Length, in.
M7	14	12	90°	12.00
M8	14	12	90°	35.13
M9	14	12	90°	56.25
M10	14	12	190°	35.63



# NASA Engineering and Safety Center Technical Assessment Report

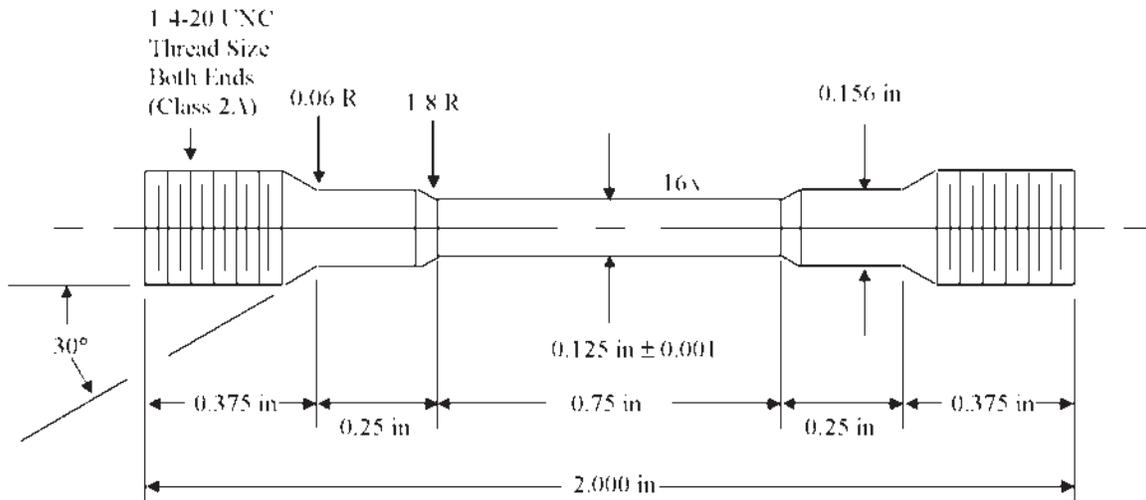
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
55 of 223



## NOTES:

1. Tolerances:  $\pm 0.005$  inch, except otherwise specified.
2. Surface finish:  $16\sqrt{\text{ }}$  for the reduced section,  $32\sqrt{\text{ }}$  for the rest.
3. Thread dimensions must be as specified. Measurement by fabricator is mandatory.
4. No undercutting of radii permitted.
5. Gage section to be concentric with axis within 0.002 inch TIR and parallel.
6. No file marks or nicks permitted within gage section.
7. Center-drilling permissible (both ends). May use a #1 size max. Chamfer diameter not to exceed 0.100 inch.
8. Break sharp edges.
9. The reduced section may have a gradual taper from the ends toward the center with the ends not more than 0.005 inch larger diameter than the center.

***Figure 8.5-2. Round Sub-Size Tensile Specimen Design used for SCC Testing***



# NASA Engineering and Safety Center Technical Assessment Report

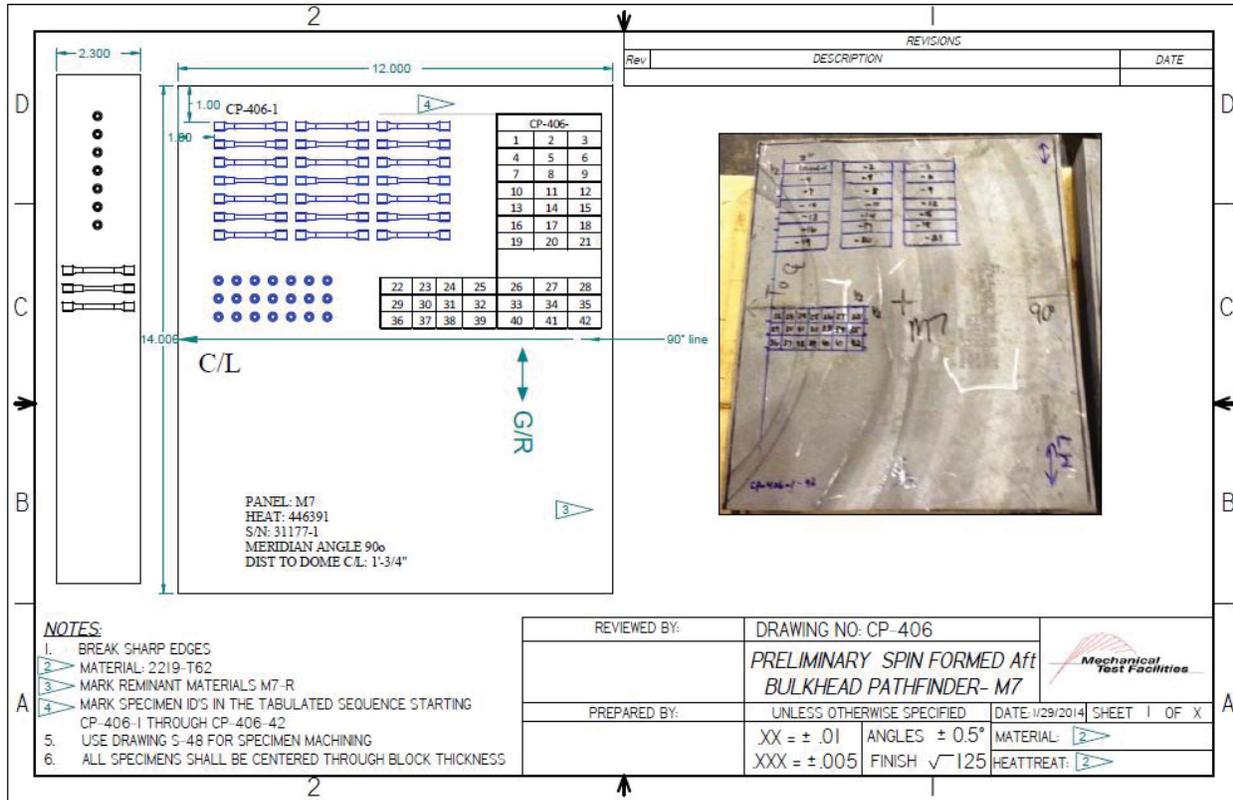
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
56 of 223



**Figure 8.5-3. Cut Plan for Machining SCC Specimens from Coupon Blank M7 (specimens CP-406-1 through CP-406-42)**



# NASA Engineering and Safety Center Technical Assessment Report

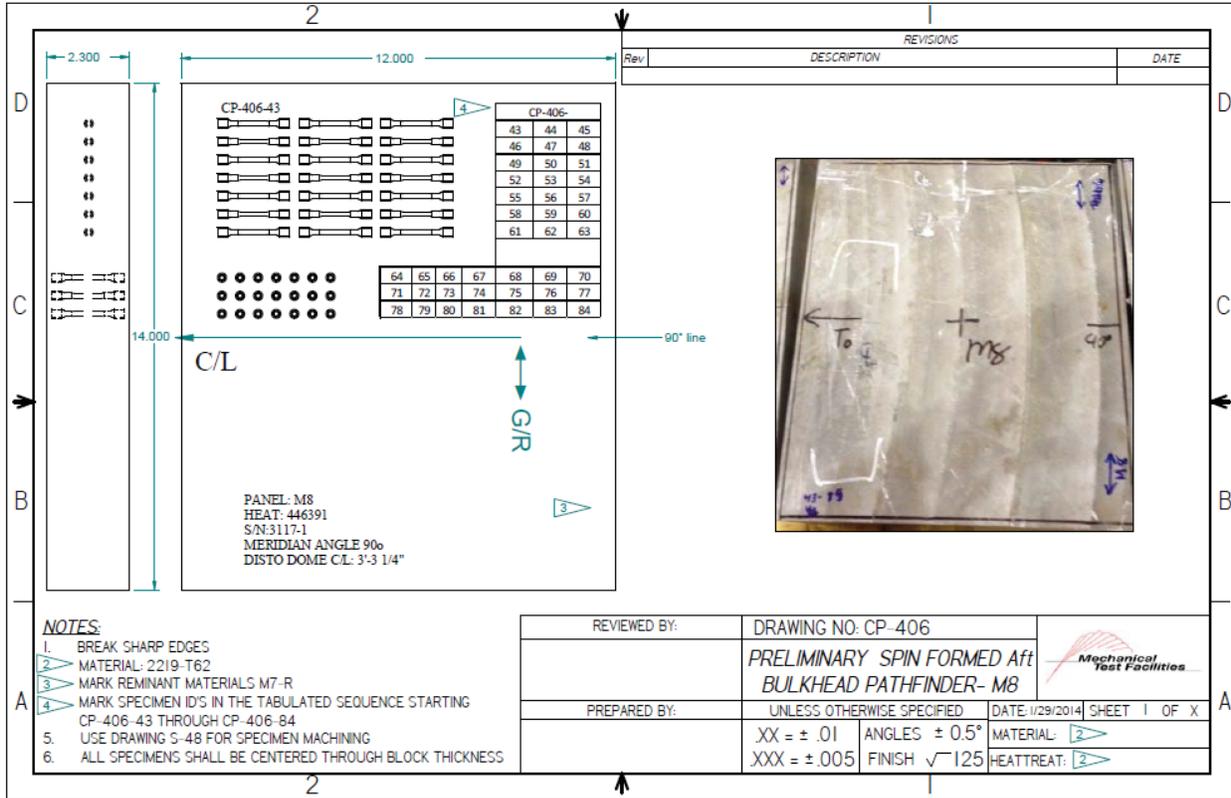
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
57 of 223



**Figure 8.5-4. Cut Plan for Machining SCC Specimens from Coupon Blank M8 (specimens CP-406-43 through CP-406-84)**



# NASA Engineering and Safety Center Technical Assessment Report

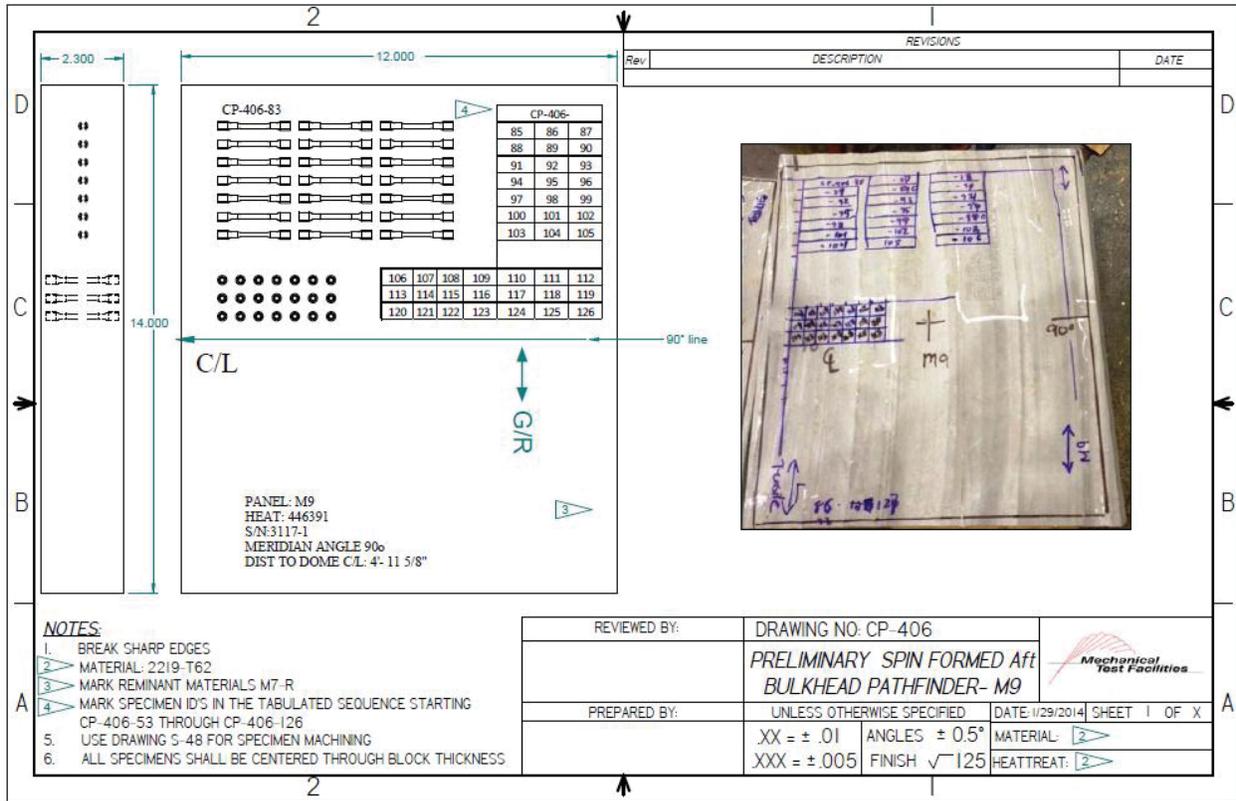
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
**58 of 223**



Note: This sequence starts with CP-406-85, not CP-406-83 as stated in the drawing, or CP-406-53 as stated in note 4.

**Figure 8.5-5. Cut Plan for Machining SCC Specimens from Coupon Blank M9 (specimens CP-406-85 through CP-406-126)**



# NASA Engineering and Safety Center Technical Assessment Report

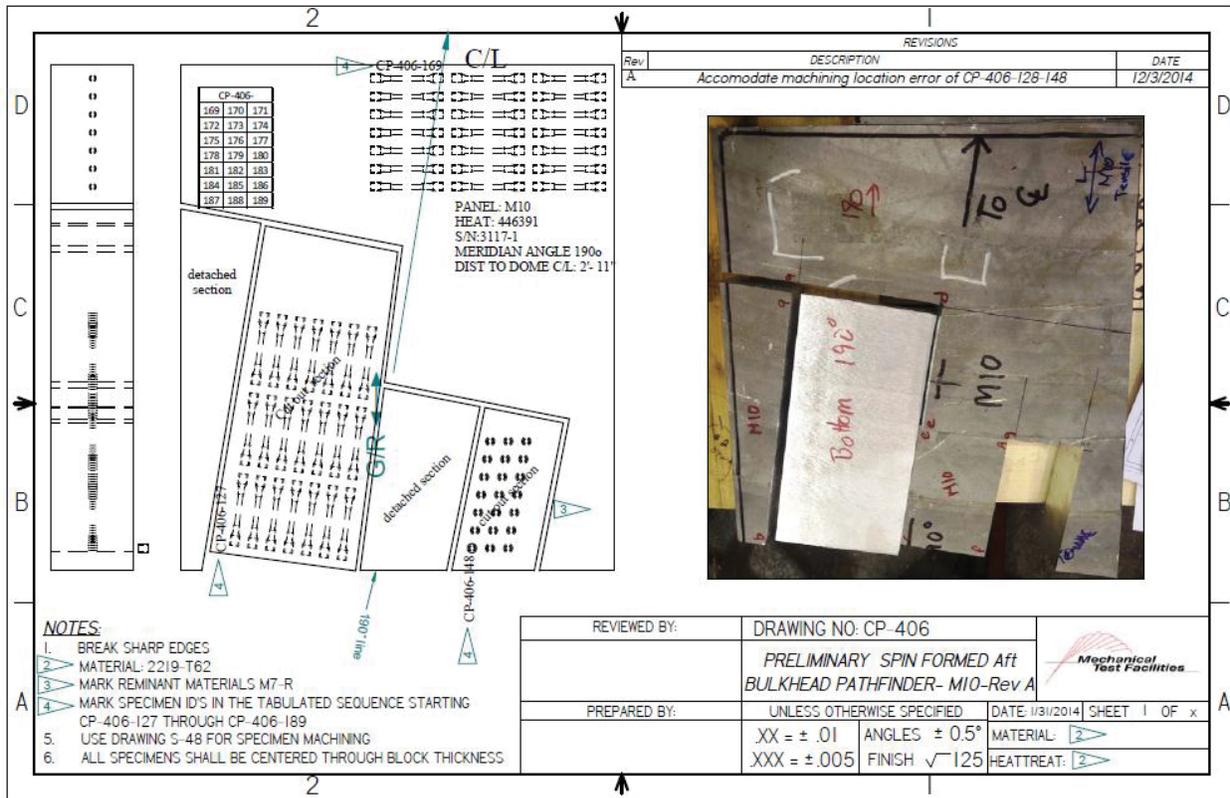
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
59 of 223



Note: The sequence for the ST specimens starts with CP-406-148 through CP-406-168. A set of 21 longitudinal specimens was also fabricated from this coupon blank, and that sequence starts with CP-406-127 through CP-406-147. The sequence for the LT specimens is as shown in the table (CP-406-169 through CP-406-189).

**Figure 8.5-6. Cut Plan for Machining SCC Specimens from Coupon blank M10 (specimens CP-406-127 through CP-406-189)**

The SCC testing, analysis, and rating were performed in accordance with MSFC-STD-3029, which provides guidelines for the selection of metallic materials for stress corrosion resistance and is the standard for Space Flight Hardware. The SCC specimens were tested using the direct tension loading method as described in ASTM G49 (9). The LT and ST SCC specimens were stressed in tension to 0, 50-, 75-, and 90% of the average YS measured from baseline tensile tests of the aft bulkhead and subjected to alternate immersion exposure in a 3.5% NaCl solution for test durations of 30 and 90 days per ASTM G44 (10). The L SCC specimens from coupon blank M10 were also stressed in tension to 0-, 50-, 75-, and 90% of the YS, but were subjected to salt spray exposure for test durations of 30 and 90 days per ASTM B117 (11). Three replicate specimens were tested for each stress level, test duration, and exposure environment per the SCC test matrices, as shown in Table 8.5-2- Table 8.5-5. Figure 8.5-7 shows the stressing device, extensometer, stressing frames, and representative SCC specimens. The alternate immersion test apparatus and salt spray chamber are shown in Figure 8.5-8.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
60 of 223

**Table 8.5-2. 30-Day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material  
Test Environment: 3.5% NaCl alternate immersion per ASTM G44**

Coupon Blank	Meridian Angle	Orientation	Stress Level % YS	Number of Replicates
M7	90°	LT	0	3
			50	3
			75	3
			90	3
		ST	0	3
			50	3
			75	3
			90	3
M8	90°	LT	0	3
			50	3
			75	3
			90	3
		ST	0	3
			50	3
			75	3
			90	3
M9	90°	LT	0	3
			50	3
			75	3
			90	3
		ST	0	3
			50	3
			75	3
			90	3
M10	190°	LT	0	3
			50	3
			75	3
			90	3
		ST	0	3
			50	3
			75	3
			90	3

**Table 8.5-3. 90-Day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material.  
Test Environment: 3.5% NaCl alternate immersion per ASTM G44**

Coupon Blank	Meridian Angle	Orientation	Stress Level % YS	Number of Replicates
M7	90°	LT	0	3
			75	3
		ST	0	3
			75	3
M8	90°	LT	0	3
			75	3
		ST	0	3
			75	3
M9	90°	LT	0	3
			75	3
		ST	0	3
			75	3
M10	190°	LT	0	3
			75	3
		ST	0	3
			75	3

**Table 8.5-4. 30-Day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material  
Test Environment: 5% salt spray per ASTM B117**

Coupon Blank	Meridian Angle	Orientation	Stress Level % YS	Number of Replicates
M10	190°	L	0	3
			75	3

**Table 8.5-5. 90-Day SCC Test Matrix for the Spin Formed Aft Bulkhead Al 2219-T62 Material  
Test Environment: 5% salt spray per ASTM B117**

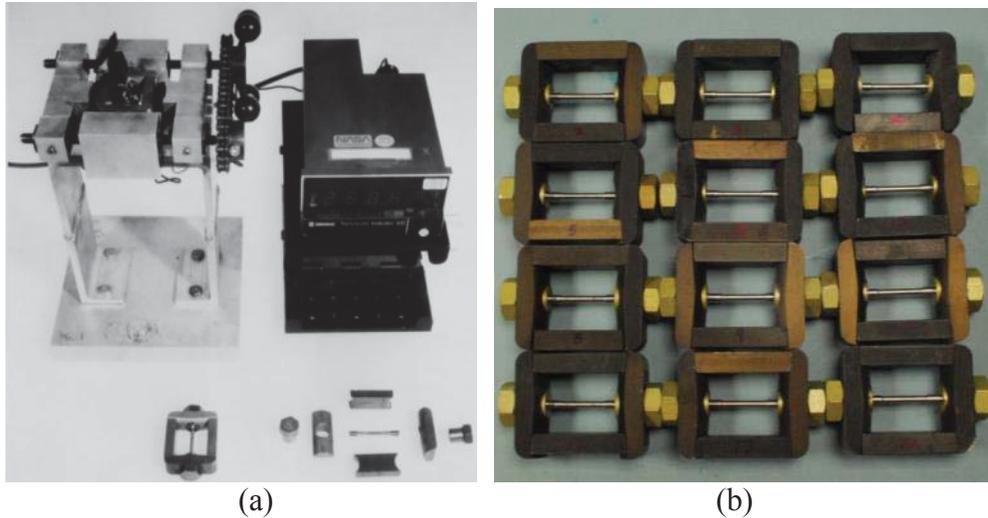
Coupon Blank	Meridian Angle	Orientation	Stress Level % YS	Number of Replicates
M10	190°	L	0	3
			50	3
			75	3
			90	3



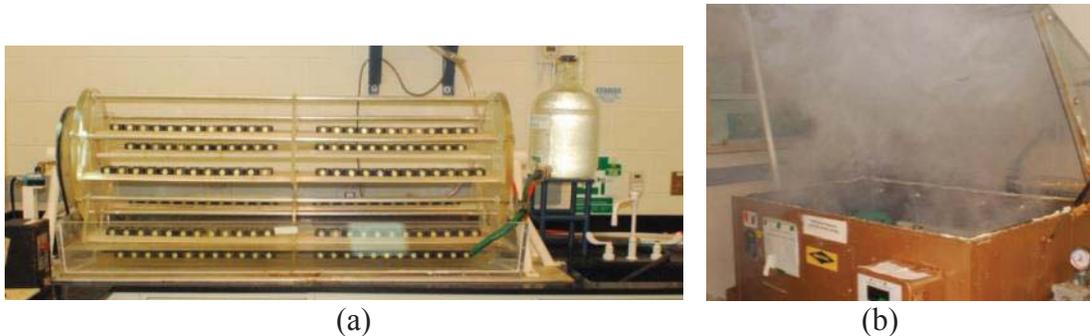
Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
62 of 223



**Figure 8.5-7. (a) Stressing Device and (b) Representative Stressed Specimens and Stressing Frames**



**Figure 8.5-8. (a) Alternate Immersion Test Apparatus and (b) Salt Spray Chamber**

Specimens were considered to have failed during the SCC test if one or more of the specimens fractured during exposure or exhibited cracking during post-exposure visual examination. If any failures occurred, then that specimen was sectioned and the morphology of the fracture examined. If no failures occurred for a given test condition, then one specimen from the set was subjected to metallographic examination while the remaining two specimens were tensile tested to failure to determine residual tensile strength. Two measures were used to evaluate the residual tensile strength of the surviving specimens: the percent tensile strength retained, which compares the residual tensile strength of the exposed specimens to typical tensile properties of unexposed specimens; and the residual strength ratio, which compares the residual tensile strength of specimens exposed with and without an applied stress.

The percent tensile strength retained provides a measure of the residual load carrying ability of the specimen as compared to unexposed specimens and is an indication of the reduction in specimen cross-sectional area, not a change in strength of the material. Loss in cross-sectional area can be due to general corrosion, pitting, and stress corrosion. Metallurgical examination is required to confirm the type of corrosion. For the specimens tested with an applied stress, the reduction in tensile strength is the combined effect of stress and the corrosive environment. For

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>63 of 223</b>

the specimens tested with no applied stress the reduction is the effect of the corrosive environment only. The percent tensile strength retained for each exposed specimen was calculated as follows:

$$\text{Percent Tensile Strength Retained} = (\text{UTS}_f / \text{UTS}_i) \times 100$$

where:

$\text{UTS}_f$  = Residual strength of the exposed specimen (failure load/original specimen cross-sectional area)

$\text{UTS}_i$  = Average ultimate tensile strength for the unexposed specimens.

The residual strength ratio provides a more direct indication of the effect of applied stress during exposure and therefore a method to separate the effects of general corrosion and pitting from stress corrosion. The  $\text{UTS}_s$  and  $\text{UTS}_0$  are calculated based on original specimen cross-sectional area, and provide an indication of the loss in area due to stress corrosion and general corrosion, respectively. For this study, specimens with residual strength ratios of less than 0.75 were considered failures. The residual strength ratio for each specimen that was exposed with an applied stress was calculated as follows:

$$\text{Residual Strength Ratio} = \text{UTS}_s / \text{UTS}_0$$

where:

$\text{UTS}_s$  = Residual strength of stressed and exposed specimen

$\text{UTS}_0$  = Averaged residual strength of non-stressed and exposed specimens

At the end of the test, the pass/fail data obtained was used to assign a stress corrosion susceptibility rating for the material based on the requirements in MSFC-STD-3029A (12). They are as follows:

### **Table I Requirements**

Alloys, tempers, and weldments in Table I are considered highly resistant to SCC in 3.5% NaCl alternate immersion or 5% salt spray. An alloy or weldment can be added to this table if no stress corrosion failures occur on specimens stressed to 75% of the YS within 30 days of exposure.

### **Table II Requirements**

Alloys, tempers, and weldments in Table II are considered moderately resistant to SCC in 3.5% NaCl alternate immersion or 5% salt spray. An alloy or weldment is added to this table if no stress corrosion failures occur on specimens stressed to 50% of the YS within 30 days of exposure.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 64 of 223	

### Table III Requirements

Alloys, tempers, and weldments in Table III are considered to have low resistance to SCC in 3.5% NaCl alternate immersion or 5% salt spray. They are placed in this table if stress corrosion failures occur on specimens stressed to 50% of the YS within 30 days of exposure.

### 8.6 Seacoast Exposure SCC Test Plan

While the 3.5% NaCl solution alternate immersion test provides a comprehensive screening method for accelerated stress corrosion testing of high-strength Al alloy product forms, a disadvantage of the test is that severe pitting may develop in the specimens (13). Such pitting in tension specimens with relatively small cross-section can markedly reduce the effective cross-sectional area and produce a net section stress greater than the nominal gross section stress, resulting in either: (1) fracture by mechanical overload of a material that is not susceptible to SCC; or (2) SCC of a material at an actual stress higher than the intended nominal test stress. The occurrence of either of these phenomena might then interfere with a valid evaluation of materials with relatively high resistance to stress corrosion. As a result, seacoast exposure SCC testing was proposed as a complementary screening test in this project. Seacoast exposure SCC testing, which is performed in a natural outdoor environment and requires longer test durations than the standard accelerated corrosion tests performed in a laboratory, is more representative of the intended service environment

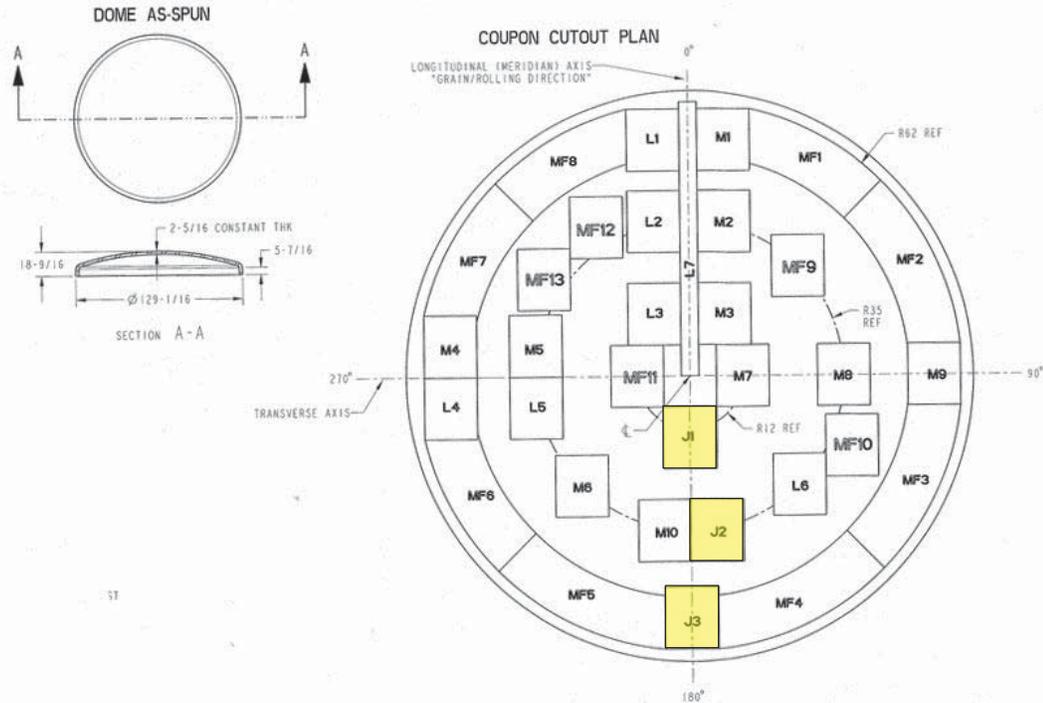
Three coupon blanks from the aft bulkhead were provided to NASA JSC for seacoast exposure SCC testing at NASA KSC. These blanks were identified as J1, J2, and J3 and were obtained from the locations highlighted in yellow in the aft bulkhead cut plan (Figure 8.6-1) and coupon blank matrix (Table 8.6-1). For each coupon blank, 9 short transverse (ST) tension specimens were machined per the ASTM E8 small-size round tension test specimen design (Figure 8.6-2). This specimen orientation is with respect to the original plate rolling direction. Specimens were machined such that the gage section was located at the mid-plane thickness ( $t/2$ ) of the coupon blank.



Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
 65 of 223



**Figure 8.6-1. Aft Bulkhead Cut Plan showing the Location of the Seacoast Exposure SCC Coupon Blanks highlighted in Yellow**

**Table 8.6-1. Seacoast Exposure SCC Coupon Blank Locations and Orientations.**

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
J1	14	12	180°	12
J2	14	12	170°	35-5/8
J3	14	12	180°	55-5/8

**NOTE:**

Prior to the start of the seacoast exposure SCC tests, the initial laboratory alternate immersion SCC tests results became available. Based upon the 30-day alternate immersion exposure in 3.5% NaCl test results (Section 10.4.1.1), the accelerated test condition provides adequate screening methodology for SCC. Longer test durations of 90 days, however, did lead to severe general corrosion and pitting (Section 10.4.1.2). Consequently, specimens scheduled for seacoast exposure testing in this project were diverted to laboratory alternate immersion testing at MSFC to generate SCC data on more locations in the aft bulkhead and to confirm initial test results. The NESC team recommends that Orion conduct seacoast exposure SCC testing of the first-article aft bulkhead in order to characterize the corrosion performance in the service

environment. The following test plans are provided as a guide for the Orion Program if they choose to conduct these tests.

The seacoast exposure SCC specimens should be tested using the direct tension loading method as described in ASTM G49. The specimens should be stressed in tension to 0-, 75-, and 90% of the YS and will be subjected to seacoast exposure for durations of up to 3 years as per ASTM G44. Table 8.6-2 shows a proposed seacoast exposure SCC test matrix. Specimens should be tested in triplicate for each test condition.

**Table 8.6-2. Test Matrix for the Seacoast Exposure SCC Tests**

Bulkhead Location	Coupon Blank	Meridian Angle	Stress Orient.	Stress Level	# Replicates
Pole	J1	180°	ST	0% YS	3
				75% YS	3
				90% YS	3
Membrane	J2	180°	ST	0% YS	3
				75% YS	3
				90% YS	3
Rim	J3	180°	ST	0% YS	3
				75% YS	3
				90% YS	3

## 9.0 LM Test Plan

This is a high-level summary of the LM test plan in support of the LM Orion Program. This information is provided for completeness and is intended to indicate the overall scope of the activities. Due to proprietary considerations, results from this work will not be published in this or addendum NESC reports.

The LM test plan focused on two activities; FSW schedule development and complementary mechanical property, and structural subcomponent testing. Further details are provided in Sections 9.1 and 9.2

### 9.1 Self-Reacting FSW and Friction Pull Plug Weld (FPPW) Development

Coupon blanks from the aft bulkhead were provided to LM-MAF for SR-FSW and FPPW schedule development. These blanks were identified as MF1, MF2, MF3, MF4, MF5, MF6, MF7, and MF8 and were obtained from the arc-shaped segments located at the rim of the aft bulkhead as shown in the aft bulkhead cut plan (Figure 9.1-1) and coupon blank matrix (Table 9.1-1).



# NASA Engineering and Safety Center Technical Assessment Report

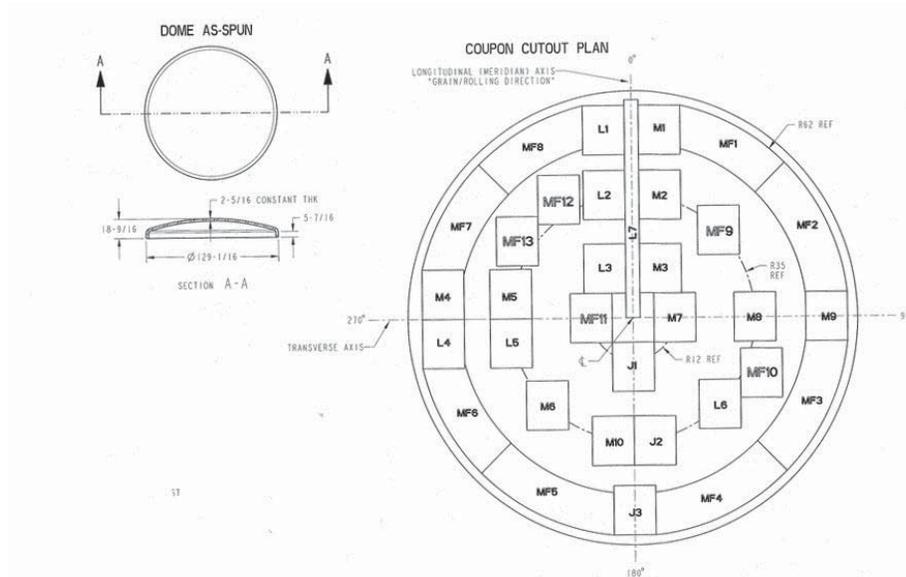
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
67 of 223



**Figure 9.1-1. Aft Bulkhead Cut Plan showing the Location of the FSW and FPPW Schedule Development Coupon Blanks**

**Table 9.1-1. FSW and FPPW Schedule Development Coupon Blank Locations and Orientations**

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
MF1	N/A	N/A	31°	56-3/4
MF2	N/A	N/A	64°	56-3/4
MF3	N/A	N/A	116°	56-3/4
MF4	N/A	N/A	154°	56-3/4
MF5	N/A	N/A	206°	56-3/4
MF6	N/A	N/A	240°	56-3/4
MF7	N/A	N/A	296°	56-3/4
MF8	N/A	N/A	329°	56-3/4

The LM Orion Program was provided with spin formed Al 2219-T62 aft bulkhead material to develop nominal SR-FSW and FPPW weld schedules. The development will be focused on schedules for the Al 2219-T6 plate and Al 2219-T8 forging weld combination that will be utilized on the Orion CM.

The SR-FSW development will generally follow three phases of development. The first phase will follow a design of experiment to evaluate the weldability of the material combination. Evaluation will consist of non-destructive phased array ultrasonic testing (PAUT) inspection, tensile testing, and metallography. Emphasis will be placed on identifying load characteristics and identifying potential nominal weld schedules that show a strength insensitivity to load. The second phase will be a verification step, aimed at characterizing the available operating load

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 68 of 223	

ranges and down-selecting a final nominal weld schedule. The final phase will involve sensitivity testing were the selected nominal schedule will be exposed to production-related variables. These verification tests will include, but not be limited to, joint fit-up, tacking, off-set, and clean time. The end of the development cycle will produce a weld schedule that the Orion Program will feel confident about going forward into the production pathfinder activity. The pathfinder activity will be the final step that certifies the weld schedule for use on production flight articles.

The FPPW development will follow a cycle similar to the SR-FSW cycle described above. The initial phase FPPW will be geared towards establishing the boundaries of the FPPW weldable space. These welds will then be evaluated using penetrant and ultrasonic inspection, tensile tests for ultimate strength, YS, elongation, and metallography. The results of the initial welding will be characterized in an attempt to understand the driving factors of FPPW and determine potential nominal FPPW schedules. The second phase will take the selected nominal schedules and run a series of verification tests to characterize the repeatability of the weld schedules performance. The final phase will evaluate sensitivity impacts. Again, these verification tests will include, but not be limited to joint fit-up, alignment, and cleaning. The end of the development cycle will produce a weld schedule that the LM Orion Program feels confident about going forward into the production pathfinder activity. The pathfinder activity will be the final step that certifies the weld schedule for use on production flight articles.

## **9.2 Mechanical Property and Structural Subcomponent Testing**

Coupon blanks from the aft bulkhead were provided to LM-MAF for mechanical property testing in support of the Orion Program. These blanks were identified as MF9, MF10, MF11, MF12, and MF13 and were obtained from the locations highlighted in yellow in the aft bulkhead cut plan (Figure 9.2-1) and coupon blank matrix (Table 9.2-1).



# NASA Engineering and Safety Center Technical Assessment Report

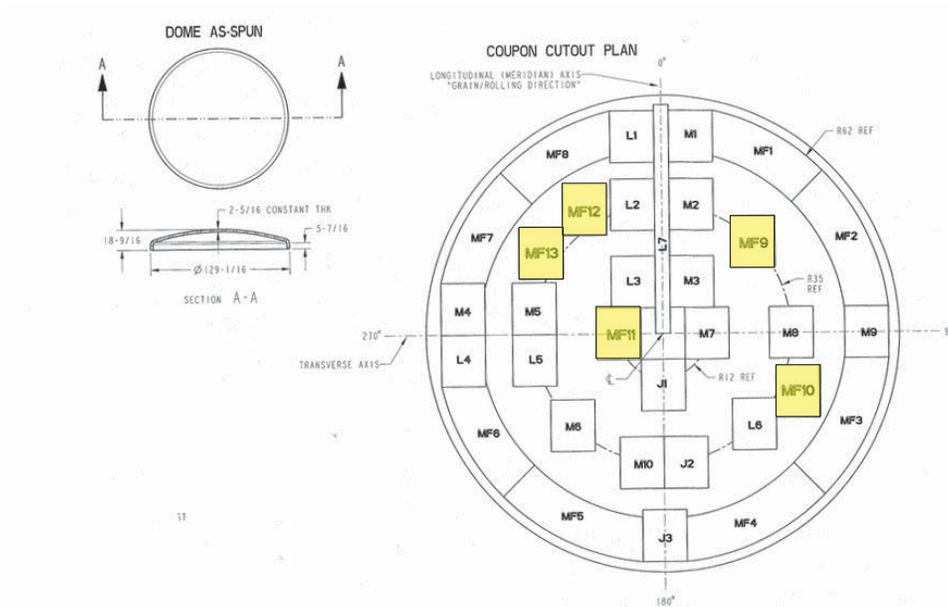
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
69 of 223



**Figure 9.2-1. Aft Bulkhead Cut Plan showing the Location of the Supplemental Mechanical Property Test Coupon Blanks highlighted in Yellow**

**Table 9.2-1. LM Mechanical Property Test Coupon Blank Locations and Orientations**

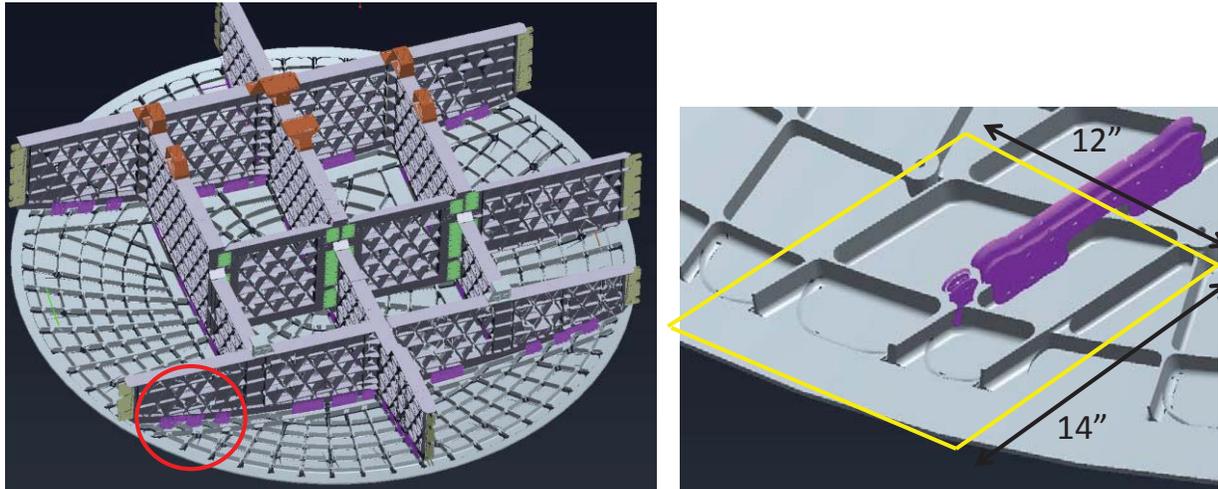
Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
MF9	14	12	45°	35-1/8
MF10	14	12	114°	40-3/8
MF11	14	12	270°	12
MF12	14	12	328°	40
MF13	14	12	304°	39-7/8

The testing program at MAF is designed to complement the mechanical property test data (tensile, fracture, and SCC) being generated by the NESC team and provide additional supporting data to aid the Orion Program in the design of the aft bulkhead. The first objective of these mechanical property tests is to characterize the fatigue properties of the spin formed Al 2219-T62 aft bulkhead material and compare it to existing reference data for both Al 2219-T6 and -T8 product forms. This fatigue testing will include surface flaw testing to a leak condition, using specimens that will be machined to the minimum membrane thickness and crack growth testing in the ST orientation. The second objective is to characterize the aft bulkhead material with bearing and insert pull tests. This testing will utilize special machined specimens that are representative of hardware attachment methods used on the Orion aft bulkhead.

After completion of the NESC test program, the skeletal remains of the spin formed aft bulkhead (Figure 7.10-2) were shipped to LM-MAF for further testing. Planned activities include structural subcomponent testing in which different configurations of the backbone-to-aft

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>70 of 223</b>

bulkhead joint will be tested to simulate the CM internal pressure load (Figure 9.2-2). The goals of these tests are to demonstrate structural performance of the aft bulkhead in the ST direction and to verify bolt and splice plate strength.



*Figure 9.2-2. Schematic showing the Simulated Location for Backbone Panel 6 Connection to Aft Bulkhead Joint*

## 10.0 Results and Discussion

### 10.1 Metallurgical Analysis

#### 10.1.1 Thickness Measurements

The thickness of the L7 coupon blank was measured at locations along the meridian line that corresponded to the locations of the UT measurements and laser scan analysis. Vernier calipers with ball end caps were used for these measurements and an effort was made to make measurements at the base of the surface scallops. The measurements are summarized in Table 10.1-1 and compared with the UT and laser scan measurements in Figure 10.1-1. The maximum thickness occurred at a distance of 4 inches from the pole, the minimum thickness at 52 inches, and the maximum reduction in thickness was 0.12 inches, values that are fairly consistent with the UT and laser scan results. Thickness measurements from all three sources indicate a 4 to 5% reduction in thickness. Also consistent with the UT and laser scan data, the thickness measured on coupon blank L7 indicates thinning from pole to rim for approximately 50 inches and then thickening to the rim. The L7 thickness profile in Figure 10.1-1 shows minimal fluctuations except toward the rim.

The deformation induced during spin forming is complex and non-uniform. Thickness reduction is a simplified metric used in this analysis to evaluate the variation over the acreage of the aft bulkhead. During convex spin forming there is generally no deliberate reduction in wall thickness as the material is shaped over the mandrel (2). During forming the blank diameter is reduced as material is pushed onto the mandrel, particularly near the rim, consequently the material experiences circumferential compressive stress superimposed on radial tensile stress,

which combine to result in nearly constant wall thickness. So many process parameters affect material response during spin forming that modeling the process has been unsuccessful. The industrial success of spin forming is based on extensive experience at the vendors.

***Table 10.1-1. Thickness Measurements of Coupon Blank L7 at Distances from the Pole***

Thickness Measurements of Coupon Blank L7	
Distance from Pole (in)	Thickness (in)
4	2.319
12	2.318
20	2.290
24	2.287
32	2.245
36	2.253
40	2.275
48	2.221
52	2.204
56	2.270



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
72 of 223

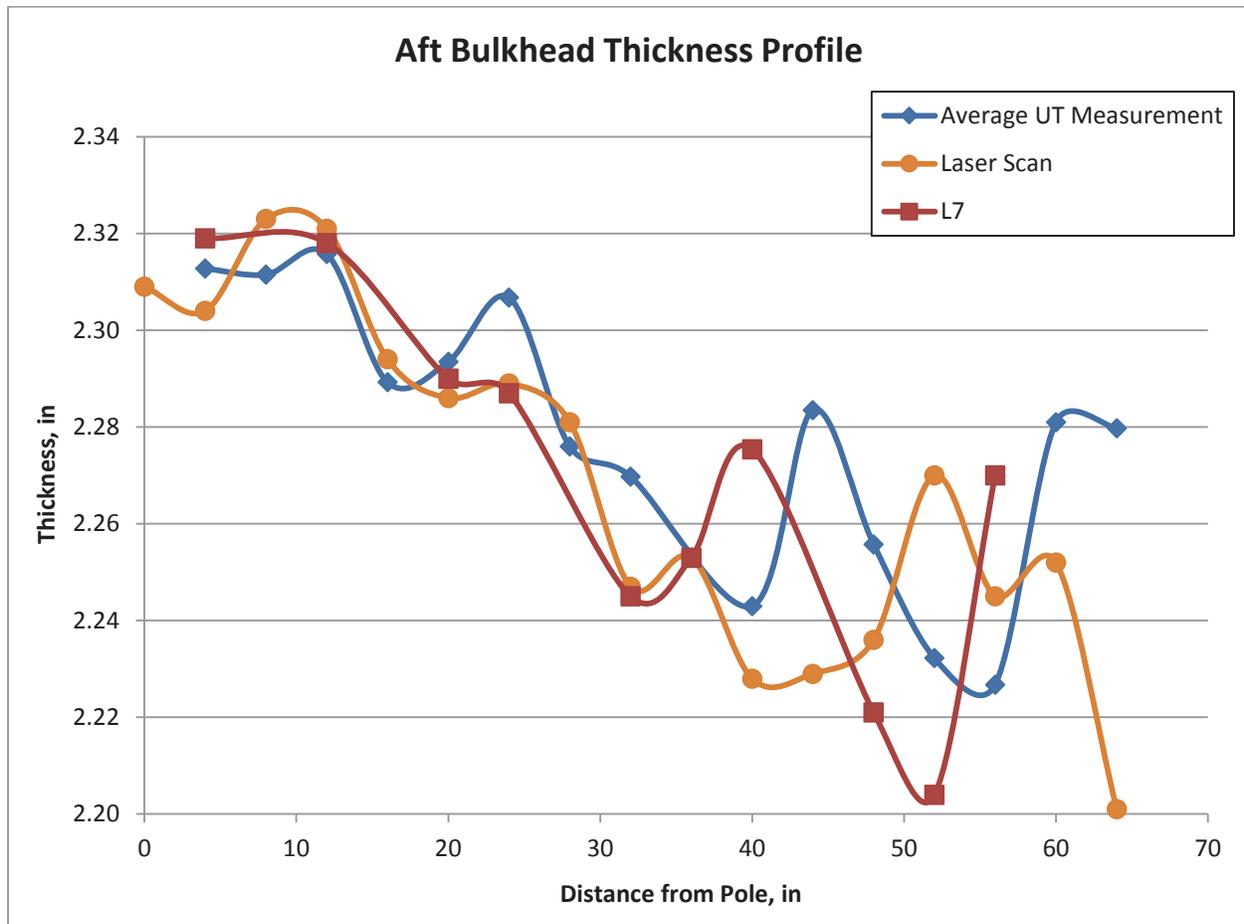


Figure 10.1-1. Thickness Profile of Coupon Blank L7 Compared with the UT and Laser Scan Data

### 10.1.2 Microstructural Analysis

Through-thickness montages shown in Figure 10.1-2 for samples L7-1 through L7-5 illustrate the variability in grain morphology with both through-thickness location and distance from the pole of the aft bulkhead. The blue lines denote through-thickness locations ( $t$  = thickness) that were examined at higher magnification and which are shown in Figure 10.1-3. Specimen L7-1 is located near the pole just inside the innermost forming tool contact area and consequently represents a region that was not deformed by spin forming. The thickness profile of coupon blank L7 indicates that the forming blank was thinned by about 4-5% during spin forming to create the aft bulkhead shape, with the thickness decreasing from pole to a minimum near the rim at a distance of approximately 50 inches from the pole and then increasing in thickness at the rim.

The through-thickness micrographs in Figure 10.1-2 show that as deformation increases, the microstructure changes from a uniform small grain size (L7-1) to a banded microstructure that



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

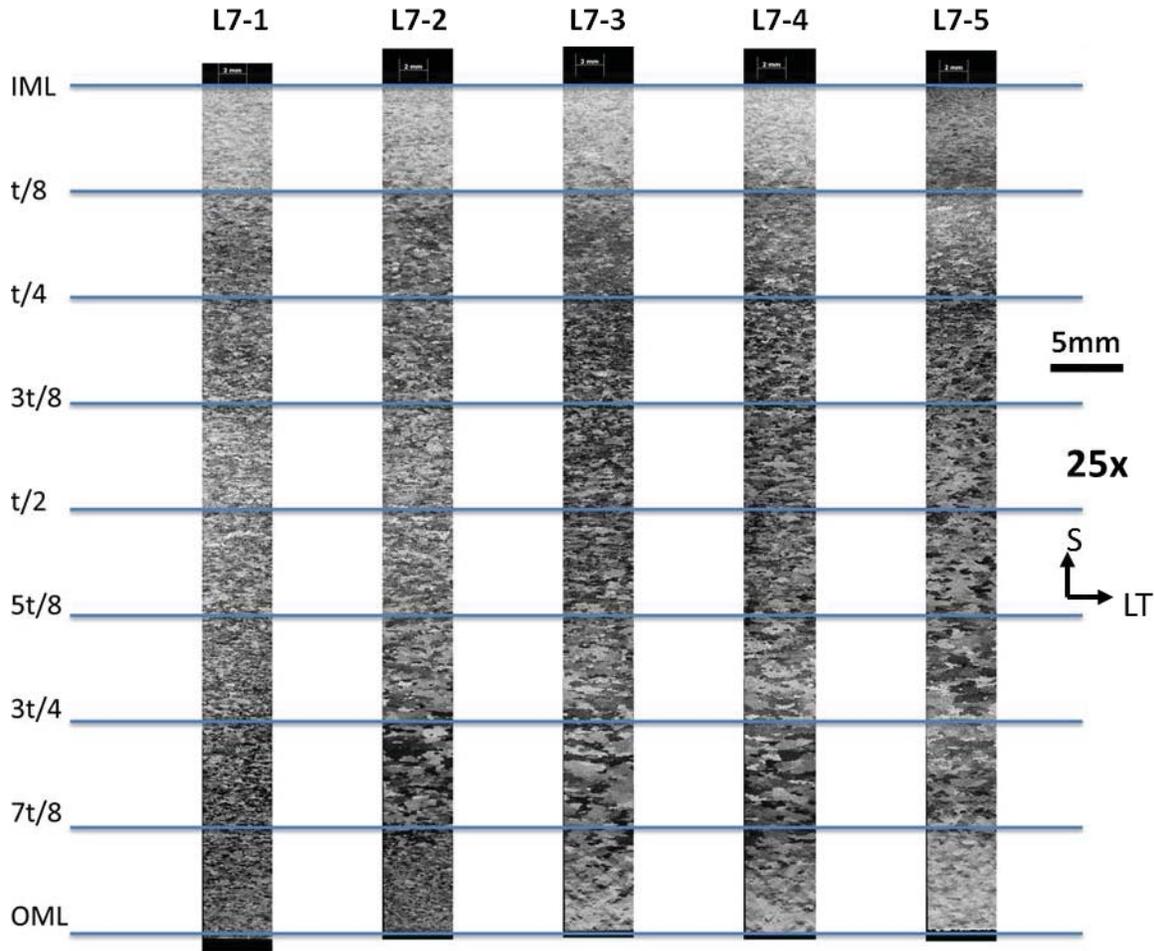
Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
73 of 223

exhibits regions of larger grain size, most likely due to strain induced recrystallization, primarily towards the OML surface where the forming tool contacts the plate. Notably larger grain size is observed between  $3t/4$  and  $7t/8$  starting with L7-2 and more pronounced in L7-3 and L7-4. Macroscopic deformation bands are observed near the OML, particularly in samples L7-3, L7-4, and L7-5.



**Figure 10.1-2. Through-thickness Microstructures of the Aft Bulkhead at Locations Along the  $0^\circ$  Meridian**

Higher magnification micrographs of each through-thickness position for meridian locations L7-1 through L7-5 are summarized in Figure 10.1-3(a-e). All samples exhibit grains slightly elongated in the LT direction. At the L7-1 location ((Figure 10.1-3(a)), no deformation) the grain size and morphology are uniform from IML to OML. All through-thickness positions at L7-1 exhibit precipitation on deformation bands, particularly from  $3t/8$  to  $5t/8$ . Sections L7-2 through L7-5 exhibit strain induced recrystallization, biased towards the OML and extending from the OML towards the mid-thickness. In sections L7-4 and L7-5, recrystallization occurs from the OML to  $3t/8$ . All through-thickness positions exhibit precipitation on deformation



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

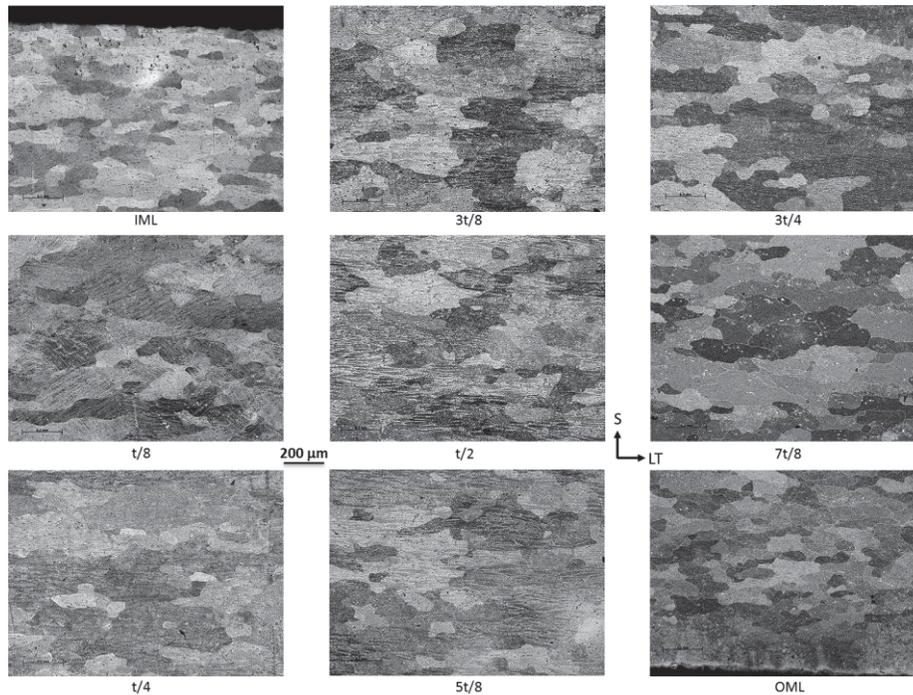
Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
74 of 223

bands, more heavily in the unrecrystallized regions. Aligned precipitation in the recrystallized regions may indicate that the prior deformation history associated with both plate rolling and spin forming is not completely erased during SHT. Alternatively, the alignment may indicate precipitation on slip planes (14), (15), (16).



**(a) Microstructure at L7-1 (L/8, 8 inches from the pole)**



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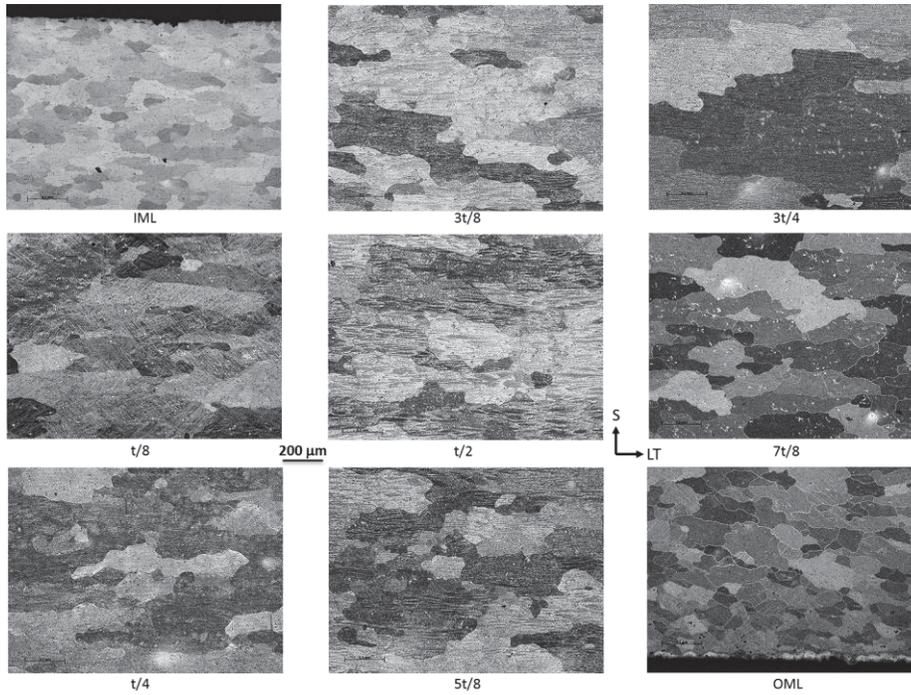
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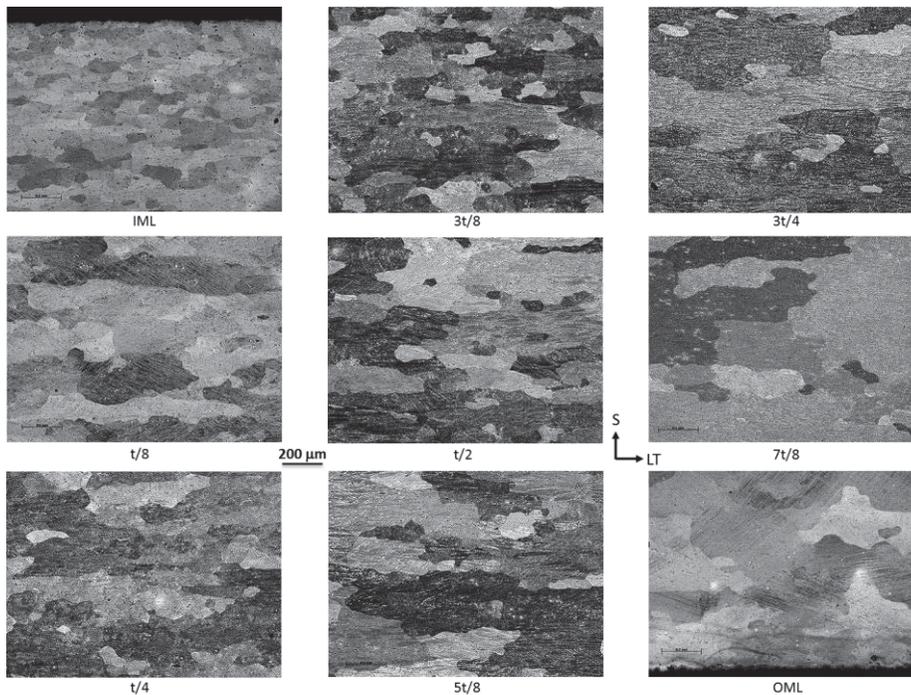
Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
75 of 223



**(b) Microstructure at L7-2 (L/4, 16 inches from the pole)**



**(c) Microstructure at L7-3 (L/2, 27 inches from the pole)**



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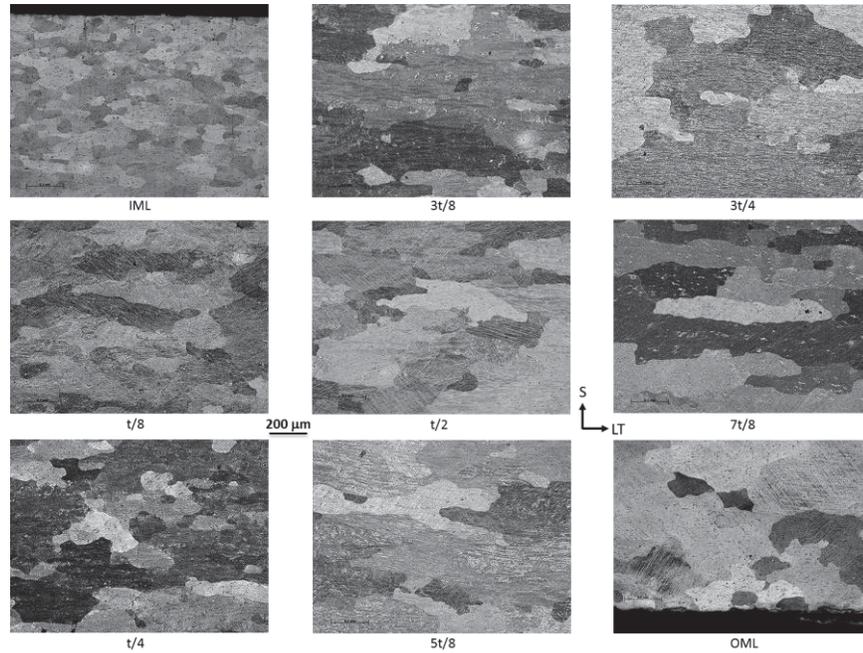
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13-00884**

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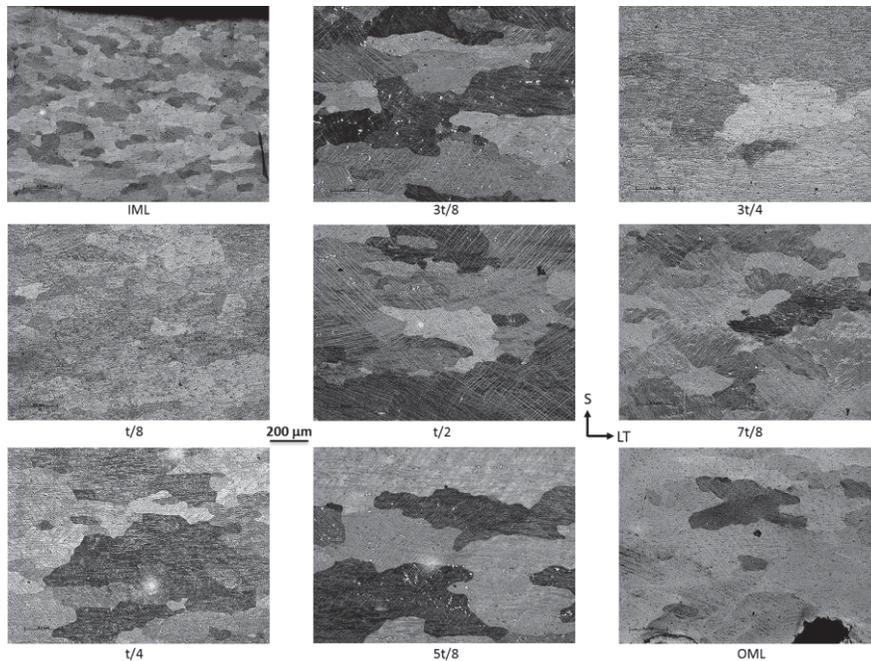
Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
76 of 223



**(d) Microstructure at L7-4 (3L/4, 43 inches from the pole)**



**(e) Microstructure at L7-5 (L, 61 inches from the pole)**

**Figure 10.1-3. Microstructure at the IML, t/8, t/4, 3t/8, t/2, 5t/8, 3t/4, 7t/8, and OML Through-Thickness Positions for (a) L7-1, (b) L7-2, (c) L7-3, (d) L7-4, and (e) L7-5 Locations along the 0° Meridian**

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 77 of 223	

Through-thickness micrographs of the thermally processed blocks shown in Figure 10.1-4 for as-received plate (F), after the pre-spin forming anneal (O), after SHT (T4), and after aging (T6). In comparison with the F and O tempers, the T4 and T6 blocks exhibit larger grain size indicative of recrystallization during SHT. In contrast to the fully processed spin formed material shown in Figure 10.1-2 and Figure 10.1-3, the microstructure of the T4 and T6 thermally processed blocks shown in Figures 10.1-5 and 10.1-6 exhibit uniform microstructures with smaller grain sizes indicating that spin forming deformation promotes larger recrystallized grain size. Tracking of the OML and IML surfaces was maintained during spin forming and subsequent thermal processing of the aft bulkhead forming blank for direct comparison with the thermally processed test blocks. Macroscopically, the microstructure of the T6 processed test block is similar to the L7-1 sample from the aft bulkhead (Figure 10.1-2). Higher magnification micrographs of the thickness positions noted in Figure 10.1-4 for the T4 and T6 conditions are shown in Figure 10.1-5. Both conditions exhibit uniform through-thickness microstructure with slightly smaller grain sizes at the OML and IML surfaces. The grain size and morphology in both T4 and T6 conditions are similar to that observed in section L7-1 (Figure 10.1-2(a)) from the aft bulkhead, which did not experience deformation. The T6 test block exhibits precipitation on residual deformation bands similar to those observed in section L7-1, at positions from  $t/2$  to  $7t/8$ , and are similarly much less apparent at the OML and IML.



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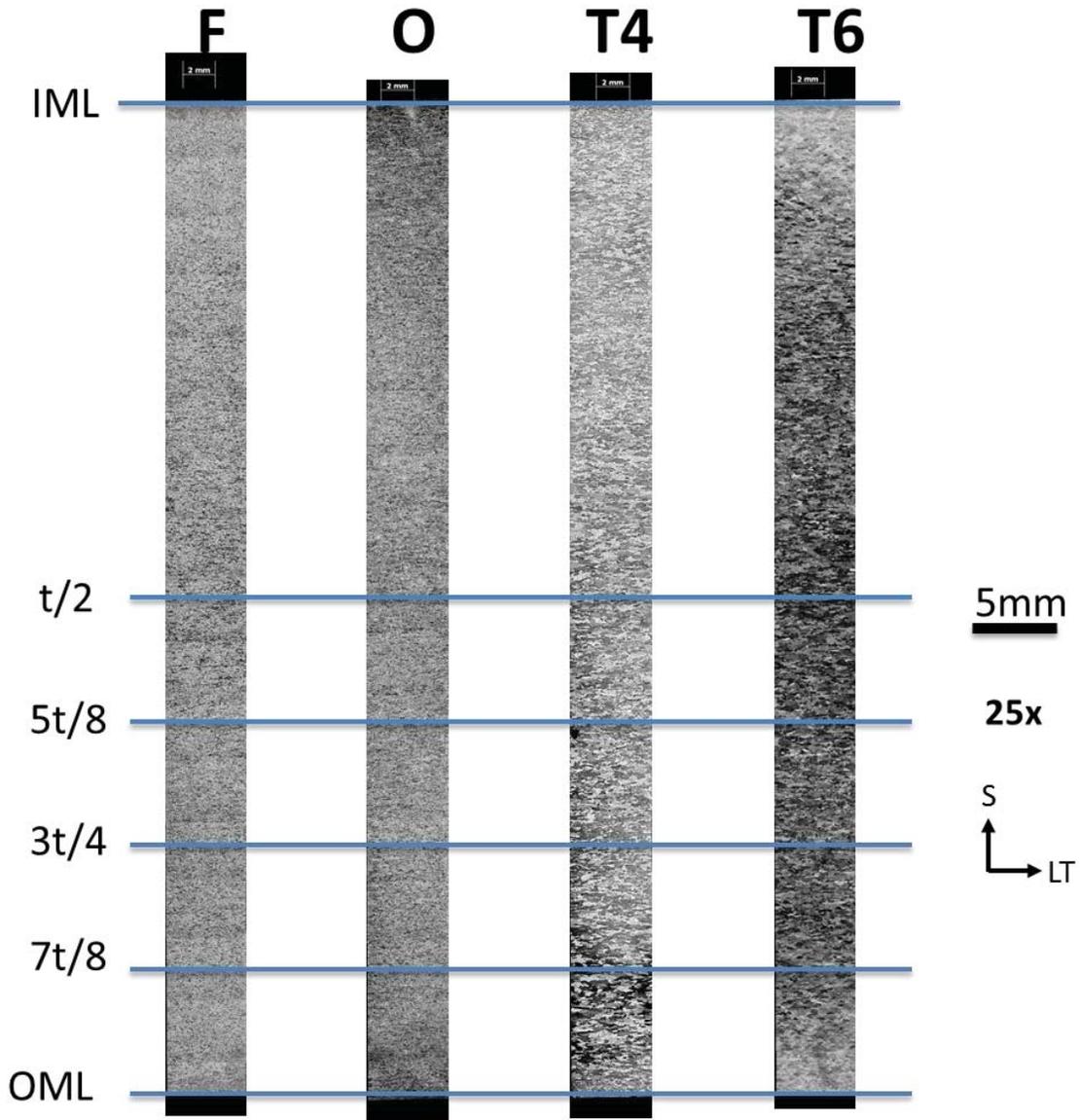
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**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
78 of 223



*Figure 10.1-4. Through-Thickness Microstructures of the Thermally Processed Test Blocks*



# NASA Engineering and Safety Center Technical Assessment Report

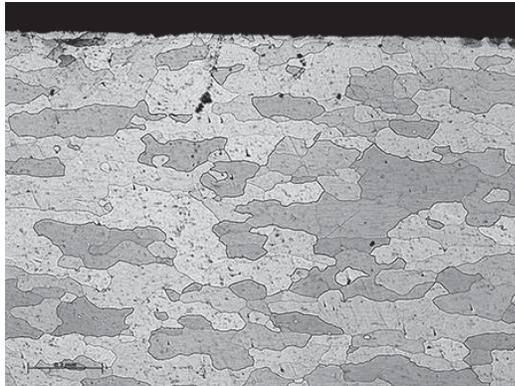
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13-00884**

Version:  
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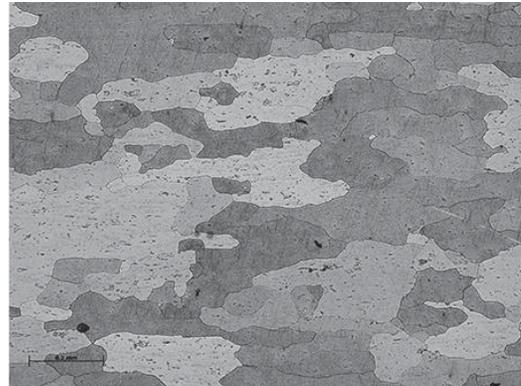
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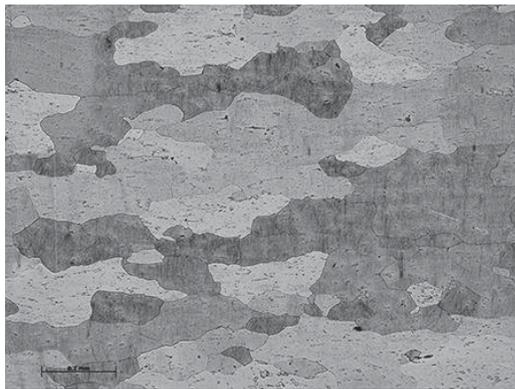
Page #:  
79 of 223



IML

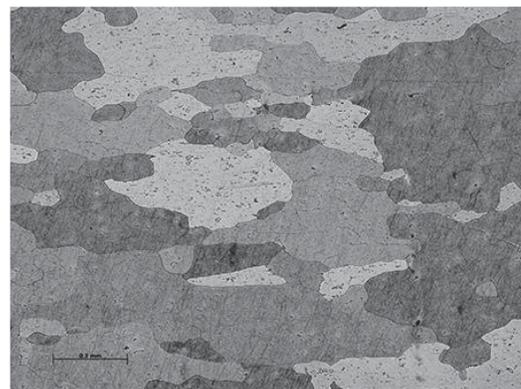
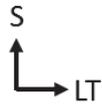


3t/4

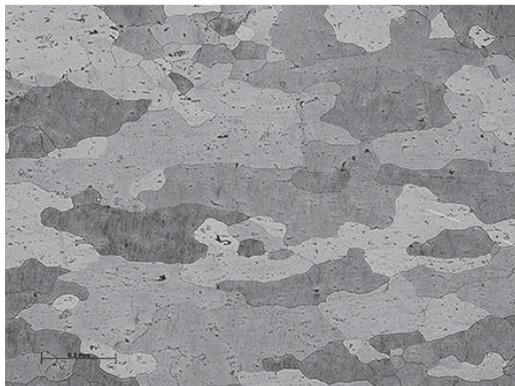


t/2

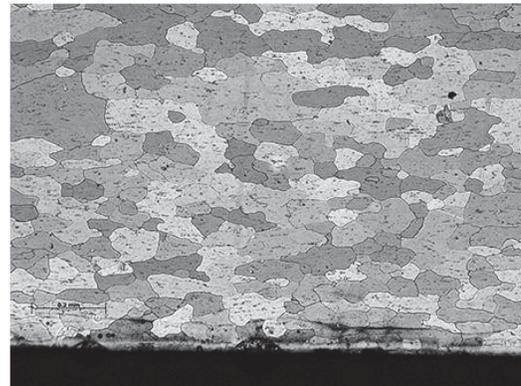
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7t/8



5t/8



OML

(a) Through-thickness microstructure of the T4 thermally processed test block.



# NASA Engineering and Safety Center Technical Assessment Report

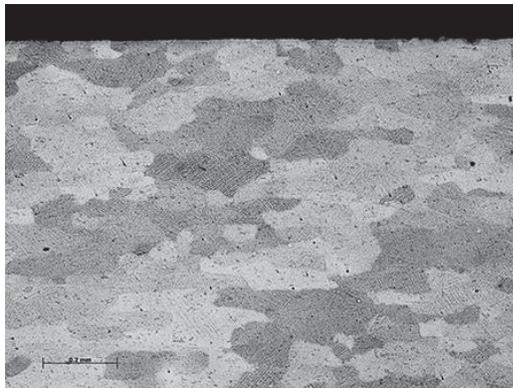
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
80 of 223



IML

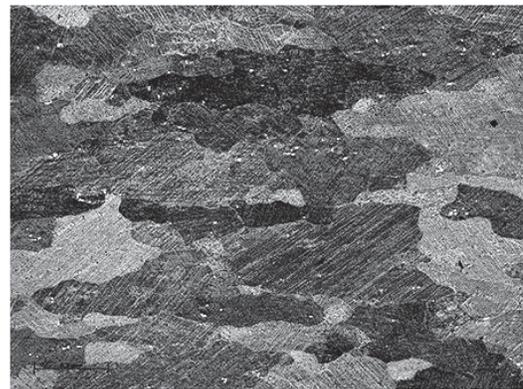
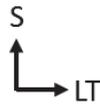


3t/4



t/2

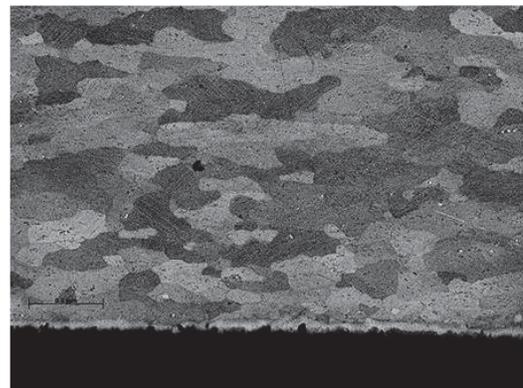
200  $\mu$ m



7t/8



5t/8



OML

**(b) Through-thickness microstructure of the T6 thermally processed test block.**

***Figure 10.1-5. Microstructure at the IML, t/2, 5t/8, 3t/4, 7t/8, and OML Through-Thickness Positions for the (a) T4 and (b) T6 Thermally Processed Test Blocks***

Microstructures of the aft bulkhead sections L7-1 through L7-5 are compared in Figure 10.1-6 with the T6 thermally processed test block at the through-thickness locations IML, t/2, 5t/8, 3t/4, 7t/8, and OML. The grain size and morphology are similar in all samples at the IML

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 81 of 223	

(Figure 10.1-6(a)), and also represent the smallest and most equiaxed grain structure at all through-thickness locations. The post-recrystallization grain size varies throughout the L7 meridian locations and through-thickness positions, with larger grain sizes associated with likely regions of higher deformation. Evidence of precipitation on prior deformation bands is noted throughout all samples. At  $t/2$  and  $5t/8$ , the grain size is largest in the L7-4 and L7-5 locations, with L7-1 through L7-3 locations exhibiting similar grain size to that in the T6 test block. At  $3t/4$ , the grain size is similar and notably larger in L7-2 through L7-5 than in L7-1 and T6. At  $7t/8$  the grain size is largest in L7-3 and L7-4. At the OML, the grain size is notably larger in L7-3 through L7-5 than L7-1 through L7-2 and T6. These variations in grain size in the aft bulkhead sections compared with T6 are indicative of the complex and varied deformation levels associated with the spin forming process, particularly when combined with the plate rolling history and post-forming heat treatment.



# NASA Engineering and Safety Center Technical Assessment Report

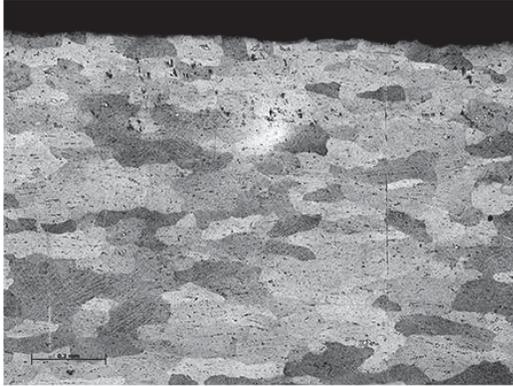
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13-00884**

Version:  
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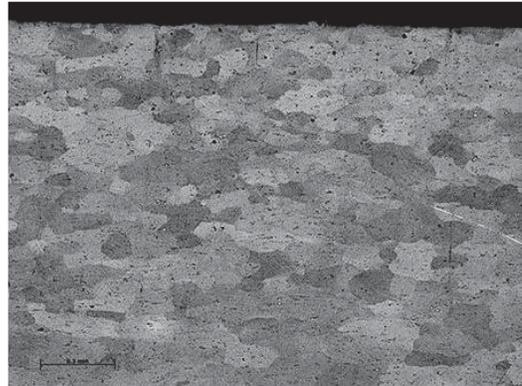
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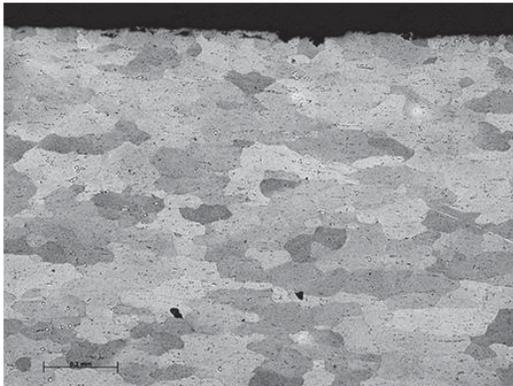
Page #:  
82 of 223



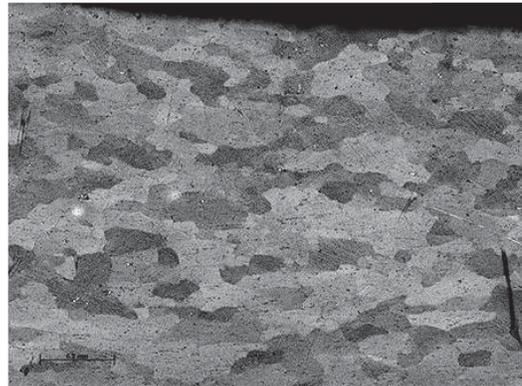
L7-1



L7-4

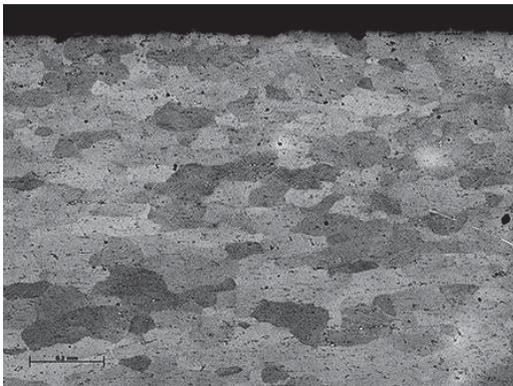
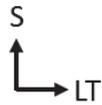


L7-2

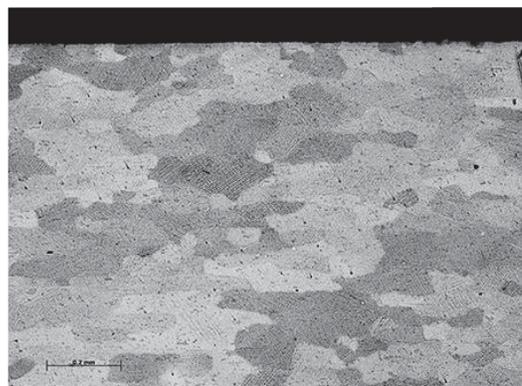


L7-5

200 μm



L7-3



T6

**Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (a) IML**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

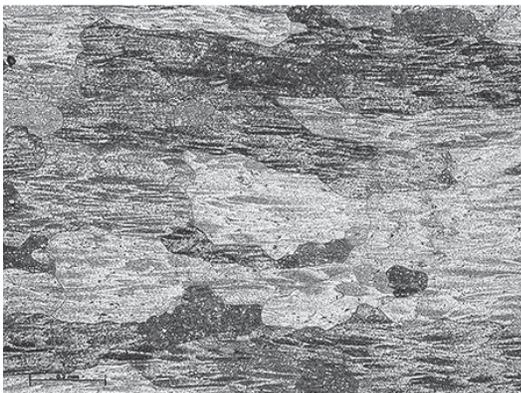
Page #:  
83 of 223



L7-1

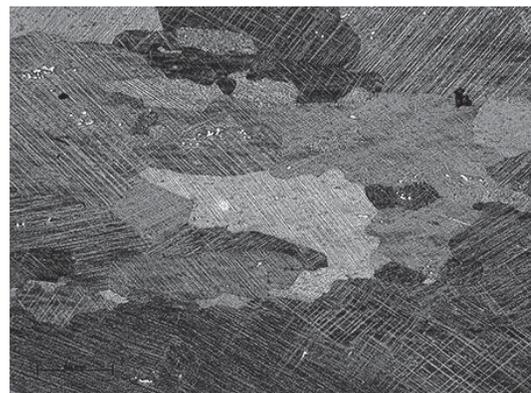
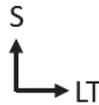


L7-4



L7-2

200 μm



L7-5



L7-3



T6

**Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (b) t/2.**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

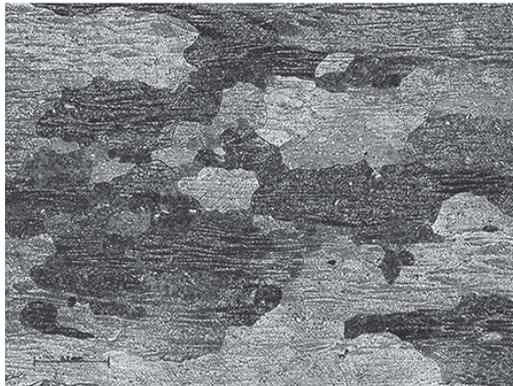
Page #:  
84 of 223



L7-1

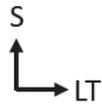


L7-4



L7-2

200  $\mu$ m



L7-5



L7-3



T6

**Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (c) 5t/8.**



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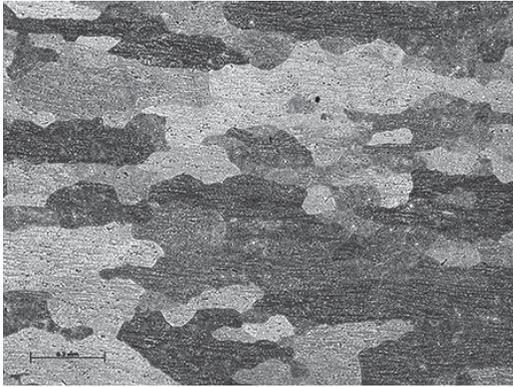
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**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
85 of 223



L7-1

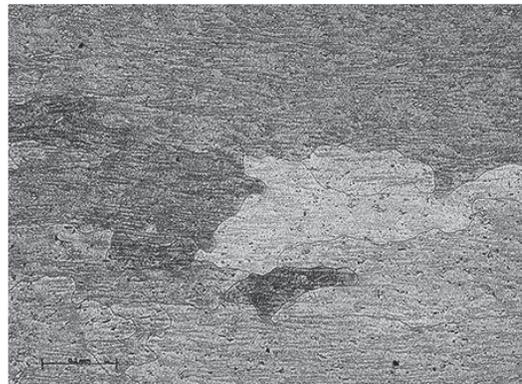
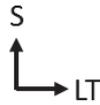


L7-4



L7-2

200 μm



L7-5



L7-3



T6

**Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (d) 3t/4.**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

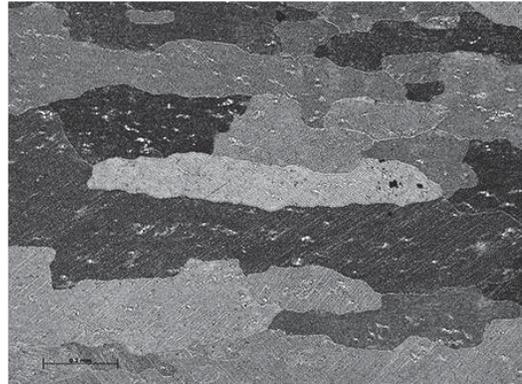
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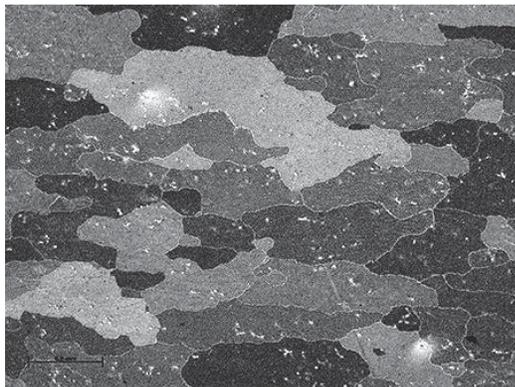
Page #:  
86 of 223



L7-1

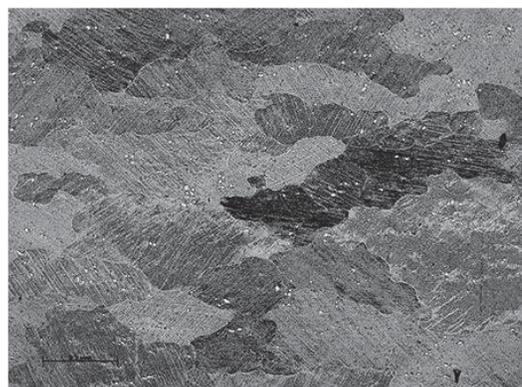
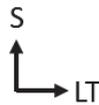


L7-4

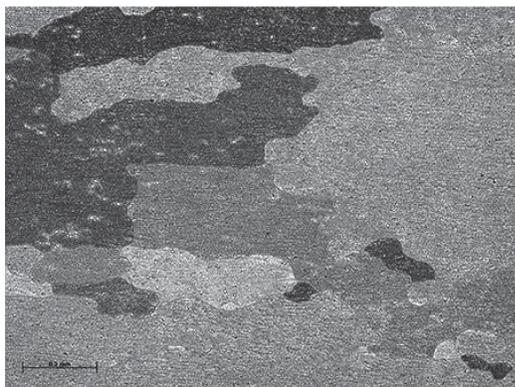


L7-2

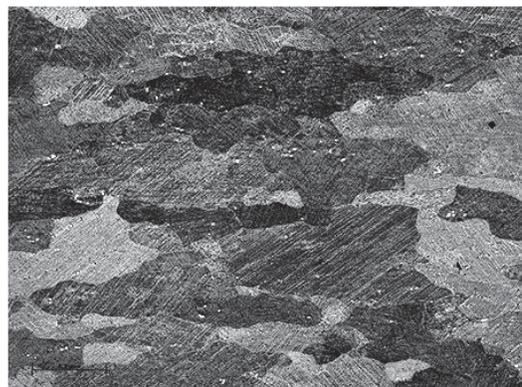
200 μm



L7-5



L7-3



T6

**Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (e) 7t/8.**



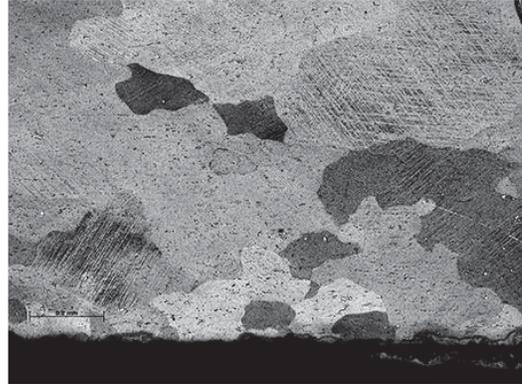
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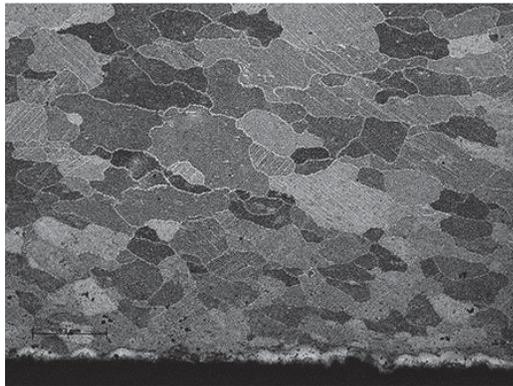
Page #:  
87 of 223



L7-1

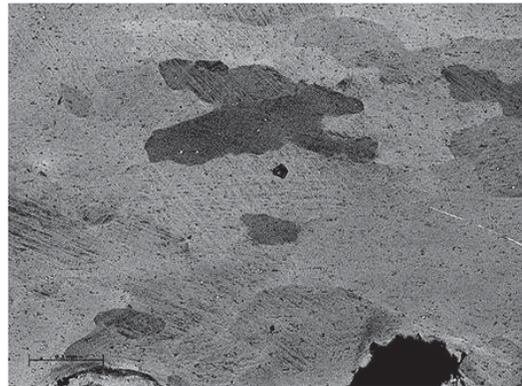
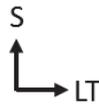


L7-4

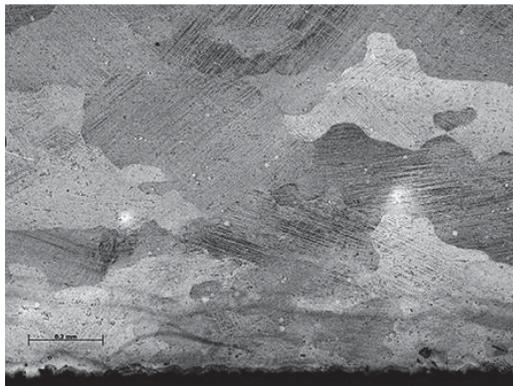


L7-2

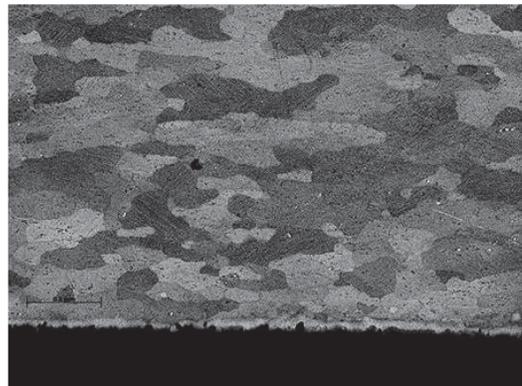
200  $\mu$ m



L7-5



L7-3



T6

Microstructure of aft bulkhead locations L7-1 through L7-5 compared with the T6 thermally processed test block at (f) OML.

*Figure 10.1-6. Microstructure of Aft Bulkhead Locations L7-1 through L7-5 Compared with the T6 Thermally Processed Test Blocks at Through-Thickness Positions (a) IML, (b)  $t/2$ , (c)  $5t/8$ , (d)  $3t/4$ , (e)  $7t/8$ , and (f) OML*

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>88 of 223</b>

Various options exist for altering the recrystallization kinetics during spin forming and heat treatment and the resulting recrystallized grain size. These include changing the spin forming temperature, incorporating a recovery anneal, or changing the SHT temperature. A higher spin forming temperature may result in lower retained deformation (reduce stored energy) in the material and thus reduce the driving force for recrystallization during SHT, whereas a lower forming temperature would increase the stored energy and provide more nucleation sites for recrystallization during SHT, which would result in lower overall grain size due to grain boundary impingement. While the change in forming parameters may result in a change in the recrystallization kinetics, they represent a major shift in the established practice for Spincraft and would require substantial empirical development and validation.

Lower SHT temperatures following spin forming would reduce the overall recrystallized grain size due to lower thermal energy for grain growth. Since the objective of the SHT is to put as much solute (alloying additions) as possible into solid solution in order to obtain optimum properties after the final heat treatment process step (aging), adopting a SHT temperature below this range may limit the peak strength that can be achieved during aging. However, depending on service requirements, sufficient strength may be developed. Extending SHT time may provide some property recovery.

A more viable option may be to incorporate a recovery anneal during heat up to the SHT temperature to reduce the driving force for recrystallization. This recovery anneal can be readily incorporated into their standard SHT cycle.

Tensile, fracture, and stress corrosion specimens extracted from the aft bulkhead were located at  $t/2$ . The microstructure at  $t/2$  for the aft bulkhead locations L7-1 through L7-5 and the T6 test block shown in Figure 10.1-6(b) exhibit the greatest similarity in grain size and morphology and extent of precipitation on prior deformation bands. Additional specimen testing will be needed to evaluate the effect of the variable microstructures at other through-thickness positions, particularly those biased toward the OML.

**F-1.** The aft bulkhead microstructure varies both through-thickness and along the meridian arc length positions, with larger grain sizes associated with likely regions of higher deformation.

- Grain size was larger toward the rim and toward the OML surface, likely associated with the combined stresses necessary to shape the material to fit the mandrel.
- These variations in grain size are indicative of the complex and varied deformation levels associated with the spin forming process, particularly when combined with the plate rolling history and post-forming heat treatment.

## 10.2 Tensile Test Results

Figure 10.2-1 shows the aft bulkhead cut plan with the location of coupon blanks from which tensile specimens were excised for mechanical property testing highlighted in yellow. Coupon blanks L1-L6 were tensile tested at LaRC while coupon blanks M1-M10 were tested at MSFC.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

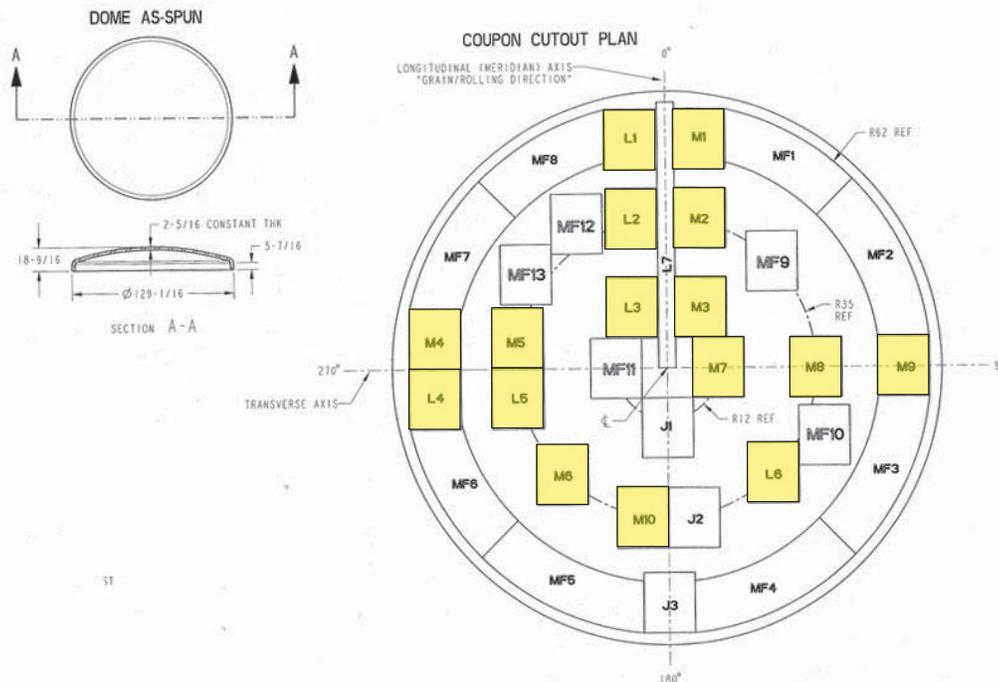
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## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
89 of 223

Table 10.2-1 shows the size and location of these coupon blanks with respect to the original plate rolling direction and distance from the aft bulkhead pole to the coupon blank center point. These coupon blank locations were designed to determine uniformity of tensile properties throughout the aft bulkhead and were evaluated along selected meridian and circumferential lines.

An additional goal of these tests was to determine how these properties compare to wrought plate in the T6 and T8 tempers and to other fabricated product forms in the T6 temper. These results will assist the Orion designers in assessing the attributes of the spin form fabrication process for the aft bulkhead and identify any deficiencies or “show stoppers” associated with this fabrication process.



**Figure 10.2-1. Aft Bulkhead Cut Plan showing the Location of the tensile Coupon Blanks highlighted in Yellow**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
90 of 223

*Table 10.2-1. Tensile Coupon Blank Locations and Orientations*

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
L1	14	12	351°	54-5/8
L2	14	12	347°	36
L3	14	12	330°	16-1/8
L4	14	12	259°	55-1/2
L5	14	12	263°	35-7/8
L6	14	12	135°	35-1/8
M1	14	12	9°	54-5/8
M2	14	12	13°	36
M3	14	12	30°	16-1/8
M4	14	12	277°	55-1/2
M5	14	12	281°	35-7/8
M6	14	12	225°	35-1/8
M7	14	12	90°	12
M8	14	12	90°	35-1/8
M9	14	12	90°	56-1/4
M10	14	12	190°	35-5/8

## 10.2.1 Uniformity of Tensile Properties

Complete tensile test results for the aft bulkhead are shown in Table 10.2-2 through Table 10.2-5, with individual specimen results for orientations L, LT, ST, and ST45, respectively. The average values and standard deviations for each coupon blank and orientation are shown in Table 10.2-6 - Table 10.2-9. The overall average tensile property values and standard deviations for all coupon blanks tested are shown in Table 10.2-10 for each orientation. Tensile values shown in red were below MMPDS A-basis allowables and will be discussed in Section 10.2.2.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
91 of 223

**Table 10.2-2. Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Longitudinal (L) Orientation**

Specimen No.	Coupon Blank	Meridian Angle	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 1.00" GL (%)
T-L1-L-1	L1	351°	L	58.75	39.11	10.09	12.90
T-L1-L-2				58.50	39.04	10.19	11.87
T-L1-L-3				58.97	39.22	10.50	12.74
T-L2-L-13	L2	347°	L	56.35	37.66	10.43	12.37
T-L2-L-14				56.56	37.79	10.47	12.68
T-L2-L-15				56.75	37.77	10.40	13.85
T-L3-L-25	L3	330°	L	54.03	36.65	10.40	14.10
T-L3-L-26				53.73	36.63	10.44	13.21
T-L3-L-27				53.41	36.52	10.42	11.92
T-L4-L-37	L4	263°	L	58.26	39.27	10.47	9.28
T-L4-L-38				58.07	38.79	10.48	10.74
T-L4-L-39				57.47	38.36	10.47	10.09
T-L5-L-49	L5	259°	L	----	----	----	----
T-L5-L-50				55.30	37.16	10.48	11.11
T-L5-L-51				56.22	37.61	10.49	11.19
T-L6-L-61	L6	135°	L	56.27	37.62	10.44	11.61
T-L6-L-62				56.27	37.75	10.46	10.54
T-L6-L-63				56.31	37.65	10.47	11.36
CP-406-190	M1	9°	L	59.66	39.48	10.55	11.77
CP-406-192				59.52	39.70	10.38	11.41
CP-406-194				58.36	38.72	11.92	11.30
CP-406-205	M2	13°	L	57.01	38.02	10.30	11.81
CP-406-207				56.95	38.08	10.15	11.64
CP-406-209				57.09	38.02	11.99	11.62
CP-406-220	M3	30°	L	54.93	37.26	10.30	13.74
CP-406-222				55.61	37.51	9.77	13.79
CP-406-224				55.02	37.18	9.38	15.23
CP-406-235	M4	277°	L	59.21	39.51	12.13	10.91
CP-406-237				59.93	39.78	9.75	11.41
CP-406-239				58.20	38.60	11.42	13.12
CP-406-250	M5	281°	L	58.49	38.44	9.59	11.38
CP-406-252				58.25	38.19	11.04	12.01
CP-406-254				56.79	37.48	10.75	12.47
CP-406-265	M6	225°	L	57.66	38.46	9.88	12.37
CP-406-267				57.54	38.14	9.88	12.41
CP-406-269				58.12	38.33	10.38	13.26
----	M7	90°	L	----	----	----	----
----				----	----	----	----
----				----	----	----	----
----	M8	90°	L	----	----	----	----
----				----	----	----	----
----				----	----	----	----
----	M9	90°	L	----	----	----	----
----				----	----	----	----
----				----	----	----	----
CP-406-127	M10	190°	L	58.48	38.99	9.92	14.37
CP-406-137				56.88	38.13	10.74	11.53
CP-406-147				55.79	37.65	10.24	12.32



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
92 of 223

*Table 10.2-3. Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Long-Transverse (LT) Orientation*

Specimen No.	Coupon Blank	Meridian Angle	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 1.00" GL (%)
T-L1-LT-4	L1	351°	LT	57.64	38.33	10.44	10.63
T-L1-LT-5				57.75	38.55	10.48	10.11
T-L1-LT-6				57.86	38.67	10.38	10.14
T-L2-LT-16	L2	347°	LT	56.33	37.49	10.38	10.73
T-L2-LT-17				56.46	37.56	10.39	10.12
T-L2-LT-18				56.10	37.35	10.44	10.61
T-L3-LT-28	L3	330°	LT	53.77	36.58	10.40	10.66
T-L3-LT-29				53.78	36.69	10.37	9.36
T-L3-LT-30				54.16	36.76	10.42	10.38
T-L4-LT-40	L4	263°	LT	56.38	38.34	10.46	7.85
T-L4-LT-41				56.69	38.33	10.37	7.99
T-L4-LT-42				57.10	38.41	10.40	8.63
T-L5-LT-52	L5	259°	LT	55.26	37.11	10.37	10.08
T-L5-LT-53				54.99	36.92	10.41	11.00
T-L5-LT-54				55.21	37.02	10.39	11.48
T-L6-LT-64	L6	135°	LT	56.37	37.42	10.41	12.98
T-L6-LT-65				56.11	37.41	10.43	11.87
T-L6-LT-66				56.27	37.66	10.41	10.48
CP-406-195	M-1	9°	LT	58.59	38.69	11.66	9.79
CP-406-197				58.53	38.71	11.06	10.09
CP-406-199				58.59	38.68	10.29	10.27
CP-406-210	M-2	13°	LT	57.49	38.03	9.38	10.49
CP-406-212				56.90	37.44	10.00	10.70
CP-406-214				57.48	38.00	10.67	11.17
CP-406-225	M-3	30°	LT	55.43	37.34	10.06	11.41
CP-406-227				55.33	37.08	10.10	12.36
CP-406-229				54.44	36.96	10.84	10.98
CP-406-240	M-4	277°	LT	58.93	38.80	11.37	10.20
CP-406-242				60.02	39.58	10.34	10.92
CP-406-244				58.14	38.88	10.13	9.21
CP-406-255	M-5	281°	LT	56.71	37.42	9.90	11.30
CP-406-257				56.82	37.48	10.02	10.87
CP-406-259				56.25	37.30	10.43	10.92
CP-406-270	M-6	225°	LT	56.50	37.45	10.94	10.36
CP-406-272				56.95	37.77	9.60	10.85
CP-406-274				56.72	37.54	9.82	10.64
CP-406-1	M7	90°	LT	53.77	36.29	9.71	10.25
CP-406-11				54.57	37.02	10.04	10.64
CP-406-21				54.07	36.60	10.15	10.86
CP-406-43	M8	90°	LT	57.61	38.57	10.64	9.67
CP-406-53				56.96	38.72	10.14	9.35
CP-406-63				58.79	39.05	10.66	10.36
CP-406-85	M9	90°	LT	59.71	39.50	9.77	8.78
CP-406-95				59.04	39.53	10.28	8.64
CP-406-105				60.00	40.01	10.87	8.95
CP-406-169	M10	190°	LT	54.37	36.93	10.06	9.63
CP-406-179				56.41	38.35	10.54	11.31
CP-406-189				56.88	38.32	9.83	9.51



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
93 of 223

*Table 10.2-4. Tensile Properties of the Spin Formed Al 2219-T62 aft Bulkhead Material, Short Transverse (ST) Orientation*

Specimen No.	Coupon Blank	Meridian Angle	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 0.50" GL (%)
T-L1-ST-7	L1	351°	ST	57.56	44.16	10.21	4.77
T-L1-ST-8				58.06	44.78	10.32	4.47
T-L1-ST-9				58.34	44.48	10.26	4.94
T-L2-ST-19	L2	347°	ST	56.96	43.13	10.13	4.41
T-L2-ST-20				57.64	43.17	10.37	5.09
T-L2-ST-21				58.37	44.08	10.40	5.16
T-L3-ST-31	L3	330°	ST	57.77	43.39	10.34	5.33
T-L3-ST-32				57.86	43.96	10.45	4.87
T-L3-ST-33				58.06	43.65	10.33	5.95
T-L4-ST-43	L4	263°	ST	58.58	44.89	10.33	4.17
T-L4-ST-44				59.29	45.20	10.39	5.13
T-L4-ST-45				59.19	44.70	10.36	5.63
T-L5-ST-55	L5	259°	ST	57.74	44.21	10.48	4.63
T-L5-ST-56				56.87	44.13	10.36	3.99
T-L5-ST-57				57.11	43.59	10.37	4.85
T-L6-ST-67	L6	135°	ST	57.24	43.79	10.27	4.74
T-L6-ST-68				57.66	43.85	10.35	4.78
T-L6-ST-69				58.44	44.36	10.38	5.07
CP-406-200	M-1	9°	ST	58.62	38.32	10.95	4.28
CP-406-202				62.08	37.82	10.58	5.35
CP-406-204				59.87	36.53	9.59	5.13
CP-406-215	M-2	13°	ST	59.52	41.96	9.14	4.61
CP-406-217				60.49	41.44	9.46	4.62
CP-406-219				59.37	40.68	10.08	4.53
CP-406-230	M-3	30°	ST	56.21	37.64	9.72	5.08
CP-406-232				57.12	37.77	10.57	3.93
CP-406-234				57.90	36.50	10.26	4.04
CP-406-245	M-4	277°	ST	58.50	38.08	10.52	4.80
CP-406-247				60.28	39.54	10.21	4.14
CP-406-249				61.48	39.88	9.24	5.70
CP-406-260	M-5	281°	ST	58.61	38.52	10.14	3.77
CP-406-262				64.14	39.42	9.91	4.55
CP-406-264				56.71	38.10	9.75	3.54
CP-406-275	M-6	225°	ST	56.89	40.83	10.53	3.34
CP-406-277				59.36	40.08	8.76	4.77
CP-406-279				59.27	40.06	10.09	4.38
CP-406-22	M7	90°	ST	58.15	43.76	10.39	4.9
CP-406-32				57.24	42.23	9.52	4.68
CP-406-42				58.21	43.61	9.76	4.83
CP-406-64	M8	90°	ST	58.13	42.59	9.84	4.38
CP-406-74				58.94	44.48	9.39	4.05
CP-406-84				59.00	44.11	9.76	5.29
CP-406-106	M9	90°	ST	60.87	45.55	9.33	4.49
CP-406-116				61.20	43.63	9.01	4.36
CP-406-126				57.50	43.80	9.44	3.52
CP-406-148	M10	190°	ST	59.44	44.57	9.98	4.76
CP-406-158				59.59	44.79	10.04	5.01
CP-406-168				59.92	43.88	10.34	4.73



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
94 of 223

*Table 10.2-5. Tensile Properties of the Spin Formed Al 2219-T62 aft Bulkhead Material, Short Transverse 45° (ST45) Orientation*

Specimen No.	Coupon Blank	Meridian Angle	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 0.50" GL (%)
T-L1-ST45-10	L1	351°	ST45	53.14	43.44	10.81	2.99
T-L1-ST45-11				49.34	37.53	10.62	2.82
T-L1-ST45-12				52.14	36.77	10.50	4.10
T-L2-ST45-22	L2	347°	ST45	54.36	38.00	10.73	5.01
T-L2-ST45-23				53.63	38.06	10.60	4.70
T-L2-ST45-24				54.01	39.28	10.82	4.58
T-L3-ST45-34	L3	330°	ST45	53.24	38.94	10.64	4.41
T-L3-ST45-35				52.85	40.71	10.31	3.25
T-L3-ST45-36				55.23	43.64	10.79	4.13
T-L4-ST45-46	L4	263°	ST45	51.76	38.65	10.84	3.33
T-L4-ST45-47				51.74	36.03	10.73	4.47
T-L4-ST45-48				49.80	36.38	10.50	3.38
T-L5-ST45-58	L5	259°	ST45	53.94	38.39	10.77	4.80
T-L5-ST45-59				53.76	37.82	10.87	4.80
T-L5-ST45-60				53.29	37.42	10.61	5.04
T-L6-ST45-70	L6	135°	ST45	55.52	47.54	10.91	2.64
T-L6-ST45-71				55.85	47.49	11.07	2.79
T-L6-ST45-72				54.30	38.62	10.90	4.48



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
95 of 223

**Table 10.2-6. Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Longitudinal (L) Orientation**

Coupon Blank	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e		Average Std Dev.
					1.00" GL (%)		
L1	L	58.74	39.12	10.26	12.5		
		0.23	0.09	0.21	0.56		
L2	L	56.55	37.74	10.44	12.97		
		0.2	0.07	0.03	0.78		
L3	L	53.72	36.6	10.42	13.08		
		0.31	0.07	0.02	1.1		
L4	L	57.93	38.81	10.47	10.04		
		0.41	0.45	0.01	0.73		
L5	L	55.76	37.38	10.48	11.15		
		0.65	0.32	0.01	0.05		
L6	L	56.28	37.68	10.46	11.17		
		0.03	0.07	0.02	0.56		
M1	L	59.18	39.3	10.95	11.49		
		0.71	0.51	0.84	0.24		
M2	L	57.02	38.04	10.81	11.69		
		0.07	0.03	1.02	0.1		
M3	L	55.19	37.32	9.82	14.25		
		0.37	0.17	0.46	0.85		
M4	L	59.11	39.29	11.1	11.81		
		0.86	0.62	1.22	1.16		
M5	L	57.84	38.04	10.46	11.95		
		0.92	0.5	0.77	0.55		
M6	L	57.77	38.31	10.04	12.68		
		0.31	0.16	0.29	0.5		
M10	L	57.05	38.26	10.3	12.74		
		1.35	0.68	0.41	1.47		



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
96 of 223

**Table 10.2-7. Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Long Transverse (LT) Orientation**

Coupon Blank	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e		Average Std Dev.
					1.00" GL (%)		
L1	LT	57.75	38.52	10.43	10.29		
		0.11	0.17	0.05	0.29		
L2	LT	56.3	37.47	10.41	10.49		
		0.18	0.11	0.03	0.32		
L3	LT	53.9	36.68	10.4	10.13		
		0.23	0.09	0.03	0.69		
L4	LT	56.72	38.36	10.41	8.16		
		0.36	0.04	0.04	0.41		
L5	LT	55.16	37.02	10.39	10.85		
		0.15	0.1	0.02	0.71		
L6	LT	56.25	37.5	10.42	11.77		
		0.13	0.14	0.01	1.25		
M1	LT	58.57	38.69	11	10.05		
		0.03	0.01	0.69	0.24		
M2	LT	57.29	37.82	10.01	10.79		
		0.34	0.33	0.64	0.35		
M3	LT	55.07	37.13	10.34	11.58		
		0.55	0.2	0.44	0.7		
M4	LT	59.03	39.09	10.61	10.11		
		0.94	0.43	0.66	0.86		
M5	LT	56.59	37.4	10.11	11.03		
		0.3	0.09	0.28	0.24		
M6	LT	56.72	37.59	10.12	10.61		
		0.22	0.17	0.72	0.25		
M7	LT	54.14	36.64	9.97	10.58		
		0.4	0.37	0.23	0.31		
M8	LT	57.79	38.78	10.48	9.79		
		0.93	0.25	0.29	0.52		
M9	LT	59.58	39.68	10.31	8.79		
		0.49	0.29	0.55	0.16		
M10	LT	55.89	37.87	10.14	10.15		
		1.33	0.81	0.36	1.01		



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
97 of 223

**Table 10.2-8. Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse (ST) Orientation**

Coupon Blank	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e	0.50" GL (%)	Average Std Dev.
L1	ST	57.99	44.48	10.26		<b>4.73</b>	
		0.4	0.31	0.05		0.24	
L2	ST	57.65	43.46	10.3		<b>4.89</b>	
		0.7	0.54	0.15		0.41	
L3	ST	57.9	43.67	10.37		<b>5.38</b>	
		0.14	0.29	0.07		0.54	
L4	ST	59.02	44.93	10.36		<b>4.98</b>	
		0.39	0.25	0.03		0.74	
L5	ST	57.24	43.98	10.4		<b>4.49</b>	
		0.45	0.34	0.07		0.45	
L6	ST	57.78	44	10.33		<b>4.87</b>	
		0.61	0.31	0.06		0.18	
M1	ST	60.19	37.55	10.37		<b>4.92</b>	
		1.75	0.93	0.7		0.57	
M2	ST	59.79	41.36	9.56		<b>4.59</b>	
		0.61	0.65	0.48		0.05	
M3	ST	57.08	37.3	10.19		<b>4.35</b>	
		0.85	0.7	0.43		0.63	
M4	ST	60.09	39.17	9.99		<b>4.88</b>	
		1.5	0.96	0.66		0.78	
M5	ST	59.82	38.68	9.93		<b>3.96</b>	
		3.86	0.68	0.2		0.53	
M6	ST	58.51	40.32	9.8		<b>4.16</b>	
		1.4	0.44	0.92		0.74	
M7	ST	57.87	43.2	9.89		<b>4.8</b>	
		0.54	0.84	0.45		0.11	
M8	ST	58.69	43.73	9.66		<b>4.57</b>	
		0.49	1	0.24		0.64	
M9	ST	59.86	44.33	9.26		<b>4.12</b>	
		2.05	1.06	0.22		0.53	
M10	ST	59.65	44.41	10.12		<b>4.83</b>	
		0.25	0.47	0.19		0.15	

**Table 10.2-9. Average Tensile Properties and Standard Deviations of the Spin Formed Al 2219-T62 Aft Bulkhead Material, Short Transverse 45° (ST45) Orientation**

Coupon Blank	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 0.50" GL (%)	Average Std Dev.
L1	ST45	51.54	39.25	10.65	3.30	
		1.97	3.65	0.16	0.69	
L2	ST45	54.00	38.44	10.72	4.77	
		0.36	0.73	0.11	0.22	
L3	ST45	53.77	41.10	10.58	3.93	
		1.28	2.37	0.25	0.61	
L4	ST45	51.10	37.02	10.69	3.73	
		1.13	1.42	0.17	0.65	
L5	ST45	53.66	37.88	10.75	4.88	
		0.33	0.49	0.13	0.14	
L6	ST45	55.22	44.55	10.96	3.30	
		0.81	5.13	0.10	1.02	

**Table 10.2-10. Average Tensile Properties and Standard Deviation Values for the Spin Formed Al 2219-T62 aft Bulkhead Material**

Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	<sup>e</sup> 1.00" GL (%)	Average Std Dev.
L	57.12	38.17	10.46	12.14	
	1.64	0.86	0.59	1.23	
LT	56.67	37.89	10.35	10.32	
	1.67	0.90	0.42	1.02	
ST*	58.69	42.16	10.05	4.66	
	1.54	2.67	0.47	0.56	
ST45*	53.22	39.71	10.72	3.98	
	1.76	3.51	0.18	0.84	

\* = 0.50" GL

The trends observed in the aft bulkhead tensile results, based on the average tensile values shown in Table 10.2-10, are representative of the trends observed for each coupon blank. Average tensile strengths and elongation values are essentially equivalent for the L and T orientations. Of note, however, is that the UTS and YS are highest in the ST orientation, by approximately 3% for UTS and 10% for YS as compared to the L and LT orientations. The ST UTS and YS values were greater than those for the ST45 orientation by approximately 10% and 6%, respectively.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>99 of 223</b>

The UTS was lowest for the ST45 orientation, but YS was higher than for the L and T orientations. Elongation values in the ST orientation were about half those for the L and LT orientations. The average elongation value was lowest for the ST45 orientation, but was still nearly 4%. It is unclear whether the measured ST properties are unique to this plate or are the result of the spin forming deformation.

To evaluate the variability in tensile properties in the aft bulkhead the average tensile test results were superimposed on the aft bulkhead cut plan as shown in Figure 10.2-2 through Figure 10.2-5 for each orientation. Trends were evaluated as a function of meridian angle and distance from the pole. Tensile values shown in red fell below MMPDS A-basis design allowables. There appears to be a trend of increasing tensile strength from pole to rim for the L and LT orientations, but uniform properties about circumferential lines. Along the 0° to 180° meridian line, which is parallel to the original plate rolling direction, for the L and LT orientations, the coupon blanks furthest from the pole (L1, M1) exhibit both higher UTS and YS by 1.5 to 2 ksi than coupon blanks at the mid arc length (L2, M2) and become progressively lower in strength as one gets closer to the pole (L3, M3). The same trend appears at the opposing 180° meridian in coupon blank M10. Similar property trends exist along the 90° to 270° meridian line. Conversely, for a given meridian distance, tensile properties are uniform as one translates through the 0° to 360° meridian angles along circumferential lines (for example, meridian distance 35 inches, M2-L6-M10-M6-L5-M5-L2). These trends are not as systematic for the ST and ST45 due to greater scatter in the values for each coupon blank for these orientations. Table 10.2-8 and Table 10.2-9 illustrate the greater standard deviations for these orientations.

To verify whether these trends are statistically significant, the individual tensile test results were plotted as a function of distance from the pole and meridian angle in Figure 10.2-6 through Figure 10.2-17. Also shown in these plots for reference are the MMPDS A-basis design allowables. Figure 10.2-6 and Figure 10.2-7 show tensile properties for the L and LT orientations along the 0° to 180° meridian line. The tensile data shows a clear trend of increasing strength with arc length distance from the pole for both of these orientations. The scatter in results for each coupon blank is less than the difference between populations of data clusters. Figure 10.2-8 and Figure 10.2-9 confirm that the trend is similar for the 90° - 270° meridian line. Similar plots for the ST and ST45 orientations, shown in Figure 10.2-10 through Figure 10.2-13 illustrate the larger scatter in this data and inability to discern any definitive trend.

Plots of tensile data as a function of meridian angle at a distance of 35 inches from the pole, shown in Figure 10.2-14 through Figure 10.2-17, confirm that the tensile data is uniform for a given circumferential line. The scatter in the L and LT data (Figure 10.2-14 and Figure 10.2-15) is sufficiently small that the tensile properties are considered constant about this circumferential line. Scatter in the ST orientation (Figure 10.2-16) is greater than that in L and LT, but the data still reflect uniformity with meridian angle. The scatter in the ST45 data (Figure 10.2-17) is small with the exception of the YS at 135 degrees and the amount of data is much less than for the other orientations, but the data is reasonably uniform with meridian angle.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			100 of 223

While this trend of increasing strength with arc length distance from the pole has been observed, budget and schedule prevent further studies on this matter. General metallurgical theory suggests that this trend may be related to the level of deformation imparted during spin forming both as a result of pressure from the forming tool as well as the strains induced during forming of the contour. The tool pressure is fairly uniform from the pole to the rim, but the imposed strain levels likely increase due to the superimposed forming stresses (tangential compressive and radial tensile and compressive) acting on the material, particularly towards the edge of the forming blank (2). However, these deformation strains should be relieved and the microstructure should undergo recovery during the high temperature solution heat treatment.

One additional source of deformation may be related to the distortion and residual stress resulting from the quench following solution heat treatment. Because of the potential for non-uniform deformation through-thickness, it is recommended that additional tensile tests be conducted to evaluate through-thickness positions other than  $t/2$ .

Variations in grain size described in Section 10.1 were attributed to the variation in forming stresses. All of the tensile tests were performed at the  $t/2$  through-thickness position. The microstructure is fairly constant at  $t/2$  throughout the regions examined in the aft bulkhead (Figure 10.1-6b) in terms of grain size and indications of residual deformation; however, there may be subtle variations that could explain the trends observed in the tensile properties. Other thickness positions exhibit greater variations, such as near the OML (Figure 10.1-6f). Of greater importance may be the effect of through-thickness grain size variations (See Figure 10.1-3a-e) on tensile properties. The through-thickness variation in microstructure should be examined for all spin formed components fabricated from Al 2219-T62 and tensile testing designed to sample the range of grain sizes.

- F-2.** Tensile tests designed to determine tensile property uniformity over the aft bulkhead acreage noted that the tensile properties varied with location in the aft bulkhead.
- For the L and LT orientations, a trend of increasing tensile and YS with arc length distance from the pole was evident.
  - Conversely, the properties were uniform in the circumferential direction.
  - The ST tensile properties were notably greater than those for the other orientations (L, LT, ST45), but elongations were about half.
- O-1.** The rationale for the variations in tensile properties with location in the aft bulkhead was not fully characterized. The microstructure at the through-thickness location tested ( $t/2$ ) was more uniform throughout the aft bulkhead than at other locations.
- R-1.** The microstructural variability of the Orion first article spin formed aft bulkhead should be determined and mechanical property testing designed to sample regions of maximum and minimum grain size in order to evaluate the effect of variable microstructures, if observed. (*F-1, F-2, O-1*)



# NASA Engineering and Safety Center Technical Assessment Report

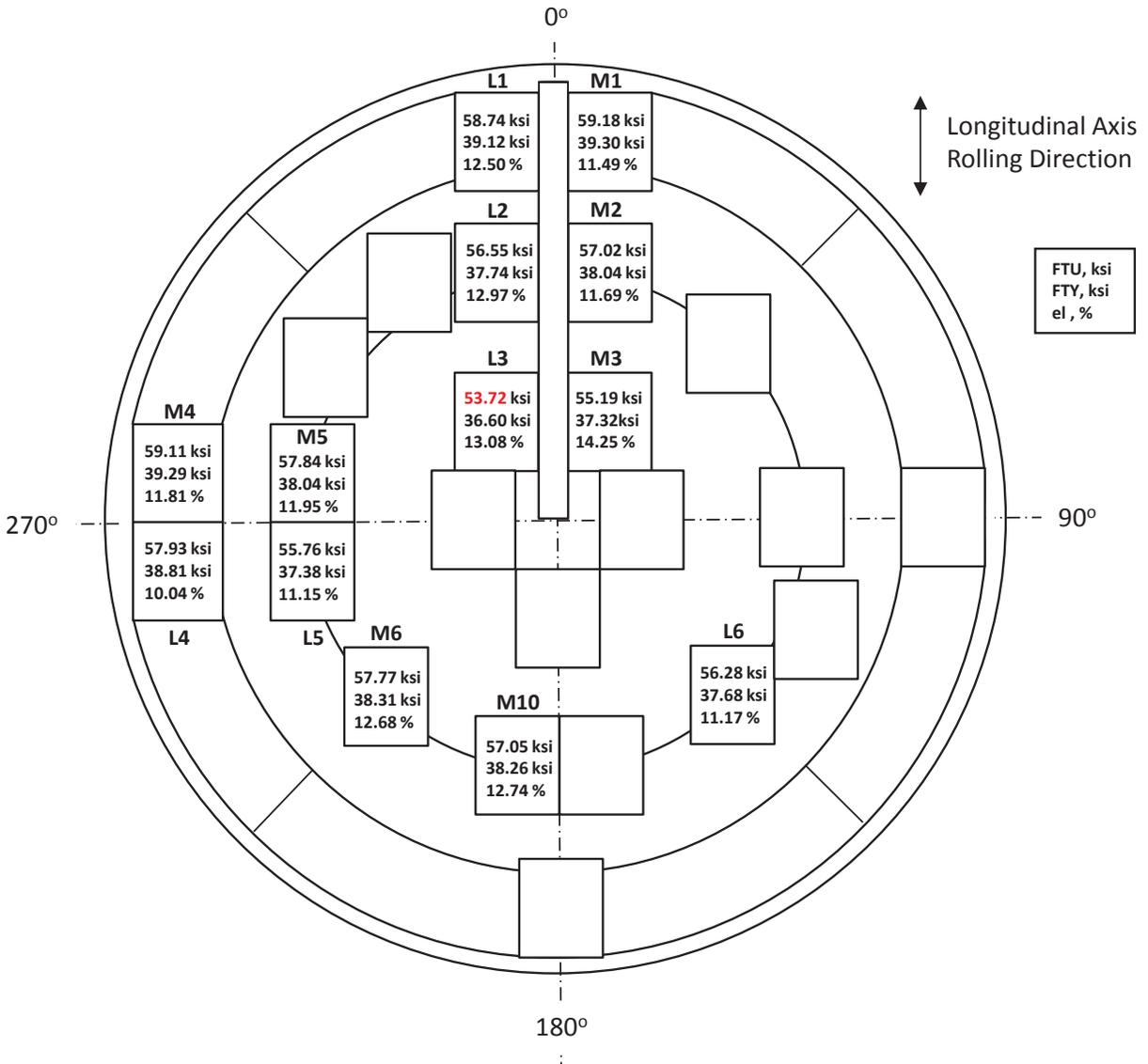
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
101 of 223



*Figure 10.2-2. Average Longitudinal (L) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan*



# NASA Engineering and Safety Center Technical Assessment Report

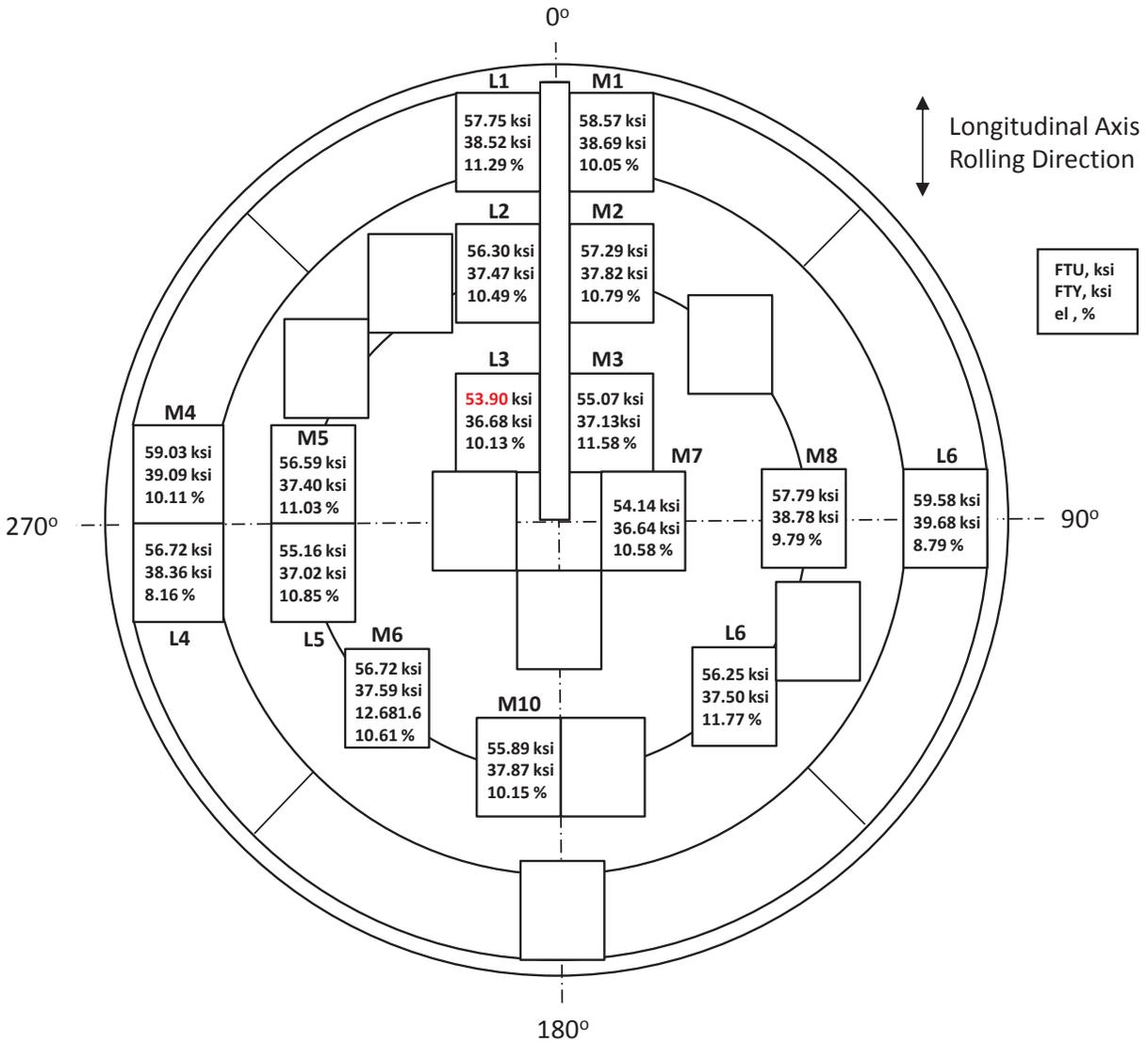
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
102 of 223



**Figure 10.2-3. Average Long Transverse (LT) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan**



# NASA Engineering and Safety Center Technical Assessment Report

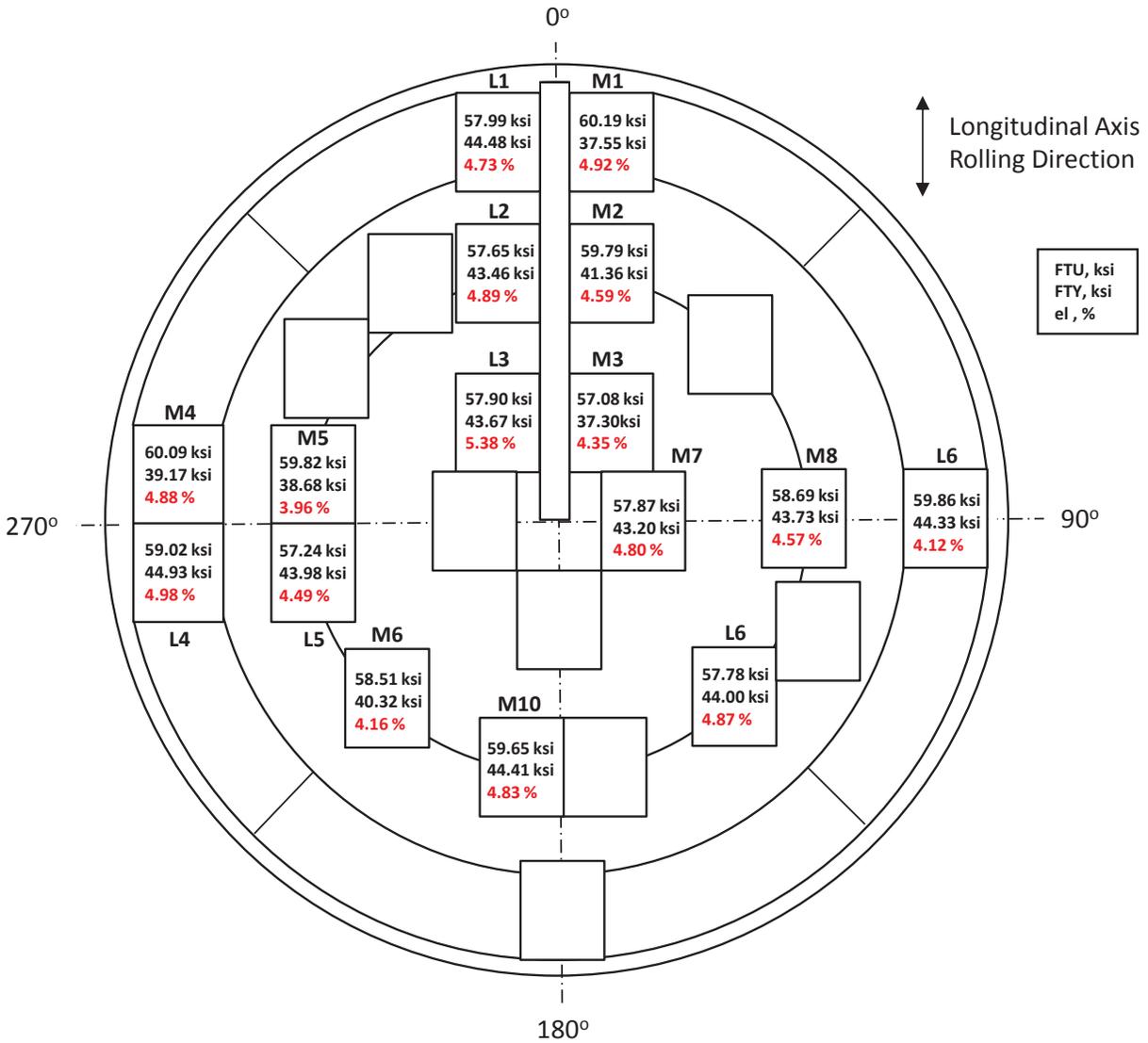
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
103 of 223



**Figure 10.2-4. Average Short Transverse (ST) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan**



# NASA Engineering and Safety Center Technical Assessment Report

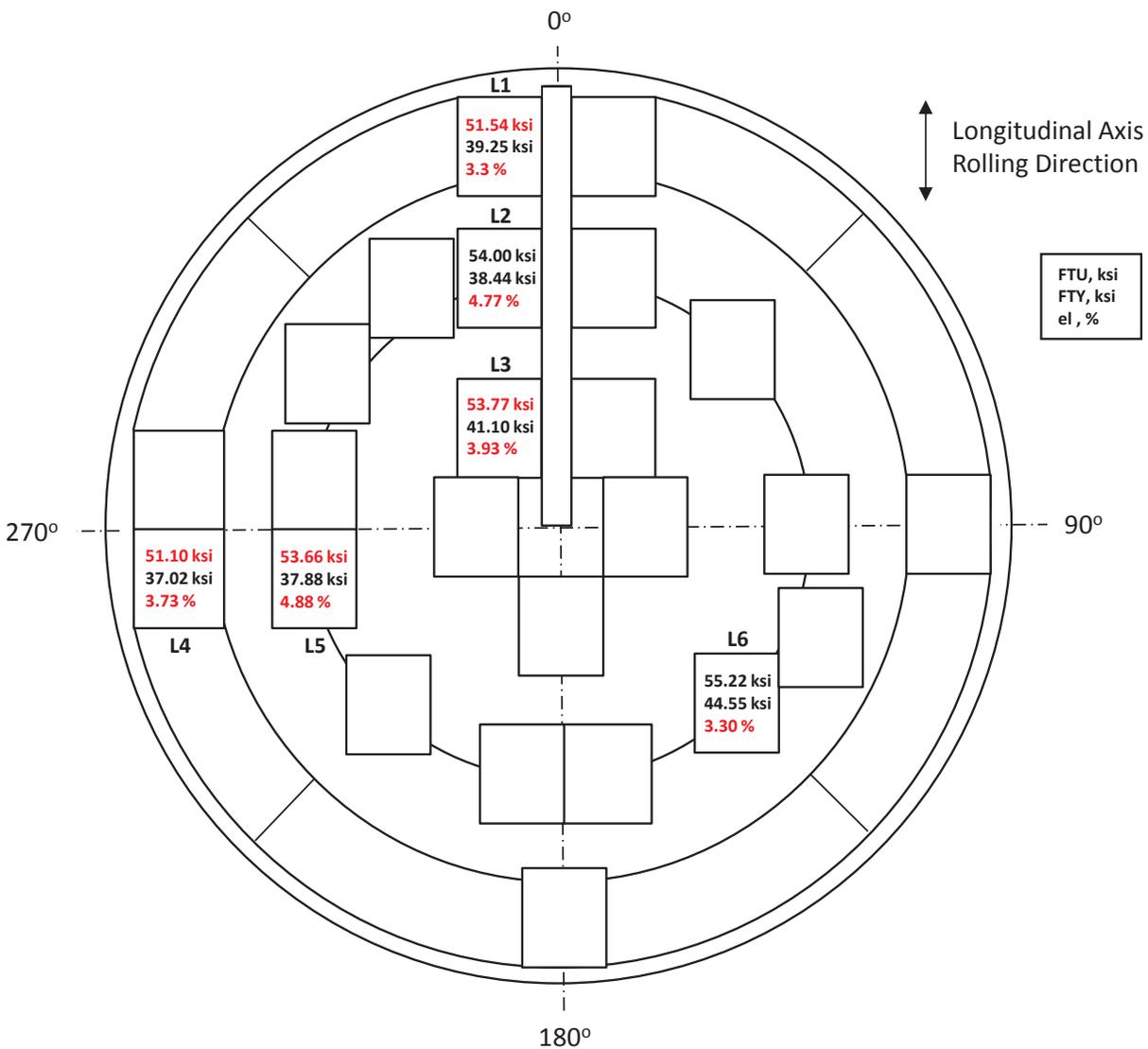
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
104 of 223



**Figure 10.2-5. Average Short Transverse 45° (ST45) Tensile Properties Superimposed on the Aft Bulkhead Cut Plan**



# NASA Engineering and Safety Center Technical Assessment Report

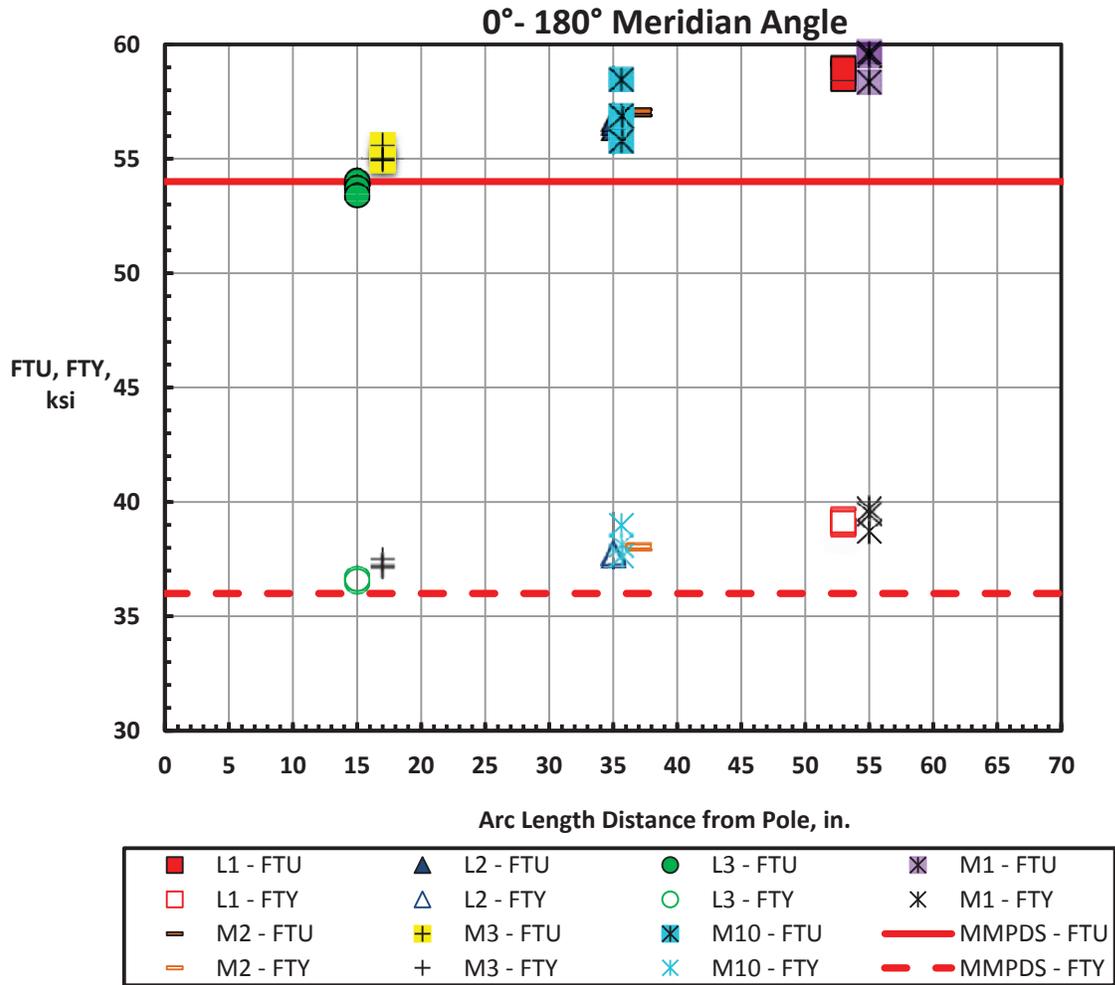
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
105 of 223



**Figure 10.2-6. Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle**



# NASA Engineering and Safety Center Technical Assessment Report

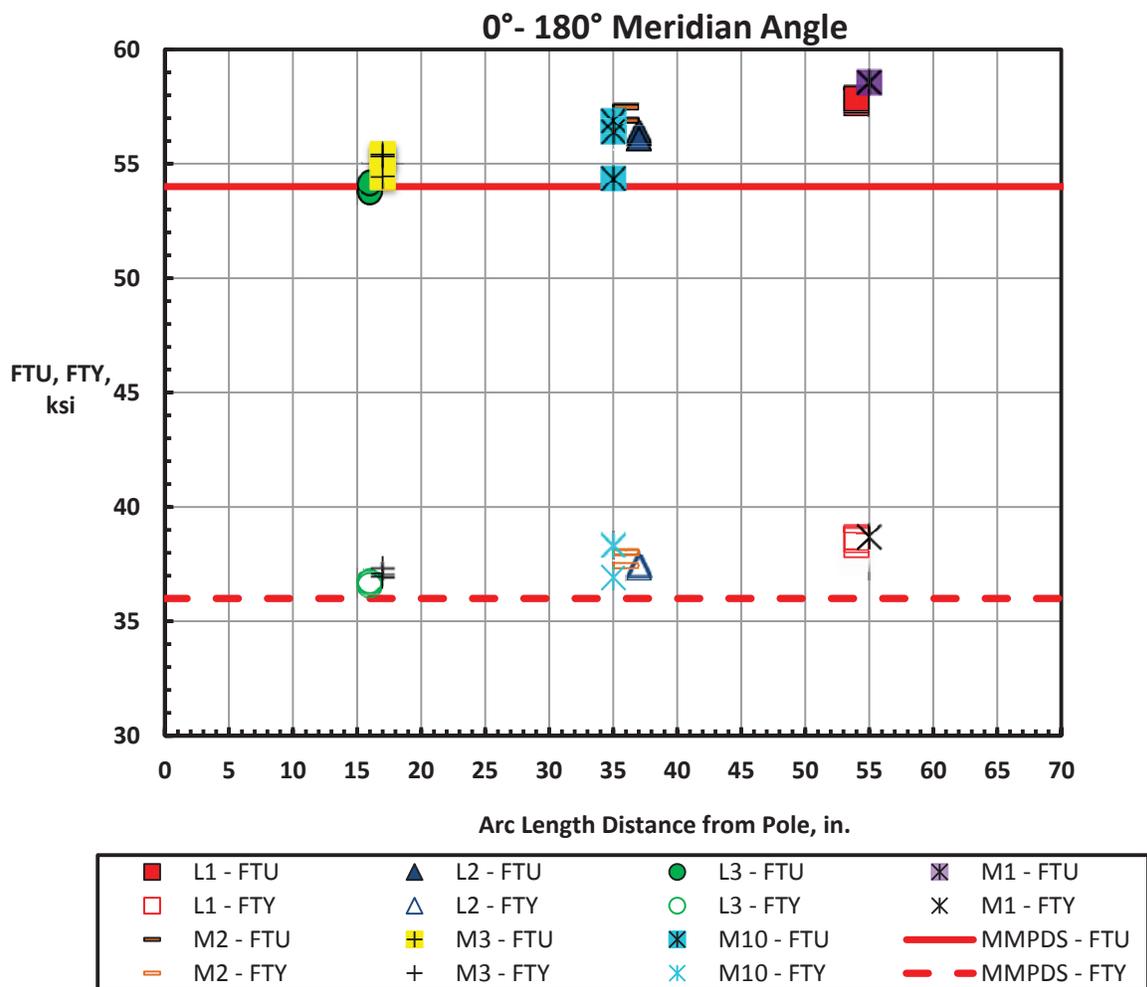
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
106 of 223



**Figure 10.2-7. Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle**



# NASA Engineering and Safety Center Technical Assessment Report

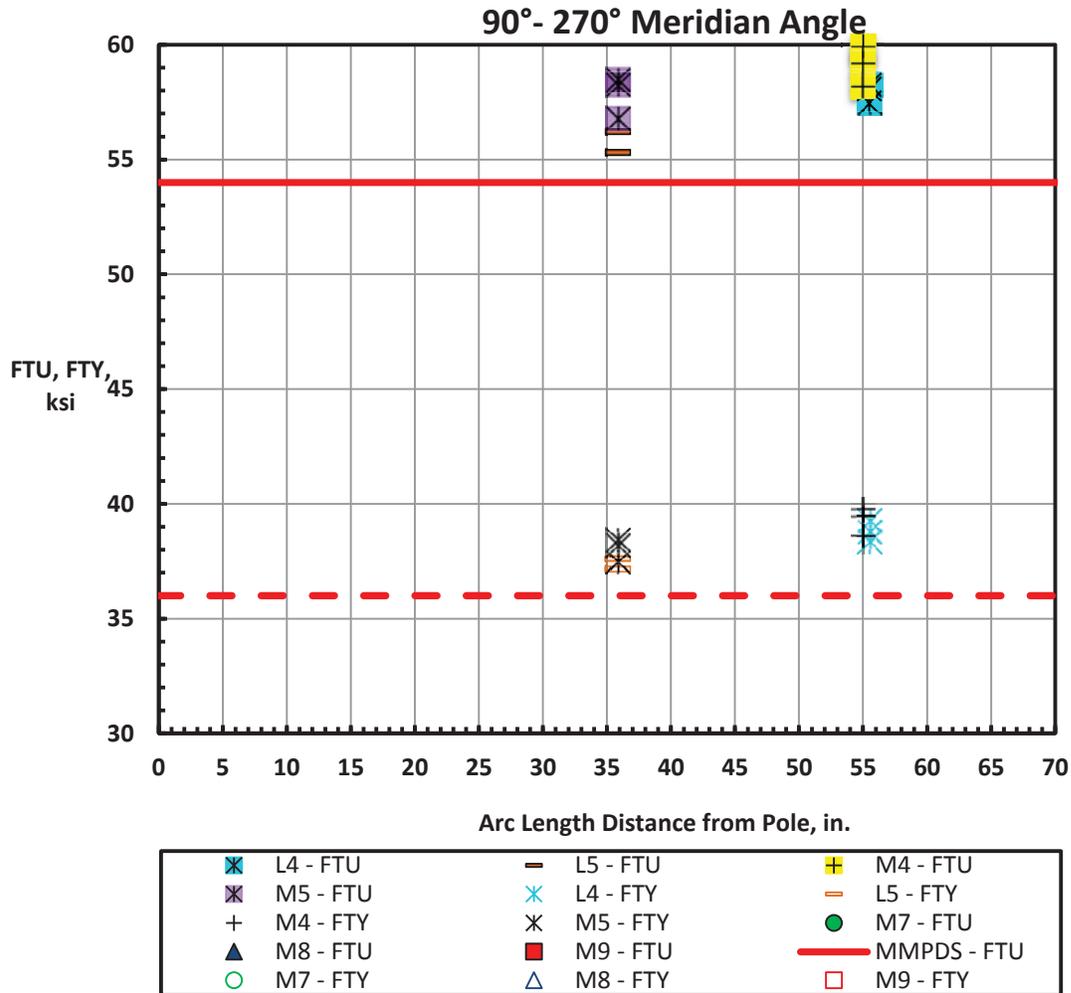
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
107 of 223



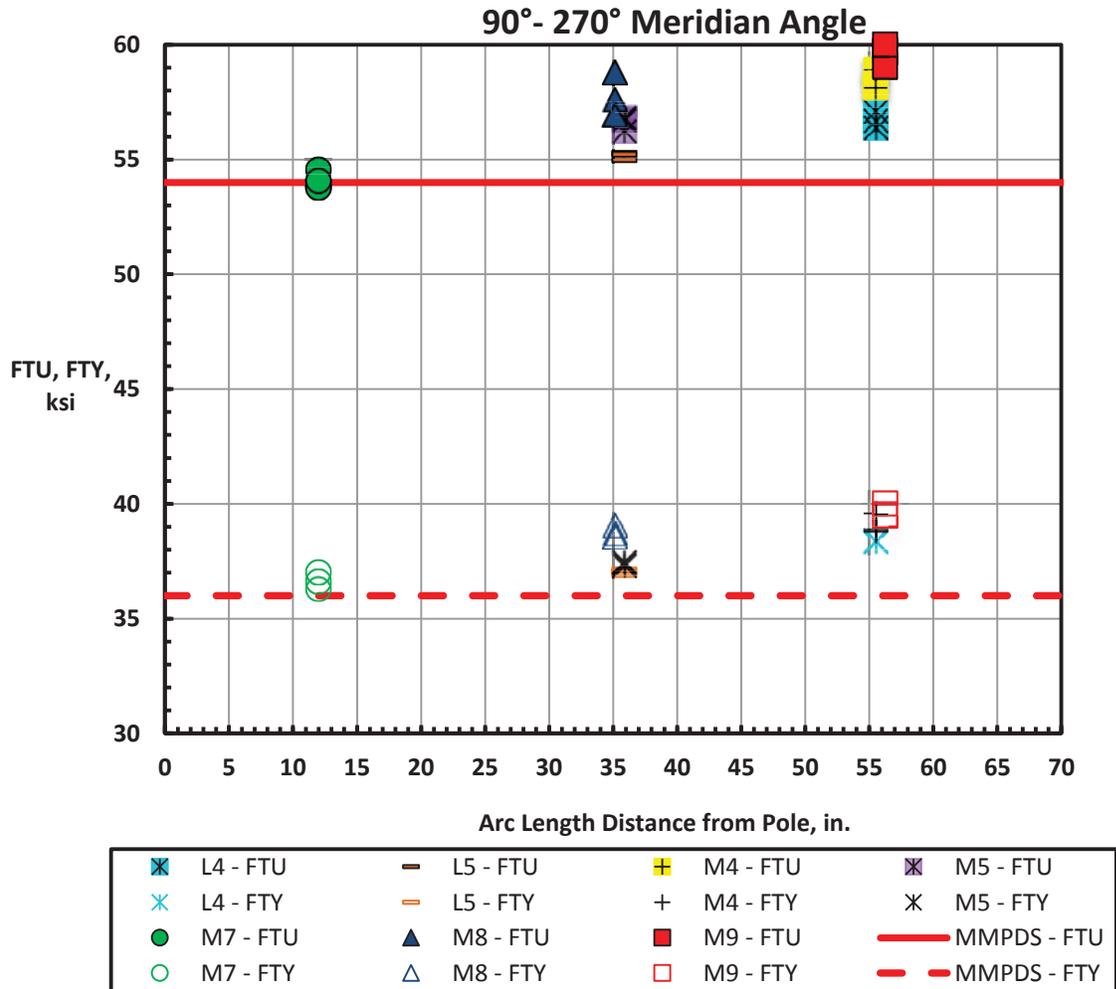
**Figure 10.2-8. Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
 108 of 223



**Figure 10.2-9. Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle**



# NASA Engineering and Safety Center Technical Assessment Report

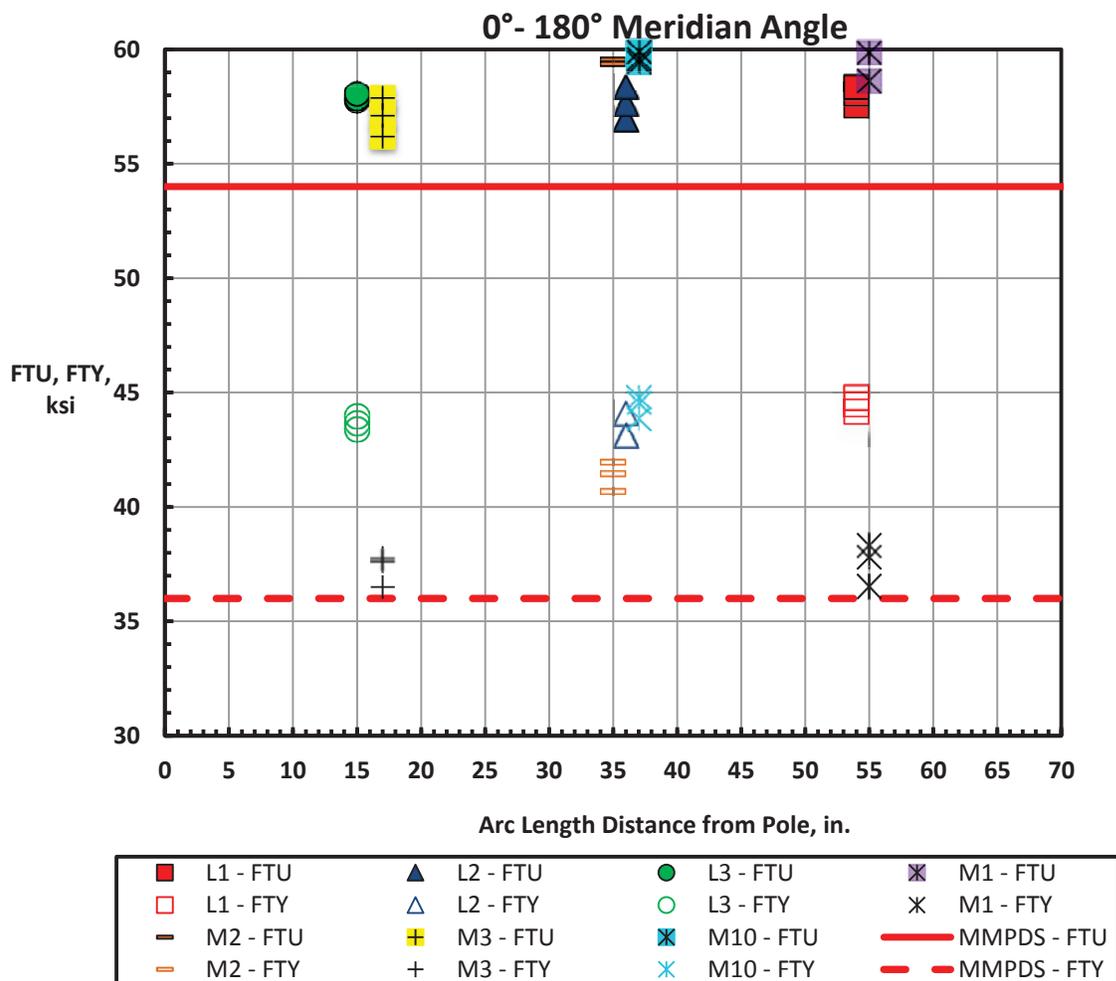
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
109 of 223



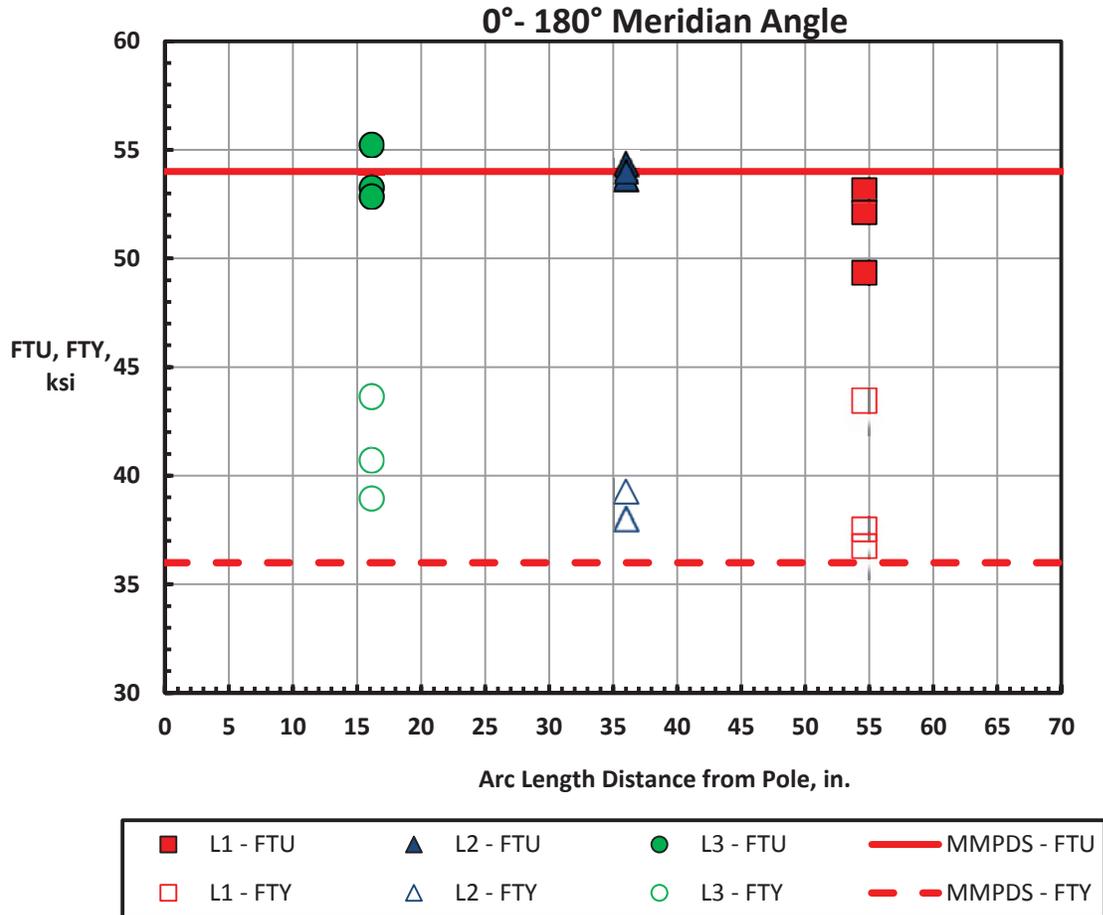
**Figure 10.2-10. Short Transverse (ST) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
110 of 223



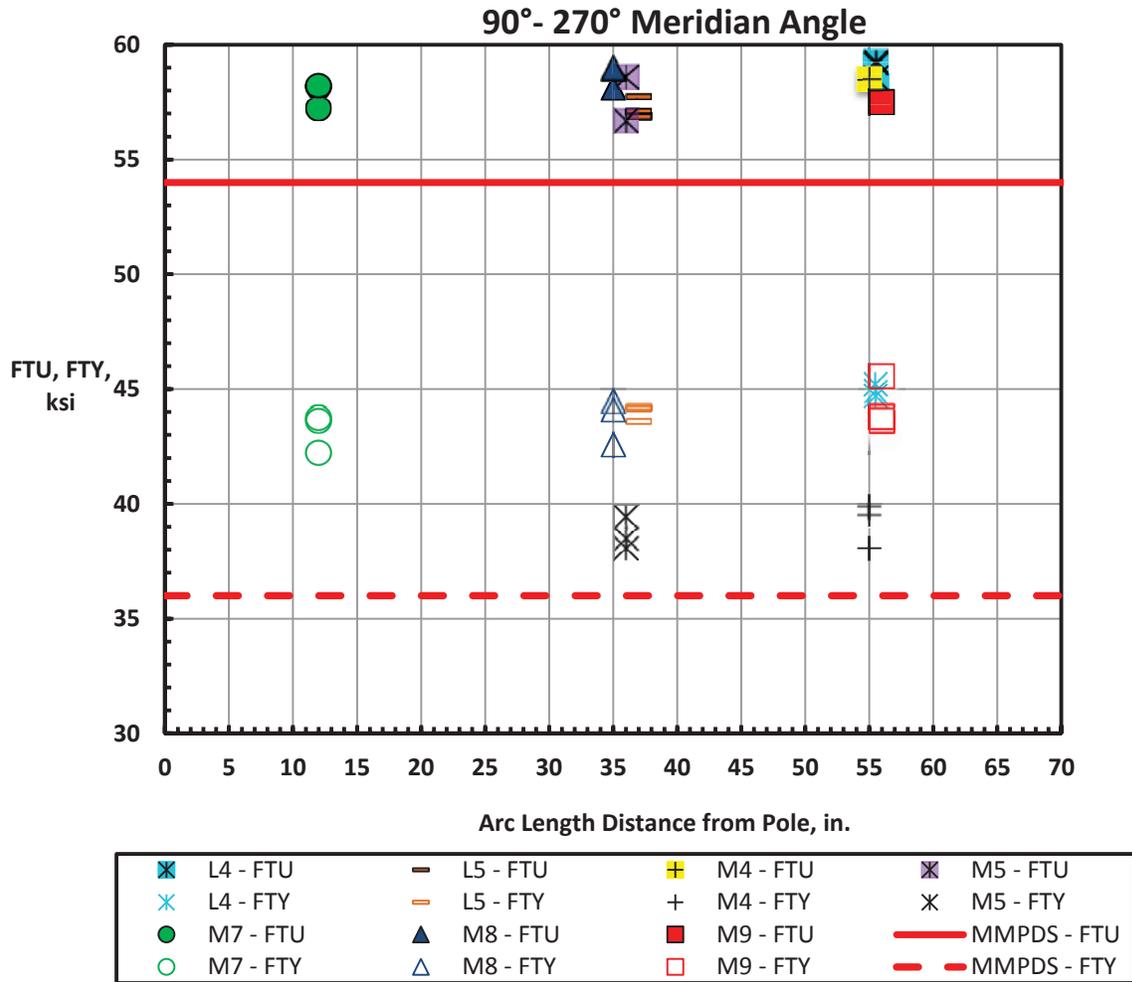
**Figure 10.2-11. Short Transverse 45° (ST45) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 0° to 180° Meridian Angle**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
 111 of 223



**Figure 10.2-12. Short Transverse (ST) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle**



# NASA Engineering and Safety Center Technical Assessment Report

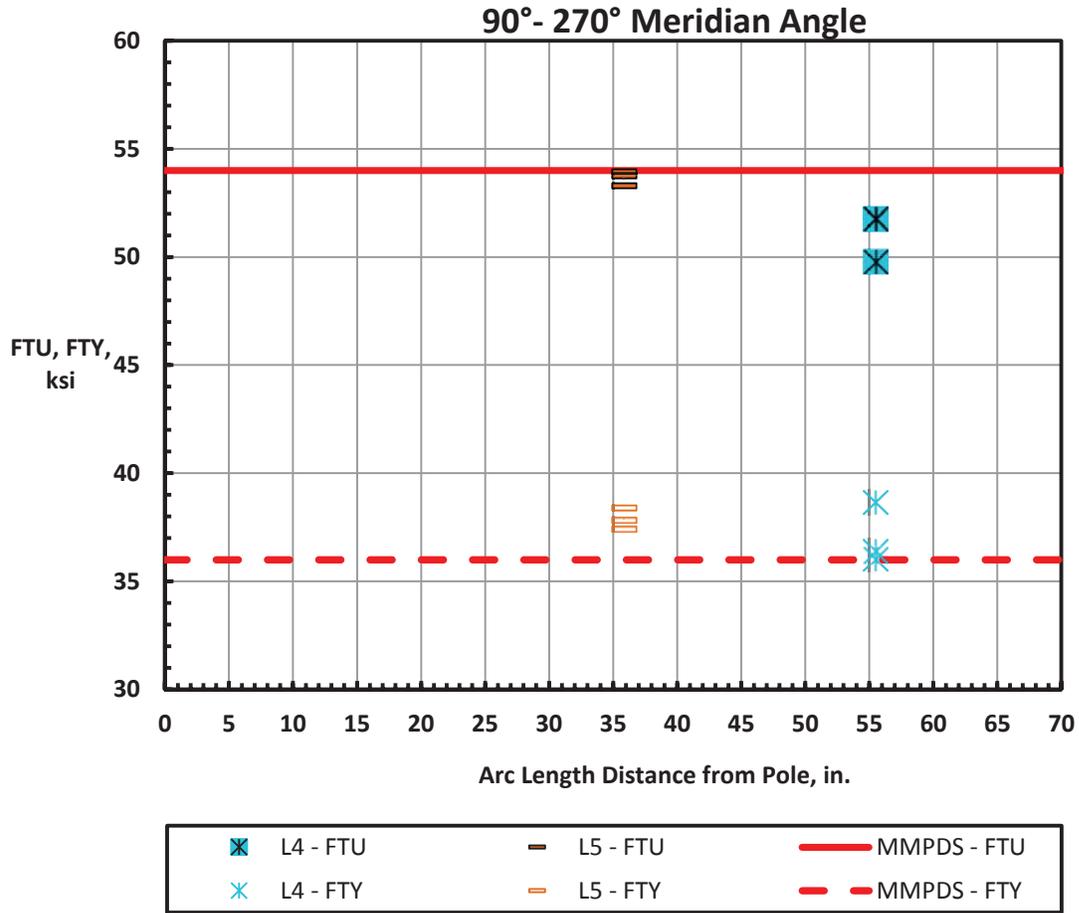
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
112 of 223



**Figure 10.2-13. Short Transverse 45° (ST45) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Arc Length Distance from the Pole along the 90° to 270° Meridian Angle**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
113 of 223

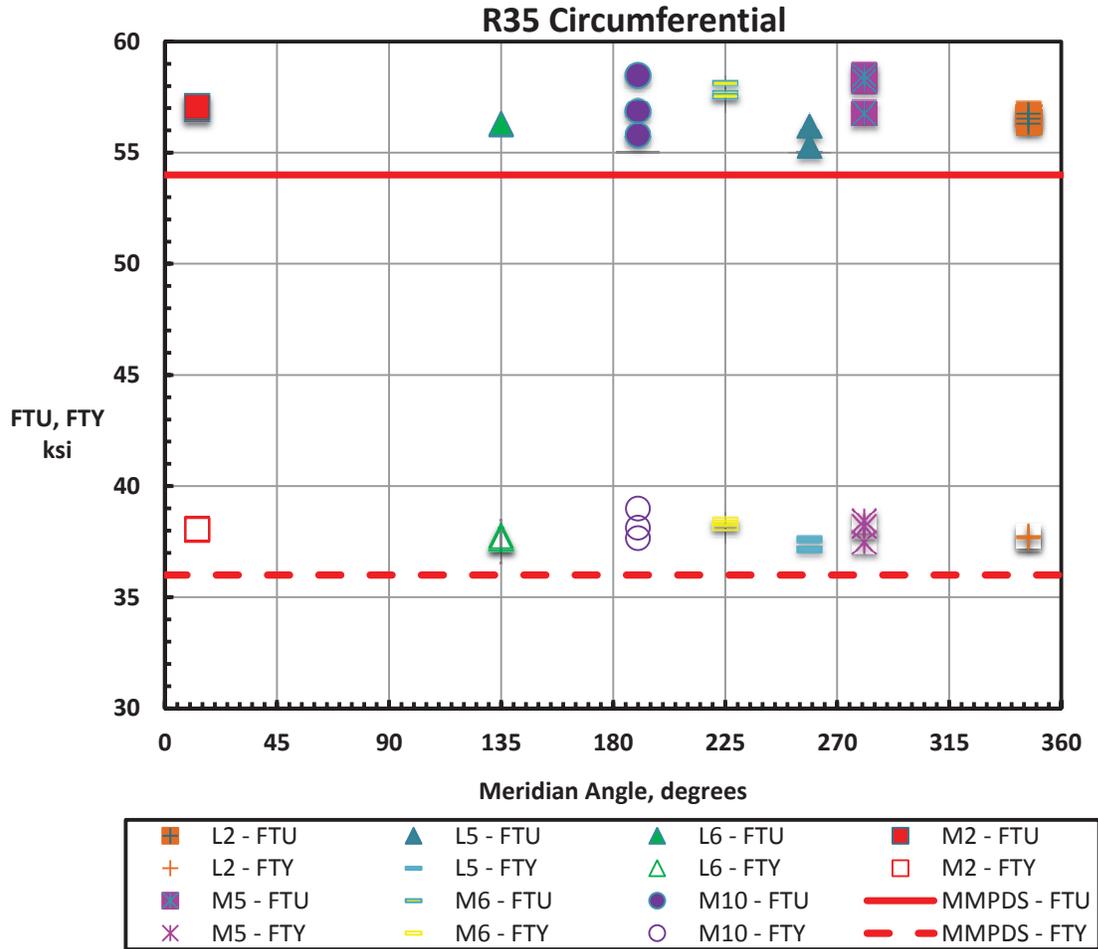


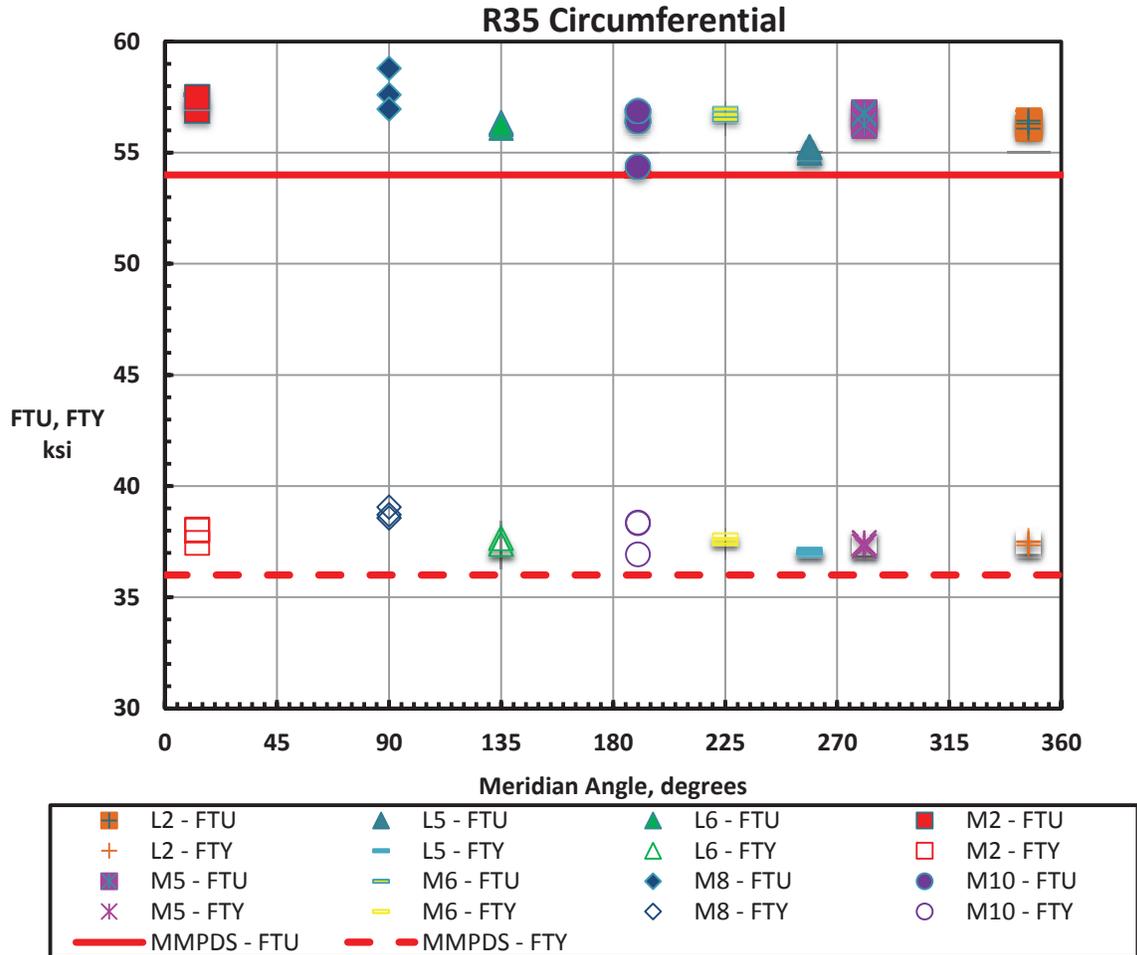
Figure 10.2-14. Longitudinal (L) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc Length



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
 114 of 223



**Figure 10.2-15. Long Transverse (LT) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc Length**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
115 of 223

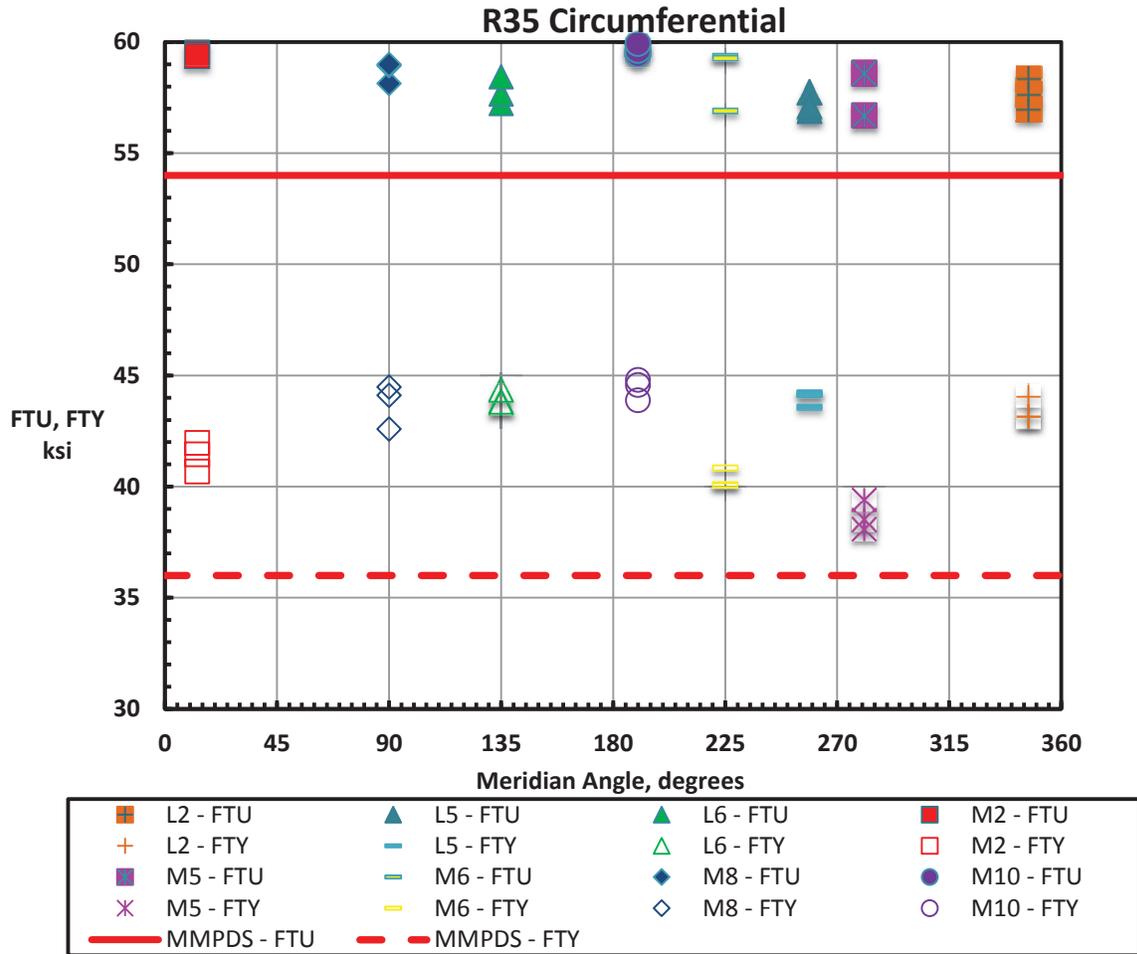


Figure 10.2-16. Short Transverse (ST) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc length



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
116 of 223

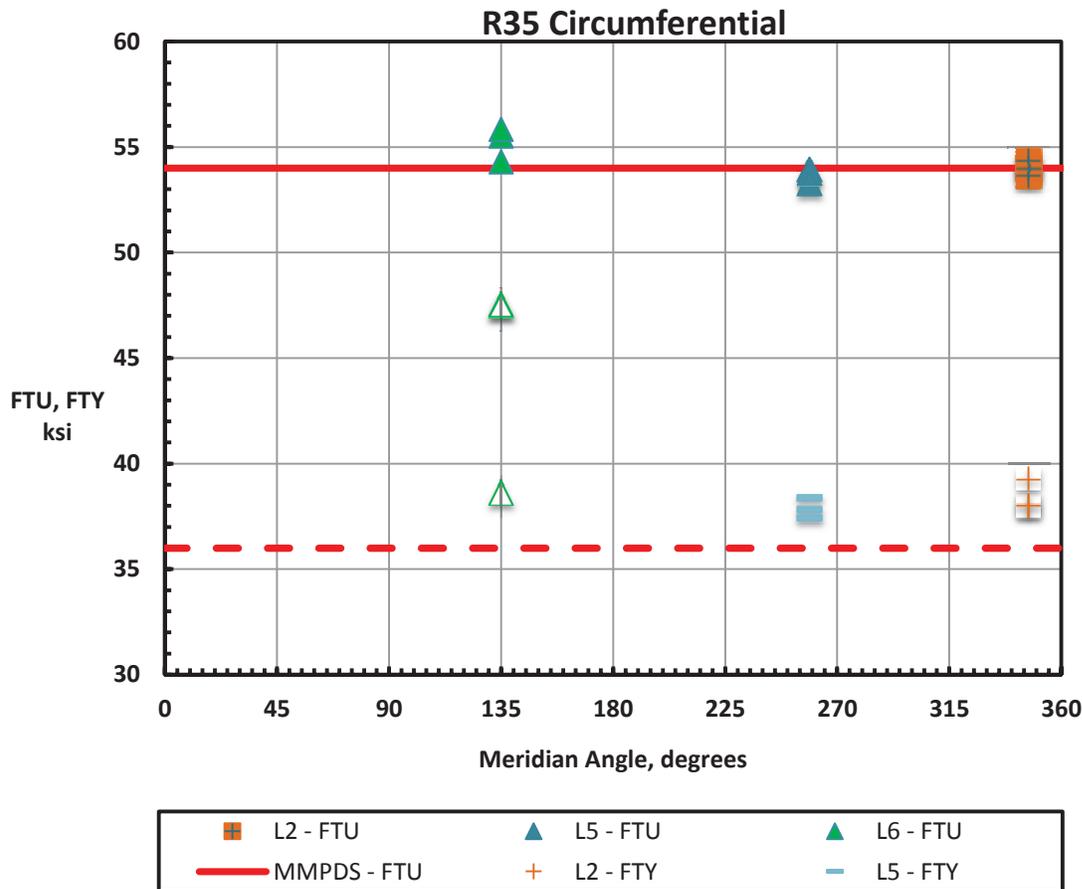


Figure 10.2-17. Short Transverse 45° (ST45) Tensile Properties of the Spin Formed Al 2219-T62 Aft Bulkhead Material as a Function of Meridian Angle along the R35 Circumferential Arc Length

### 10.2.2 Comparison with Handbook Data and Other T6 and T8 Products

The average tensile properties of the spin formed aft bulkhead shown in Table 10.2-10 were compared with data from numerous sources to assess the effects of spin forming when compared with rolled plate and other formed products heat treated to the T6 temper. Limited data were found in handbooks and open literature publications for Al 2219-T6 products so a variety of product forms were used in this evaluation. Comparisons were also made with T8 products to determine the reduction in tensile properties that designers will need to accommodate if spin forming is adopted for the aft bulkhead. In most cases, data for 2219-T6 and T8 products were available for L and T orientations; however, very little data were available for the ST orientation and no published values were available for the ST45 orientation.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			117 of 223

For comparison with wrought plate products, the MMPDS A- and B-basis design properties (17) and the Aluminum Association’s typical properties (18) for wrought Al 2219-T62, T851, and T87 plate are shown in Table 10.2-11 and Table 10.2-12, respectively. It is recognized that in this study typical properties of the aft bulkhead are compared with statistically derived allowables; however, these represent the material properties typically used by designers and provide an indication of whether the aft bulkhead properties will have the properties assumed in the design. It is also noteworthy that the ST orientation data from the aft bulkhead was compared with L and LT allowables since there are no allowables for the ST orientation specified in MMPDS. Typical tensile properties for spin formed Al 2219-T62 products were obtained from three sources for direct comparison to determine whether the aft bulkhead was “in family” with similar products. These included the FPVBH demonstration article presented in Table 10.2-13 (1), (19), (20); domes produced for NASA’s Cryogenic Propellant Storage and Transfer (CPST) Program (Table 10.2-14) (21); and other domes produced for commercial customers (Table 10.2-15) (22). For comparison with other fabricated product forms, minimum tensile properties for Al 2219-T6 forgings and rolled or forged rings are shown in Table 10.2-16 (23).

Based on the overall averages (Table 10.2-10), tensile strengths of the aft bulkhead in the L and LT orientations were about 5% higher than the MMPDS A-basis allowables for T62 plate (Table 10.2-11). The ST properties were even higher with UTS 8% and YS 15% higher than the L and LT orientation allowables. The elongation values exceeded the design values. The L and LT strengths were slightly lower, but within 5% of typical values reported by the Aluminum Association (Table 10.2-12). Al 2219 is generally considered an isotropic material with properties in the L, LT, and ST orientations generally agreeing within less than approximately 5% (see Table 10.2-11 and Table 10.2-16). The ST YS in the aft bulkhead was 10% greater than for L and T. It is unclear whether the higher ST YS is inherent in the plate used in fabrication of the spin forming blank or is related to the spin forming process.

Individual specimen results and average values for each coupon blank were compared with MMPDS A-basis allowables to determine whether there were any regions of concern in the aft bulkhead. Values below MMPDS are highlighted in red in Tables 10.2-2 through 10.2-10 for individual specimens, averages for the coupon blanks, and the overall average. To illustrate the aft bulkhead locations that have strength or elongation values below MMPDS, those values are shown in red in Figures 10.2-2 through 10.2-5. In addition, the MMPDS value is shown on the data plots in Figures 10.2-7 through 10.2-15. Two of three L and LT specimens from coupon blank L3, which is near the pole, exhibit UTS values just below the MMPDS A-basis UTS. This is reflected in the coupon blank average UTS; however, the overall average L and LT UTS is well above the MMPDS value. Strength values for the ST orientation were above, but elongations below MMPDS values at all locations. For the ST45 orientation, all elongation values and all except one UTS value were below MMPDS. All YS values for all locations and orientations were above the MMPDS YS.

The tensile properties of the aft bulkhead agreed well with the typical properties for other Al 2219-T62 spin formed products. The aft bulkhead strength levels were slightly lower than the spin formed FPVBH and the domes produced for the CPST Program and commercially by

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP-13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 118 of 223

Spincraft. The L and LT UTS and YS were within 3% and 6%, respectively, of values for the FBVBH (Table 10.2-13). The UTS was about 5% lower and YS 10% lower than the CPST and Spincraft domes (Table 10.2-14 and Table 10.2-15). Conversely, the ST tensile properties of the aft bulkhead were higher than those of the CPST domes. The UTS was about 2% higher and the YS 5% higher than the values for the CPST domes. The variations in tensile strength may be related to the amount of deformation related to forming these different geometries. The FPVBH experienced some thinning during spin forming and the complex geometry likely generated greater deformation. While some details of the Spincraft domes are proprietary it was confirmed that the domes were of larger scale than the aft bulkhead and had a complex thickness profile. The deformation was likely lower in the aft bulkhead than the FPVBH and Spincraft domes due to the gradual curvature and comparatively simple geometry of the aft bulkhead.

Tensile strengths in the L and LT orientation compared well with minimum values for hand and die forgings and rolled or forged rings (Table 10.2-16), with some values higher and some lower, but all within 5% of the published minimums. However, strengths in the ST orientation were 10 to 15% higher than values for hand forgings. Typical elongation values were higher in all comparisons.

The L and LT tensile properties of the spin formed aft bulkhead are consistent (in family) with wrought plate and other fabricated product forms in the T62 temper. Orion design trade studies use the MMPDS A-basis values for T62 wrought plate to analyze the benefits of spin forming the aft bulkhead because design values do not exist for spin formed products. The tensile results of this aft bulkhead should build confidence in the spin forming fabrication method. Currently, some elements of the Orion CM are multi-piece welded construction of machined thick Al 2219-T851 plate. The tensile properties of the spin formed aft bulkhead are lower than for T851 plate (Table 10.2-11 and Table 10.2-12) as expected due to the increased precipitation strengthening in T851 wrought products that is imparted by the 1.5 to 3.0% cold stretch prior to artificial aging. The thick-plate convex spin forming process cannot accommodate stretch or cold work thus only T6 final temper can be produced. The properties of the spin formed aft bulkhead are comparable to T62 plate and other wrought products. The UTS values in the L and LT orientations of the aft bulkhead are about 10% lower than MMPDS A-basis allowables for T851 plate (Table 10.2-11) and 15% less than typical values (Table 10.2-12). The YS values in both orientations are about 20% lower than the MMPDS A-basis allowables and 30% lower than typical values. It should be recognized that, based on MMPDS A-basis values, the UTS and YS of T62 plate are lower than for T851 plate by 10% and 30%, respectively, and lower than for T87 plate by 17% and 40%, respectively. The lower tensile strength of the spin formed 2219-T62 aft bulkhead material compared with 2219-T851 and T87 plateS is due differences in material temper and not the spin forming process.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 119 of 223	

- F-3.** The tensile properties of the spin formed Al 2219-T62 aft bulkhead material were typical for established 2219-T62 products.
- Tensile properties were comparable to the MMPDS design properties for T62 wrought plate and other fabricated products in the T6 temper, such as spin formed domes, forgings and rolled rings.
  - Tensile properties were lower than those for Al 2219-T851 and T87 plate, as expected due to the increased precipitation strengthening in T8 temper wrought products that is imparted by the cold stretch/work prior to artificial aging.
  - The lower tensile strength of the spin formed Al 2219-T62 aft bulkhead material compared with Al 2219-T851 and T87 plate is due to differences in material temper and not the spin forming process.
- O-2.** Limited data was available in handbooks or open literature publications for Al 2219-T6 material for comparison with the aft bulkhead properties, consequently it was difficult to assess the aft bulkhead in the context of other commercial Al 2219-T6 products.
- Tensile data were unavailable in handbooks or open literature publications for the ST and ST45 orientations, consequently these properties could only be assessed in comparison with established values for the L and LT orientations.
- R-2.** Additional testing should be performed on first article and initial serial production aft bulkhead components to generate data to populate the material property database for Al 2219-T6 spin formed products. (**O-2**)
- Tensile testing should be continued until sufficient data is generated to demonstrate consistency in material properties and build confidence that the spin forming process is reproducible.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
120 of 223

**Table 10.2-11. Design Tensile Properties of Al 2219-T62, T851 and T87 Sheet and Plate (17)**

Specification Form Temper Thickness, in Basis	AMS-QQ-250/30, AMS 4031		AMS-QQ-250/30, AMS 4599												
	Sheet and Plate														
	T62		T851												
	0.020-2.000		0.250 - 1.000		1.001 - 2.000		2.001 - 3.000		3.001 - 4.000		4.001 - 5.000		5.001 - 6.000		
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
<b>Mechanical Properties:</b>															
$F_{tU}$ , ksi															
L	54	55	61	62	61	62	----	----	----	----	----	----	----	----	----
LT	54	55	62	63	62	63	62	63	60	61	59	60	57	58	
$F_{tY}$ , ksi															
L	36	37	47	48	47	48	----	----	----	----	----	----	----	----	----
LT	36	37	46	47	46	47	45	46	44	45	43	44	42	43	
$e$ , % (S-basis)															
LT	d	----	8	----	7	----	6	----	5	----	5	----	4	----	
$E$ , $10^3$ ksi	10.5														

d T62: 0.250-1.000 in: 8%; 1.001-2.000 in.: 7%

Specification Form Temper Thickness, in Basis	AMS-QQ-250/30, AMS 4031		AMS-QQ-250/30, AMS 4613												
	Sheet and Plate														
	T62		T87												
	0.020-2.000		0.250 - 1.000		1.001 - 1.500		1.501 - 2.000		2.001 - 3.000		3.001 - 4.000		4.001 - 5.000		
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	
<b>Mechanical Properties:</b>															
$F_{tU}$ , ksi															
L	54	55	63	64	63	64	63	64	63	64	61	62	----	----	
LT	54	55	64	65	64	65	64	65	64	65	62	63	61	62	
ST	----	----	----	----	----	----	59	60	56	57	52	53	----	----	
$F_{tY}$ , ksi															
L	36	37	50	51	50	51	50	51	50	51	49	50	----	----	
LT	36	37	51	52	51	52	51	52	51	52	51	51	49	50	
ST	----	----	----	----	----	----	51	52	50	51	48	49	----	----	
$e$ , % (S-basis)															
LT	d	----	7	----	6	----	6	----	6	----	4	----	3	----	
$E$ , $10^3$ ksi	10.5														

d T62: 0.250-1.000 in: 8%; 1.001-2.000 in.: 7%

**Table 10.2-12. Typical Tensile Properties of Al 2219-T62, T851, and T87 Sheet and Plate (18)**

	UTS (ksi)	YS (ksi)	E (Msi)	e (%)
2219-T62	58	40	10.5	12
2219-T851	66	50	10.5	12
2219-T87	68	56	10.5	10

*Table 10.2-13. Average Tensile Properties for the Spin Formed Al 2219-T62 FPVBH Material (1), (19), (20)*

Location	Orient.	UTS (ksi)	0.2% YS (ksi)	E (Msi)	e (%)	
Pole	L	60.05	40.8	10.6	9.25	<b>Average Std Dev.</b>
		0.92	0.71	0.71	1.06	
	LT	60.65	40	10.85	9	
		0.21	0.14	0.78	1.41	
Cone	L	57.53	40.53	10.03	9.25	
		0.67	2.08	0.22	0.96	
	LT	58.05	40.73	10.1	10.63	
		0.59	1.64	0.22	1.7	
Barrel	L	57.3	40.45	9.85	6.5	
		0.14	0.64	0.21	2.12	
	LT	56.95	39.6	9.55	13	
		0.07	0.85	0.78	0	
All coupon blank locations	L	58.29	40.59	10.16	8.33	<b>Average Std Dev.</b>
		1.53	0.18	0.39	1.59	
	LT	58.55	40.11	10.17	10.88	
		1.9	0.57	0.65	2.01	



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
122 of 223

**Table 10.2-14. Tensile Properties of Spin Formed Al 2219-T62 Domes for the CPST Program (21)**

Dome S/N	Specimen ID	Location	Orient.	Condition*	Source	UTS, ksi	YS, ksi	e, %
31140-1	31140-1-P2-L	pole	in-plane (L)	T62	LAT	59.0	41.0	12
31140-2	31140-2-P2-L	pole	in-plane (L)	T62	LAT	60.0	42.2	13
31140-3	31140-3-P2-L	pole	in-plane (L)	T62	LAT	60.0	41.7	13
31140-1	31140-1-P1-LT	pole	in-plane (LT)	T62	LAT	60.5	42.0	10
31140-2	31140-2-P1-LT	pole	in-plane (LT)	T62	LAT	60.5	41.1	11
31140-3	31140-3-P1-LT	pole	in-plane (LT)	T62	LAT	60.0	43.6	11
31140-1	120551001	pole	in-plane	T62	MSFC	57.0	35.4	10.4
31140-1	120551005	pole	in-plane	T62	MSFC	57.5	39.0	11.7
31140-1	120551003	pole	ST	T62	MSFC	57.1	37.8	4.2
31140-2	120551013	pole	in-plane	T62 + SR	MSFC	57.3	35.8	10.1
31140-2	120551017	pole	in-plane	T62 + SR	MSFC	56.7	39.6	11.2
31140-2	120551015	pole	ST	T62 + SR	MSFC	59.3	41.3	3.9
31140-1	31140-1-E2-L	rim	in-plane (L)	T62	LAT	59.5	41.9	11
31140-2	31140-2-E2-L	rim	in-plane (L)	T62	LAT	60.5	42.2	11
31140-3	31140-3-E2-L	rim	in-plane (L)	T62	LAT	59.5	41.4	12
31140-1	31140-1-E1-LT	rim	in-plane (LT)	T62	LAT	59.0	41.5	11
31140-2	31140-2-E1-LT	rim	in-plane (LT)	T62	LAT	58.5	41.3	11
31140-3	31140-3-E1-LT	rim	in-plane (LT)	T62	LAT	59.0	40.6	11
31140-1	120551021	rim	in-plane	T62 + SR	MSFC	57.1	35.4	10.6
31140-1	120551023	rim	in-plane	T62 + SR	MSFC	59.4	38.9	9.3
31140-1	120551019	rim	ST	T62 + SR	MSFC	55.4	40.0	4.0
31140-2	120551009	rim	in-plane	T62 + SR	MSFC	58.4	39.0	12.3
31140-2	120551011	rim	in-plane	T62 + SR	MSFC	58.8	40.9	9.9
31140-2	120551007	rim	ST	T62 + SR	MSFC	58.3	41.3	4.9

**LAT** lot acceptance test  
**SR** Stress relief thermal cycle at 300°F ± 15°F for 8 hours



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
123 of 223

*Table 10.2-15. Typical tensile properties of spin formed Al 2219-T62 domes commercially produced by Spincraft. Also shown for comparison is the Alcoa plate lot certification tensile properties. (22).*

Spincraft Dome S/N	Alcoa Plate Lot H/N	Orient.	Spin Formed Dome Tensile Properties								
			Alcoa Plate Lot Cert. Data			Polar Tensile Coupons			Equator Tensile Coupons		
			UTS (ksi)	YS (ksi)	EL4D (%)	UTS (ksi)	YS (ksi)	EL4D (%)	UTS (ksi)	YS (ksi)	EL4D (%)
31152-1	660931-1	LT	58.9	41.0	11.1	59.0	42.7	12.0	59.0	41.3	10.0
		L	58.5	40.6	11.5	60.0	43.4	13.0	59.0	41.6	12.0
31152-2	660941-1	LT	59.2	40.7	11.1	60.5	43.9	10.0	60.5	41.7	9.0
		L	59.3	40.8	11.3	60.0	42.9	10.0	59.0	40.4	10.0
31153-2	478411-1	LT	59.7	40.8	11.8	60.5	44.0	13.0	60.5	42.4	10.0
		L	60.0	41.0	10.6	60.5	44.3	11.0	59.5	42.1	10.0
31153-3	660951-1	LT	58.5	40.8	11.7	59.5	42.5	10.0	60.0	42.5	10.0
		L	58.7	41.0	11.8	59.5	42.8	12.0	59.5	42.8	10.0
31172-1R	528431-1	LT	60.9	42.0	8.2	55.8	37.7	13.0	60.1	43.4	8.5
		LT	60.3	41.5	8.5	58.3	38.5	11.0	59.8	42.7	10.0
		L	-----	-----	-----	56.9	40.4	12.0	58.8	43.9	10.0
		L	-----	-----	-----	57.7	39.3	14.0	59.7	42.4	11.0
31163-1	414091-1	LT	60.9	41.9	10.7	62.5	45.3	11.0	60.0	42.1	11.0
		LT	61.3	41.8	10.2	61.5	43.4	10.0	60.0	42.1	11.0
		L	-----	-----	-----	60.5	43.3	10.0	59.5	41.7	11.0
		L	-----	-----	-----	61.0	43.5	11.0	59.5	42.0	11.0
31163-2	414081-1	LT	59.7	40.6	11.1	60.0	42.9	10.0	58.0	41.8	8.0
		LT	59.6	40.8	11.0	59.5	42.3	10.0	58.5	41.7	10.0
		L	-----	-----	-----	60.5	42.9	10.0	57.5	41.4	8.0
		L	-----	-----	-----	59.5	42.3	10.0	58.0	40.8	10.0
Average	Std. Dev.	LT	59.9	41.2	10.5	59.7	42.3	11.0	59.6	42.2	9.8
			0.93	0.55	1.24	1.83	2.40	1.25	0.85	0.61	0.98
Average	Std. Dev.	L	59.1	40.9	11.3	59.6	42.5	11.3	59.0	41.9	10.3
			0.68	0.19	0.51	1.32	1.52	1.42	0.73	1.00	1.06

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			124 of 223

*Table 10.2-16. Minimum Tensile Properties for Al 2219-T6 Forgings and Rolled or Forged Rings (23)*

**Die Forgings**

Minimum tensile properties

<u>Orient.</u>	<u>UTS</u> <u>ksi</u>	<u>0.2% YS</u> <u>ksi</u>	<u>e</u> <u>% in 4D</u>
L	58.0	38.0	8
LT	56.0	36.0	4

**Hand Forgings**

Minimum tensile properties

<u>Orient.</u>	<u>UTS</u> <u>ksi</u>	<u>0.2% YS</u> <u>ksi</u>	<u>e</u> <u>% in 4D</u>
L	58.0	40.0	6
LT	55.0	37.0	4
ST	53.0	35.0	2

**Rolled or Forged Rings**

Minimum tensile properties

<u>Orient.</u>	<u>UTS</u> <u>ksi</u>	<u>0.2% YS</u> <u>ksi</u>	<u>e</u> <u>% in 4D</u>
Tangential	56.0	40.0	6
Axial	55.0	37.0	4

**10.2.3 Tensile Fractography**

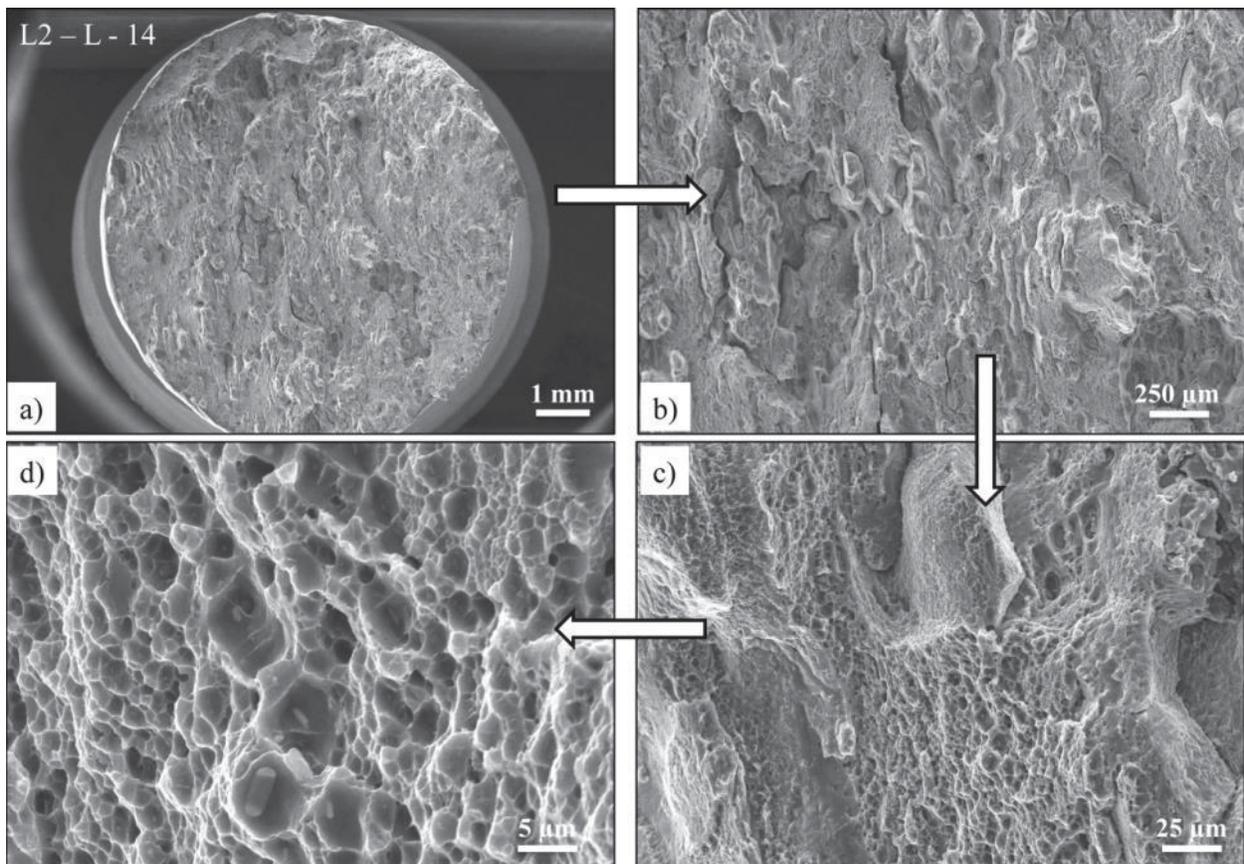
Representative tensile specimens were chosen for examination of the fracture surfaces with a combination of macroscopic and microscopic techniques. Macroscopic evaluation was performed with a digital camera and stereo microscope. Microscopic examination was conducted via scanning electron microscopy. Eighteen specimens were tested for the L, LT, ST, and ST45 orientations. All specimens were inspected visually after failure and representative samples were selected for more detailed examination to evaluate fracture morphology.

Three specimens representing the typical tensile failures observed for the L and LT orientations are shown in Figure 10.2-18. In general, the fracture surfaces as seen from the top-view in Figure 10.2-18 appear similar with macroscopic dimples, which indicate a ductile fracture mode. In all cases the specimens exhibited strain bands, which can be seen in the side view in Figure 10.2-19. Differences in the overall fracture path were observed as can be seen in the side-view of the fracture surfaces, with specimens exhibiting two slant fracture modes: full-slant or double-slant tensile fracture, both of which are typical of tensile fractures in Al plate. Of the 18 L



	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			126 of 223

revealing a fibrous appearance with noticeable ridges and valleys, which is typical of fracture in Al alloy plate. The fibrous features are associated with transgranular fracture of elongated grains in rolled plate and the ridges with transition between grains. At 50x (Figure 10.2-19b), regions of transgranular microvoid coalescence are observed along with regions of lower ductility fracture and small delaminations, features that generally correlated with grain size. Higher magnification (500x, Figure 10.2-19c) confirms that all regions exhibit microvoid coalescence consistent with ductile fracture, with dimple sizes larger in the regions of transgranular fracture. At 2,000x (Figure 10.2-19d), dimples ranging from sub-micron size to approximately 5  $\mu\text{m}$  are observed. Overall, fractography indicates the L and LT tensile specimens failed in a typical, ductile manner, which correlates well with the elongation values measured during the tensile tests.



**Figure 10.2-19. SEM Images of the Fracture Surface of Tensile Specimen L2-L-14 at a) 14x; b) 50x; c) 500x and d) 2,000x Magnifications**

SEM fractography results are shown in Figure 10.2-20 and Figure 10.2-21 for representative ST and ST45 specimens. The ST fracture surface shown in Figure 10.2-20 represents the flatter slant fracture mode. Low magnifications (views a and b) exhibit a stepwise fracture surface illustrating propagation on elongated grain boundaries. Higher magnification (view c) reveals shallow microvoid coalescence initiated at constituent particles, often presented as clusters and



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

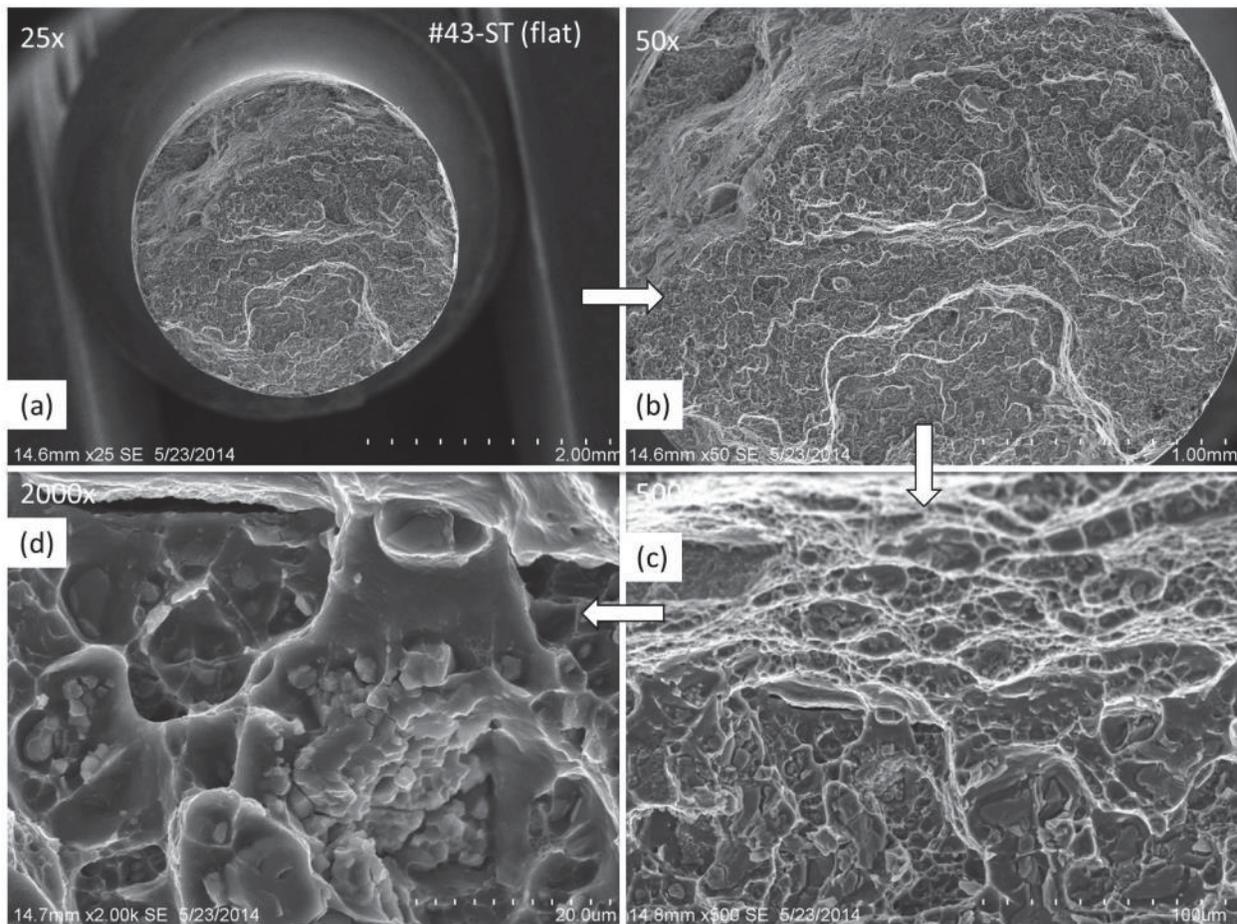
Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
127 of 223

stringers of smaller particles (view (d)). The ST45 fracture surface shown in Figure 10.2-21 exhibits some fibrous texture associated with transgranular crack propagation, but without the pronounced ridges and valleys noted on the L and LT fracture surfaces. Large microvoids are noted, again forming at constituent particle populations; however, more colonies of small microvoids are noted than in the ST fracture. The features noted in the ST and ST45 fractures are consistent with the lower ductility levels measured during tensile tests when compared with the L and LT orientations.



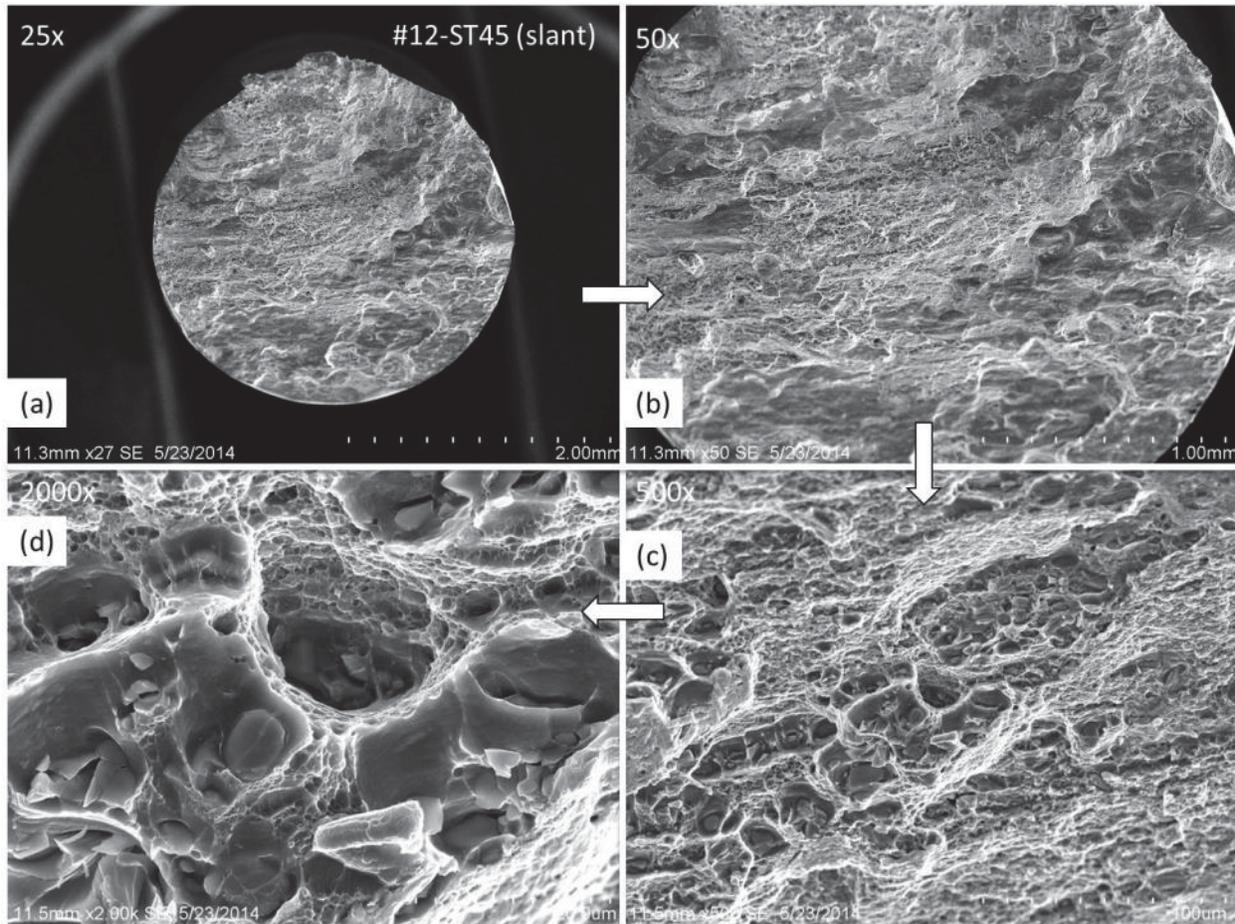
**Figure 10.2-20. SEM Images of the Fracture Surface of Tensile Specimen ST-43 at (a) 25x; (b) 50x; (c) 500x; and (d) 2,000x Magnifications**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
128 of 223



**Figure 10.2-21. SEM Images of the Fracture Surface of Tensile Specimen ST45-12 at (a) 25x; (b) 50x; (c) 500x; and (d) 2,000x Magnifications**

### 10.3 Fracture Toughness Test Results

Figure 10.3-1 shows the aft bulkhead cut plan with the location of coupon blanks from which fracture specimens were excised for fracture toughness testing highlighted in yellow. Table 10.3-1 shows the size and location of these coupon blanks with respect to the original plate rolling direction and distance from the aft bulkhead pole to the coupon blank center point. These coupon blank locations were designed to determine uniformity of fracture properties throughout the aft bulkhead and were evaluated along selected meridian and circumferential lines.

An additional goal of these tests was to determine how these properties compare to wrought plate in the T6 and T8 tempers and to other fabricated product forms in the T62 temper. These results will assist the Orion designers in assessing the attributes of the spin form fabrication process for the aft bulkhead and identify any deficiencies or “show stoppers” associated with this fabrication process.



# NASA Engineering and Safety Center Technical Assessment Report

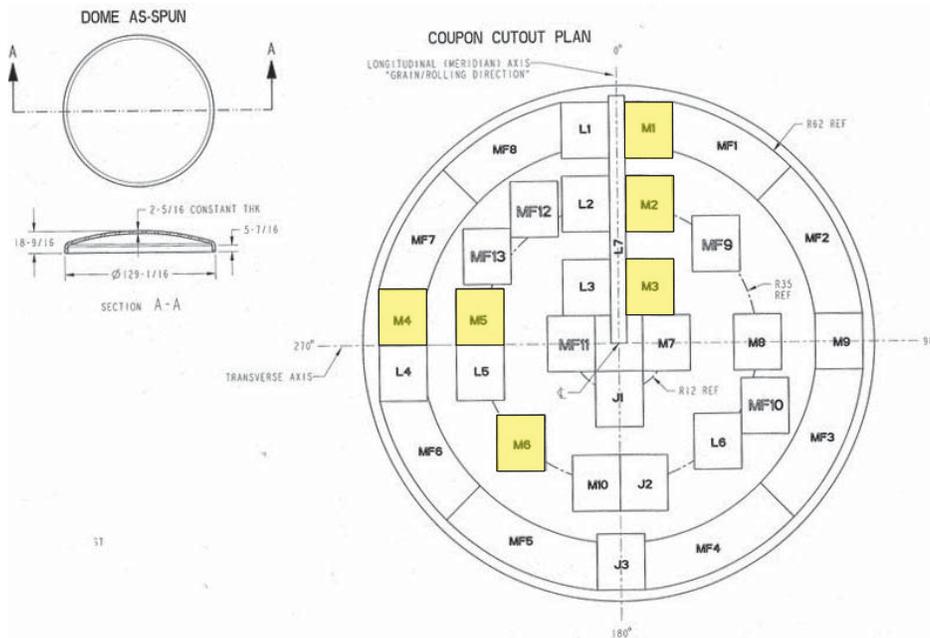
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
129 of 223



**Figure 10.3-1. Aft Bulkhead Cut Plan showing the Location of the Fracture Coupon Blanks highlighted in Yellow**

**Table 10.3-1. Fracture Toughness Coupon Blank Locations and Orientations**

Coupon Blank	Coupon Blank Size		Coupon Center Point	
	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Arc Length from dome CL in.
M1	14	12	9°	54-5/8
M2	14	12	13°	36
M3	14	12	30°	16-1/8
M4	14	12	277°	55-1/2
M5	14	12	281°	35-7/8
M6	14	12	225°	35-1/8

### 10.3.1 Uniformity of Fracture Properties

A summary of the fracture toughness test results for the Al 2219-T62 aft bulkhead material is provided in Table 10.3-2. All but five specimens were valid per the ASTM E1820 (8) specification. In each case the invalidity was related to the difference between the estimated crack extension and the measured crack extension. In each case the deviation was considered minor and inconsequential to the toughness results. Comprehensive data analyses are provided in the Appendix (see Section 20.3). Fracture toughness comparisons were based on  $K_{JIC}$  values listed in Table 10.3-2.

**Table 10.3-2. Summary of Fracture Data for the Spin Formed Al 2219-T62 Aft Bulkhead Material**

Specimen ID	Coupon Blank	Orientation	J <sub>IC</sub> (in-lb/in <sup>2</sup> )	K <sub>JIC</sub> (ksi√in)
CP-406-191	M1	L-T	105.6	35.1
CP-406-193			114.8	36.6
CP-406-196		T-L	91.5*	32.7
CP-406-198			90.6*	32.5
CP-406-201		S-T	62.6	27.0
CP-406-203			62.2	26.9
CP-406-206	M2	L-T	115.1	36.6
CP-406-208			112.8	36.3
CP-406-211		T-L	86.2*	31.7
CP-406-213			91.0	32.6
CP-406-216		S-T	89.9	32.4
CP-406-218			56.0	25.6
CP-406-221	M3	L-T	117.2	37.0
CP-406-223			125.7	38.3
CP-406-226		T-L	84.9	31.5
CP-406-228			93.1	32.9
CP-406-231		S-T	66.0	27.7
CP-406-233			90.7	32.5
CP-406-236	M4	L-T	102.5	34.6
CP-406-238			99.1	34.0
CP-406-241		T-L	86.0	31.7
CP-406-243			93.4*	33.0
CP-406-246		S-T	78.0	30.1
CP-406-248			50.9	24.4
CP-406-251	M5	L-T	108.4	35.5
CP-406-253			107.3	35.4
CP-406-256		T-L	86.3	31.7
CP-406-258			85.6	31.6
CP-406-261		S-T	67.8	28.1
CP-406-263			77.4	30.0
CP-406-266	M6	L-T	118.7	37.2
CP-406-268			114.0	36.4
CP-406-271		T-L	86.5	31.7
CP-406-273			85.0	31.5
CP-406-276		S-T	59.1	26.2
CP-406-278			57.4*	25.9

\* Not fully valid J<sub>IC</sub> value.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

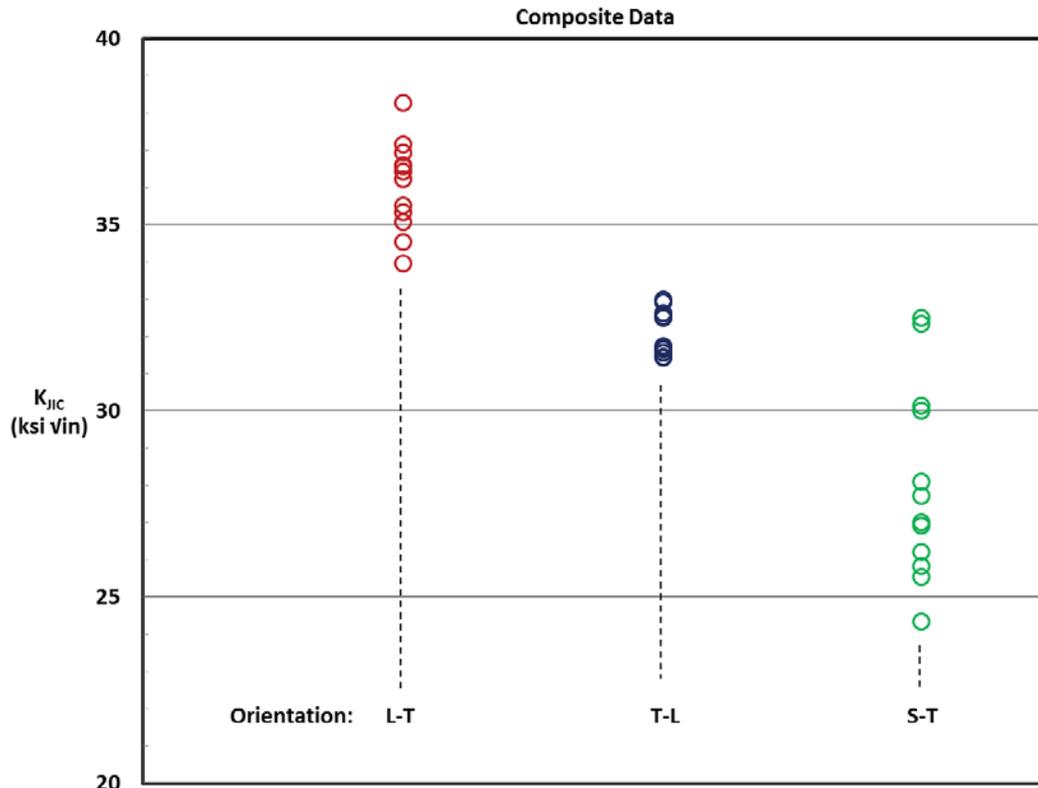
Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
131 of 223

The composite fracture data is shown in Figure 10.3-2. This figure reflects all data taken from various locations across the aft bulkhead and is plotted for each orientation. Fracture toughness values vary with orientation as expected. Specifically, toughness in the L-T orientation is higher than toughness in the T-L orientation, which in turn is higher than toughness in the S-T orientation.



**Figure 10.3-2. Fracture Toughness Data as a Function of Orientation**

In order to examine trends in the toughness with respect to location within the aft bulkhead, plots were made along selected meridian angle and circumferential lines as shown in Figure 10.3-3 through Figure 10.3-7. The first plot, shown in Figure 10.3-3, is a composite of all toughness data as a function of orientation and coupon blank ID. For each coupon blank, the local L-T orientation toughness exceeds the T-L and S-T toughness. In blanks M1, M4, M5, and M6, the T-L toughness exceeds the S-T toughness. However, in coupon blanks M2 and M3, the S-T toughness overlaps the T-L toughness. Note that in coupon blanks M1, M2, and M4, the S-T toughness values exhibit a range in values on the order of 20% of their average. Subsequent analysis of data did not identify a trend in the range as a function of coupon blank location. With respect to the range in values for the in-plane orientations, the local L-T toughness values and the T-L toughness values were tightly grouped. The largest range for the local in-plane toughness values was 4%. In general, the data reflect the local toughness pattern that the L-T toughness is greater than the T-L toughness, which is greater than the S-T toughness.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 132 of 223

Toughness as a function of arc length distance for the 0° to 180° and 90° to 270° meridian angles is shown in Figure 10.3-4 and Figure 10.3-5, respectively. Along both meridian lines, the L-T orientation toughness shows a slight decrease in toughness from the pole to the rim. The T-L data appear to be uniform across the arc length of the aft bulkhead. The average S-T data exhibit a slight decrease in toughness along the arc length, although the scatter in the S-T data makes it difficult to conclusively describe the trend. The drop in L-T toughness from pole to rim is in contrast to the tensile data, but consistent with such trends in Al wrought products.

Toughness as a function of the meridian angle for circumferential lines of 36-inch and 55-inch arc length is shown in Figure 10.3-6 and Figure 10.3-7, respectively. The L-T and T-L data are uniform. The S-T data also appear uniform, but again, the scatter in the data makes it difficult to definitively identify a trend.

From a damage tolerance perspective, in each orientation, the toughness-to-YS ratios are greater than 60%. For structural designs limited by yield stress margins of safety, this translates into critical flaw sizes that should be readily detectable by conventional non-destructive evaluation techniques.

The fracture toughness of Al alloys is sensitive to many metallurgical parameters, including grain size. Generally, larger grain size microstructures exhibit lower fracture toughness due to preferential fracture paths along large grain boundaries which are often populated by precipitates. The fracture toughness specimens used in this study were machined such that the crack extension region was centered about the mid-plane ( $t/2$ ) of the aft bulkhead. The microstructure is less variable over the aft bulkhead at the mid-plane as compared with other through-thickness positions which likely contributed to the relatively uniform fracture toughness values. Additional testing is recommended in the large grain regions to assess the effect on fracture toughness.



# NASA Engineering and Safety Center Technical Assessment Report

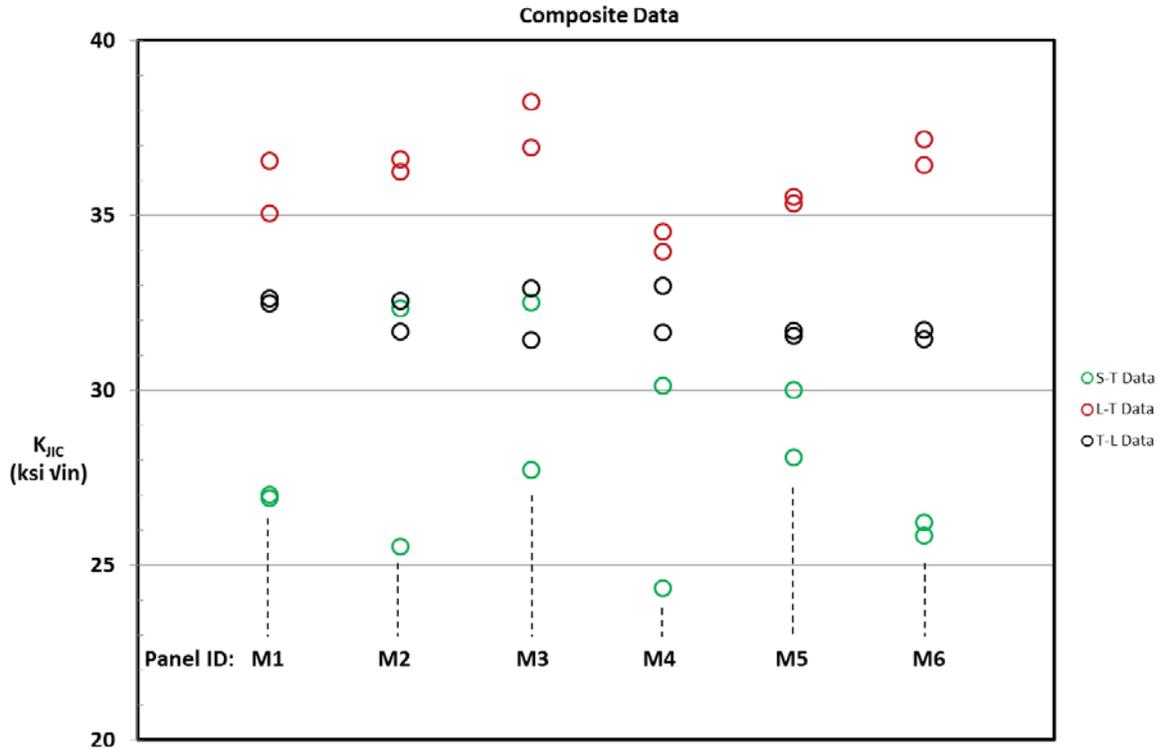
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
133 of 223



*Figure 10.3-3. Fracture Toughness Data as a Function of Coupon Blank Location and Grain Orientation*



# NASA Engineering and Safety Center Technical Assessment Report

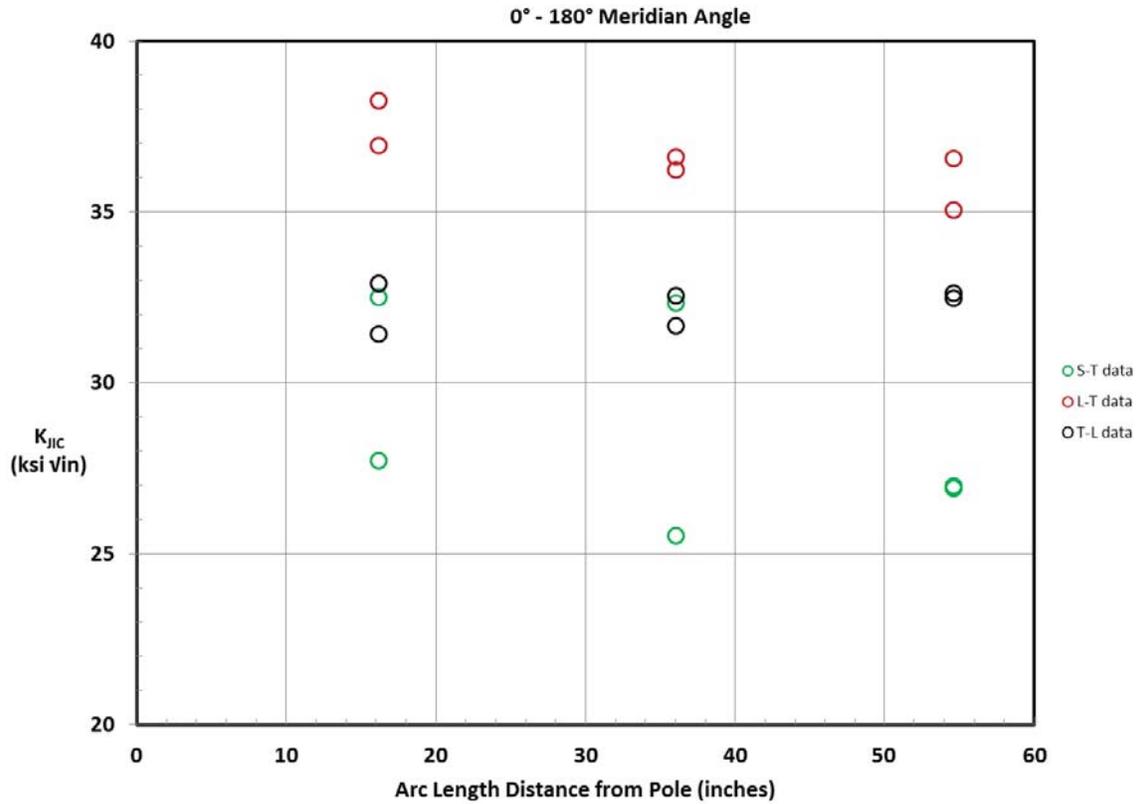
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
134 of 223



**Figure 10.3-4. Fracture Toughness Data as a Function of Arc Length Distance from Pole for the 0° to 180° Meridian**



# NASA Engineering and Safety Center Technical Assessment Report

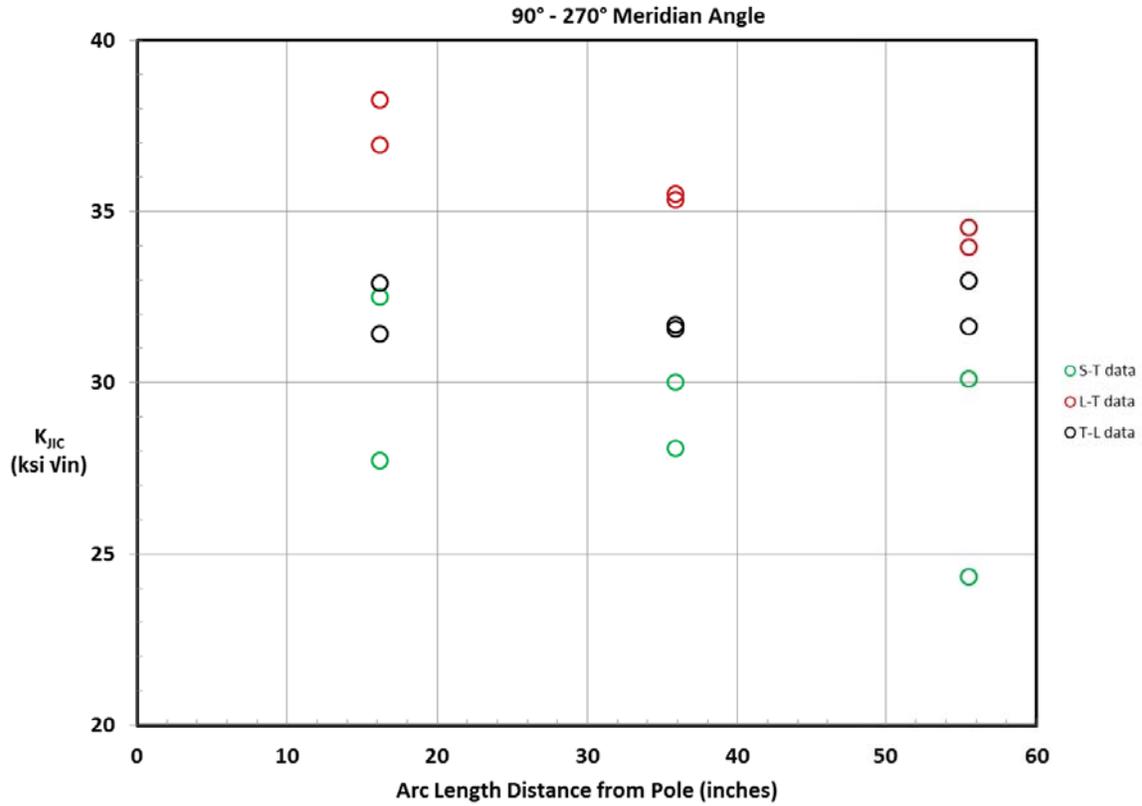
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**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
135 of 223



*Figure 10.3-5. Fracture Toughness Data as a Function of Arc Length Distance from Pole for the 90° to 270° Meridian*



# NASA Engineering and Safety Center Technical Assessment Report

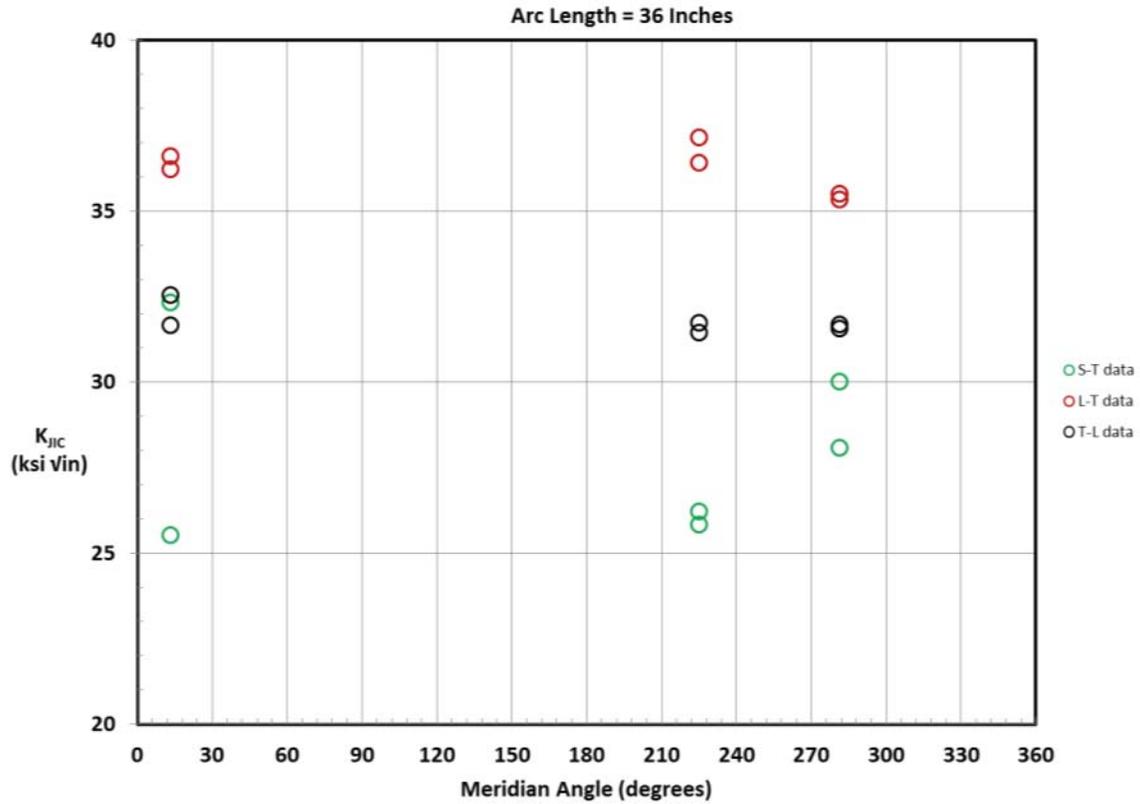
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
136 of 223



*Figure 10.3-6. Fracture Toughness Data as a Function of Meridian Angle for Arc Length Distance of 36 Inches*



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
137 of 223

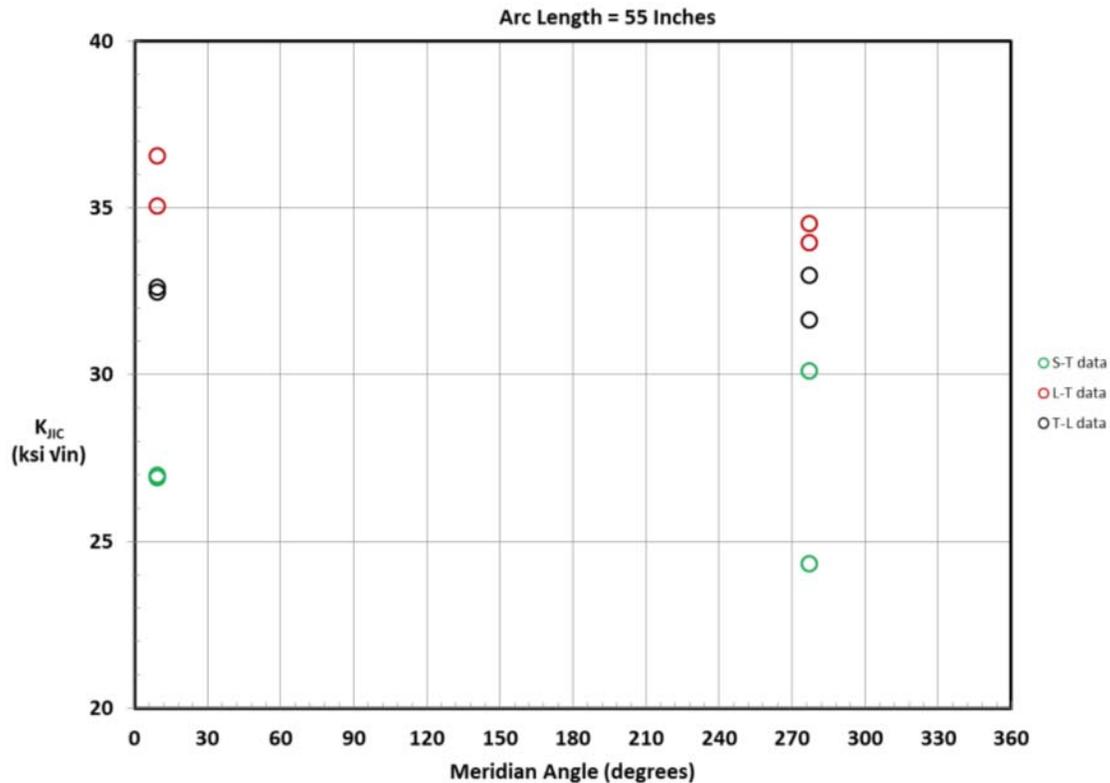


Figure 10.3-7. Fracture Toughness Data as a Function of Meridian Angle for Arc Length Distance of 55 Inches

Another critical element in fracture behavior is the ability of the material to tear in a stable manner. This is generally measured in terms of the fracture toughness (J) versus crack extension ( $\Delta a$ ) for the material. This is also known as the resistance or R-curve. The fracture specimens exhibited rising R-curves for all coupon blank locations and test orientations. This reflects ability of the material to tear in a stable manner after crack initiation. Specimens in the L-T orientation tended to have steeper R-curves than specimens in the S-T or T-L orientation. Steeper R-curves reflect greater ability to resist tearing (i.e., the material is less likely to experience unstable crack propagation) (24). Representative R-curves (J vs  $\Delta a$ ) are shown in Figures 10.3-8 through 10.3-10. From a damage tolerance perspective, the combination of high toughness and rising R-curve behavior are very positive attributes for the material.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

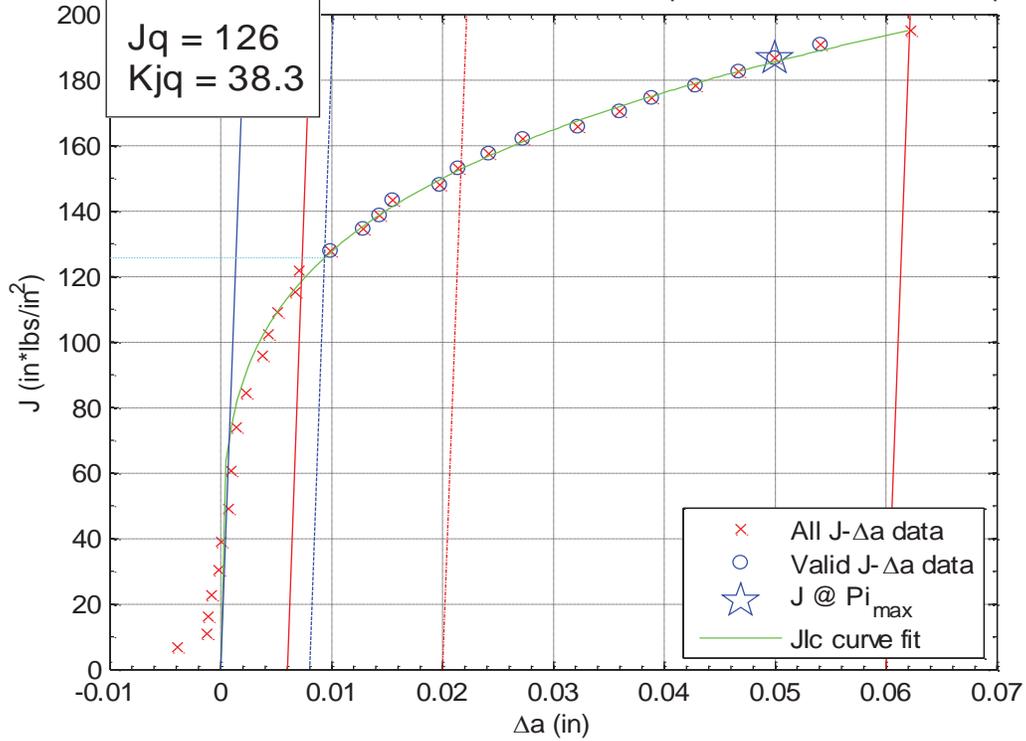
Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
138 of 223

File:CP-406-223 T1 WO:2014-0061 Matl:2219-T62 Specimen:CP-406-223 Temp:72F



**Figure 10.3-8. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the L-T Orientation; Coupon Blank M3, Specimen CP-406-223**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

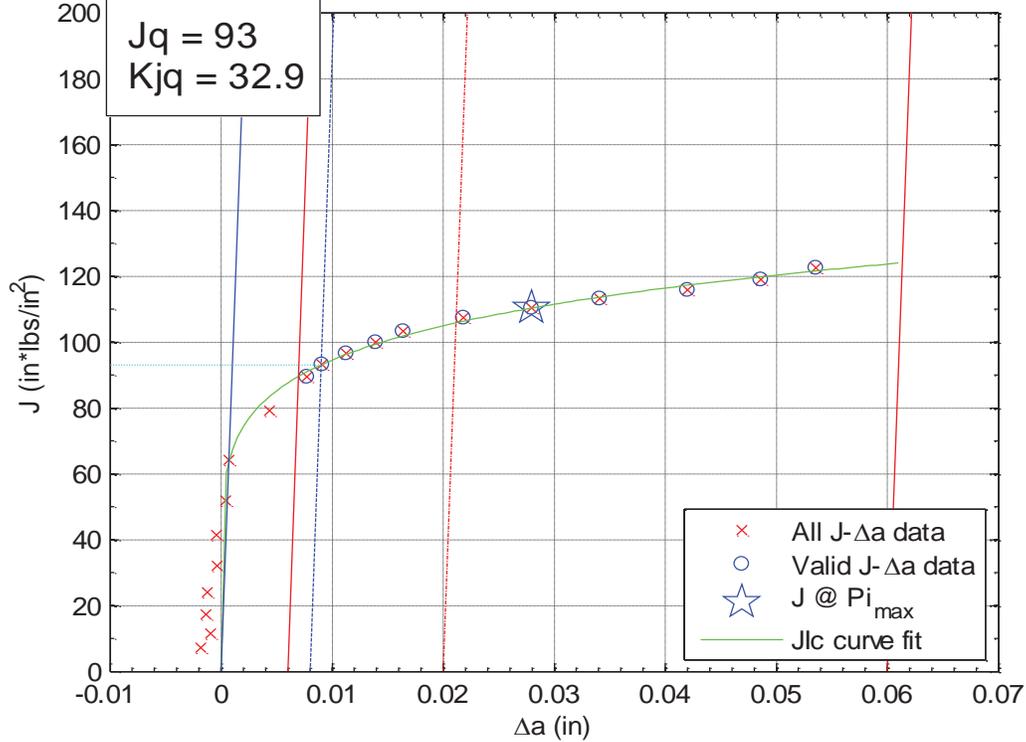
Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
139 of 223

File: CP-406-228 T1 WO:2014-0061 Matl:2219-T62 Specimen:CP-406-228 Temp:72F



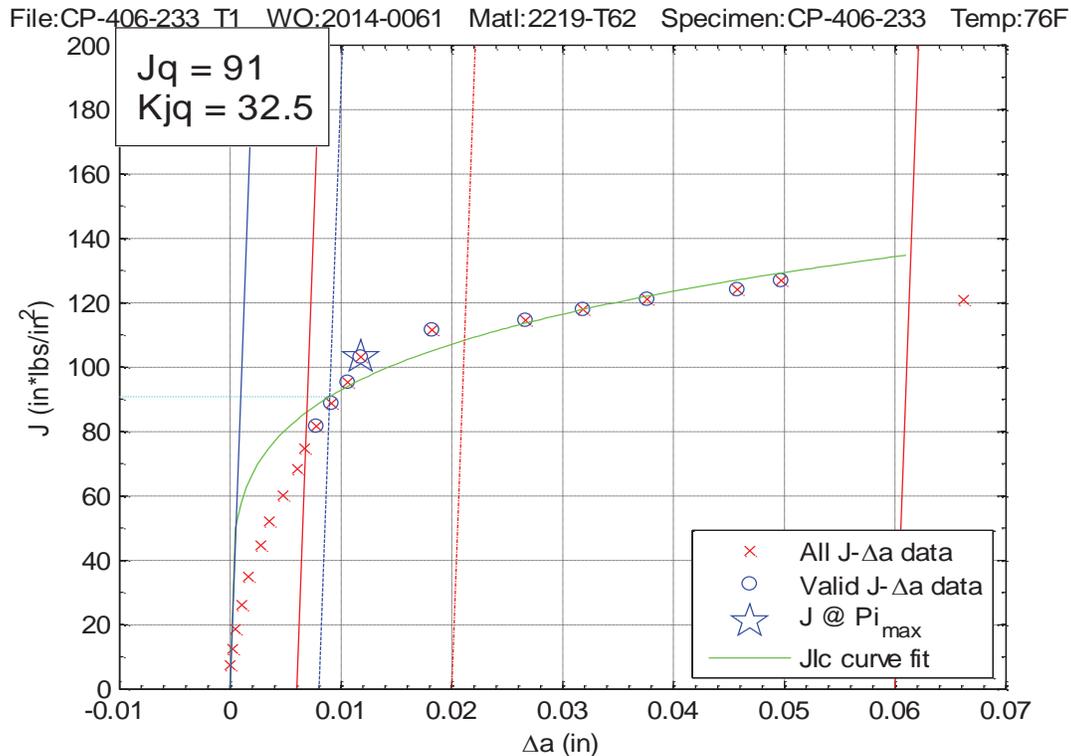
**Figure 10.3-9. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the T-L Orientation; Coupon Blank M3, Specimen CP-406-228**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
140 of 223



**Figure 10.3-10. J-R Curve for Spin Formed Al 2219-T62 Aft Bulkhead Material in the S-T Orientation; Coupon Blank M3, Specimen CP-406-233**

**F-4.** Fracture toughness was uniform with location in the aft bulkhead and indicated excellent damage tolerance capability.

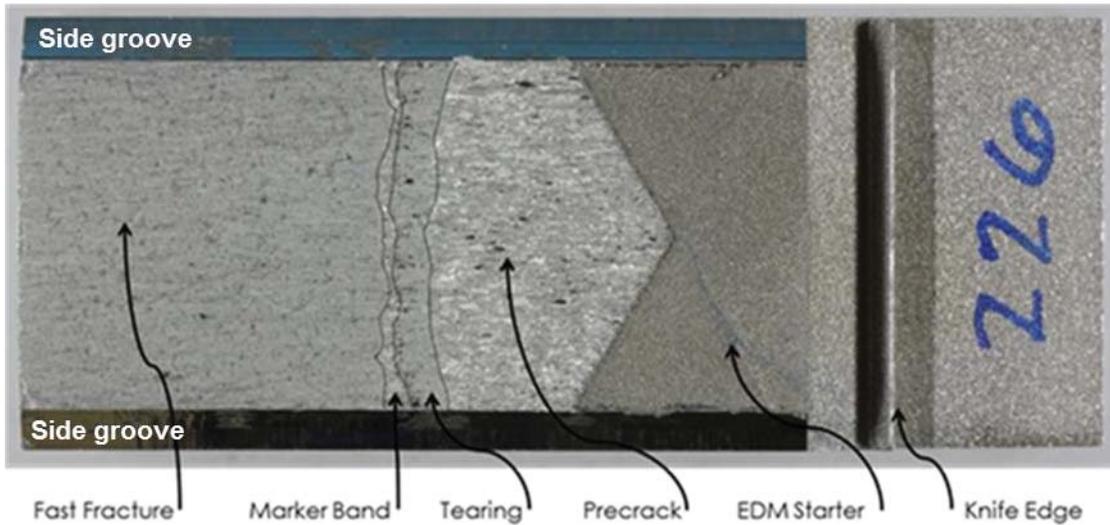
- In-plane (T-L and L-T) toughness values are relatively constant for a given orientation and do not vary significantly across the aft bulkhead acreage.
- Through-thickness (S-T) toughness appears uniform as well, but exhibits significant data scatter for a given bulkhead location.
- Spin formed 2219-T62 aft bulkhead material exhibited rising R-curve for all orientations and locations and toughness-to-YS ratios in excess of 60%.
- High toughness values, high toughness-to-YS ratios, and rising R-curve behavior suggest excellent damage tolerance capability for the spin formed Al 2219-T62 aft bulkhead material.

### 10.3.2 Fractography

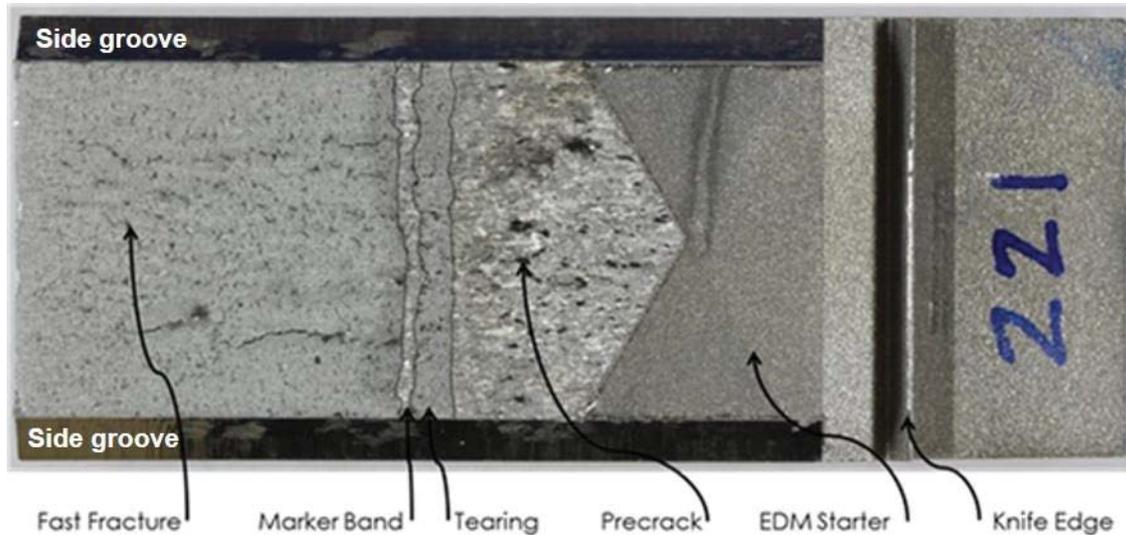
Photomicrographs of typical fracture surfaces from compact tension fracture specimens tested in the T-L, L-T, and S-T orientations are shown in Figure 10.3-11 - Figure 10.3-13. For the T-L and L-T orientations (Figure 10.3-11 and Figure 10.3-12), the tearing region is relatively flat and

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			141 of 223

uniform. Conversely, the tearing region for the S-T specimen (Figure 10.3-13) is more irregular and exhibited more topography than the T-L and L-T regions.

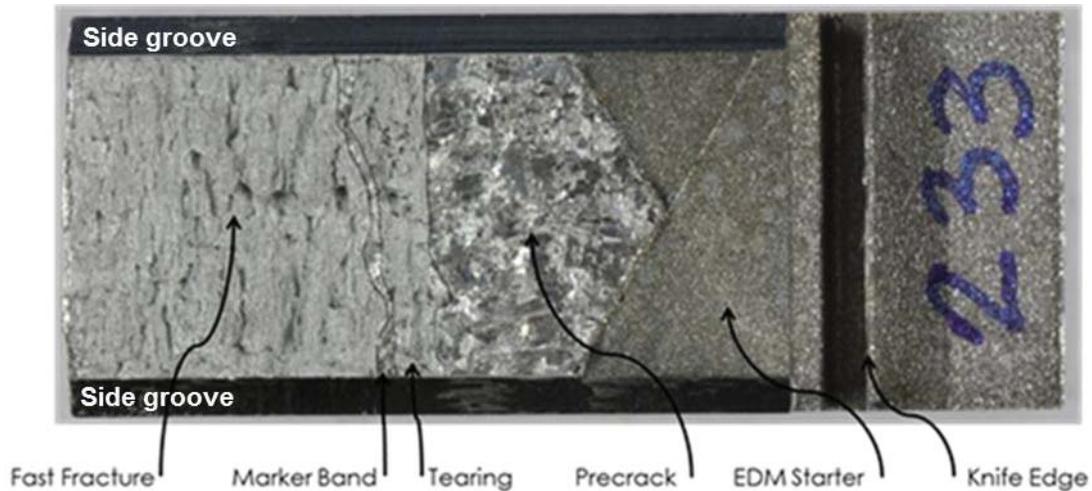


**Figure 10.3-11. Photomicrograph of Fracture Surface of T-L Fracture Specimen from Coupon Blank M2**



**Figure 10.3-12. Photomicrograph of Fracture Surface of L-T Fracture Specimen from Coupon Blank M2**

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			142 of 223



**Figure 10.3-13. Photomicrograph of Fracture Surface of S-T Fracture Specimen from Coupon Blank M2**

### 10.3.3 Comparison with Handbook Data and Other T6 and T8 Products

A comparison of fracture toughness behavior between the spin formed Al 2219-T62 aft bulkhead material and Al 2219-T87 plate material in three grain orientations is shown in Figure 10.3-14 (25). As shown in the plot, on average, the spin formed material exhibits higher toughness values than the plate material for each of the orientations. Limited additional data in the T-L orientation was obtained for Al 2219-T62 plate and Al 2219-T851 plate. The data is shown in Figure 10.3-15 (25). Data for Al 2219-T87 plate is repeated from Figure 10.3-14. The T62 spin formed aft bulkhead material toughness is comparable to the toughness in the T62 and T851 plate material. As noted earlier, the T62 spin formed aft bulkhead material toughness is higher than the toughness in the T87 plate material. For the most part, this behavior can likely be attributed to the general behavior of 2000 series Al alloys that reflect an increase in fracture toughness with a decrease in YS (26). In general, per MMPDS-08 (17), the A-Basis YSs for Al 2219-T87 temper is higher than the T851 temper which is higher than the T62 temper.

The fracture parameter  $K_{JIC}$  was used in this study to evaluate the fracture toughness of the Al 2219-T6 aft bulkhead. To more fully evaluate damage tolerance fracture toughness with pre-existing surface flaws and fatigue crack, growth rate should be determined. Such damage tolerance testing would typically be required before using a material in fracture critical pressure vessel or structural applications. Crack growth rate testing (27) would provide data to support safe-life assessments based on assumed or NDE based initial flaw sizes. Surface crack toughness testing (28) would provide critical stress intensity data required to evaluate part-through crack toughness of the material. Surface crack and crack growth rate data could be used to evaluate leak or burst behavior of the structure. Collectively, this data could be used to assess damage tolerance of hardware as outlined in NASA-STD-5019, “Fracture Control Requirements

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 143 of 223	

for Spaceflight Hardware (29),” and the American Petroleum Institutes’ “Recommended Practice 579 – Fitness-For-Service (30).”

**F-5.** The fracture toughness of the spin formed Al 2219-T62 aft bulkhead material was typical for established 2219-T62 products.

- Fracture toughness values exhibited the typical variation with orientation: L-T orientation > T-L orientation > S-T orientation.
- Fracture toughness was in-family with conventional Al 2219 Al tempers and product forms. Toughness values were comparable to Al 2219-T62 and T851 plate and are greater than for T87 plate, which is consistent with the tensile strength being lower than for T87 plate.

**O-2.** Limited data was available in handbooks or open literature publications for Al 2219-T6 material for comparison with the aft bulkhead properties, consequently it was difficult to assess the aft bulkhead in the context of other commercial Al 2219-T6 products.

- Fracture toughness data was only available in handbooks and open literature publications for Al 2219-T6 and –T8 plate. No fracture toughness data was publicly available for 2219 spin formed products.

**O-3.** Fracture toughness data suggests excellent damage tolerance in the 2219-T6 spin formed material; however, surface crack tension and da/dN testing is necessary to more fully characterize damage tolerance.

**R-2.** Additional testing should be performed on first article and initial serial production aft bulkhead components to generate data to populate the material property database for Al 2219-T6 spin formed products. (**O-2**)

- Fracture testing should generate data to more substantially populate the  $K_{JIC}$  fracture toughness database.

**R-3.** Perform surface crack tension fracture toughness and fatigue crack growth rate (da/dN) testing in order to fully characterize damage tolerance. (**O-3**)



# NASA Engineering and Safety Center Technical Assessment Report

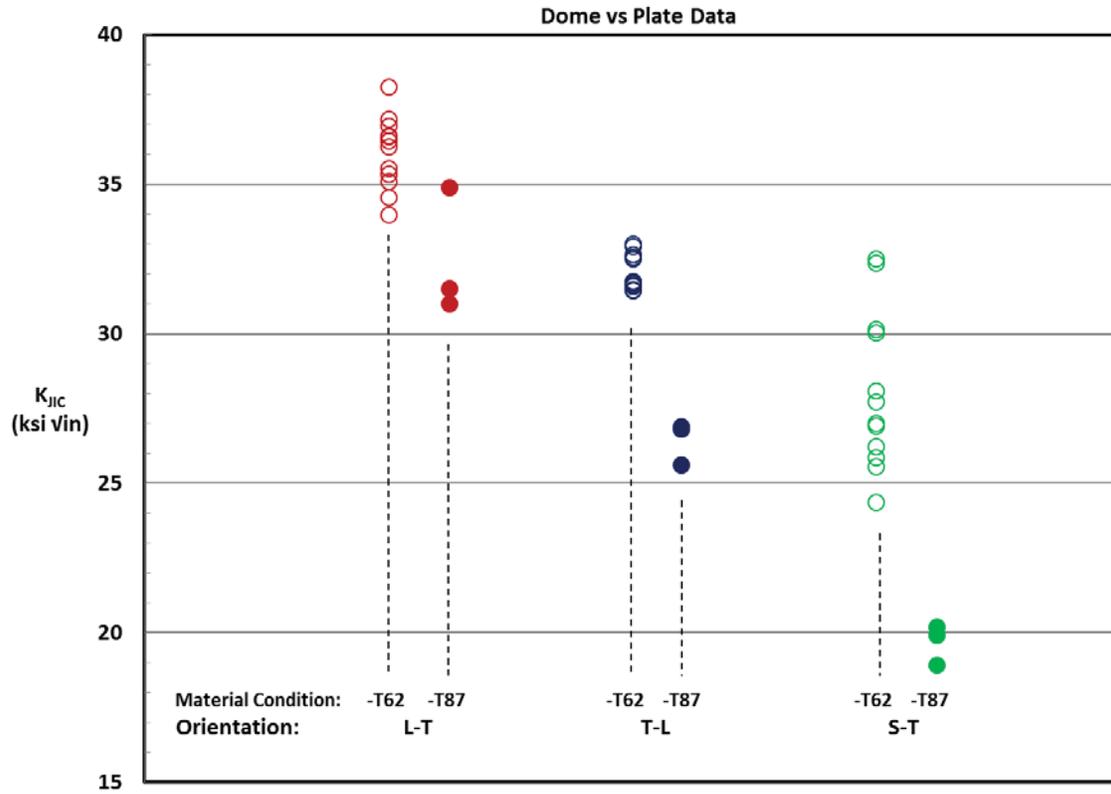
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
144 of 223



**Figure 10.3-14. Fracture Toughness Comparison between Spin Formed Al 2219-T62 Aft Bulkhead Material and Al 2219-T87 Plate (25)**



Title:

Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
145 of 223

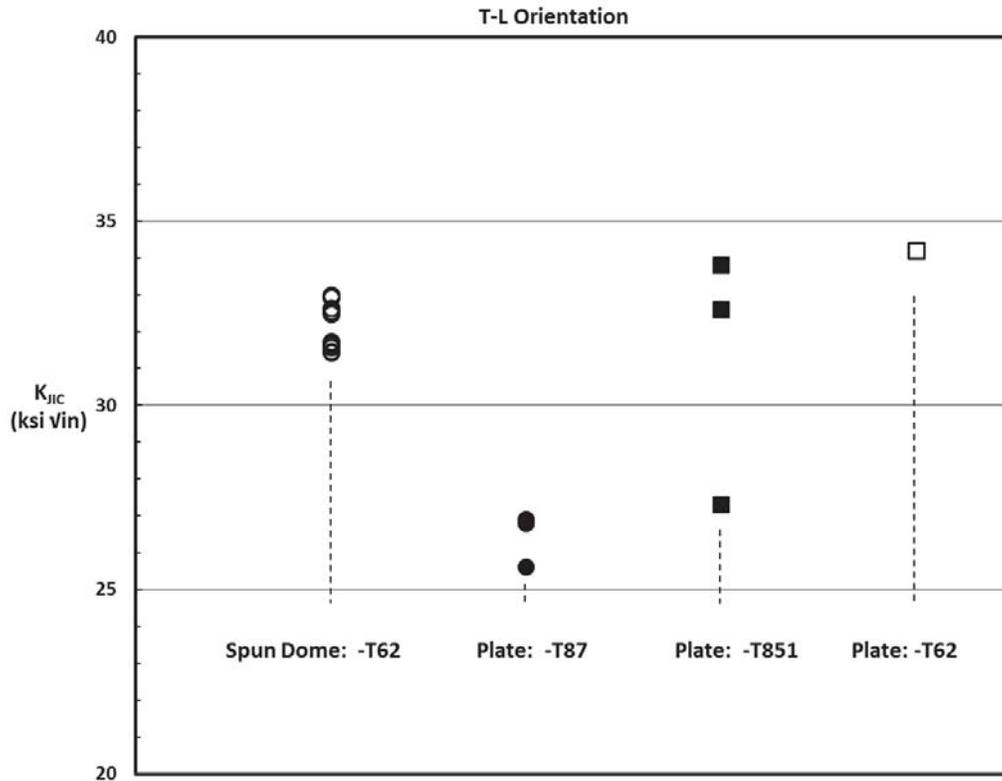


Figure 10.3-15. Fracture Toughness Comparison between Spin Formed Al 2219-T62 Aft Bulkhead Material and other Al 2219 Tempers in the T-L Orientation (25)

## 10.4 SCC Test Results

Figure 10.4-1 shows the aft bulkhead cut plan with the location of coupon blanks from which specimens were excised for SCC testing highlighted in yellow. Table 10.4-1 shows the size and location of these coupon blanks with respect to the original plate rolling direction and distance from the aft bulkhead pole to the coupon blank center point. These coupon blank locations were designed to determine uniformity of SCC properties throughout the aft bulkhead and were evaluated along selected meridian and circumferential lines.

An additional goal of these tests was to determine how these properties compare to wrought plate in the T6 and T8 tempers and to other fabricated product forms in the T62 temper. These results will assist the Orion designers in assessing the attributes of the spin form fabrication process for the aft bulkhead and identify any deficiencies or “show stoppers” associated with this fabrication process.



# NASA Engineering and Safety Center Technical Assessment Report

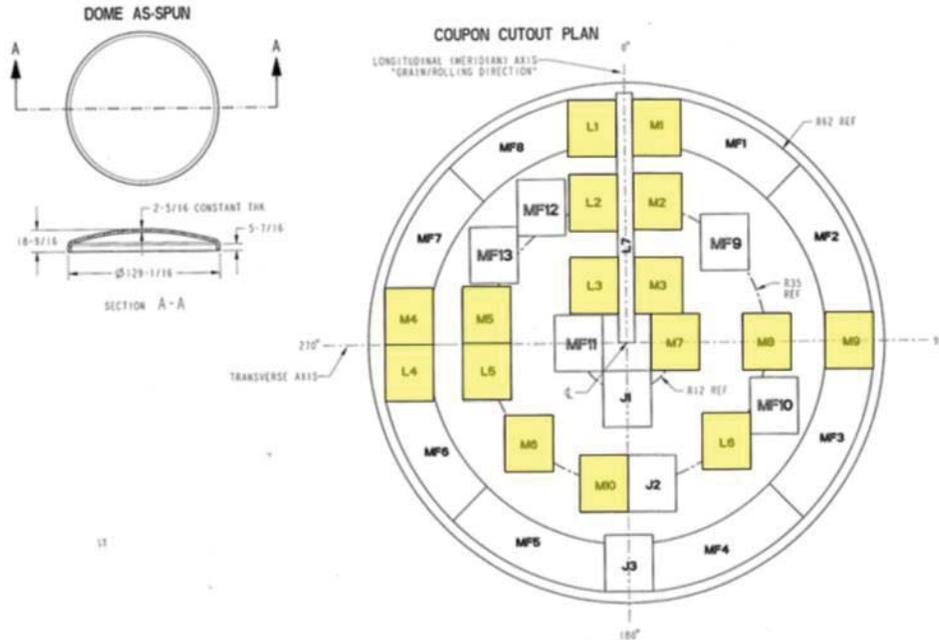
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
146 of 223



**Figure 10.4-1. Aft Bulkhead Cut Plan showing the Location of the SCC Coupon Blanks highlighted in Yellow**

**Table 10.4-1. SCC Coupon Blank Locations and Orientations**

Coupon Blank	Longitudinal Dimension, in.	Transverse Dimension, in.	Meridian Angle, degrees	Center Point Arc Length, in.
M7	14	12	90°	12.00
M8	14	12	90°	35.13
M9	14	12	90°	56.25
M10	14	12	190°	35.63

## 10.4.1 Alternate Immersion Test Results

### 10.4.1.1 30-day Alternate Immersion Exposure Test Results

The tests results for the 30-day alternate immersion exposure SCC testing are shown in Table 10.4-2. The baseline tensile data used to establish the applied stress levels for the SCC tests is shown in Table 10.4-3.

#### LT Specimens:

No SCC failures occurred in the LT specimens after 30-day alternate immersion exposure, even at 90% YS applied stress levels (Table 10.4-2). One of the three replicate specimens from each test group was metallographically examined. Representative photomicrographs at 0 and 90% YS applied stress levels are shown in Figure 10.4-2 through Figure 10.4-5. One 90% YS LT specimen from coupon blank M8 appears to be cracked, as can be observed in specimen #54

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			147 of 223

(Figure 10.4-3). The 50% and 75% YS LT specimens, although not shown in the figures, did not show cracks.

The remaining two replicate specimens from each test group were tensile tested to determine residual tensile strength remaining after exposure; the results are presented in Table 10.4-4 - Table 10.4-7. The percent tensile strength retained (defined in Section 8.5) ranged from 42 to 71% for the LT specimens. The residual strength ratio (also defined in Section 8.5) for each LT specimen exceeded 0.75, which was defined as the minimum value required to be considered a passing test.

### ST Specimens:

Eighteen SCC failures occurred in the reduced section of the ST specimens within 30 days of alternate immersion exposure to 3.5% NaCl (Table 10.4-2). The failures can be divided into groups as follows:

- Nine failures occurred out of 12 specimens tested at 90% YS; three from coupon blank M7, two from M8, one from M9, and three from M10.
- Eight failures out of 12 specimens tested at 75% YS; three specimens from coupon blank M7, three from coupon blank M8, none from coupon blank M9, and two from coupon M10.
- One failure out of 12 specimens tested at 50% YS; one from coupon blank M10.

Metallographic examinations were performed on ST specimens that failed and the control ST specimens that were exposed without stress. Significant pitting corrosion was observed (Figure 10.4-2 - Figure 10.4-5). In addition to pitting, intergranular cracks were also observed on several ST specimens that failed. The cracks were more prominent on the 75 and 90% YS ST specimens, although intergranular cracking was observed on - one 50 % YS specimen. Examples of the most visible cracks are shown in Figure 10.4-2 (specimens #29 (75% YS) and # 34 (90% YS)); Figure 10.4-3 (specimen #73 (75% YS)); and Figure 10.4-5 (specimen #157 (75% YS)). The 50% YS ST specimen that failed in 29 days (Figure 10.4-5, specimen #152) showed intergranular attack, which is associated with stress corrosion on Al alloys. As was the case for all specimens tested, pitting corrosion was also present. This was the only 50% YS specimen that failed within a 30-day period. The 0% YS control ST specimens and the non-failed 50% YS ST specimens were metallographically examined and did not show evidence of SCC. Based on the tabulated data shown in Table 10.4-2 and the metallographic examination, the ST specimens furthest from the pole (coupon blank M9) appear to be less prone to SCC than the other regions

The residual tensile strength values for the LT and ST specimens that survived the 30 day alternate immersion exposure in 3.5% NaCl are shown in Table 10.4-4 through Table 10.4-7. All of the LT specimens passed the residual strength criteria test of  $\geq 0.75$ . The percent tensile strength retained for the ST specimens was significantly less than that of the LT specimens. All of the ST specimens passed except those from coupon blank M10 stressed at 50% YS (see Table 10.4-7). Specimen 153 (50% YS) had a ratio of 0.29 and specimen 154 (50% YS) had a ratio of 0.13.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			148 of 223

It can be observed from the data that the SCC susceptibility of the material varied with the aft bulkhead location from which the coupon blanks were obtained. Based on the 30-day alternate immersion results, the proposed SCC ratings per MSFC-3029 (Tables I, II, or III) for different coupon blank locations and the corresponding rationale are presented in Table 10.4-8. The aft bulkhead rim region represented by coupon blank M9 was found the most resistant to SCC (Table I). Pole and membrane regions represented by coupon blanks M7 and M8, respectively, were found moderately resistant (Table II), and the membrane region represented by coupon blank M10 was the least resistant (Table III).

#### **10.4.1.2 90-day Alternate Immersion Exposure Test Results**

The test results for the 90-day alternate immersion exposure in 3.5% NaCl are presented in Table 10.4-9. The baseline tensile data used to establish the applied stress levels for the SCC tests is shown in Table 10.4-3. Half of the LT specimens and all but one of the ST specimens failed during the 90-day exposure. All the ST specimens stressed to 75% YS failed within the range of 26 to 85 days. Failures also occurred in the LT specimens stressed to 75% YS within the range of 70 to 90 days; two from coupon blank M7, two from coupon blank M8, and three from coupon blank M10. Many ST and LT control specimens (0% YS) failed due to general corrosion within the range of 48 to 90 days. Eleven of them were from the ST direction and five from the LT direction.

Tensile tests were performed on the surviving specimens to determine residual strength; the results are presented in Table 10.4-10. The percent strength retained for the 90-day alternate immersion exposure specimens ranged from 11 to 45%. Most specimens that survived the 90-day SCC exposure test show extremely low load carrying capability.

Metallographic views of representative failed ST and LT specimens are presented in Figure 10.4-6. All failed specimens exhibited severe pitting corrosion with some intergranular cracking.

The severe pitting corrosion and low load carrying capability suggest that the 90-day exposure to 3.5% NaCl is too long and not suitable for the spin formed Al 2219-T62 aft bulkhead material. The 3.5% NaCl alternate immersion exposure should be limited to 30 days. In addition, corrosion protection for this material should be considered when exposed to corrosive environments.

#### **10.4.1.3 Discussion of Alternate Immersion Exposure Test Results**

Two of the ST specimens in the 90-day test matrix exposed at 75% of the YS failed before 30 days; consequently, the two data sets were combined and evaluated as 30-day exposure tests. The combined test results show that twenty SCC failures occurred out of a total of 48 ST specimens tested within 30 days of alternate immersion exposure to 3.5% NaCl. The failures can be divided into groups as follows:

- Nine failures occurred out of 12 specimens tested at 90% YS; three from coupon blank M7, two from M8, one from M9, and three from M10.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			149 of 223

- Ten failures occurred out of 24 specimens tested at 75% YS; four specimens from coupon blank M7, three from coupon blank M8, none from coupon blank M9, and three from coupon M10.
- One failure out of 12 specimens tested at 50% YS; one from coupon blank M10.

Results from the 30-day exposure tests for specimens exposed at 75% YS and lower are used to establish SCC rankings and table ratings so it is this combined data set that is of primary interest. The ST results have raised some concern and prompted much discussion. Failures occurred in all four locations in the aft bulkhead at the highest exposure stress level (90% of YS) and in most locations when exposed at 75% YS. One specimen failed during exposure at 50% YS. Metallography confirmed that this was an SCC failure and was not due to general corrosion. The significance of the 50% YS stress level failure is that (1) the rating will be Table III, and (2) the design allowable stress level will need to be reduced. The resulting table ratings are provided and explained in Table 10.4-7.

**F-6.** The SCC resistance of the spin formed 2219-T6 material varied with location in the aft bulkhead and in some locations exhibited lower resistance than previously established for 2219-T6 material.

- Regions near the pole exhibited moderate resistance to SCC (Table II per MSFC-3029), near the rim a high resistance to SCC (Table I), and one of the areas in the membrane a low resistance to SCC (Table III).
- The LT orientation appeared to be significantly more resistant to SCC than the ST orientation. Residual strength after exposure was significantly higher for LT specimens than ST specimens.
- The 90-day alternate immersion exposure appears to be too long for the spin formed 2219-T62 material since failures can occur by corrosion mechanisms (general and pitting corrosion) different than those for SCC, which can interfere with the SCC evaluation.

## 10.4.2 Salt Spray Test Results

### 10.4.2.1 30-day Salt Spray Exposure Test Results

The test results for the L specimens from coupon blank M10 exposed to 5% salt spray are presented in Table 10.4-11. The baseline tensile data used to establish the applied stress levels for the SCC tests is shown in Table 10.4-3. None of the specimens exposed to salt spray and stressed to 0% and 75% YS failed.

Post exposure tensile testing was performed to determine residual strength. The results are presented in Table 10.4-13. The percent tensile strength retained for the 30-day salt spray exposure specimens ranged from 93 to 98% which is significantly greater than the specimens exposed for 30 days to 3.5% NaCl alternate immersion (see Table 10.4-4 through Table 10.4-7). The superior SCC resistance for the 30-day salt spray testing is likely related to the inherently better SCC resistance in the L orientation.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:		Page #:	
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>		<b>150 of 223</b>	

#### 10.4.2.2 90-day Salt Spray Exposure Test Results

The test results for the L specimens from coupon blank M10 exposed to 5% salt spray are presented in Table 10.4-12. The baseline tensile data used to establish the applied stress levels for the SCC tests is shown in Table 10.4-3. None of the specimens exposed to salt spray and stressed to 0%, 50%, 75%, and 90% YS failed.

Post exposure tensile testing to determine residual strength was performed; the results are presented in Table 10.4-13. The percent tensile strength retained for the 90-day salt spray exposure specimens ranged from 90 to 97%. These specimens retained significantly more of the initial strength than the specimens that survived 90 day 3.5% NaCl alternate immersion exposure (Table 10.4-9). The improved SCC results of the 90-day salt spray testing is likely related to the inherently better SCC resistance in the L orientation.

#### 10.4.3 Comparison with Handbook Data and Other T6 and T8 Products

There is little SCC data available in open literature publications for Al 2219-T6 products in general and none for spin formed components. A review of the available literature for Al 2219-T6 material suggests excellent SCC properties for this material. This is in stark contrast to the SCC ratings determined for the aft bulkhead material in various locations. However, a closer examination of the data and sources reveals that the SCC ratings for Al 2219-T6 were either poorly documented, assumed based on testing of other tempers and exposure conditions, or were based on non-standardized test methodologies. Many of these studies were from the 1960's and were conducted prior to the established ASTM G44 standard practice for alternate immersion testing.

Alcoa Green Letters 176 and 188 indicate excellent resistance to SCC for Al 2219 in the T62, T6, T81, T851, and T87 tempers, but also indicates that non-standard aging treatments may decrease the resistance of Al 2219 to an unsatisfactory level (31), (32). Similar ratings were published in MSFC-STD-3029. ASTM G64 states that 2219-T6 products do not have an assigned rating because the product is not offered commercially (33). However, no specific test data was published in these summary level reports so the sources were reviewed to determine possible explanations for the discrepancy in SCC ratings.

NASA-CR-88110 (1966-10-06, prepared by Alcoa under contract NAS 8-5340) (34) indicates that rolled rod of alloy 2219-T62 demonstrated immunity to SCC in seacoast and industrial atmosphere when stressed to 75% of the actual YS. Table III of that documents shows no failures out of 5 specimens stressed to 75% YS and exposed to alternate immersion for 84 days. It must be mentioned that when that test was performed the alternate immersion test method had not been standardized, and Alcoa used tap water when preparing the test solutions for testing 2219-T62. In a meeting that took place at Alcoa and that was documented in Memo 3-4820-194 (on a letter to Alcoa) it was concluded that tap water was causing Alcoa results to be better than results obtained in other laboratories because pH tends to be higher when tap water is used (35). The MSFC STD 3029 uses deionized water when preparing the 3.5% NaCl solution to comply with ASTM G44. That may explain the lower SCC performance of 2219-T62 material from the aft bulkhead when compared to the Alcoa study.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			151 of 223

NASA-CR-155461 (1964-08-14, prepared by Alcoa under contract NAS 8-5340) indicates on page two that 2219-T62 would be expected to have a high degree of resistance to SCC (36). A Chapter Prepared for ARPA Handbook (1976-00-00, SCC of Al Alloys, Speidel, Ohio State University) indicates a SCC threshold for 2219-T62 plate in the ST direction of 32 ksi (37).

The Al 2219-T62 literature search suggests excellent SCC properties for this material. Highly susceptible Al alloys usually start failing within the first or second week of exposure. In the alternate immersion testing of the aft bulkhead material, the specimens survived several weeks of exposure before failures started to occur. This suggests that even though the Al 2219-T62 aft bulkhead material is not highly resistant to SCC, it is not highly susceptible either, when compared to other tempers, such as T3 or T4. It appears that the tests performed on this material in the 1960's were performed when the technique had not been standardized and rendered a slightly elevated rating. It also seems that the excellent results from seacoast and industrial atmospheres had a significant weighting on the established rating. Based on the paucity of relevant SCC data, the NESC team recommends that Orion conduct further SCC testing of the Al 2219-T62 aft bulkhead material to establish SCC ratings as well as SCC threshold levels.

SCC data on Al-Li 2195-T8 and Al 2219-T87 wrought plate is presented in Table 10.4-14 for comparison. These data were generated at MSFC and most of it was reported in MSFC Memos EH24 (94-107) and EH24 (95-57) (38), (39). Based on the 30-day SCC rating criteria in MSFC-STD-3029, Al-Li 2195-T8 material can be assigned at Table II rating and Al 2219-T87 material a Table I rating. The rationale for these ratings is shown in Table 10.4-15. Although Al-Li 2195-T8 material met Table II requirements of 30 days exposure at 50% YS with no failures, a failure did occur after 31 days, which is not too far from the 29 days to failure for the spin formed Al 2219-T62 aft bulkhead material stressed at 50% YS. It can also be noticed that the Al-Li 2195 specimens stressed to 75% and 90% YS, in general, failed in a shorter time than the Al 2219-T62 specimens.

For Al 2219-T87 (a Table I material) tested in the ST orientation, the 75% YS failures started to occur after 38 days and the 50% YS failures after 41 days. Failures in the ST orientation for the Al 2219-T62 aft bulkhead material began after 26 days for the 75% YS exposures and the one failure at 50% YS occurred after 29 days exposure. This indicates that the spin formed Al 2219-T62 aft bulkhead material has inferior SCC properties compared to Al 2219-T87 material based on the 30-day alternate immersion exposure tests.

For Al-Li 2195-T8 (a Table II material) tested in the ST orientation, the 75% YS failures started to occur after 11 and 27 days depending on heat treatment and the 50% YS failures after 31 days. This indicates that the spin formed Al 2219-T62 material has comparable SCC properties to Al-Li 2195-T8 material based on the 30-day alternate immersion exposure tests.

**O-2.** Limited data was available in handbooks or open literature publications for Al 2219-T6 material for comparison with the aft bulkhead properties, consequently it was difficult to assess the aft bulkhead in the context of other commercial Al 2219-T6 products.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			152 of 223

- The SCC data for the aft bulkhead provides insight about the SCC resistance of spin formed 2219-T62 material, but is insufficient to establish a threshold stress level.

#### 10.4.4 Discussion of Stress Corrosion Results

SCC tests were performed on material from four coupon blank locations in the aft bulkhead corresponding to the rim (M9), membrane (M8), and pole (M7) along the 90° meridian line, and a second membrane region (M10) located along the 180° meridian line. Both LT and ST orientations were tested using alternate immersion and salt fog for either 30 or 90 day exposures. There were no failures during the salt fog tests and the 90-day alternate immersion results are clouded by general corrosion problems.

The primary data of interest are the 30-day alternate immersion exposure since results from this test method and exposure time are typically the basis for handbook and table ratings of SCC resistance. No failures occurred for the LT orientation, even at the highest stress levels, and all specimens had passing post-exposure residual strength levels. The ST results raise some concern. Failures occurred in all four locations in the aft bulkhead at the highest exposure stress level (90% of YS) and in most locations when exposed at 75% YS. One specimen failed during exposure at 50% YS. Metallography confirmed that this was an SCC failure and was not due to general corrosion. The significance of the 50% YS stress level failure is that (1) the rating will be Table III, and (2) the design allowable stress level will need to be reduced. (See Table 10.4-8 for an explanation of the ratings). For comparison, Al 2219-T8 material is rated Table I and Al-Li 2195-T8 is Table II (see Table 10.4-15).

There are some important points to make regarding this data. The aft bulkhead tests followed MSFC test standard MSFC-STD-3029 in which the exposure stress levels are based on the measured strength of the material. Handbook values are based on standards that use MMPDS A-basis allowable strengths for plate to determine applied stress levels. Actual strength is always higher than the allowables due to statistical knockdown; consequently the aft bulkhead specimens were exposed at higher stress levels than handbook data being used for comparison. In addition, since there are no allowables for the ST orientation for 2219-T6 plate, standards that base exposure stress on allowables use the L orientation allowables regardless of the orientation of the SCC specimen. For the aft bulkhead SCC testing, the ST YS was used to determine the exposure stress. The ST YS was 10% greater than the L YS, which further contributed to the high exposure stress levels.

An additional caveat for these test results is the test duration as specified in MSFC-STD-3029. One disadvantage of the accelerated laboratory 3.5% NaCl alternate immersion test is that severe pitting may develop in the test specimens. As per ASTM G47, such pitting in tensile specimens with relatively small cross-sections can markedly reduce the effective cross-sectional area and result in net sectional stresses greater than nominal gross section stress. This end result is that the pitting may interfere with the valid evaluation of the SCC resistance of the material. For this reason, ASTM G47 and G64 recommend a 10 day alternate immersion exposure period for 2xxx series Al alloys when tested in the ST orientation and a 40-day exposure period when tested in

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			153 of 223

the L and LT orientations. These exposure periods are believed to be long enough to detect susceptibility to intergranular SCC yet short enough to avoid excessive pitting that can lead to failure by another mechanism. General pitting, which served as initiation sites for SCC, was noted in the aft bulkhead material following 30-day alternate immersion exposure. The NESC team recommends that further evaluation of the aft bulkhead material be evaluated at shorter exposure times.

For alloys requiring microstructural control to avoid susceptibility to SCC, resistance is obtained by using heat treatments that produce uniform precipitation throughout the microstructure. The susceptibility of the Al 2219 aft bulkhead material to SCC is further exacerbated by the T62 temper which results in a non-uniform distribution of precipitates. Because of the pitting potential of this material and a susceptible heat treat temper to SCC, deployment of this material for the aft bulkhead may require a MUA prior to acceptance for service.

Alternative explanations for the reduced SCC resistance are that (1) the spin forming process has a negative effect, (2) the SCC properties are typical for T62 temper plate, and (3) that the reduced quench rate associated with the glycol/water mixture reduces the SCC resistance.

Metallurgical theory recognizes that variations in thermal treatments, such as solution heat treatment, quenching, and aging treatment can have marked effects on the SCC resistance of 2xxx series Al alloys. Ideally, all alloying elements should be fully dissolved during solution heat treatment, and the quench cooling rate should be rapid enough to keep them in solid solution. The quench medium for the spin formed aft bulkhead was a 15 to 17% polymer solution (see Section 7.8), which is intended to reduce distortion problems associated with water quenched Al alloys. Although this quench operation is permissible per AMS 2770, a sufficiently rapid quench rate might not be obtained because of the inherent cooling rate limitations of the polymer solution. The slower cooling rate affects the precipitation kinetics during subsequent aging and will lead to less uniform precipitation at and/or adjacent to the grain boundaries and hence this could lower the SCC resistance. Supplemental SCC testing, described in Section 11.3, will be performed in an attempt to answer these questions. Results of the supplemental testing will be provided in an addendum to this report.

All SCC test specimens evaluated in this study were machined at the t/2 position through the thickness. The grain size varies less at t/2 with location in the aft bulkhead compared with other through-thickness positions and also represents an intermediate grain size. The SCC properties may be different in locations that have larger grain sizes. Generally, the larger grain size areas may be more prone to SCC than the smaller grain size areas because the larger grain size areas would require less energy for the crack to propagate. In order to determine to what extent the SCC susceptibility is higher in large grain size areas additional testing is recommended. Additional specimens should be obtained from the rim at the OML surface, which has been found to have very large grains in comparison to other areas. Successful completion of additional testing will add more confidence for the use of this material.

While the SCC results provide insight into the material behavior, the data sets generated are very small and caution should be exercised in assigning table ratings. Additionally, the LM Orion

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:		Page #:	
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>		<b>154 of 223</b>	

design team will require definition of a threshold stress level for SCC to bracket service stress limits. There is not sufficient data in this study to define the threshold stress level for SCC. The NESC team recommends that additional SCC testing be performed on the first spin formed aft bulkhead articles fabricated for Orion to define the SCC threshold stress level.

- O-4.** Questions arose regarding SCC test procedures, particularly the basis for exposure stress level and test duration, which may impact direct comparison of the aft bulkhead SCC results with the very limited handbook and open literature data.
- O-5.** The SCC tests performed provided an initial indication of the SCC susceptibility of the spin formed 2219-T62 material; however, environmentally assisted fracture toughness (KEAC) and fatigue ((da/dN)<sub>SCC</sub>) in the S-T orientation in a 3.5% NaCl environment is required to understand the impact of the SCC susceptibility on fracture and fatigue.
- O-6.** The laboratory 30-day alternate immersion accelerated test condition provides adequate screening methodology for SCC; however, longer test durations of 90 days did lead to severe general corrosion and pitting. For determining actual serviceability of the material, other stress corrosion tests should be performed in the intended service environment-
- R-2.** Additional testing should be performed on first article and initial serial production aft bulkhead components to generate data to populate the material property database for Al 2219-T6 spin formed products. **(O-2)**
  - Stress corrosion cracking testing should be continued until sufficient data is generated to establish the SCC threshold stress level.
- R-4.** Exercise caution in using published handbook and table ratings for the SCC resistance of Al 2219-T6. Handbook and open literature publications should be reviewed in order to substantiate that the SCC test procedures and data generated are directly comparable to the MSFC-STD-3029 standard used in the SCC evaluation of the Al 2219-T62 aft bulkhead **(O-4)**
- R-5.** Perform environmentally assisted fracture toughness (KEAC) and fatigue ((da/dN)<sub>SCC</sub>) tests in the S-T orientation in a 3.5% NaCl environment in order to understand the impact of the SCC susceptibility of the material on fracture toughness and fatigue. **(O-5)**
- R-6.** Perform seacoast exposure SCC testing to characterize the corrosion performance of the aft bulkhead in the natural service environment. **(O-6)**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
155 of 223

**Table 10.4-2. 30-day SCC test results for spin formed Al 2219-T62 aft bulkhead material. Test environment: 3.5% NaCl alternate immersion per ASTM G44.**

Coupon Blank	Meridian Angle	Orient.	UTS ksi	YS ksi	Stress Level % YS	Stress Level ksi	Failure Ratio	Days to Failure
M7	90°	LT	54.14	36.64	0	0.00	0/3	No failures
					50	18.32	0/3	No failures
					75	27.48	0/3	No failures
					90	32.98	0/3	No failures
		ST	57.87	43.20	0	0.00	0/3	No failures
					50	21.60	0/3	No failures
					75	32.40	3/3	26, 28, 30
					90	38.88	3/3	26, 26, 28
M8	90°	LT	57.79	38.78	0	0.00	0/3	No failures
					50	19.39	0/3	No failures
					75	29.09	0/3	No failures
					90	34.90	0/3	No failures
		ST	58.69	43.73	0	0.00	0/3	No failures
					50	21.87	0/3	No failures
					75	32.80	3/3	27, 30, 30
					90	39.36	2/3	26, 30
M9	90°	LT	59.58	39.68	0	0.00	0/3	No failures
					50	19.84	0/3	No failures
					75	29.76	0/3	No failures
					90	35.71	0/3	No failures
		ST	59.86	44.33	0	0.00	0/3	No failures
					50	22.17	1/3 <sup>(2)</sup>	30 <sup>(2)</sup>
					75	33.25	0/3	No failures
					90	39.90	1/3	26
M10	190°	LT	55.89	37.87	0	0.00	0/3	No failures
					50	18.94	0/3	No failures
					75	28.40	0/3	No failures
					90	34.08	0/3	No failures
		ST	59.65	44.41	0	0.00	0/3	No failures
					50	22.21	1/3 <sup>(3)</sup>	29
					75	33.31	2/3	26, 30
					90	39.97	3/3	29, 29, 30

<sup>(1)</sup> Exposure started on 3-5-2014 and ended on 4-4-2014.

<sup>(2)</sup> Invalid failure. Failed in the shoulder (out of the gage length).

<sup>(3)</sup> The two specimens that did not break apart during exposure did not pass the residual tensile strength ratio test and can also be considered failures.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>156 of 223</b>

**Table 10.4-3. Baseline tensile properties of spin formed Al 2219-T62 aft bulkhead material. Data is the average of three replicate tests and was used to establish stress levels for the SCC tests.**

Coupon Blank	Meridian Angle	Orient.	UTS, ksi	YS, ksi	e, %	RA, %	E, Msi
M7	90°	LT	54.14	36.64	10.58	17.42	9.97
		ST	57.87	43.20	4.80	6.51	9.89
M8	90°	LT	57.79	38.78	9.79	9.52	10.48
		ST	58.69	43.73	4.57	9.89	9.66
M9	90°	LT	59.58	39.68	8.79	16.82	10.31
		ST	59.86	44.33	4.12	6.54	9.26
M10	190°	LT	55.89	37.87	10.15	17.15	10.14
		ST	59.65	44.41	4.83	6.57	10.12
		L	57.05	38.26	12.74	25.78	10.30



# NASA Engineering and Safety Center Technical Assessment Report

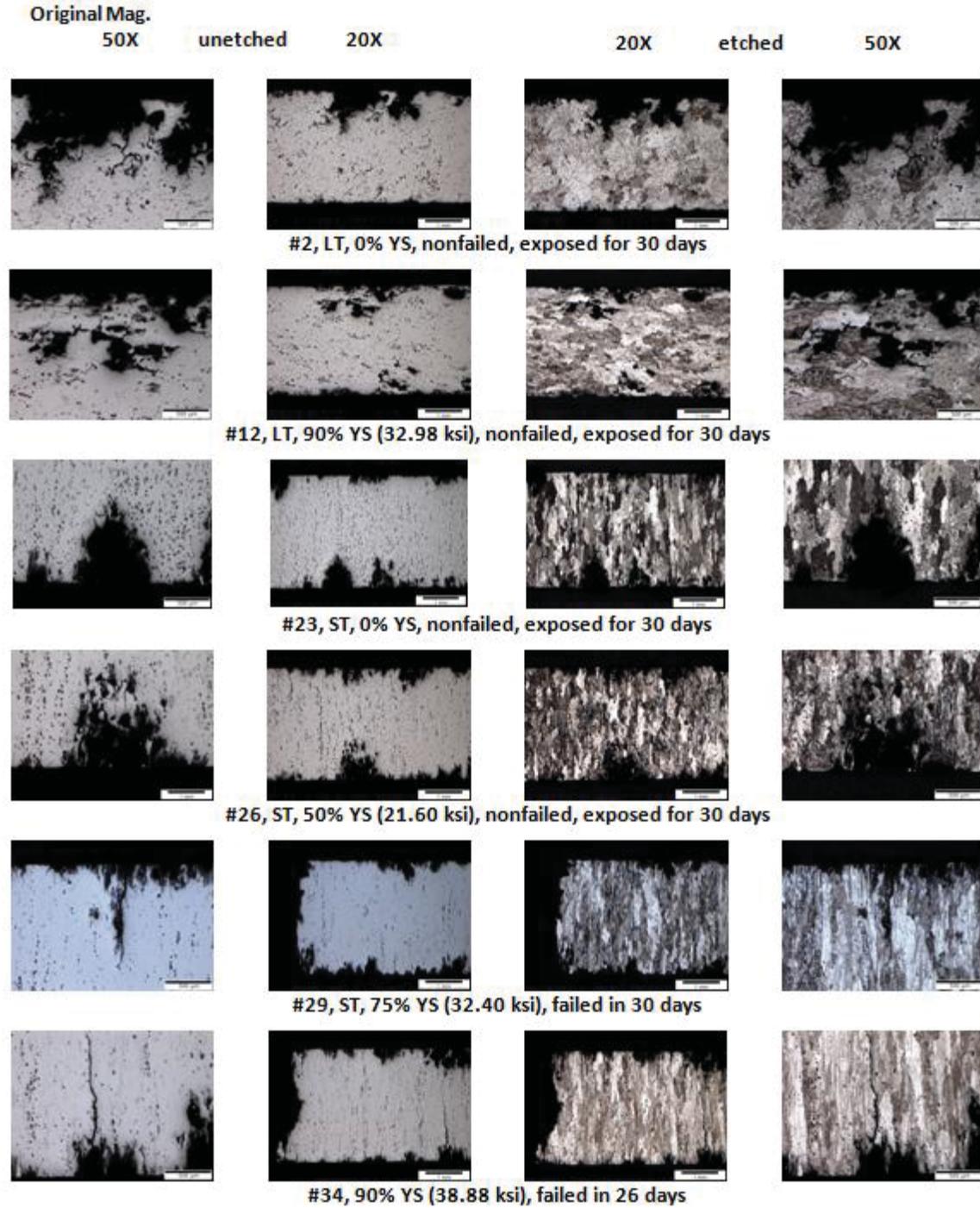
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
157 of 223



**Figure 10.4-2. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M7 following 3.5% NaCl Alternate Immersion Exposure (30-day test)**



# NASA Engineering and Safety Center Technical Assessment Report

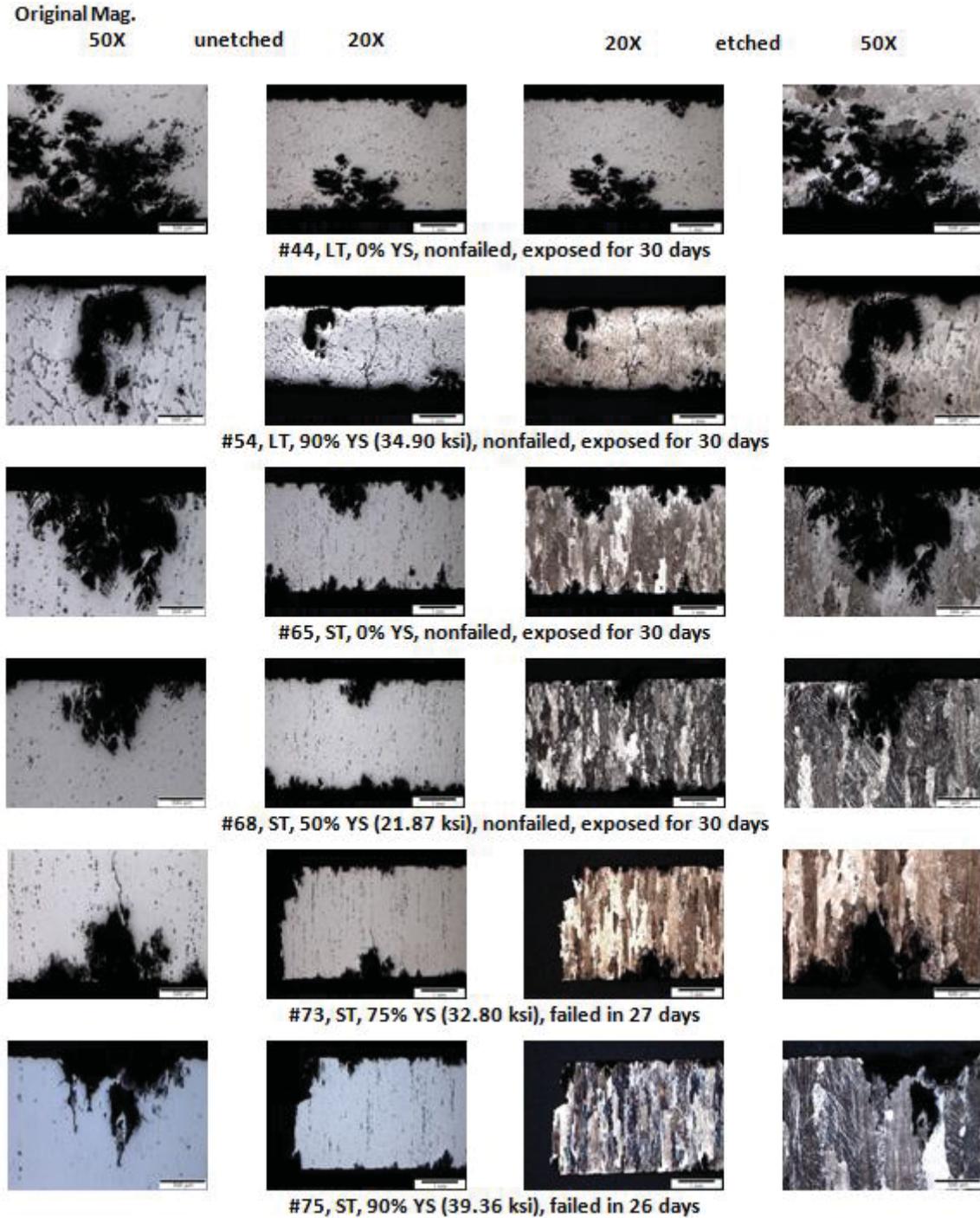
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
158 of 223



**Figure 10.4-3. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M8 following 3.5% NaCl Alternate Immersion Exposure (30-day test)**



# NASA Engineering and Safety Center Technical Assessment Report

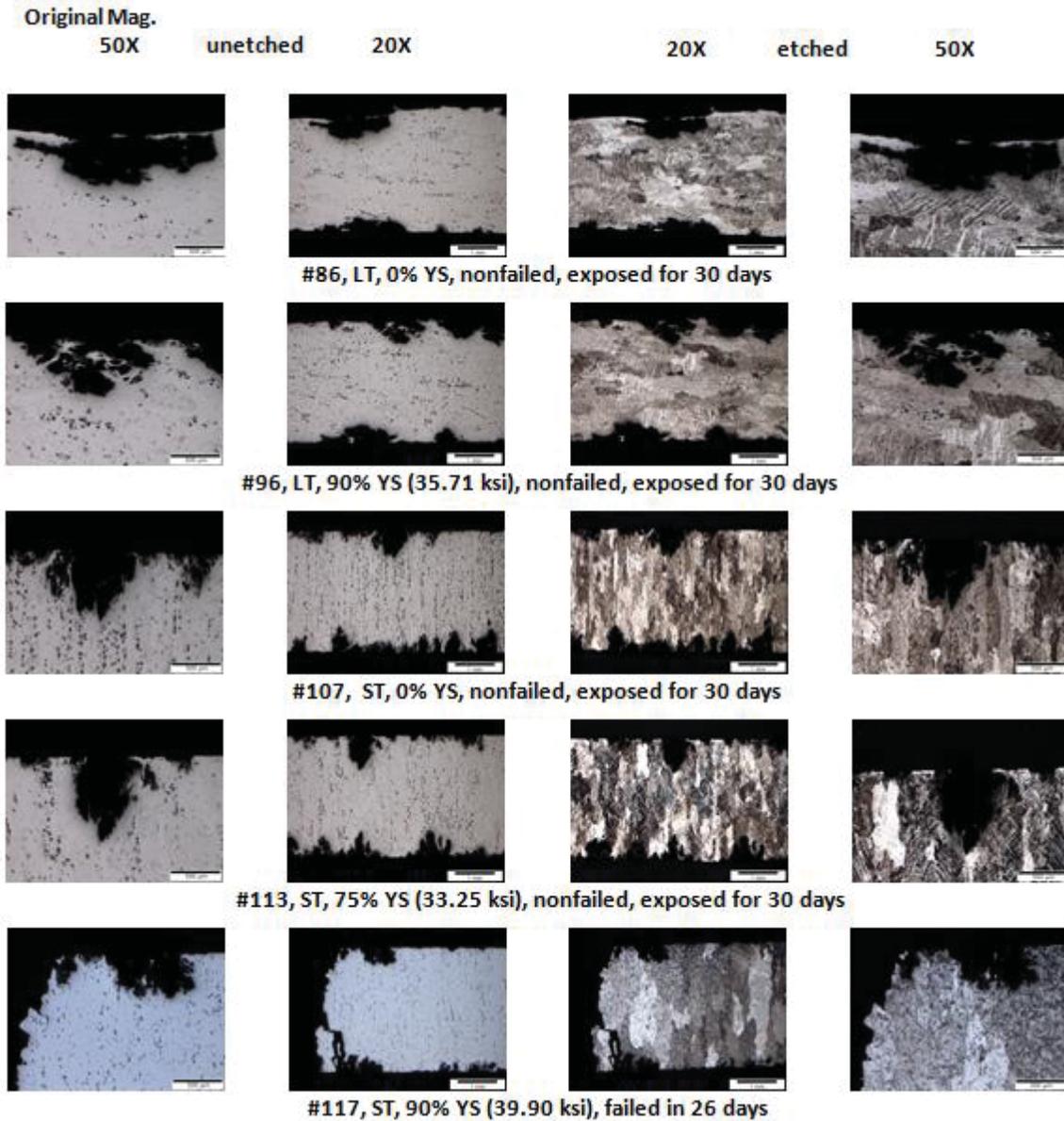
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
159 of 223



**Figure 10.4-4. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M9 following 3.5% NaCl Alternate Immersion Exposure (30-day test)**



# NASA Engineering and Safety Center Technical Assessment Report

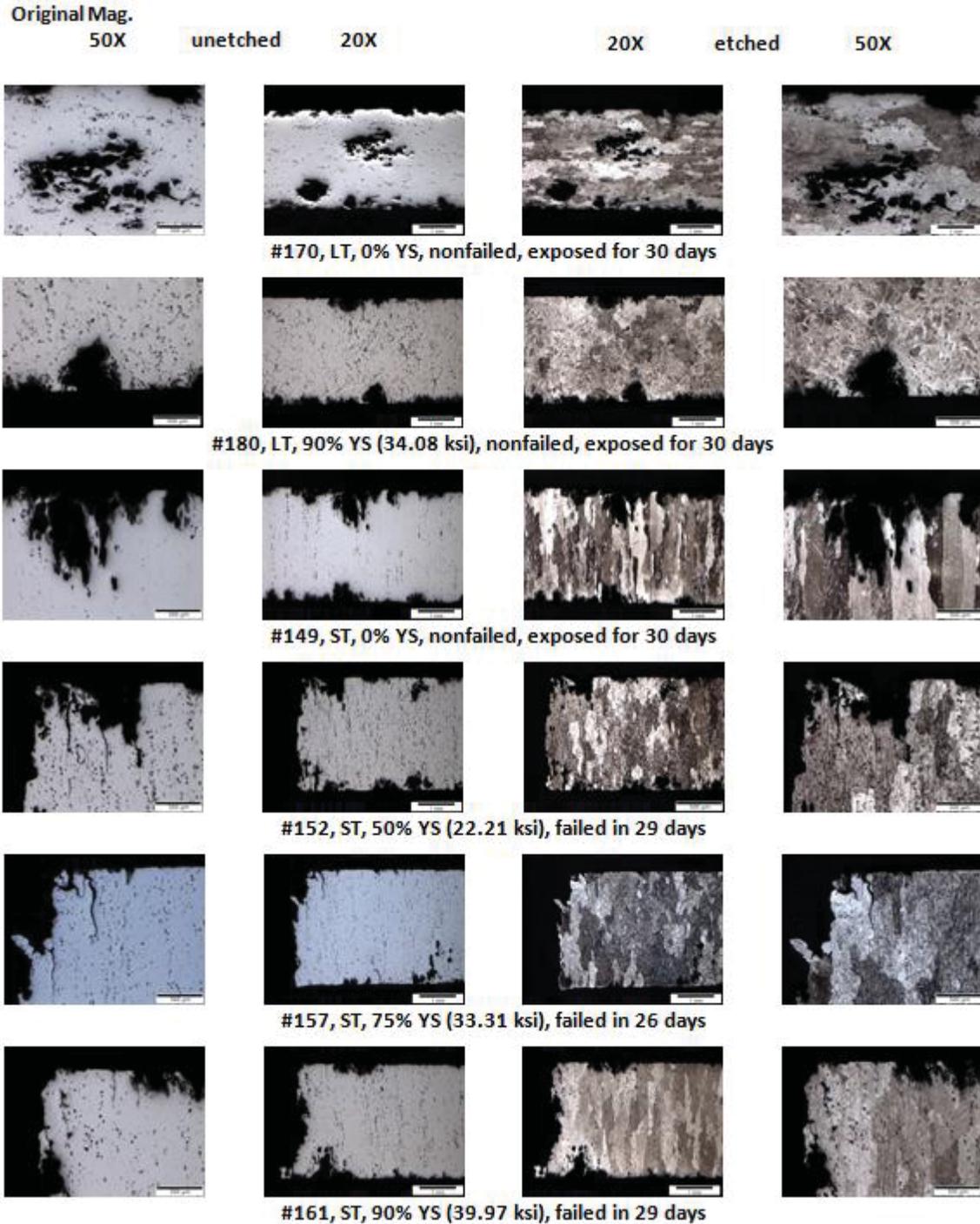
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
160 of 223



**Figure 10.4-5. Photomicrographs of Representative SCC Specimens obtained from Coupon Blank M10 following 3.5% NaCl Alternate Immersion Exposure (30-day test)**

**Table 10.4-4. Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-Day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44**  
 Bulkhead location: coupon blank: M7; meridian angle: 90°; arc length: 12.00 inches

Orient.	Initial UTS, ksi	Specimen Number	Stress Level, % YS	Stress Level, ksi	Residual UTS, ksi	% Strength Retained	Residual <sup>(1)</sup>	
							Strength Ratio UTS <sub>s</sub> /UTS <sub>0</sub>	Pass/Fail <sup>(2)</sup> UTS Ratio Test
LT	54.14	CP-406-3	0	0.00	28.23	52	NA	NA
		CP-406-4	0	0.00	30.98	57	NA	NA
					<b>Avg:</b>	<b>29.61</b>	<b>54.5</b>	
	CP-406-6	50	18.32	22.75	42	0.77	passed	
	CP-406-7	50	18.32	29.65	55	1	passed	
	CP-406-9	75	27.48	31.53	58	1.06	passed	
	CP-406-10	75	27.48	25.62	47	0.87	passed	
	CP-406-13	90	32.98	28.51	53	0.96	passed	
	CP-406-14	90	32.98	25.04	46	0.85	passed	
	ST	57.87	CP-406-24	0	0.00	28.40	49	NA
CP-406-25			0	0.00	18.61	32	NA	NA
				<b>Avg:</b>	<b>23.51</b>	<b>40</b>		
CP-406-27		50	21.60	22.51	39	0.96	passed	
CP-406-28		50	21.60	20.97	36	0.89	passed	

<sup>(1)</sup> UTS<sub>s</sub> = residual strength of stressed and exposed specimen

UTS<sub>0</sub> = averaged residual strength of non-stressed and exposed specimens

<sup>(2)</sup> Passed if ratio ≥ 0.75, failed if ratio < 0.75. The 90% YS data is not used for the ratings, but is presented for information.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
162 of 223

**Table 10.4-5. Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-Day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44**

Bulkhead location: coupon blank: M8; meridian angle: 90°; arc length: 35.13 inches

Orient.	Initial UTS, ksi	Specimen Number	Stress Level, % YS	Stress Level, ksi	Residual UTS, ksi	% Strength Retained	Residual <sup>(1)</sup>	
							Strength Ratio UTS <sub>s</sub> /UTS <sub>0</sub>	Pass/Fail <sup>(2)</sup> UTS Ratio Test
LT	57.79	CP-406-45	0	0.00	33.98	59	NA	NA
		CP-406-46	0	0.00	33.23	58	NA	NA
					Avg:	33.60	58.5	
	CP-406-48	50	19.39	32.54	56	0.97	passed	
	CP-406-49	50	19.39	32.68	57	0.97	passed	
	CP-406-51	75	29.09	37.74	65	1.12	passed	
	CP-406-52	75	29.09	31.38	54	0.93	passed	
	CP-406-55	90	34.90	32.84	57	0.98	passed	
	CP-406-56	90	34.90	37.41	65	1.11	passed	
	ST	58.69	CP-406-66	0	0.00	23.25	40	NA
CP-406-67			0	0.00	19.44	33	NA	
				Avg:	21.35	36.5		
CP-406-69		50	21.87	16.52	28	0.77	passed	
CP-406-70		50	21.87	32.45	55	1.52	passed	
CP-406-77		90	39.36	22.51	38	1.05	passed	

<sup>(1)</sup> UTS<sub>s</sub> = residual strength of stressed and exposed specimen

UTS<sub>0</sub> = averaged residual strength of non-stressed and exposed specimens

<sup>(2)</sup> Passed if ratio ≥ 0.75, failed if ratio < 0.75. The 90% YS data is not used for the ratings, but is presented for information.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
163 of 223

**Table 10.4-6. Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-Day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44**

Bulkhead location: coupon blank: M9; meridian angle: 90°; arc length: 56.25 inches

Orient.	Initial UTS, ksi	Specimen Number	Stress Level, % YS	Stress Level, ksi	Residual UTS, ksi	% Strength Retained	Residual <sup>(1)</sup>	
							Strength Ratio UTS <sub>s</sub> /UTS <sub>0</sub>	Pass/Fail <sup>(2)</sup> UTS Ratio Test
LT	59.58	CP-406-87	0	0.00	39.10	66	NA	NA
		CP-406-88	0	0.00	39.16	66	NA	NA
					<b>Avg:</b>	<b>39.13</b>	<b>66</b>	
	CP-406-90	50	19.84	38.96	65	1	passed	
	CP-406-91	50	19.84	40.50	68	1.04	passed	
	CP-406-93	75	29.76	39.58	66	1.01	passed	
	CP-406-94	75	29.76	42.41	71	1.08	passed	
	CP-406-97	90	35.71	34.08	57	0.87	passed	
	CP-406-98	90	35.71	39.06	66	1	passed	
	ST	59.86	CP-406-108	0	0.00	26.95	45	NA
CP-406-109			0	0.00	19.55	33	NA	NA
				<b>Avg:</b>	<b>23.25</b>	<b>39</b>		
CP-406-110		50	22.17	28.09	47	1.21	passed	
CP-406-112		50	22.17	19.66	33	0.85	passed	
CP-406-114		75	33.25	24.50	41	1.05	passed	
CP-406-115		75	33.25	27.58	46	1.19	passed	
CP-406-118		90	39.90	24.62	41	1.06	passed	

<sup>(1)</sup> UTS<sub>s</sub> = residual strength of stressed and exposed specimen.

UTS<sub>0</sub> = averaged residual strength of non-stressed and exposed specimens.

<sup>(2)</sup> Passed if ratio ≥ 0.75, failed if ratio < 0.75. The 90% YS data is not used for the ratings, but is presented for information.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
164 of 223

**Table 10.4-7. Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 30-Day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44**

Bulkhead location: coupon blank: M10; meridian angle: 190°; arc length: 35.63 inches

Orient.	Initial UTS, ksi	Specimen Number	Stress Level, % YS	Stress Level, ksi	Residual UTS, ksi	% Strength Retained	Residual <sup>(1)</sup>	Pass/Fail <sup>(2)</sup>
							Strength Ratio UTS <sub>s</sub> /UTS <sub>0</sub>	UTS Ratio Test
LT	55.89	CP-406-171	0	0.00	34.10	61	NA	NA
		CP-406-172	0	0.00	29.47	53	NA	NA
				<b>Avg:</b>	<b>31.79</b>	<b>57</b>		
	CP-406-174	50	18.94	31.51	56	0.99	passed	
	CP-406-175	50	18.94	29.44	53	0.93	passed	
	CP-406-177	75	28.40	34.70	62	1.09	passed	
	CP-406-178	75	28.40	32.52	58	1.02	passed	
	CP-406-181	90	34.08	30.03	54	0.94	passed	
	CP-406-182	90	34.08	34.24	61	1.08	passed	
	ST	59.65	CP-406-150	0	0.00	18.88	32	NA
CP-406-151			0	0.00	19.36	32	NA	NA
			<b>Avg:</b>	<b>19.12</b>	<b>32</b>			
CP-406-153		50	22.21	5.51	9	0.29	failed	
CP-406-154		50	22.21	2.56	4	0.13	failed	
CP-406-155		75	33.31	20.32	34	1.06	passed	

(1) UTS<sub>s</sub> = residual strength of stressed and exposed specimen

UTS<sub>0</sub> = averaged residual strength of non-stressed and exposed specimens

(2) Passed if ratio ≥ 0.75, failed if ratio < 0.75. The 90% YS data is not used for the ratings, but is presented for information.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
165 of 223

**Table 10.4-8. Rating of spin formed Al 2219-T62 aft bulkhead material per MSFC-STD-3029.  
Based on a 30-day exposure to 3.5% NaCl alternate immersion per ASTM G44.**

<b>Coupon Blank</b>	<b>Meridian Angle, degrees</b>	<b>Arc Length from CL, in.</b>	<b>Rating</b>	<b>Rationale for Rating</b>
M7	90°	12.00	Table II	4 out of 6 ST specimens failed at 75% YS within 30 days of exposure (26, 26, 28, and 30 days) to 3.5% NaCl alternate immersion. None out of 3 ST specimens failed at 50% YS within 30 days of exposure. Residual tensile strength ratio (UTS <sub>s</sub> /UTS <sub>0</sub> ) of the 50% YS specimens that survived and were tensile tested was greater than 0.75 (see Table 10.4-4).
M8	90°	35.13	Table II	3 out of 6 ST specimens failed at 75% YS within 30 days of exposure (27, 30, and 30 days) to 3.5% NaCl alternate immersion. None out of 3 ST specimens failed at 50% YS within 30 days of exposure. Residual tensile strength ratio (UTS <sub>s</sub> /UTS <sub>0</sub> ) of the 50% YS specimens that survived and were tensile tested was greater than 0.75 (see Table 10.4-5).
M9	90°	56.25	Table I	No ST specimens failed at 75% YS within 30 days of exposure to 3.5% NaCl alternate immersion. Residual tensile strength ratio (UTS <sub>s</sub> /UTS <sub>0</sub> ) of the 75% YS specimens that survived and were tensile tested was greater than 0.75 (see Table 10.4-6).
M10	190°	35.63	Table III	1 out of 6 ST specimen failed at 50% YS within 30 days of exposure (29 days) to 3.5% NaCl alternate immersion. Residual tensile strength ratio (UTS <sub>s</sub> /UTS <sub>0</sub> ) of the two 50% YS specimens that survived and were tensile tested was significantly less than 0.75 (0.29 and 0.13) (see Table 10.4-7).

Table I = A rating\* = Highly resistant to SCC in a sodium chloride environment

Table II = B rating = Moderately resistant to SCC in a sodium chloride environment

Table III = C rating = Low resistance to SCC in a sodium chloride environment

\*A, B, C ratings based on ASTM G64 (33)

**Table 10.4-9. 90-day SCC test results for spin formed Al 2219-T62 aft bulkhead material. Test environment: 3.5% NaCl alternate immersion per ASTM G44.**

Coupon Blank	Meridian Angle	Orient.	UTS, ksi	YS, ksi	Stress Level		Failure Ratio	Days to Failure		
					% YS	ksi				
M7	90°	LT	54.14	36.64	0	0	3/3 <sup>(2)</sup>	48 <sup>(2)</sup> , 90 <sup>(2)(5)</sup> , 90 <sup>(2)(5)</sup>		
					75	27.48	2/3	76, 90 <sup>(5)</sup>		
		ST			57.87	43.2	0	0	3/3 <sup>(2)</sup>	54 <sup>(2)</sup> , 64 <sup>(2)</sup> , 89 <sup>(2)</sup>
							75	32.4	3/3	26, 33, 33
M8	90°	LT	57.79	38.78			0	0	1/3 <sup>(2)(5)</sup>	90 <sup>(2)(5)</sup>
							75	29.09	2/3 <sup>(5)</sup>	90 <sup>(5)</sup> , 90 <sup>(5)</sup>
		ST			58.69	43.73	0	0	3/3 <sup>(2)</sup>	89 <sup>(2)</sup> , 90 <sup>(2)(5)</sup> , 90 <sup>(2)(5)</sup>
							75	32.8	3/3	33, 64, 83 <sup>(3)</sup>
M9	90°	LT	59.58	39.68			0	0	1/3 <sup>(2)(5)</sup>	90 <sup>(2)(5)</sup>
							75	29.76	0/3	No failures
		ST			59.86	44.33	0	0	2/3 <sup>(2)</sup>	58 <sup>(2)(4)</sup> , 90 <sup>(2)(5)</sup>
							75	33.25	3/3	56, 64 <sup>(3)</sup> , 85
M10	190°	LT	55.89	37.87			0	0	0/3	No failures
							75	28.4	3/3	70, 74, 74
		ST			59.65	44.41	0	0	3/3 <sup>(2)</sup>	70 <sup>(2)(4)</sup> , 89 <sup>(2)</sup> , 89 <sup>(2)</sup>
							75	33.31	3/3	26, 54, 70

<sup>(1)</sup>Exposure started on 3-5-2014 and ended on 6-3-2014.

<sup>(2)</sup>Failed due to corrosion since this specimen was not loaded.

<sup>(3)</sup>Failed in the shoulder, out of the reduced section.

<sup>(4)</sup>Failed in 2 places.

<sup>(5)</sup>Failed during disassembly.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
167 of 223

*Table 10.4-10. Residual Tensile Strength Data for Spin Formed Al 2219-T62 Aft Bulkhead Material following a 90-Day Exposure to 3.5% NaCl Alternate Immersion per ASTM G44*

Coupon Blank	Orient.	Initial UTS, ksi	Specimen Number	Stress Level		Residual UTS, ksi	% Strength Retained
				% YS	ksi		
M7	LT	54.14	CP-406-20	75	27.48	15.6	29
M8	LT	57.79	CP-406-57	0	0	17.5	30
M8	LT	57.79	CP-406-58	0	0	13.1	23
M8	LT	57.79	CP-406-62	75	29.09	16.4	28
M9	LT	59.58	CP-406-100	0	0	20.7	35
M9	LT	59.58	CP-406-101	0	0	20.2	34
M9	LT	59.58	CP-406-102	75	29.76	13.7	23
M9	LT	59.58	CP-406-103	75	29.76	18.4	31
M9	LT	59.58	CP-406-104	75	29.76	25.6	43
M9	ST	59.86	CP-406-121	0	0	6.3	11
M10	LT	55.89	CP-406-183	0	0	6.0	11
M10	LT	55.89	CP-406-184	0	0	12.0	21
M10	LT	55.89	CP-406-185	0	0	25.2	45



# NASA Engineering and Safety Center Technical Assessment Report

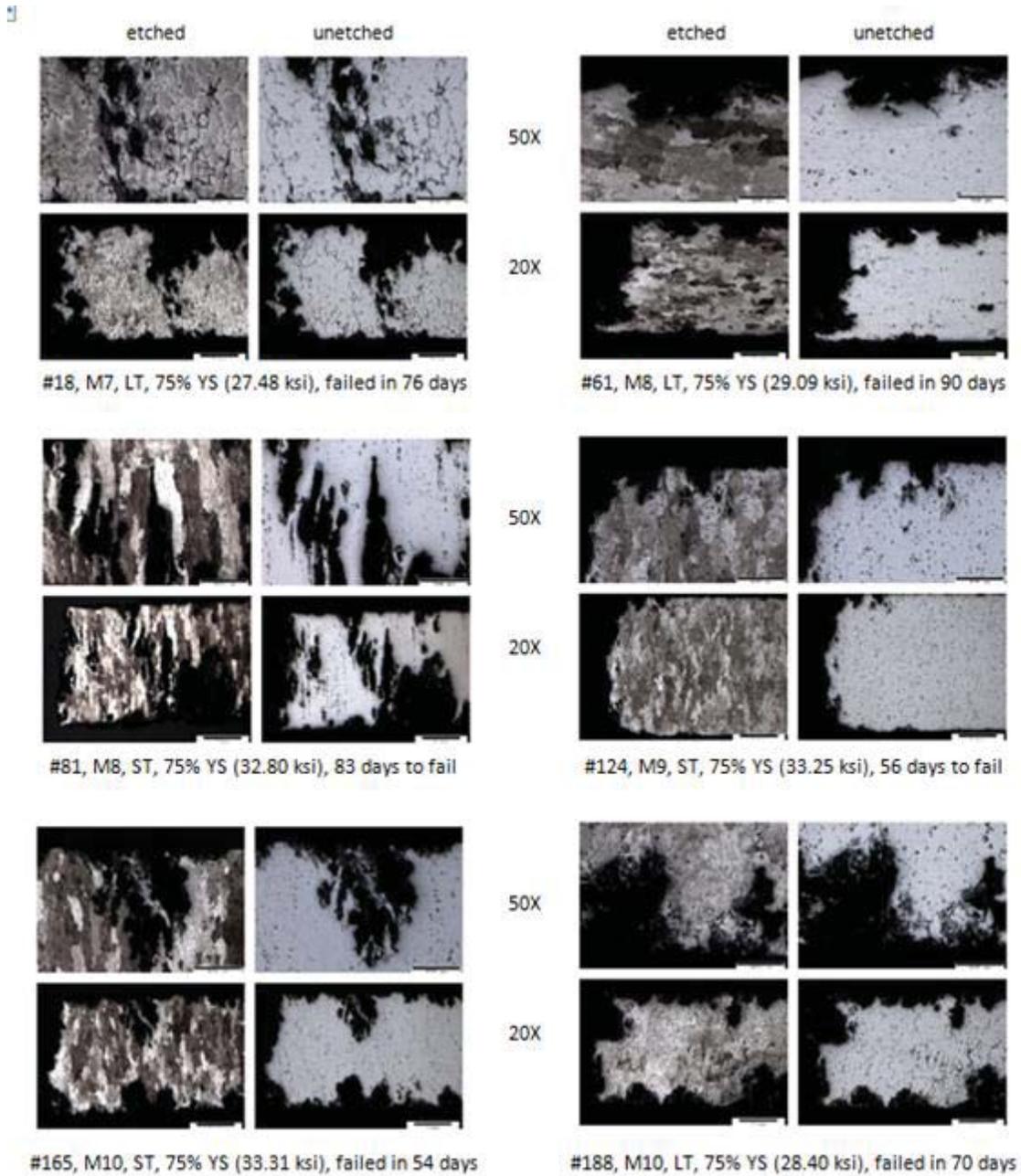
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
168 of 223



**Figure 10.4-6. Photomicrographs of Representative SCC Specimens obtained from Various Coupon Blanks following 3.5% NaCl Alternate Immersion Exposure (90-day test)**



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
169 of 223

**Table 10.4-11. 30-day SCC test results for spin formed Al 2219-T62 aft bulkhead material. Test environment: 5% salt fog per ASTM B117.**

Coupon Blank	Meridian Angle	Orient.	UTS ksi	YS ksi	Stress Level % YS	Stress Level ksi	Failure Ratio	Days to Failure
M10	190°	L	57.05	38.26	0	0	0/3	No failures
					75	28.70	0/3	No failures

(1) Exposure started on 3-5-2014 and ended on 4-4-2014.

**Table 10.4-12. 90-day SCC test results for spin formed Al 2219-T62 aft bulkhead material. Test environment: 5% salt spray per ASTM B117.**

Coupon Blank	Meridian Angle	Orient.	UTS ksi	YS ksi	Stress Level % YS	Stress Level ksi	Failure Ratio	Days to Failure
M10	190°	L	57.05	38.26	0	0	0/3	No failures
					50	19.13	0/3	No failures
					75	28.7	0/3	No failures
					90	34.43	0/3	No failures

(1) Exposure started on 3-5-2014 and ended on 6-3-2014.

**Table 10.4-13. Residual tensile strength data for spin formed Al 2219-T62 aft bulkhead material following exposure to 5% salt spray per ASTM B117.**

Coupon Blank	Orient.	Initial UTS, ksi	Test Duration, Days	Specimen Number	Stress Level		Residual UTS, ksi	% Strength Retained
					% YS	ksi		
M10	L	57.05	30	CP-406-141	0	0	54.3	95
				CP-406-142	0	0	55.8	98
				CP-406-143	0	0	53.2	93
				CP-406-144	75	28.7	53.3	93
				CP-406-145	75	28.7	54.5	96
				CP-406-146	75	28.7	54.6	96
M10	L	57.05	90	CP-406-128	0	0	54.3	95
				CP-406-129	0	0	54.5	96
				CP-406-130	0	0	55.1	97
				CP-406-131	50	19.13	51.5	90
				CP-406-132	50	19.13	51.9	91
				CP-406-133	50	19.13	52.7	92
				CP-406-134	75	28.7	54.7	96
				CP-406-135	75	28.7	53.7	94
				CP-406-136	75	28.7	55.0	96
				CP-406-138	90	34.43	54.5	96
				CP-406-139	90	34.43	51.8	91
				CP-406-140	90	34.43	53.5	94

**Table 10.4-14. SCC Test Data for other 2xxx Series Al Alloys for Comparison (38), (39)**

Alloy	Heat Treatment	Orient.	UTS, ksi	YS, ksi	Test Environ.	Stress Level, % YS	Stress Level, ksi	Failure Ratio	Days to Failure	
2195-T8 (1.7" thick plate)	290°F/16h	ST	86.2	74.1	Alt. Imm.	50	37.1	4/4	31, 40, 41, 69	
						75	55.6	4/4	11, 12, 18, 31	
						90	66.7	4/4	11, 17, 17, 17	
	290°F/20h	ST	89.1	75.7	Alt. Imm.	75	56.8	3/3	27, 30, 31	
						KSC	75	56.8	1/3	423
						Seacoast	90	68.1	3/3	315, 454, 513
High Hum.	75	56.8	0/3	NF in 115 days						
	90	68.1	0/3	NF in 115 days						
2195-T8 (0.32" thick plate)	320°F/20h	LT	86.4	81.1	Alt. Imm.	50	40.6	0/5	NF in 90 days	
						75	60.8	0/5	NF in 90 days	
						90	73	3/5	74, 88, 90	
2219-T87 (4" thick plate)	350°F/18h	ST <sup>1</sup> (midthick.)	60.7	52	Alt. Imm.	50	26	4/5	41, 52, 58, 62	
		ST <sup>1</sup> (edge)	63.5	53.3		75	39	4/5	38, 44, 48, 58, 62	
						90	48	12/12	20, 28, 30, 31, 33, 46, 49, 64, 73, 76, 81, 87	
		LT	66.4	52.4		50	26.2	0/5	NF in 90 days	
						75	39.3	2/5	90, 91	

<sup>(1)</sup>The 2219 ST specimens tested at 50% and 75% YS were obtained from the plate mid-thickness whereas the ST specimens tested at 90% YS were obtained from the plate edge.

**Table 10.4-15. Rating of Al 2195-T8 and Al 2219-T87 per MSFC-STD-3029. Based on a 30-day exposure to 3.5% NaCl alternate immersion per ASTM G44.**

Alloy	Temper	Rating	Rationale for Rating
2195	T8 (Various conditions)	Table II	5 out of 7 ST specimens failed at 75% YS within 30 days of exposure (11, 12, 18, 27, and 30 days) to 3.5% NaCl alternate immersion. None out of 4 ST specimens failed at 50% YS within 30 days of exposure.
2219	T87	Table I	None out of 5 ST specimens failed at 75% YS within 30 days of exposure to 3.5% NaCl alternate immersion.

Table I = A rating = Highly resistant to SCC in a sodium chloride environment

Table II = B rating = Moderately resistant to SCC in a sodium chloride environment

Table III = C rating = Low resistance to SCC in a sodium chloride environment

## 11.0 Supplemental Mechanical Test Program

During the execution of the mechanical property testing and analysis of the aft bulkhead, several issues arose which the NESC team attempted to address to assist the Orion designers team in their first article test program. In addition, several findings were observed that the team wished to further analyze to clarify the results. The NESC team proposed a limited number of supplemental tensile, fracture, and SCC tests, which were accepted by the NESC advisory team. Further details on these supplemental tests are addressed in Sections 11.1 through 11.3. Due to project milestones and schedule, the results from these supplemental tests will not be included in this final report, but will be published as an addendum at a later date.

## 11.1 Tensile

Based on the results of the tensile tests performed on the aft bulkhead and the limited amount of handbook data available for interpretation of the results, a limited quantity of additional tensile tests will be conducted to address key questions. Table 11.1-1 shows the supplemental tensile test matrix and lists questions being addressed.

**Table 11.1-1. Supplemental Tensile Test Matrix**

Material Source	Location / Heat Treatment	Orient.	Through-thickness position	# of Specimens	Question Addressed
Aft Bulkhead	L2	L	t/8	3	1. What are the tensile properties at other through-thickness locations in the aft bulkhead?
			7t/8	3	
		LT	t/8	3	2. What effect does the inhomogeneous microstructure have on the tensile properties of the aft bulkhead?
			7t/8	3	
Typical Plate	SHT + water quench + age, 375°F/36h	L	t/2	3	3. How do the tensile properties of thh aft bulkhead compare to wrought plate?
		LT	t/2	3	4. What effect does a slower quench during heat treat processing have on the tensile properties of the material?
		ST	t/2	3	
Modified Plate	SHT + water/glycol quench + age, 375°F/36h	L	t/2	3	5. Are the high ST tensile properties in the aft bulkhead inherent to the plate lot or are they an artifact of spin form processing?
		LT	t/2	3	
		ST	t/2	3	

Based on microstructural characterization of the aft bulkhead, the post-recrystallization grain morphology varies with meridian distance and through-thickness position, with larger grain sizes associated with likely regions of higher deformation. These grain size differences are biased toward the OML, which is in direct contact with the forming tool. To characterize these effects on the tensile properties, tensile specimens from coupon blank L2 (arc length = 36.0 in; meridian angle 347°) will be tested at both the t/8 (near the IML surface) and 7t/8 (near the OML surface) through-thickness locations for comparison to tensile test results previously acquired at the t/2 location only. These through-thickness positions showed the most variation in grain size. In addition, the membrane region of the finished machined aft bulkhead will likely be located near the OML surface so tensile properties from this region will be of interest to the Orion designers.

Additional testing was designed to address the heat treat practice used in the processing of the aft bulkhead as described in Section 7.8. The solution heat treat and quench operation used by Spincraft consisted of a quench in a water/glycol mixture which results in a slower overall cooling rate to reduce part distortion and residual stress in the final product. Although this

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			172 of 223

quench operation is permissible per AMS 2770, the slower cooling rate affects the precipitation kinetics during subsequent aging and may impact material properties (40).

Remnant –F temper plate machining drops from the aft bulkhead forming blank were heat treated to the –T62 temper as per AMS 2770. Two heat treat conditions were evaluated: typical plate which was quenched in water following solution heat treatment (SHT) and modified plate which was quenched in a water/glycol mixture similar to that used by Spincraft. Tensile tests will be conducted on both heat treated plates to determine if the slower quench rate has any impact on the tensile properties.

The tensile tests of the aft bulkhead revealed that the ST tensile properties were substantially higher than the L and LT orientations (by ~ 4-6 ksi) depending on the aft bulkhead location. The NESC team was not able to find any comparable data for wrought plate or other product forms in the –T62 temper for the ST orientation. A search of the literature for other 2xxx series Al alloys did show that the ST tensile properties are typically lower than the L and LT orientations. Additional tensile tests will be conducted in the ST orientation for both heat treated plate conditions and compared to the aft bulkhead tensile test results to determine if the high ST tensile properties are a result of the spin forming processing or are they inherent to the starting material condition and subsequent processing. The ST YS is additionally of interest because this data was used to define the exposure stress levels for the SCC testing and may have resulted in the specimens being exposed at a higher stress level than comparable handbook data.

## 11.2 Fracture Toughness

Due to the lack of available fracture data in the literature, and in response to the questions regarding plate processing, supplemental fracture toughness tests shown in Table 11.2-1 will be performed on the typical and modified plates. Specific questions being addressed by this supplemental fracture toughness testing include whether the spin form processing compromises the fracture toughness of the material and whether the slower quench used during heat treatment of the aft bulkhead has any effect on the fracture toughness compared to the normal water quench rate.

**Table 11.2-1. Supplemental Fracture Toughness Test Matrix**

Material Source	Location/Heat Treatment	Orient.	Through-thickness position	# of Specimens	Question Addressed
Typical Plate	SHT + water quench + age, 375°F/36h	L-T	t/2	2	1. How does the fracture toughness properties of the aft bulkhead compare to wrought plate?  2. What is the impact of a slower quench rate during heat treat processing have on the fracture toughness of the material?
		T-L	t/2	2	
		S-T	t/2	2	
Modified Plate	SHT + water/glycol quench + age, 375°F/36h	L-T	t/2	2	
		T-L	t/2	2	
		S-T	t/2	2	

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			173 of 223

### 11.3 Stress Corrosion

When evaluating the SCC test results and making comparisons with handbook or published data in an attempt to interpret the SCC results, several questions and issues arose. The primary question was whether the failure that occurred in the ST orientation at the exposure stress of 50% YS for coupon blank M10 was an outlier?

A complication that impeded interpreting the results is that there is very little SCC data available for Al 2219-T6 products. In addition, several questions arose regarding the available data for Al 2219-T8 products, both in terms of SCC test practices and the available data to substantiate published ratings. Specifically, what the appropriate basis for the applied stress level should be. There are a number of applicable standards for SCC testing that use different applied stress levels, exposure periods, and criterion ratings. Most are based on MMPDS allowable YS, but the MSFC SCC test standard, MSFC-STD-3029, Revision A, uses typical YS for the product being tested. The ST YS of the aft bulkhead is higher than typical values which may have resulted in a more severe test than the handbook data being used for comparison.

All of the SCC testing procedures used in the evaluation of the aft bulkhead and SCC resistance table ratings were based on MSFC-STD-3029, Revision A, which is more conservative than ratings listed in ASTM G64 (33). The applied stress levels for these tests were based on the actual material properties, whereas the handbook data is based on the MMPDS design allowable material properties, which are typically lower than actuals or typicals due to the statistical analysis. Since the susceptibility of metallic materials to stress corrosion tends to increase with the applied stress, the higher reported ST properties in the aft bulkhead result in a more aggressive test conditions compared to the reference data in the literature. To address this issue, additional SCC tests will be conducted on coupon blank M10 using applied stress levels based on MMPDS A-basis design allowables for Al 2219-T62 plate.

Additional general questions arose regarding how the SCC ratings in published literature were established. What type of SCC data will Orion use to base their design? What is the threshold stress level for SCC for the aft bulkhead? Due to limited funds and schedule, not all of these questions can be addressed in the scope of this supplemental SCC test program.

Table 11.3-1 lists the SCC test matrix, test priorities, and the questions being addressed. These supplemental SCC tests will consist of 30-day alternate immersion in a 3.5% NaCl environment and will only evaluate the ST orientation since this is the most susceptible grain orientation to SCC and the orientation of the failures in question. The goal of the supplemental SCC test matrix is to ensure confidence in the data that has been generated, and characterize the aft bulkhead component as best as possible.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
174 of 223

*Table 11.3-1. Supplemental SCC Test Matrix*

Material Source	Location/Heat Treatment	Applied Stress Level, % YS	Applied Stress Level, ksi	Orient.	# of Specimens	# of Specimens per Group	Question Addressed	Priority
Aft Bulkhead	M10	50 based on M10 avg. ST YS	22.2	ST	3	6	Is failure at 50% exposure stress repeatable? Was this data point an outlier or it is representative of this aft bulkhead location?	1
		75 based on M10 avg. ST YS	33.3	ST	3			
Aft Bulkhead	M10	50 based on MMPDS LT YS	18.0	ST	3	6	Does material pass at exposure stress levels based on MMPDS design properties rather than actual material yield strength?	1
		75 based on MMPDS LT YS	27.0	ST	3			
Aft Bulkhead	J1	0	0.0	ST	3	9	What is the SCC behavior in other coupon blank locations along a different meridian line?  <b>Note:</b> These specimens have already been machined and installed in stressing frames.	2
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			
Aft Bulkhead	J2	0	0.0	ST	3	9	What is the SCC behavior in other coupon blank locations along a different meridian line?  <b>Note:</b> These specimens have already been machined and installed in stressing frames.	2
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			
Aft Bulkhead	J3	0	0.0	ST	3	9	What is the SCC behavior in other coupon blank locations along a different meridian line?  <b>Note:</b> These specimens have already been machined and installed in stressing frames.	2
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			
Typical Plate	SHT + water quench + age, 375F/36h	0	0.0	ST	3	9	Does spin forming alter the SCC resistance of plate?	3
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			
Modified Plate	SHT + water/glycol quench + age, 375F/36h	0	0.0	ST	3	9	Does the quench rate affect SCC resistance of plate?	3
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			
CPST Spin Formed Dome	T62	0	0.0	ST	3	9	How does the aft bulkhead compare with other spin formed domes?	3
		50 based on MMPDS LT YS	18.0	ST	3			
		75 based on MMPDS LT YS	27.0	ST	3			

The first priority of these supplemental SCC tests was to repeat the tests on coupon blank M10 to determine whether the one failure in the ST orientation that occurred at 50% YS applied stress level was an anomaly. The concern was the viability of the limited data set and its potential impact on the SCC rating. Typically, a larger number of replicate tests are conducted to establish a statistical basis for SCC resistance due to inherent variability in corrosion and stress corrosion testing. The first priority tests will repeat the tests for material from coupon blank M10 with the applied stress levels based on the actual test data for the coupon blank to see if the results are repeatable. Additional tests from the same coupon blank will be conducted at applied stress levels based on MMPDS design values to determine whether or not the material would pass exposure at lower stress levels.

The second priority tests are in response to input from the LM Orion Program to better understand the SCC resistance throughout the aft bulkhead. The SCC specimens from coupon blank J1, J2, and J3 designated for seacoast exposure SCC testing were re-directed to alternate immersion SCC testing in order to examine more locations in the aft bulkhead. Seacoast exposure SCC testing was proposed in the original test program because of concerns based on testing in the past where the alternate immersion test results become obscured because of general corrosion in the form of pitting and concerns on whether the SCC test results were valid. Seacoast exposure SCC testing, which is performed in a natural outdoor environment and requires longer test durations than the standard accelerated corrosion tests performed in a laboratory, is used as a complementary test to alternate immersion. Based on the preliminary alternate immersion SCC test results, the NESC team decided that there was no longer a need to

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			175 of 223

conduct the seacoast exposure SCC testing. These seacoast exposure SCC specimens had already been machined and loaded in the stressing frames; the only change required was to change the applied stress levels and install them in the alternate immersion test apparatus. For these tests, the applied stress level will be based upon MMPDS A-basis design properties. These specimens offered a ready opportunity to generate the additional data while staying within the prescribed budget and schedule.

The third priority tests are in response to the lack of available SCC data for Al 2219-T6 products. The tests also address whether the lower SCC resistance of the aft bulkhead is inherent in this plate lot or due to the spin forming process. Tests will be performed on plate processed to the T62 temper using the typical and modified heat treat procedures to evaluate the effect of spin forming. Remnant spin formed Al 2219-T62 dome material from the CPST Program (21) will provide data for a comparable product form. For these tests, the applied stress level will be based upon MMPDS A-basis design properties.

## 12.0 Findings, Observations, and NESC Recommendations

The following findings, observations, and recommendations are based on the results of a study for which the main objective was to determine whether there are technical obstacles relative to the spin forming a single piece APVHB.

The Phase II M&P studies did not identify any potential insurmountable technical issues that would preclude spin forming the APVBH. The potential benefits of spin forming an Al 2219 APVBH include reduced weight and production costs, which are associated with eliminating welds and weld lands, and improved performance and design margins.

### 12.1 Findings

The following findings were identified:

- F-1.** The aft bulkhead microstructure varies both through-thickness and along the meridian arc length positions, with larger grain sizes associated with likely regions of higher deformation.
- Grain size was larger toward the rim and toward the OML surface, likely associated with the combined stresses necessary to shape the material to fit the mandrel.
  - These variations in grain size are indicative of the complex and varied deformation levels associated with the spin forming process, particularly when combined with the plate rolling history and post-forming heat treatment.
- F-2.** Tensile tests designed to determine tensile property uniformity over the aft bulkhead acreage noted that the tensile properties varied with location in the aft bulkhead.
- For the L and LT orientations, a trend of increasing tensile and YS with arc length distance from the pole was evident.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			176 of 223

- Conversely, the properties were uniform in the circumferential direction.
  - The ST tensile properties were notably greater than those for the other orientations (L, LT, ST45), but elongations were about half.
- F-3.** The tensile properties of the spin formed Al 2219-T62 aft bulkhead material were typical for established 2219-T62 products.
- Tensile properties were comparable to the MMPDS design properties for T62 wrought plate and other fabricated products in the T6 temper, such as spin formed domes, forgings and rolled rings.
  - Tensile properties were lower than those for Al 2219-T851 and T87 plate, as expected due to the increased precipitation strengthening in T8 temper wrought products that is imparted by the cold stretch/work prior to artificial aging.
  - The lower tensile strength of the spin formed Al 2219-T62 aft bulkhead material compared with Al 2219-T851 and T87 plate is due to differences in material temper and not the spin forming process.
- F-4.** Fracture toughness was uniform with location in the aft bulkhead and indicated excellent damage tolerance capability.
- In-plane (T-L and L-T) toughness values are relatively constant for a given orientation and do not vary significantly across the aft bulkhead acreage.
  - Through-thickness (S-T) toughness appears uniform as well, but exhibits significant data scatter for a given bulkhead location.
  - Spin formed 2219-T62 aft bulkhead material exhibited rising R-curve for all orientations and locations and toughness-to-YS ratios in excess of 60%.
  - High toughness values, high toughness-to-YS ratios, and rising R-curve behavior suggest excellent damage tolerance capability for the spin formed Al 2219-T62 aft bulkhead material.
- F-5.** The fracture toughness of the spin formed Al 2219-T62 aft bulkhead material was typical for established 2219-T62 products.
- Fracture toughness values exhibited the typical variation with orientation: L-T orientation > T-L orientation > S-T orientation.
  - Fracture toughness was in-family with conventional Al 2219 Al tempers and product forms. Toughness values were comparable to Al 2219-T62 and T851 plate and are greater than for T87 plate, which is consistent with the tensile strength being lower than for T87 plate.
- F-6.** The SCC resistance of the spin formed 2219-T6 material varied with location in the aft bulkhead and in some locations exhibited lower resistance than previously established for 2219-T6 material.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			<b>177 of 223</b>

- Regions near the pole exhibited moderate resistance to SCC (Table II per MSFC-3029), near the rim a high resistance to SCC (Table I), and one of the areas in the membrane a low resistance to SCC (Table III).
- The LT orientation appeared to be significantly more resistant to SCC than the ST orientation. Residual strength after exposure was significantly higher for LT specimens than ST specimens.
- The 90-day alternate immersion exposure appears to be too long for the spin formed 2219-T62 material since failures can occur by corrosion mechanisms (general and pitting corrosion) different than those for SCC, which can interfere with the SCC evaluation.

## 12.2 Observations

The following observations were identified:

- O-1.** The rationale for the variations in tensile properties with location in the aft bulkhead was not fully characterized. The microstructure at the through-thickness location tested (t/2) was more uniform throughout the aft bulkhead than at other locations.
- O-2.** Limited data was available in handbooks or open literature publications for Al 2219-T6 material for comparison with the aft bulkhead properties, consequently it was difficult to assess the aft bulkhead in the context of other commercial Al 2219-T6 products.
  - Tensile data were unavailable in handbooks or open literature publications for the ST and ST45 orientations, consequently these properties could only be assessed in comparison with established values for the L and LT orientations.
  - Fracture toughness data was only available in handbooks and open literature publications for Al 2219-T6 and -T8 plate. No fracture toughness data was publicly available for 2219 spin formed products.
  - The SCC data for the aft bulkhead provides insight about the SCC resistance of the spin formed 2219-T62 material, but is insufficient to establish a threshold level.
- O-3.** Fracture toughness data suggests excellent damage tolerance in the 2219-T6 spin formed material; however, surface crack tension and da/dN testing is necessary to more fully characterize damage tolerance.
- O-4.** Questions arose regarding SCC test procedures, particularly the basis for exposure stress levels and test durations, which may impact direct comparison of the aft bulkhead SCC results with the very limited handbook and open literature data.
- O-5.** The SCC tests performed provided an initial indication of the SCC susceptibility of the spin formed 2219-T62 material; however, environmentally assisted fracture toughness (KEAC) and fatigue (da/dN)<sub>SCC</sub>) in the S-T orientation in a 3.5% NaCl environment is required to understand the impact of the SCC susceptibility on fracture and fatigue.

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			178 of 223

**O-6.** The laboratory 30-day alternate immersion accelerated test condition provides adequate screening methodology for SCC; however, longer test durations of 90 days did lead to severe general corrosion and pitting. For determining actual serviceability of the material, other stress corrosion tests should be performed in the intended service environment-

### 12.3 NESC Recommendations

The following NESC recommendations were identified and directed towards the MPCV Program and the NESC:

- R-1.** The microstructural variability of the Orion first article spin formed aft bulkhead should be determined and mechanical property testing designed to sample regions of maximum and minimum grain size in order to evaluate the effect of variable microstructures, if observed. *(F-1, F-2, O-1)*
- R-2.** Additional testing should be performed on first article and initial serial production aft bulkhead components to generate data to populate the material property database for Al 2219-T6 spin formed products. *(O-2)*
- Tensile testing should be continued until sufficient data is generated to demonstrate consistency in material properties and build confidence that the spin forming process is reproducible.
  - Fracture testing should generate data to more substantially populate the  $K_{JIC}$  fracture toughness database.
  - Stress corrosion cracking testing should be continued until sufficient data is generated to establish the SCC threshold stress level.
- R-3.** Perform surface crack tension fracture toughness and fatigue crack growth rate (da/dN) testing in order to fully characterize damage tolerance. *(O-3)*
- R-4.** Exercise caution in using published handbook and table ratings for the SCC resistance of Al 2219-T6. Handbook and open literature publications should be reviewed in order to substantiate that the SCC test procedures and data generated are directly comparable to the MSFC-STD-3029 standard used in the SCC evaluation of the Al 2219-T62 aft bulkhead *(O-4)*
- R-5.** Perform environmentally assisted fracture toughness (KEAC) and fatigue ((da/dN)<sub>SCC</sub>) tests in the S-T orientation in a 3.5% NaCl environment in order to understand the impact of the SCC susceptibility of the material on fracture toughness and fatigue. *(O-5)*
- R-6.** Perform seacoast exposure SCC testing to characterize the corrosion performance of the aft bulkhead in the natural service environment. *(O-6)*

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 179 of 223

### 13.0 Alternate Viewpoint

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

### 14.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

### 15.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS) as a result of this assessment.

### 16.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

### 17.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Lessons Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			180 of 223

occurrence and, if eliminated or modified, would have prevented the undesired outcome.

**Recommendation** A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.

**Root Cause** One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

**Supporting Narrative** A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions. Avoid squeezing all of this information into a finding or observation

## 18.0 Acronyms List

AM	Additive Manufacturing
AMA	Analytical Mechanics Associates
AMS	Aerospace Material Specifications
APVBH	Aft Pressure Vessel Bulkhead
ASTM	American Society for Testing and Materials
BH	Bulkhead
C(T)	Compact Tension
CL	Centerline
CM	Crew Module
CPST	Cryogenic Propellant Storage and Transfer
COD	Crack-Mouth Opening Displacement
E	Modulus
EBSD	Electron Backscatter Diffraction
ESCG	Engineering and Science Contract Group
FPPW	Friction Pull Plug Welding
FPVBH	Forward Pressure Vessel Bulkhead
FSW	Friction Stir Weld
FSWSFD	Friction Stir Welded Spin Formed Dome
FTU	Design Ultimate Tensile Strength, Tension
FTY	Design Yield Strength, Tension
IML	Inner Mold Line
in	Inch
ipm	Inches Per Minute
JIC	J integral



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
181 of 223

JSC	Johnson Space Center
K	Crack Tip Stress Intensity, ksi $\sqrt{\text{in}}$
K <sub>IC</sub>	Critical Crack Tip Stress Intensity
K <sub>IC</sub>	Plane Strain Fracture Toughness
kips	1,000 pounds
K <sub>JIC</sub>	Plane Strain Fracture Toughness
KSC	Kennedy Space Center
ksi	Kilopound per square inch, 10 <sup>3</sup>
L	Length
L	Longitudinal (direction parallel to plate rolling direction)
LALab	Light Alloy Laboratory
LaRC	Langley Research Center
LM	Lockheed Martin
LT	Long Transverse (direction perpendicular to rolling direction)
M&P	Materials and Processes
MAF	Michoud Assembly Facility
MUA	Materials Usage Agreement
MMPDS	Metallic Material Properties Development and Standardization
MPCV	Multi-Purpose Crew Vehicle
MSFC	Marshall Space Flight Center
Msi	Megapound per square inch, 10 <sup>6</sup>
NaCl	Sodium Chloride
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OML	Outer Mold Line
psi	Pounds Per Square Inch
R-curve	Resistance Curve
S/N	Serial Number
SCC	Stress Corrosion Cracking
SHT	Solution Heat Treatment
SiC	Silicon Carbide
SLS	Space Launch System
SR-FSW	Self-Reacting Friction Stir Weld
SSC	Stennis Space Center
ST	Short Transverse (direction perpendicular to rolling direction)
ST45	45 Degree Through-Thickness (direction perpendicular to rolling direction)
t	Thickness
WCM	Welded Crew Module
YS	Yield Strength

	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			182 of 223

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #:	Version:
		<b>NESC-RP-13-00884</b>	<b>1.0</b>
Title:			Page #:
<b>Spin Forming Al CM Metallic APVBH – Phase II</b>			183 of 223

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP- 13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>		Page #: 184 of 223	

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	<b>NASA Engineering and Safety Center Technical Assessment Report</b>	Document #: <b>NESC-RP-13-00884</b>	Version: <b>1.0</b>
Title: <b>Spin Forming Al CM Metallic APVBH – Phase II</b>			Page #: 185 of 223

## 20.0 Appendix

### 20.1 Appendix A: Temper Designations (41)

- F As fabricated (no mechanical property limits specified).
- O Annealed - products achieving the required annealed properties after hot forming processes may be designated as O temper.
- T4 Solution heat treated and naturally aged to a substantially stable condition.
- T6 Solution heat treated and then artificially aged by the material producer.
- T62 Solution heat treated and then artificially aged. Applies to test material heat treated from annealed or F temper or to products heat treated from any temper by the user.
- T8 Solution heat treated, cold worked and then artificially aged.
- T851 Solution heat treated, stress relieved by controlled stretching (permanent set 1.5% to 3% for plate, 1% to 5% for hand or ring forging and rolled ring) and then artificially aged.
- T87 Solution heat treated, cold worked by a thickness reduction of approximately 7% and then artificially aged.

### 20.2 Appendix B: Material Certification

A material certification report was provided by Alcoa for the plate used in fabrication of the pathfinder aft bulkhead and is shown in Figure 20.2-1.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
186 of 223

**CERTIFIED INSPECTION REPORT** **Alcoa Inc.** DAVENPORT WORKS 4879 State Street Bettendorf, IA 52722

We hereby certify that the material covered by this certificate has been inspected with, and has been found to meet the applicable requirements described herein, including any specifications forming a part of the description and that samples representative of the material met the composition limits and had the mechanical properties shown on the face of this sheet.

This test report shall not be reproduced except in full, without the written approval of the Quality Department. No alteration, addition or other change is authorized to be made to this certificate. The recording of false, fictitious, or otherwise fraudulent statements or entries on this certificate by any recipient may be punished as a felony under applicable law.

For: *Rob Woodall* Director of Manufacturing Davenport Works *Terence Thom* Quality Assurance Manager

1629397 Ship Date 0 B.I. No. Invoice No. Alcoa No. Item  
2013-10-08 8828477 00000 1000527171-1 DP-27171-1  
P.O. No./Govt Contract No. Customer Alcoa Item  
31064 Lot#: 1 STANDEX-SPINCRRAFT 0041130911801

Ship From: 2722

Page 1 of 2

Ship To: STANDEX INTERNATIONAL CORP  
SPINCRRAFT DIV  
500 IRON HORSE PARK  
NORTH BILLERICA, MA 01862

Item Description  
2.3 IN TK (+.015 -.100) X 141.0 IN W (+.500 - 0.000) X 141.0 IN LN (+.5 -0.0) (N) A/T 2219-F RECTANGULAR MILL FINISH, US1 3MM DEAD ZONE, SAWED 2219-F PLATE, AMS-QQ-A-250/30 IS 2010 AMS-STD-2154 REV A AS9103 D6-82479 REV F  
(MARKED) NOT INTERLEAVED  
MAX GROSS EXID WGT: 10000 LB QUAN TOL +/- 10 % US1 CL. A 3 MM CQR 0240249 REV 01 CUST REQ 13-10-04 \*\*\* M/E 13-09-28 \*\*\*

Num	Package Ticket	Lot	Weight	Quantity	UCM	Inspector Clock Numbers
1	561380	446391	4849	1	PC	37331

Notes for CQR: 0240249.1  
PRODUCT PRODUCED TO THE REQUIREMENTS OF MIL-STD-2154 ALSO MEET THE REQUIREMENTS OF AMS-STD-2154 REV A. PRODUCT PRODUCED TO THE REQUIREMENTS OF AMS-STD-2154 REV A ALSO MEET THE REQUIREMENTS OF MIL-STD-2154.  
THIS MATERIAL HAS BEEN ULTRASONICALLY INSPECTED FULLY IMAGE REGION - TYPE I.  
PRODUCT PRODUCED AND MARKED TO THE REQUIREMENTS OF AMS-QQ-A-250/30 ALSO MEETS THE REQUIREMENTS OF QQ-A-250/30A, AMEN DSENT 1. PRODUCT PRODUCED AND MARKED TO THE REQUIREMENTS OF QQ-A-250/30A, AMENDMENT 1, ALSO MEETS THE REQUIREMENTS OF AMS-QQ-A-250/30.

CQR: 0240249.1 -Specification Limits -----

Temp Dir	UTS	TYS	HEAD
T62 Long Transv.	KSI	KSI	PCT
Max			
Min	54	36	6

Chemical Composition

Alloy	SI	FE	CU	MN	MG	V	ZN	TI	ER	Other Each	Other Total	Aluminum
Alloy 2219	Max	0.20	0.30	6.8	0.40	0.02	0.15	0.10	0.10	0.25	0.05	0.15
	Min			5.8	0.20		0.05	0.02	0.10			REMAIN

S/N 31177-1

---

**CERTIFIED INSPECTION REPORT** **Alcoa Inc.** DAVENPORT WORKS 4879 State Street Bettendorf, IA 52722

We hereby certify that the material covered by this certificate has been inspected with, and has been found to meet the applicable requirements described herein, including any specifications forming a part of the description and that samples representative of the material met the composition limits and had the mechanical properties shown on the face of this sheet.

This test report shall not be reproduced except in full, without the written approval of the Quality Department. No alteration, addition or other change is authorized to be made to this certificate. The recording of false, fictitious, or otherwise fraudulent statements or entries on this certificate by any recipient may be punished as a felony under applicable law.

For: *Rob Woodall* Director of Manufacturing Davenport Works *Terence Thom* Quality Assurance Manager

1629397 Ship Date 0 B.I. No. Invoice No. Alcoa No. Item  
2013-10-08 8828477 00000 1000527171-1 DP-27171-1  
P.O. No./Govt Contract No. Customer Alcoa Item  
31064 Lot#: 1 STANDEX-SPINCRRAFT 0041130911801

Ship From: 2722

Page 2 of 2

CQR: 0240249.1 -Specification Limits (cont.) -----

Lot: 446391 - Mechanical, Physical, Metallography, Quantometer Results -----

Temp Dir	Mo-Test	UTS	TYS	HEAD
T62 Long Transv.	2	KSI	KSI	PCT
		60.9	42.3	11.4
		61.4	42.4	10.7

Cast Number Chemical - OBS Actuals SI FE CU MN MG V ZN TI ER  
H9134063 0.06 0.14 6.3 0.25 0.01 0.09 0.02 0.04 0.13

This material was melted in the United States or a Qualifying Country [DEF DFARS 225.872.1(a)]; it was manufactured in the United States

Figure 20.2-1. Material certification report for the 2219-F plate.



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

**Spin Forming Al CM Metallic APVBH – Phase II**

Page #:  
187 of 223

## 20.3 Appendix C: Fracture Toughness Data

A complete data report for each fracture toughness specimen is provided.



EM10  
**Fracture Toughness  $J_{Ic}$  Task Results**  
Version 4.1



<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td>NESC Work Order</td><td>2014-0061</td></tr> <tr><td>Work Order Task</td><td>5</td></tr> <tr><td>Testing Organization</td><td>MTF</td></tr> <tr><td>Customer Work Order</td><td>N/A</td></tr> <tr><td>Test Standard</td><td>ASTM C1620-9</td></tr> </table>	NESC Work Order	2014-0061	Work Order Task	5	Testing Organization	MTF	Customer Work Order	N/A	Test Standard	ASTM C1620-9	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td>Control Mode</td><td>Stroke</td></tr> <tr><td>Test Frame</td><td>TS-5</td></tr> <tr><td>Drawing Number</td><td>5-2947/5-295</td></tr> <tr><td>Pre-Load (LBS)</td><td>25</td></tr> </table>	Control Mode	Stroke	Test Frame	TS-5	Drawing Number	5-2947/5-295	Pre-Load (LBS)	25	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr><td>Nominal Temperature (°F)</td><td>73</td></tr> <tr><td>Nominal Pressure (psia)</td><td>0</td></tr> <tr><td>Material</td><td>AL 2124-T62</td></tr> </table>	Nominal Temperature (°F)	73	Nominal Pressure (psia)	0	Material	AL 2124-T62
NESC Work Order	2014-0061																									
Work Order Task	5																									
Testing Organization	MTF																									
Customer Work Order	N/A																									
Test Standard	ASTM C1620-9																									
Control Mode	Stroke																									
Test Frame	TS-5																									
Drawing Number	5-2947/5-295																									
Pre-Load (LBS)	25																									
Nominal Temperature (°F)	73																									
Nominal Pressure (psia)	0																									
Material	AL 2124-T62																									

**Results**

EM10 Specimen ID	Other Specimen ID	Coupon #	Orientation	Jq (in <sup>3</sup> /in <sup>2</sup> )	KJq (ksi(in) <sup>3</sup> /in <sup>2</sup> )	Jq Validity as $J_{Ic}$ (See test results for specifics)
1400E1359	CP-406-191	M1	L-T	105.6	35.08	Not fully valid $J_{Ic}$
1400E1361	CP-406-193	M1	L-T	114.80	36.58	Not fully valid $J_{Ic}$
1400E1364	CP-406-196	M1	T-L	91.50	32.65	Not fully valid $J_{Ic}$
1400E1366	CP-406-198	M1	T-L	90.80	32.49	Not fully valid $J_{Ic}$
1400E1369	CP-406-201	M1	S-T	62.60	27.01	Not fully valid $J_{Ic}$
1400E1371	CP-406-203	M1	S-T	62.20	26.92	Not fully valid $J_{Ic}$
1400E1374	CP-406-206	M2	L-T	115.10	36.61	Not fully valid $J_{Ic}$
1400E1376	CP-406-208	M2	L-T	112.80	36.25	Not fully valid $J_{Ic}$
1400E1379	CP-406-211	M2	T-L	86.20	31.69	Not fully valid $J_{Ic}$
1400E1381	CP-406-213	M2	T-L	93.00	32.56	Not fully valid $J_{Ic}$
1400E1384	CP-406-216	M2	S-T	89.90	32.35	Not fully valid $J_{Ic}$
1400E1386	CP-406-218	M2	S-T	56.00	25.55	Not fully valid $J_{Ic}$
1400E1389	CP-406-221	M2	L-T	117.20	36.95	Not fully valid $J_{Ic}$
1400E1391	CP-406-223	M2	L-T	125.70	38.27	Not fully valid $J_{Ic}$
1400E1394	CP-406-226	M2	T-L	84.90	31.45	Not fully valid $J_{Ic}$
1400E1396	CP-406-228	M2	T-L	93.30	32.93	Not fully valid $J_{Ic}$
1400E1399	CP-406-231	M2	S-T	66.00	27.73	Not fully valid $J_{Ic}$
1400E1401	CP-406-233	M2	S-T	90.30	32.51	Not fully valid $J_{Ic}$
1400E1404	CP-406-236	M4	L-T	102.50	34.55	Not fully valid $J_{Ic}$
1400E1406	CP-406-238	M4	L-T	99.20	33.97	Not fully valid $J_{Ic}$
1400E1409	CP-406-241	M4	T-L	86.00	31.65	Not fully valid $J_{Ic}$
1400E1411	CP-406-243	M4	T-L	93.40	32.99	Not fully valid $J_{Ic}$
1400E1414	CP-406-246	M4	S-T	78.00	30.34	Not fully valid $J_{Ic}$
1400E1416	CP-406-248	M4	S-T	50.90	24.35	Not fully valid $J_{Ic}$
1400E1419	CP-406-251	M5	L-T	108.40	35.53	Not fully valid $J_{Ic}$
1400E1421	CP-406-253	M5	L-T	107.20	35.35	Not fully valid $J_{Ic}$
1400E1424	CP-406-256	M5	T-L	86.30	31.71	Not fully valid $J_{Ic}$
1400E1426	CP-406-258	M5	T-L	85.60	31.57	Not fully valid $J_{Ic}$
1400E1429	CP-406-261	M5	S-T	67.80	28.10	Not fully valid $J_{Ic}$
1400E1431	CP-406-263	M5	S-T	77.40	30.03	Not fully valid $J_{Ic}$
1400E1434	CP-406-266	M6	L-T	118.70	37.18	Not fully valid $J_{Ic}$
1400E1436	CP-406-268	M6	L-T	114.00	36.44	Not fully valid $J_{Ic}$
1400E1439	CP-406-271	M6	T-L	86.50	31.74	Not fully valid $J_{Ic}$
1400E1441	CP-406-273	M6	T-L	85.00	31.47	Not fully valid $J_{Ic}$
1400E1444	CP-406-276	M6	S-T	59.20	26.23	Not fully valid $J_{Ic}$
1400E1446	CP-406-278	M6	S-T	57.40	25.85	Not fully valid $J_{Ic}$



# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
188 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061138
Other Specimen ID	CP-406-191
Operator	Charles Kay
Test Date	4/3/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIA)	0
Relative Humidity (%)	NA
Soak Time (min)	0

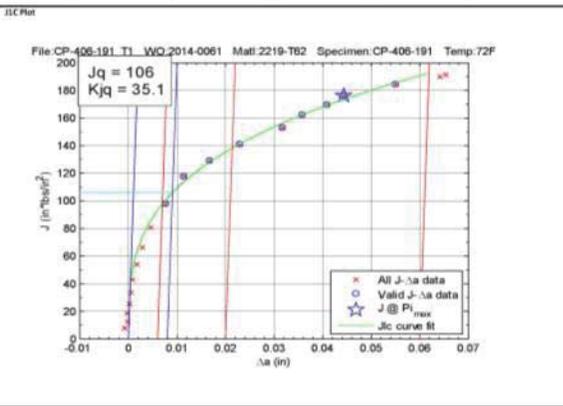
Geometry	CTT
"W" (in)	2.0010
"B" (in)	1.0000
"B <sub>0</sub> " (in)	0.7500
"B <sub>1</sub> " (in)	0.9530
Orientation	L-T
"A <sub>0</sub> " (in)	0.8000
Hole Spacing "W" (in)	0.7500
COO Span/2 "D" (in)	0.1060
Crugon #	M1

"E" (ksi)	10.60
"E <sub>c</sub> " (ksi)	10.60
% off E & E <sub>c</sub>	0.00
"Y <sub>0</sub> " (ksi)	0.30
"Y <sub>1</sub> " (ksi)	39.30
"Y <sub>2</sub> " (ksi)	59.20
Flow Stress (ksi)	89.24
"E"/"Y <sub>0</sub> "	0.27

Pre-crack Pmax (lbf)	3711.0
Pre-crack Final "a" (in)	3.0436
Stress Ratio	0.10
Kmax (ksi√in)	8.00
A <sub>0p</sub> (in)	1.0496
A <sub>0q</sub> (in)	1.0188
A <sub>1p</sub> (in)	1.1261
A <sub>1q</sub> (in)	1.0991

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi√in)	$K_{Ic}$ at $J_{Ic}$ (ksi√in)	$K_{Ic}$ (ksi√in)	Req Ligament (in)	Pmax/Pq
	105.60	94.60	11.00	35.08	33.20	30.61	1.517	1.29

Summary of Test Validities Required for All Tests:			
7.4.5	Initial pre-crack force	≥ 0.45 c/w or 0.27	Valid
7.4.5.1	Initial Kmax	±40% of Pre-crack Y5	Valid
7.4.5.2	Final Kmax	±60% of K result	Valid
8.1.4.1	Pre-crack straightness	None > 0.05in	Valid
7.4.5.3	Pre-crack length	±0.028 or 0.05inch, wide notch	Valid
7.5	Side groove depth	± 0.258	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :			
7.4.2	a/W Range for J <sub>Ic</sub>	0.45 ≤ a/W ≤ 0.77	Valid
9.1.5.1	Even Crack Fat.	None < 50% of avg crk ext.	Valid
9.1.5.2	Accuracy of crk ext. prof.	DIF = 0.15 d <sub>ap</sub>	Valid
A9.4.4	# pts in region A	# pts = 3 or 4	Valid
A9.4.4	# pts in region B	# pts = 3 or 4	Valid
A9.4.4	# Valid - d <sub>ap</sub> pts	# pts = 3	Valid
A9.4.1	d <sub>ap</sub> fit coeff C2	C2 = 1.0	Valid
A9.4.2.1	Accuracy of a <sub>0q</sub>	a <sub>0q</sub> - a <sub>0p</sub>   ≤ 0.01W or 0.5mm	Valid
A9.4.2.2	Number of a <sub>0q</sub> fit	# points = 3	Valid
A9.4.2.3	Accuracy of a <sub>0q</sub> fit	# points = 3	Valid
A9.2.2	Thickness requirement	B ≥ 2d <sub>ap</sub> /Flow Stress	Valid
A9.2.1	Ligament requirement	B ≥ 2d <sub>ap</sub> /Flow Stress	Valid
A9.3.3	Regression line slope	Slope < flow of d <sub>ap</sub>	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .			
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for K <sub>Ic</sub> :			
7.4.2	a/W Range for K <sub>Ic</sub>	0.45 ≤ a/W ≤ 0.55	Valid
A5.4.3	Ligament length	B <sub>0</sub> ≥ 2.5(d <sub>ap</sub> /Y <sub>0</sub> ) <sup>2</sup>	NOT valid
A5.4.2	Pmax/Pq ratio	Less than 1.10	NOT valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .			
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.			



Method File: J-Ic Plot  
 File: J-Ic Plot  
 Comments:  
 N/A

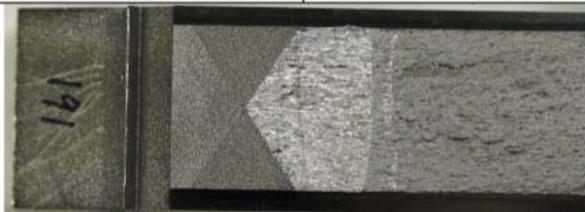
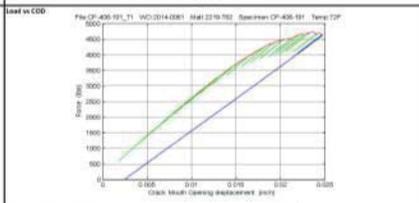
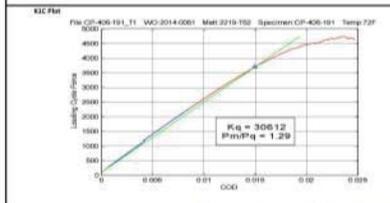
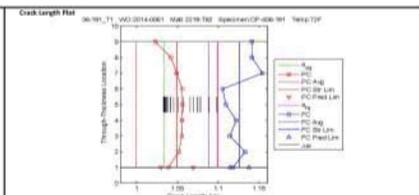
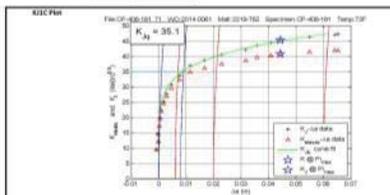


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061138
Other Specimen ID	CP-406-191
Operator	Charles Kay
Test Date	4/3/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
189 of 223



### EM10 Fracture Toughness $J_{IC}$ Test Results

Version 4.3



EM10 Specimen ID	140061193	Geometry	CTT	"E" (ksi)	10.60	Precrack Pmax (lbf)	1405.0
Other Specimen ID	CP-406-193	"W" (in)	2.0000	"E <sub>c</sub> " (ksi)	10.60	Precrack Final "a" (in)	1.0466
Operator	Charles Kay	"B" (in)	1.0000	% diff E & E <sub>c</sub>	0.00	Stress Ratio	0.10
Test Date	4/6/2014	"B <sub>u</sub> " (in)	0.7990	"v"	0.30	Kmax (ksi $\sqrt{in}$ )	8.00
Environment	air	"B <sub>d</sub> " (in)	0.9600	"VS" (ksi)	39.30		
Temperature (°F)	73	Orientation	L-T	"UTS" (ksi)	39.20	A <sub>0q</sub> (in)	1.0466
Pressure (PSIG)	0	"a <sub>0</sub> " (in)	0.7990	Flow Stress (ksi)	49.24	A <sub>0q</sub> (in)	1.0272
Relative Humidity (%)	NA	Hole Span/2 "W" (in)	0.7100	"E"/"VS"	0.27	A <sub>1p</sub> (in)	1.1234
Soak Time (min)	0	COO Span/2 "D" (in)	0.1050			A <sub>1q</sub> (in)	1.1061
		Coupon #	M1				

Results	$J_q$ (in $\sqrt{lb}/in^2$ )	$J_{e,q}$ (in $\sqrt{lb}/in^2$ )	$J_p$ (in $\sqrt{lb}/in^2$ )	$K_{Iq}$ (ksi $\sqrt{in}$ )	$K_{Ie,q}$ (ksi $\sqrt{in}$ )	$K_{Ip}$ (ksi $\sqrt{in}$ )	$K_{Iq50er}$ (ksi $\sqrt{in}$ )	$K_{Req}$ Ligament (in)	Pmax/Pq
	114.80	100.20	14.60	30.58	34.17	29.36	1.995		1.33

Summary of Test Validities Required for All Tests:

7.4.5.1	Initial precrack force	$P \leq P_m$ for sample type	Valid
7.4.5.1	Initial Kmax	$< 80\%$ of Precrack YS	Valid
7.4.5.2	Final Kmax	$< 80\%$ of K result	Valid
8.1.4.1	Precrack straightness	None $> 0.05\%$	Valid
7.4.5.1	Precrack length	$< 0.05B$ or $0.5$ inch, wide notch	Valid
7.5	Side groove depth	$< 0.25B$	Valid

Summary of Test Validities Required for  $J_{IC}$ :

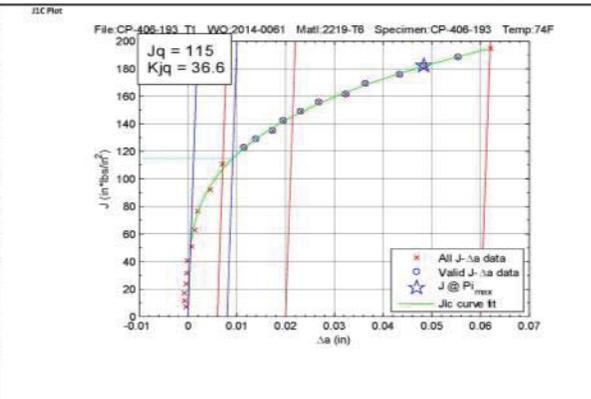
7.4.2	$a/W$ Range for $J$	$0.45 \leq a/W \leq 0.7$	Valid
8.1.5.1	Even Crack Ext.	None $< 50\%$ of avg crk ext.	Valid
8.1.5.2	Accuracy of crk ext. prof.	Diff $< 0.15$ of $a_p$	Valid
A9.6.4	# pts in region A	# pts $\geq 3$ or 4	Valid
A9.6.4	# pts in region B	# pts $\geq 3$ or 4	Valid
A9.6.6	# Valid $a$ -pts	# pts $\geq 5$	Valid
A9.8.1	$d$ -fit coeff $C2$	$C2 < 1.0$	Valid
A9.8.2.1	Accuracy of $d$ -fit	$ J_{e,q} - J_{q,fit}  \leq 0.01W$ or $0.5$ mm	Valid
A9.8.2.2	Num pts in $d$ -fit	# points $\geq 8$	Valid
A9.8.2.3	$d$ -fit $R^2$	# points $\geq 3$	Valid
A9.8.2.4	Thickness requirement	$B \geq 2J_{Iq}/FlowStress$	Valid
A9.8.2.5	Ligament requirement	$B \geq 2J_{Iq}/FlowStress$	Valid
A9.8.3	Regression line slope	Slope $< flow$ at $d_a, q$	Valid

All validity criteria for  $J_{IC}$  NOT met.  $J_{IC}$  is not fully valid  $J_{IC}$ .  
Non valid  $J_{IC}$  values may still convey valuable fracture toughness information.

Summary of Test Validities Required for  $K_{Ic}$ :

7.4.2	$a/W$ Range for $K_{Ic}$	$0.45 \leq a/W \leq 0.55$	Valid
A5.4.3	Ligament length	$B \geq 2.5J_{Iq}/YS^2$	NOT valid
A5.4.2	Precr/Pn ratio	Ratio $> 1.0$	NOT valid

All validity criteria for  $K_{Ic}$  NOT met.  $K_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non valid  $K_{Ic}$  values may still convey valuable fracture toughness information.

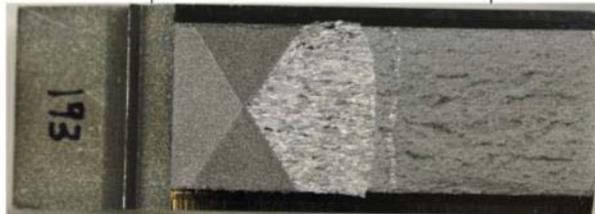
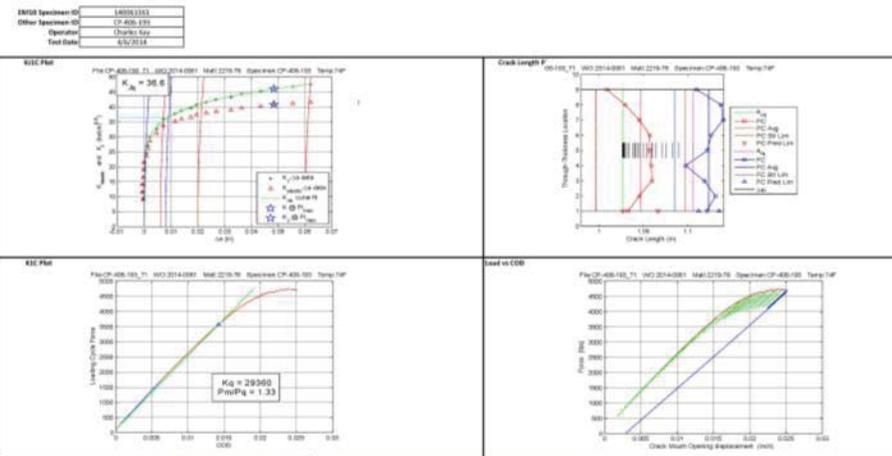


Method File: FTA.NCFT  
Comments: N/A



### EM10 Fracture Toughness $J_{IC}$ Test Results

Version 4.3





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

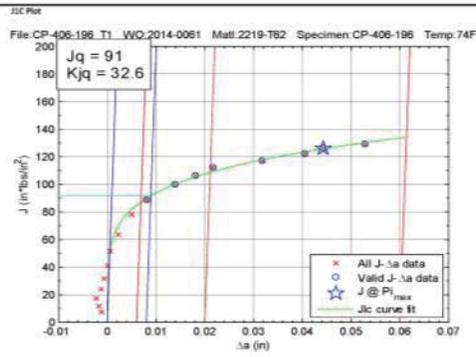
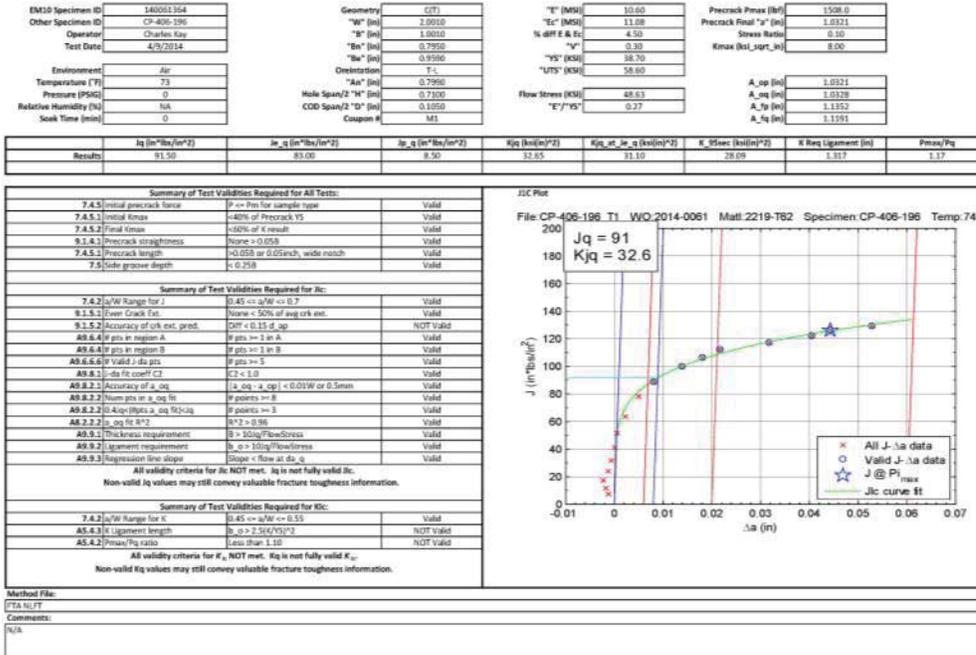
## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
190 of 223



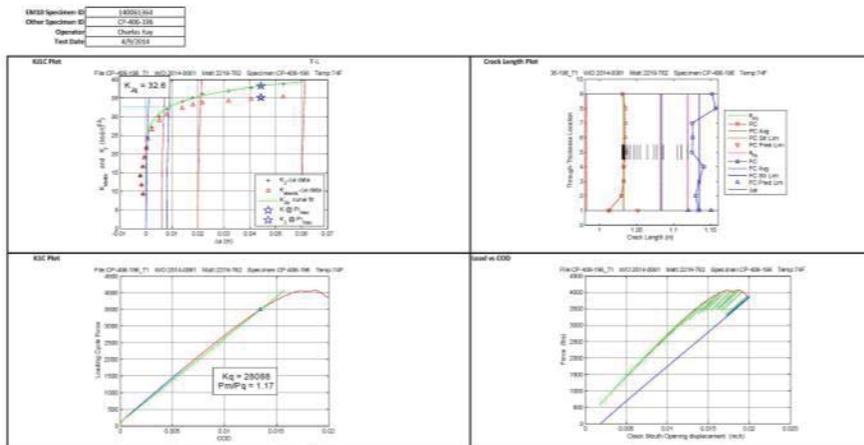
### EM10 Fracture Toughness $J_{IC}$ Test Results

Version 4.3



### EM10 Fracture Toughness $J_{IC}$ Test Results

Version 4.2





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
191 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.1



<b>EM10 Specimen ID</b>	140061366	<b>Geometry</b>	CTI	<b>"E" (MS)</b>	10.60	<b>Precrack Pmax (lbf)</b>	1301.0
<b>Other Specimen ID</b>	CP-406-198	<b>"W" (in)</b>	2.0000	<b>"Ee" (MS)</b>	11.08	<b>Precrack Final "a" (in)</b>	1.0301
<b>Operator</b>	Charles Key	<b>"B" (in)</b>	0.9990	<b>% diff E &amp; Ee</b>	4.60	<b>Stress Ratio</b>	0.10
<b>Test Date</b>	4/30/2014	<b>"Bb" (in)</b>	0.7570	<b>"v"</b>	0.30	<b>Kmax (ksi_sqr_in)</b>	9.00
<b>Environment</b>	Air	<b>"Bc" (in)</b>	0.9580	<b>"YS" (ksi)</b>	38.70		
<b>Temperature (°F)</b>	73	<b>Orientation</b>	T_L	<b>"UTS" (ksi)</b>	58.60	<b>A<sub>avg</sub> (in)</b>	1.0201
<b>Pressure (PSI)</b>	0	<b>"An" (in)</b>	0.3500	<b>Flow Stress (ksi)</b>	48.63	<b>A<sub>avg</sub> (in)</b>	1.0290
<b>Relative Humidity (%)</b>	NA	<b>Hole Span/2 "H" (in)</b>	0.1650	<b>"E"/"YS"</b>	0.77	<b>A<sub>1/4</sub> (in)</b>	1.1345
<b>Soak Time (min)</b>	0	<b>COD Span/2 "D" (in)</b>	0.1650			<b>A<sub>1/8</sub> (in)</b>	1.1169
		<b>Coupon #</b>	M1				

Results	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$K_{Ic}$ (ksi√in)	$K_{Ic}$ at $J_{Ic}$ (ksi√in)	$K_{Ic}$ (ksi√in)	$K_{Ic}$ Req (ksi√in)	$K_{Ic}$ Req Ligament (in)	Pmax/P <sub>0</sub>
	90.60	81.00	7.60	32.49	11.10	28.11	1.18		1.22

**Summary of Test Validities Required for All Tests:**

7.4.5 Initial precrack force	$P < P_m$ for sample type	Valid
7.4.5.1 Initial Kmax	$< 40\%$ of Precrack YS	Valid
7.4.5.2 Final Kmax	$< 50\%$ of K result	Valid
9.1.4.1 Precrack straightness	None $> 0.05$	Valid
7.4.5.3 Precrack length	$\pm 0.008$ or $0.05$ inch, wide notch	Valid
7.5 Side groove depth	$< 0.35d$	Valid

**Summary of Test Validities Required for  $J_{Ic}$ :**

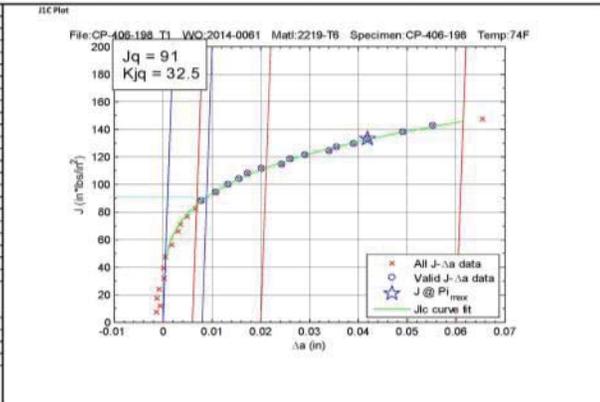
7.4.2 a/W Range for $J_{Ic}$	$0.45 \leq a/W \leq 0.7$	Valid
9.1.5.1 Even Crack Ext.	None $< 50\%$ of avg crk ext.	Valid
9.1.5.2 Accuracy of crk ext. par.	Diff $< 0.15 d$ at ap	NOT Valid
A9.6.4 # pts in region A	# pts $\geq 3$ in A	Valid
A9.6.4 # pts in region B	# pts $\geq 1$ in B	Valid
A9.6.8 # Valid J-ds per C	# pts $\geq 5$	Valid
A9.8.1 J-ds fit coeff C2	$C2 < 1.0$	Valid
A9.8.2 Accuracy of $a_{avg}$	$(a_{avg} - a_{app}) \leq 0.01W$ or $0.5$ mm	Valid
A9.8.2.2 Num pts in $a_{avg}$ fit	# points $\geq 8$	Valid
A9.8.2.2 0.4 slope (pts a <sub>avg</sub> fit) vs	# points $\geq 3$	Valid
A9.8.2.2 a <sub>avg</sub> fit R <sup>2</sup>	$R^2 > 0.96$	Valid
A9.9.1 Thickness requirement	$B \geq 10(J_{Ic}/\text{Flow Stress})$	Valid
A9.9.2 Ligament requirement	$D \geq 2(J_{Ic}/\text{Flow Stress})$	Valid
A9.9.3 Regression line slope	Slope $< \text{flow at } d_{a, g}$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-valid  $J_{Ic}$  values may still convey valuable fracture toughness information.

**Summary of Test Validities Required for  $K_{Ic}$ :**

7.4.2 a/W Range for $K_{Ic}$	$0.45 \leq a/W \leq 0.55$	Valid
A5.4.2 Ligament length	$D \geq 2.5(J_{Ic}/\text{YS})^2$	NOT Valid
A5.4.2 Pmax/P <sub>0</sub> ratio	Less than 1.10	NOT Valid

All validity criteria for  $K_{Ic}$  NOT met.  $K_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non-valid  $K_{Ic}$  values may still convey valuable fracture toughness information.



Method File:  
FTA\_NFT  
Comments:  
N/A

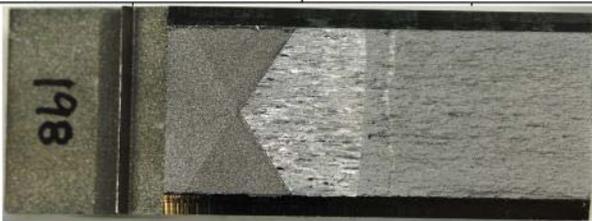
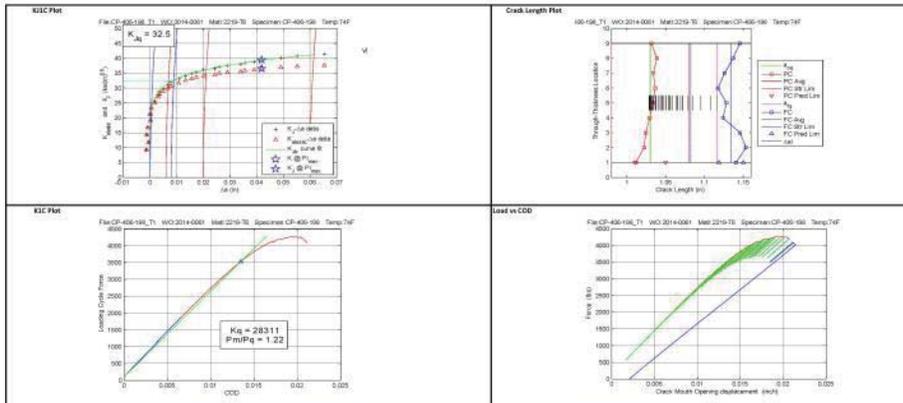


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.1



<b>EM10 Specimen ID</b>	140061366
<b>Other Specimen ID</b>	CP-406-198
<b>Operator</b>	Charles Key
<b>Test Date</b>	4/30/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
192 of 223



EM10

### Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061399
Other Specimen ID	CP-406-201
Operator	Charles Koy
Test Date	4/11/2014
Environment	Air
Temperature (T)	73
Pressure (PSID)	0
Relative Humidity (%)	NA
Soak Time (min)	0

Geometry	CTI
"W" (in)	1.0000
"B" (in)	0.4930
"Bc" (in)	0.4060
"Be" (in)	0.4780
Orientation	S-T
"A <sub>0</sub> " (in)	0.4020
Hole Span/2 "H" (in)	0.3550
COD Span/2 "D" (in)	0.0990
Coupon #	M1

"E" (MSI)	10.60
"E <sub>c</sub> " (MSI)	10.60
% diff E & E <sub>c</sub>	0.00
"V"	0.30
"YS" (KSI)	37.50
"UTS" (KSI)	60.20
Flow Stress (KSI)	48.87
"E"/"YS"	0.28

Pre-crack Pmax (lbf)	525.0
Pre-crack Final "a" (in)	0.5334
Stress Ratio	0.10
Kmax (ksi√in)	0.60

A <sub>0</sub> (in)	0.5334
A <sub>0</sub> (in)	0.5262
A <sub>0</sub> (in)	0.6062
A <sub>0</sub> (in)	0.5951

Results	Iq (in <sup>3</sup> /lbz/m <sup>2</sup> )	J <sub>c,q</sub> (in <sup>3</sup> /lbz/m <sup>2</sup> )	J <sub>p,q</sub> (in <sup>3</sup> /lbz/m <sup>2</sup> )	K <sub>Iq</sub> (ksi√in) <sup>2</sup>	K <sub>Iq,at,J<sub>c,q</sub></sub> (ksi√in) <sup>2</sup>	K <sub>I,95sec</sub> (ksi√in) <sup>2</sup>	K <sub>I,Res Ligament</sub> (in)	Pmax/Pq
	62.60	53.60	6.90	27.01	25.01	23.87	0.850	1.21

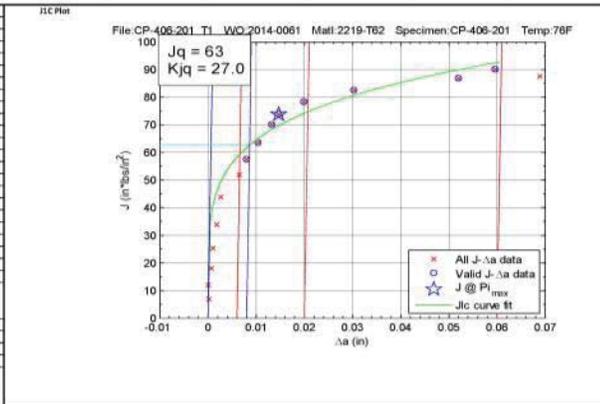
Summary of Test Validities Required for All Tests:

7.4.5.1	Initial precrack force	F < Pm for sample type	Valid
7.4.5.1	Initial Kmax	<40% of Pre-crack YS	Valid
7.4.5.2	Final Kmax	<60% of K result	Valid
9.1.4.2	Precrack sharpness	None = 0.05B	Valid
7.4.5.3	Precrack length	<0.05B or 0.05inch, wide notch	Valid
7.5	Side groove depth	< 0.25B	Valid

Summary of Test Validities Required for J<sub>Ic</sub>:

7.4.2	a/W Range for T	0.45 < a/W < 0.7	Valid
9.1.5.1	Event Crack Ext.	None < 50% of avg crk ext.	Valid
9.1.5.2	Accuracy of crk ext. pred.	Diff < 0.15 d <sub>ap</sub>	Valid
A9.6.4	# pts in region A	# pts >= 1 in A	Valid
A9.6.4	# pts in region B	# pts >= 1 in B	Valid
A9.6.4	# Valid J-ds pts	# pts >= 5	Valid
A9.8.1	J-ds fit coeff C2	C2 < 1.0	Valid
A9.8.2	Accuracy of a <sub>0</sub> - a <sub>g</sub>	a <sub>0</sub> - a <sub>g</sub>   <= 0.031W or 0.5mm	Valid
A9.8.2	Num pts in a <sub>0</sub> - a <sub>g</sub> fit	# points >= 8	Valid
A9.8.2.2	G.4 slope (a <sub>0</sub> - a <sub>g</sub> ) fit	# points >= 3	Valid
A9.8.2.2	a <sub>0</sub> - a <sub>g</sub> fit R <sup>2</sup>	R <sup>2</sup> > 0.96	Valid
A9.9.1	Thickness requirement	B >= 10tq/√K <sub>I,95sec</sub> stress	Valid
A9.9.2	Ligament requirement	B <sub>0</sub> >= 10tq/√K <sub>I,95sec</sub> stress	Valid
A9.9.3	Regression line slope	Slope < flow at d <sub>0</sub>	Valid

All validity criteria for J<sub>Ic</sub> NOT met. J<sub>Ic</sub> is not fully valid J<sub>Ic</sub>.  
Non-valid J<sub>Ic</sub> values may still convey valuable fracture toughness information.



Method File:  
FTA.TLIT  
Comments:  
N/A



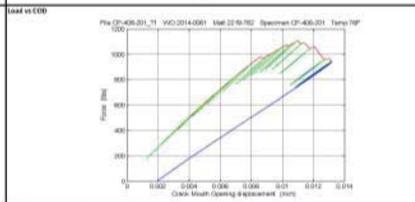
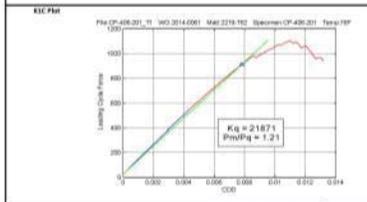
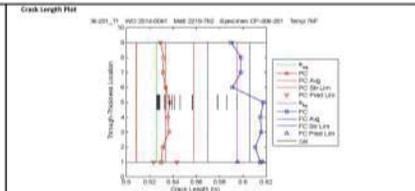
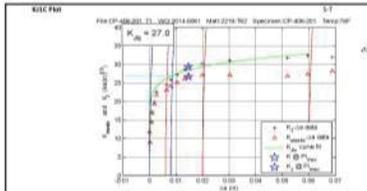
EM10

### Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061399
Other Specimen ID	CP-406-201
Operator	Charles Koy
Test Date	4/11/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
193 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



<b>EM10 Specimen ID</b>	140061371	<b>Geometry</b>	(CT)	<b>"t" (MSI)</b>	10.60	<b>Precrack Pmax (lbf)</b>	525.0
<b>Other Specimen ID</b>	CP-406-203	<b>"W" (in)</b>	1.0000	<b>"E" (MSI)</b>	11.15	<b>Precrack Final "a" (in)</b>	0.5370
<b>Operator</b>	Charles Kay	<b>"B" (in)</b>	0.5000	<b>% diff E &amp; E<sub>0</sub></b>	2.60	<b>Stress Ratio</b>	0.20
<b>Test Date</b>	4/11/2014	<b>"Ba" (in)</b>	0.3970	<b>"v"</b>	0.30	<b>Kmax (ksi_sqt_in)</b>	8.00
<b>Environment</b>	Air	<b>"Bb" (in)</b>	0.4760	<b>"YS" (KSI)</b>	37.50		
<b>Temperature (°F)</b>	73	<b>Orientation</b>	5-T	<b>"UTS" (KSI)</b>	60.20	<b>A<sub>ap</sub> (in)</b>	0.5370
<b>Pressure (PSIG)</b>	0	<b>"a<sub>0</sub>" (in)</b>	0.4010	<b>Flow Stress (KSI)</b>	79.87	<b>A<sub>aq</sub> (in)</b>	0.5369
<b>Relative Humidity (%)</b>	NA	<b>Hole Span/2 "H" (in)</b>	0.3550	<b>"E"/"YS"</b>	0.28	<b>A<sub>tp</sub> (in)</b>	0.6196
<b>Soak Time (min)</b>	0	<b>COD Span/2 "D" (in)</b>	0.0990			<b>A<sub>lq</sub> (in)</b>	0.6184
		<b>Coupon #</b>	M1				

<b>Results</b>	<b>J<sub>q</sub> (in<sup>3</sup>/ft<sup>2</sup>)</b>	<b>J<sub>q</sub> (in<sup>3</sup>/ft<sup>2</sup>)</b>	<b>J<sub>q</sub> (in<sup>3</sup>/ft<sup>2</sup>)</b>	<b>K<sub>Iq</sub> (ksi√in)</b>	<b>K<sub>Iq</sub> at J<sub>q</sub> (ksi√in)</b>	<b>K<sub>I</sub> (ksi√in)</b>	<b>K<sub>I</sub> Req Ligament (in)</b>	<b>Pmax/Pq</b>
	62.20	55.00	7.30	20.92	25.32	21.11	0.792	1.41

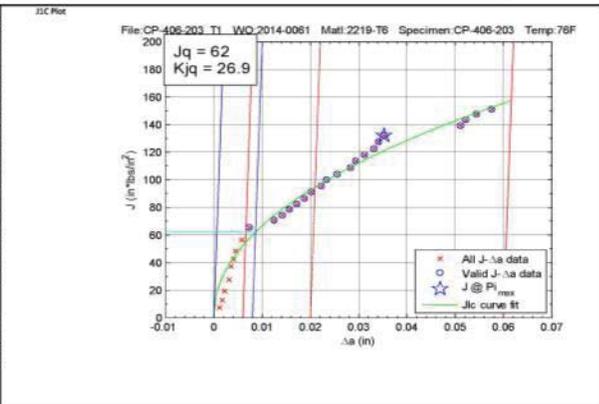
**Summary of Test Validity Required for All Tests:**

7.4.5.1	Initial precrack force	P < P <sub>m</sub> for sample type	Valid
7.4.5.1	Initial Kmax	< 40% of Precrack YS	Valid
7.4.5.2	Final Kmax	< 50% of K <sub>residual</sub>	Valid
8.1.4.1	Precrack straightness	None > 0.050	Valid
7.4.5.1	Precrack length	< 0.05B or 0.05in, wide match	Valid
7.5	Side groove depth	< 0.25B	Valid

**Summary of Test Validity Required for J<sub>Ic</sub>:**

7.4.2	a/W Range for J	0.45 < a/W < 0.7	Valid
8.1.5.1	Even Crack Ext.	None < 50% of avg crk ext.	Valid
8.1.5.2	Accuracy of crk ext. pred.	Diff < 0.15 d <sub>ap</sub>	Valid
A8.4.1	J <sub>q</sub> pts in region A	If pts = 3 in A	Valid
A8.4.2	J <sub>q</sub> pts in region B	If pts = 1 in B	Valid
A8.6.6	Valid J <sub>q</sub> data	If pts = 5	Valid
A8.8.1	J <sub>q</sub> fit coeff C2	C2 < 3.0	Valid
A8.8.2	Accuracy of J <sub>q</sub> fit	J <sub>q</sub> - J <sub>q,fit</sub>   < 0.01W or 0.5mm	Valid
A8.8.2.1	Mean pts in a <sub>ap</sub> fit	If points = 8	Valid
A8.8.2.2	σ <sub>a<sub>ap</sub></sub> fit B <sup>3/2</sup>	B <sup>3/2</sup> > 8.96	Valid
A8.9.1	Thickness requirement	B > 10J <sub>q</sub> /Flow Stress	Valid
A8.9.2	Ligament requirement	b <sub>o</sub> > 3J <sub>q</sub> /Flow Stress	Valid
A8.9.3	Regression line slope	Slope < flow at d <sub>o</sub> q	Valid

All validity criteria for J<sub>Ic</sub> NOT met. J<sub>q</sub> is not fully valid J<sub>Ic</sub>.  
Non-valid J<sub>q</sub> values may still convey valuable fracture toughness information.



Method File:  
FTA\_NJT  
Comments:  
N/A

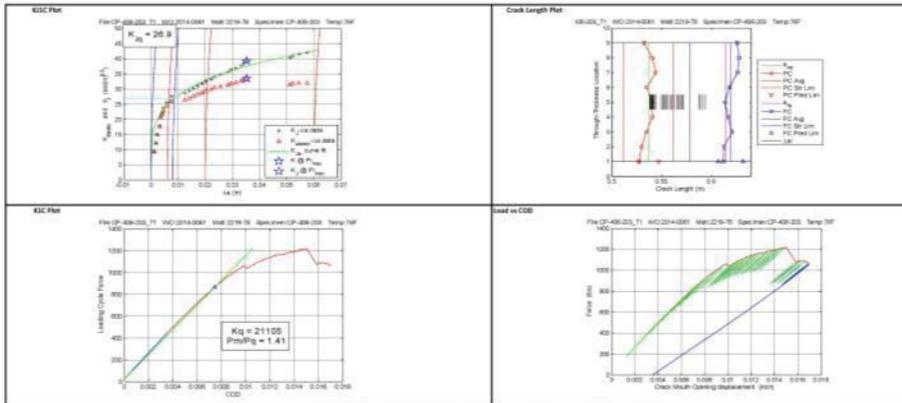


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



<b>EM10 Specimen ID</b>	140061371
<b>Other Specimen ID</b>	CP-406-203
<b>Operator</b>	Charles Kay
<b>Test Date</b>	4/11/2014





# NASA Engineering and Safety Center Technical Assessment Report

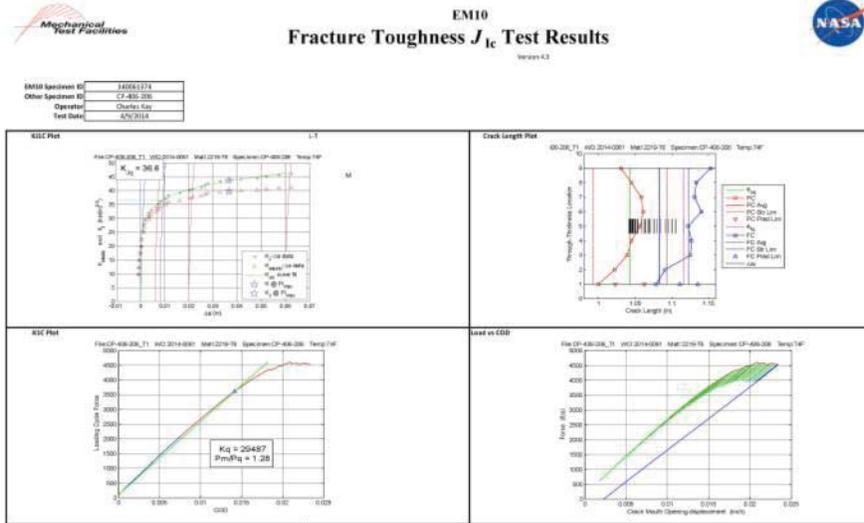
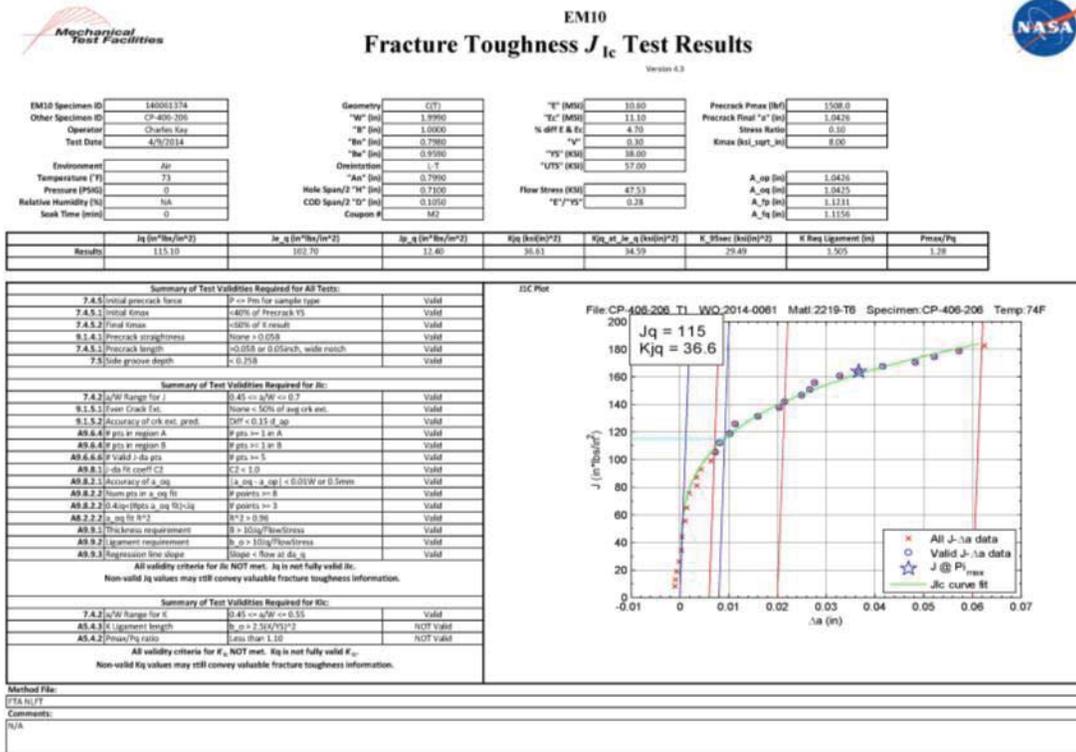
Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
194 of 223





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
195 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 140061376	Geometry: CT	"W" (in): 10.60	Precrack Pmax (lbf): 1500.0
Other Specimen ID: CP-406-208	"W" (in): 2.0000	"E" (in): 10.60	Precrack Final "a" (in): 1.0134
Operator: Charles King	"B" (in): 0.9760	% diff E & E1: 0.00	Stress Ratio: 0.10
Test Date: 4/9/2014	"B" (in): 0.7960	"Y" (in): 0.30	Kmax (ksi): 9.00
	"B" (in): 0.9570	"YS" (ksi): 38.00	
Environment: Air	Orientation: L-T	"UTS" (ksi): 57.00	A <sub>10g</sub> (in): 1.0134
Temperature (°F): 73	"A" (in): 0.8000	Flow Stress (ksi): 47.53	A <sub>10g</sub> (in): 0.9937
Pressure (PSIG): 0	Hole Span/2 "H" (in): 0.7100	"E"/"YS": 0.28	A <sub>1p</sub> (in): 1.0827
Relative Humidity (%): NA	COD Span/2 "D" (in): 0.1050		A <sub>1q</sub> (in): 1.0538
Soak Time (min): 0	Coupon #: M2		

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi√in)	$K_{Ic}$ at $J_{Ic}$ (ksi√in)	K <sub>15sec</sub> (ksi√in)	δ Req Ligament (in)	Pmax/Pq
	113.80	99.90	13.50	36.25	34.03	30.46	1.907	1.28

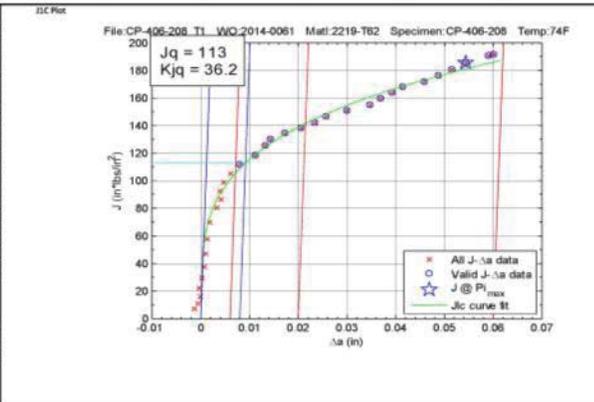
Summary of Test Validities Required for All Tests:

7.4.5.1 Initial precrack force	$P < P_m$ for sample type	Valid
7.4.5.2 Initial Kmax	<40% of Precrack YS	Valid
7.4.5.3 Final Kmax	<50% of $K_{max}$ result	Valid
8.1.4.2 Precrack straightness	None > 0.050	Valid
7.4.5.4 Precrack length	$\pm 0.050$ or 0.05crack, wider match	Valid
7.5.1 Side groove depth	< 0.25B	Valid

Summary of Test Validities Required for  $J_{Ic}$ :

7.4.2.1 a/W Range for $J_{Ic}$	$0.45 \leq a/W \leq 0.7$	Valid
8.1.5.1 Even Crack Ext.	None < 50% of avg crk ext.	Valid
8.1.5.2 Accuracy of crk ext. prof.	$Diff < 0.15 \cdot d_{avg}$	Valid
A9.6.4.1 $P_{max}$ in region A	$P_{max} \geq 1 \text{ an } A$	Valid
A9.6.4.2 $P_{max}$ in region B	$P_{max} \geq 1 \text{ an } B$	Valid
A9.6.6.1 $P_{max}$ valid $J_{Ic}$ data	$P_{max} \geq 5$	Valid
A9.8.1.1 $J_{Ic}$ data fit coeff $C2$	$C2 < 3.0$	Valid
A9.8.1.2 Accuracy of $J_{Ic}$ data	$ J_{Ic} - J_{Ic,fit}  < 0.01W$ or 0.5mm	Valid
A9.8.2.1 $J_{Ic}$ points in $J_{Ic}$ fit	$J_{Ic}$ points $\geq 8$	Valid
A9.8.2.2 $J_{Ic}$ slope (fits a. avg $J_{Ic}$ )	$J_{Ic}$ points $\geq 3$	Valid
A9.8.2.3 $J_{Ic}$ slope (fits a. avg $J_{Ic}$ )	$R^2 > 0.98$	Valid
A9.8.3.1 Thickness requirement	$B \geq 10(J_{Ic}/\text{FlowStress})$	Valid
A9.8.3.2 Ligament requirement	$B \geq 2.5(J_{Ic}/\text{FlowStress})$	Valid
A9.8.3.3 Regression line slope	Slope < flow at $d_{Ic}$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-valid  $J_{Ic}$  values may still convey valuable fracture toughness information.



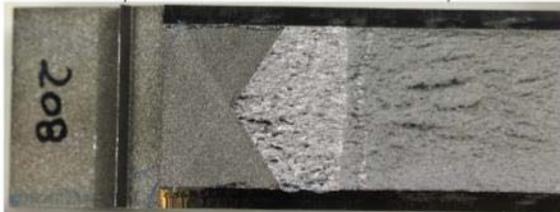
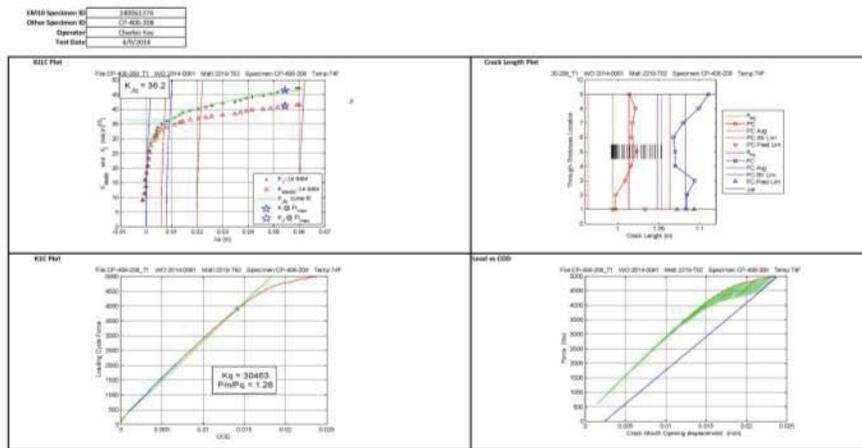
Method File: JIc\_1017

Comments: N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
196 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

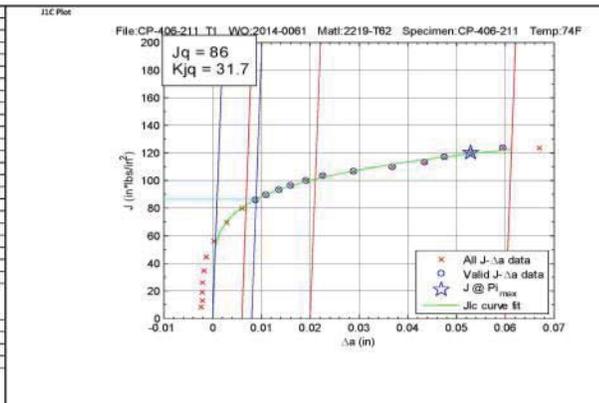
Version 4.3



EM10 Specimen ID	140061379	Geometry	CT	"E" (MSI)	10.69	Precrack Pmax (lbf)	1510.0
Other Specimen ID	CP-406-211	"W" (in)	3.0000	"Ec" (MSI)	11.113	Precrack Final "a" (in)	1.0415
Operator	Charles Kay	"B" (in)	0.9980	% diff E & Ec	5.00	Stress Ratio	0.10
Test Date	4/9/2014	"Bn" (in)	0.7980	"N"	0.30	Kmax (ksi_sqr_in)	8.00
Environment	Air	"Bc" (in)	0.9380	"Np" (KSI)	37.80		
Temperature (°F)	73	Orientation	T-L	"UTS" (KSI)	57.30	A_op (in)	1.0415
Pressure (PSIG)	0	"An" (in)	0.7980	Flow Stress (KSI)	47.40	A_oq (in)	1.0450
Relative Humidity (%)	106	Hole Span/2 "H" (in)	0.7100	"r"/"vs"	0.28	A_sp (in)	1.1247
Soak Time (min)	0	COD Span/2 "D" (in)	0.1050			A_w (in)	1.1131
		Coupon #	MS				

Results	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lb <sup>3/2</sup> )	$K_{Ic}$ (ksi/in <sup>3/2</sup> )	$K_{Ic}$ at $J_{Ic}$ (ksi/in <sup>3/2</sup> )	K 95sec (ksi/in <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	86.20	78.60	7.60	31.69	30.26	27.61	1.334	1.14

Summary of Test Validities Required for All Tests:	
7.4.5 Initial precrack force	P < Pm for sample type
7.4.5.1 Initial Kmax	< 60% of Precrack YS
7.4.5.2 Final Kmax	< 60% of K result
8.1.4.1 Precrack straightness	None > 0.05B
7.4.5.3 Precrack length	> 0.05B or 0.05in, wide notch
7.5 Side groove depth	< 0.25B
Summary of Test Validities Required for $J_{Ic}$ :	
7.4.2 $a/W$ Range for J	0.45 <= a/W <= 0.7
9.1.5.1 Initial Crk Len.	None < 50% of avg crk est.
9.1.5.2 Accuracy of crk est. prec.	Diff < 0.15 of avg
A9.6.4 If pts in region A	If pts >= 1 in A
A9.6.4 If pts in region B	If pts >= 1 in B
A9.6.4 If valid > 4B pts	If pts >= 5
A9.8.1 - da/dN coeff C2	C2 < 1.0
A9.8.2.1 Accuracy of $a_{oq}$	a_oq - a_opt  < 0.01W or 0.5mm
A9.8.2.2 Num pts in $a_{oq}$ fit	If points >= 8
A9.8.2.2 $d(a_{oq})/pts$ $a_{oq}$ fit	If points >= 3
A9.8.2.2 $d(a_{oq})/pts$ $a_{oq}$ fit	C2 < 0.5
A9.9.1 Thickness requirement	B > 10(a <sub>oq</sub> ) <sup>2</sup> /FlowStress
A9.9.2 Ligament requirement	B > 10(a <sub>oq</sub> ) <sup>2</sup> /FlowStress
A9.9.3 Regression line slope	Slope < flow at $d_{oq}$
All validity criteria for Jc NOT met. Jc is not fully valid Jc.	
Non-valid Jc values may still convey valuable fracture toughness information.	
Summary of Test Validities Required for K <sub>Ic</sub> :	
7.4.2 $a/W$ Range for K	0.45 <= a/W <= 0.55
A5.4.3 K Ligament length	B > 2.5(a <sub>oq</sub> ) <sup>2</sup>
A5.4.2 Pmax/Pq ratio	Less than 1.10
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .	
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.	

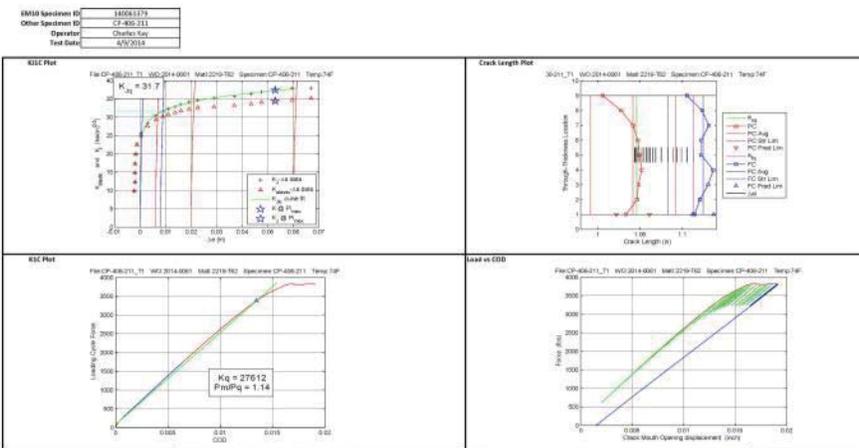


Method File: FTA.H1.FT  
Comments: N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
197 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001383	Geometry	CTT	"E" (ksi)	10.60	PreCrack Pmax (lbf)	1313.0
Other Specimen ID	CP-406-213	"W" (in)	2.0010	"Ee" (ksi)	10.60	PreCrack Final "a" (in)	1.8333
Operator	Charles Kay	"B" (in)	0.9980	% diff E & Ee	0.00	Stress Ratio	0.10
Test Date	4/9/2014	"b0" (in)	0.7980	"W"	0.90	Kmax (ksi_sqr_in)	8.00
Environment	Air	"b1" (in)	0.9580	"YS" (ksi)	37.80		
Temperature (°F)	73	Orientation	T-1	"UTS" (ksi)	57.30	A_op (in)	1.0331
Pressure (PSIG)	0	"a0" (in)	0.8010	Flow Stress (ksi)	47.50	A_w (in)	1.0150
Relative Humidity (%)	NA	Hole Spn/2 "D" (in)	0.7100	"E"/"YS"	0.28	A_tp (in)	1.1152
Soak Time (min)	0	COO Spn/2 "D" (in)	0.1050			A_tq (in)	1.0875
		Crackon #	M3				

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi/in <sup>3/2</sup> )	$K_{Ic}$ at $J_{Ic}$ (ksi/in <sup>3/2</sup> )	$K_{Ic}$ (ksi/in <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	91.00	81.60	8.40	32.50	30.83	27.81	1.351	1.19

Summary of Test Validities Required for All Tests:

7.4.5.1	Initial precrack force	$P \leq P_m$ for sample type	Valid
7.4.5.1	Initial Kmax	$\pm 40\%$ of Precrack YS	Valid
7.4.5.2	Final Kmax	$\pm 80\%$ of K result	Valid
5.1.4.1	Precrack straightness	None $> 0.05\%$	Valid
7.4.1.1	Precrack length	$\pm 0.058$ or $0.65$ inch, wide notch	Valid
7.5	Side groove depth	$\pm 0.258$	Valid

Summary of Test Validities Required for  $J_{Ic}$ :

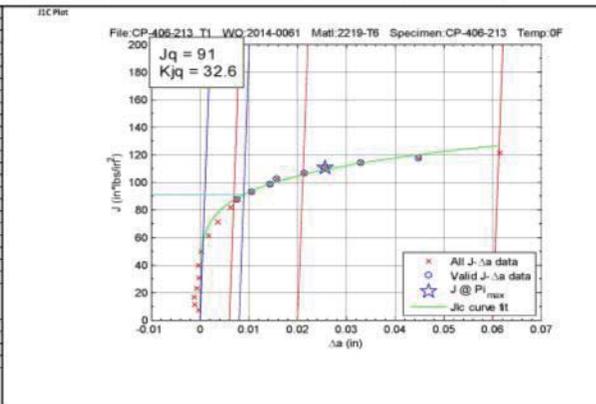
7.4.2	a/W Range for k	$0.45 \leq a/W \leq 0.7$	Valid
9.1.5.1	Even Crack Ext.	None $< 50\%$ of avg crk ext.	Valid
9.1.5.2	Accuracy of crk ext. pred.	Diff $< 0.13$ d_op	Valid
A9.4.4	g vs a region A	If g vs a = 1 or A	Valid
A9.4.4	g vs a region B	If g vs a = 1 or B	Valid
A9.4.6	Valid J-da g vs a	If g vs a = 5	Valid
A9.8.1	J-da fit coeff C2	$C2 \geq 1.0$	Valid
A9.8.2	Accuracy of a_0	$ a_0 - a_0 \text{ app}  < 0.01W$ or $0.5$ mm	Valid
A9.8.2.2	Num g vs a_0 fit	If points = 8	Valid
A9.8.2.2	0.45a_0 - 0.5a_0 fit	If points = 3	Valid
A9.2.2.2	a_0 fit R^2	$R^2 \geq 0.95$	Valid
A9.9.1	Thickness requirement	$B \geq 10(J_{Ic}/\text{Flow Stress})$	Valid
A9.9.2	Ligament requirement	$B \geq 10(J_{Ic}/\text{Flow Stress})$	Valid
A9.9.3	Regression line slope	Slope $< \text{Flow at da}_0$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-void  $J_{Ic}$  values may still convey valuable fracture toughness information.

Summary of Test Validities Required for  $K_{Ic}$ :

7.4.2	a/W Range for k	$0.45 \leq a/W \leq 0.55$	Valid
A5.4.3	Ligament length	$B \geq 2.5(J_{Ic}/Y^2)$	NOT valid
A5.4.3	Pmax/Pq ratio	Ratio $\geq 1.10$	NOT valid

All validity criteria for  $K_{Ic}$  NOT met.  $K_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non-void  $K_{Ic}$  values may still convey valuable fracture toughness information.



Method File: C:\A\107  
Comments: N/A

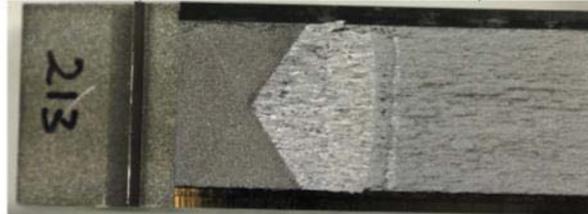
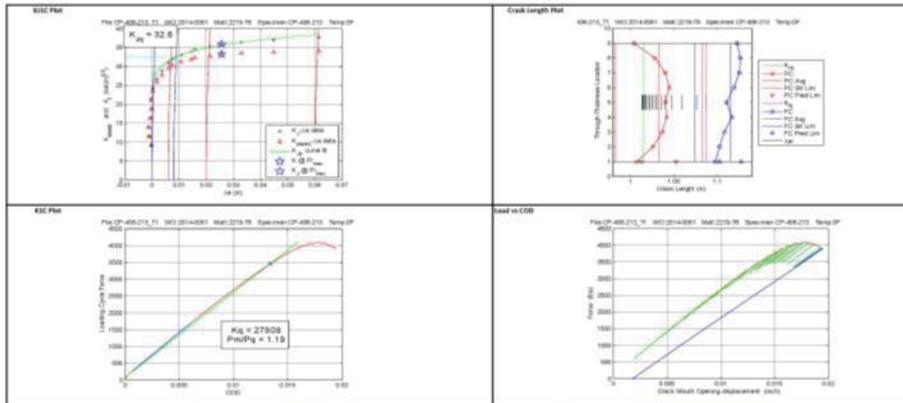


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001383
Other Specimen ID	CP-406-213
Operator	Charles Kay
Test Date	6/9/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
198 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.0



EM10 Specimen ID	140001354
Other Specimen ID	CP-406-216
Operator	Charles Kay
Test Date	4/3/2014
Environment	Air
Temperature (T)	70
Pressure (PPHG)	0
Relative Humidity (RH)	N/A
Soak Time (min)	0

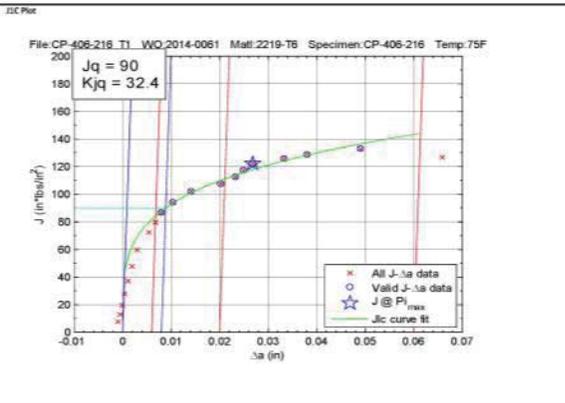
Geometry	CTT
"W" (in)	1.0000
"B" (in)	0.5020
"B <sub>0</sub> " (in)	0.4000
"B <sub>1</sub> " (in)	0.4800
Orientation	S-T
"A <sub>0</sub> " (in)	0.4020
Hole Span/2 "H" (in)	0.3550
CCD Span/2 "D" (in)	0.1000
Coupon #	M2

"E" (Msi)	10.60
"E <sub>c</sub> " (Msi)	10.60
% diff E & E <sub>c</sub>	0.00
"N"	0.30
"K <sub>1C</sub> " (ksi)	41.40
"UTS" (ksi)	59.80
Flow Stress (ksi)	30.58
"E"/"YS"	256.00

Precrack Pmax (lbf)	409.8
Precrack Final "a" (in)	0.5197
Stress Ratio	6.00
Kmax (ksi√in)	8.00
A <sub>0p</sub> (in)	0.5197
A <sub>0q</sub> (in)	0.5184
A <sub>0r</sub> (in)	0.5211
A <sub>0</sub> (in)	0.5843

Results	$J_q$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{e,q}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{p,q}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Iq}$ (ksi√in)	$K_{Iq,c}$ (ksi√in)	$K_{Iq,sec}$ (ksi√in)	K Req Ligament (in)	Pmax/Pq
	89.90	73.80	35.30	32.30	29.32	21.30	0.674	1.58

Summary of Test Validities Required for All Tests:			
7.4.3.1	Initial precrack force	P <= Pm for sample type	Valid
7.4.5.1	Initial time	> 40% of PreCrack VS	Valid
7.4.5.2	Final time	< 50% of K result	Valid
8.1.4.1	PreCrack straightness	None > 0.05B	Valid
7.4.5.3	PreCrack length	+0.05B or 0.05crack, wide match	Valid
7.5	Side groove depth	< 0.25B	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :			
7.4.2.1	a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1	Open Crack Init.	None < 50% of ang/crk ext.	Valid
9.1.5.2	Accuracy of crk ext. prod.	DOF < 0.15 d <sub>ap</sub>	Valid
A9.6.4	# pts in region A	# pts >= 1 in A	Valid
A9.6.4	# pts in region B	# pts >= 1 in B	Valid
A9.6.4	# valid > d <sub>0</sub> pts	# pts >= 5	Valid
A9.8.1	-da/dN coeff C2	C2 < 1.0	Valid
A9.8.2.1	Accuracy of a <sub>0q</sub>	a <sub>0q</sub> - a <sub>0p</sub>   < 0.01W or 0.5mm	Valid
A9.8.2.2	Num pts in a <sub>0q</sub> fit	# points >= 8	Valid
A9.8.2.3	Accn/Region or use R <sup>2</sup> /J <sub>Ic</sub>	# points >= 3	Valid
A9.2.2.1	a <sub>0</sub> fit R <sup>2</sup>	R <sup>2</sup> > 0.98	Valid
A9.9.1	Thickness requirements	B > 10log(FlowStress)	Valid
A9.9.2	Ligament requirements	b <sub>0</sub> > 10log(FlowStress)	Valid
A9.9.3	Regression line slope	Slope < flow at d <sub>0</sub> , J <sub>Ic</sub>	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .			
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for K <sub>Ic</sub> :			
7.4.2.1	a/W Range for K <sub>Ic</sub>	0.45 <= a/W <= 0.55	Valid
A5.4.3	Ligament length	b <sub>0</sub> > 2.5(a <sub>0</sub> /YS) <sup>2</sup>	NOT Valid
A5.4.2	Pmax/Pq ratio	Less than 1.50	NOT Valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .			
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.			



Method File:  
FTA.NLFT  
Comments:  
N/A

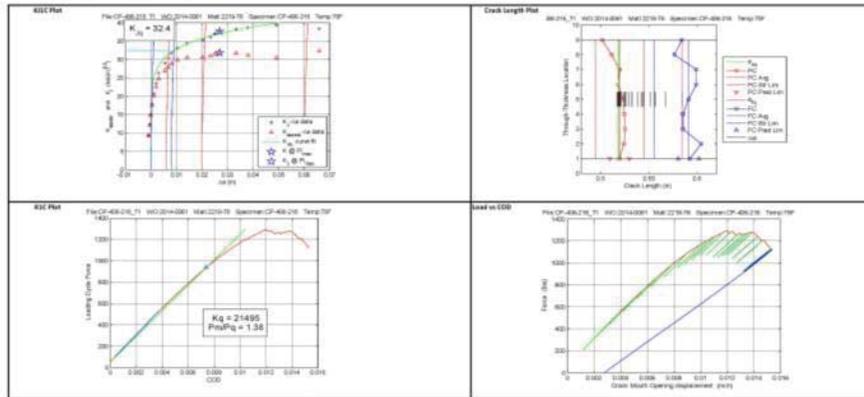


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.0



EM10 Specimen ID	140001354
Other Specimen ID	CP-406-216
Operator	Charles Kay
Test Date	4/3/2014





# NASA Engineering and Safety Center Technical Assessment Report

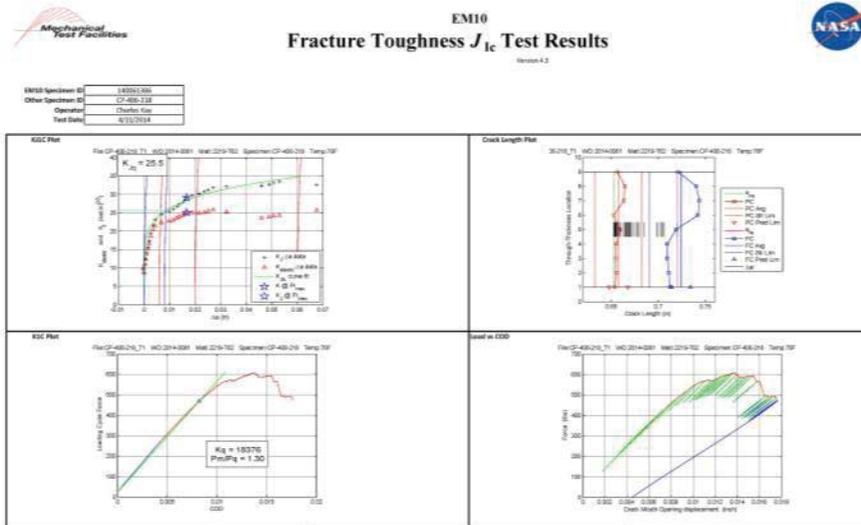
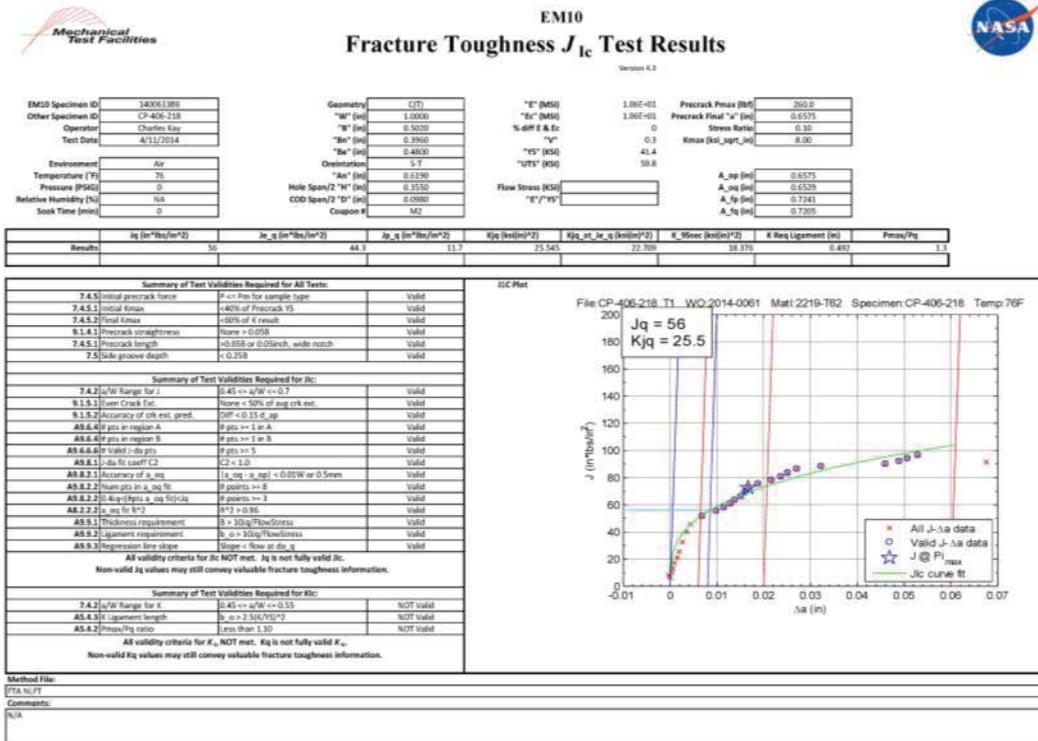
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
199 of 223





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
200 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 140061389	Geometry: CT	"t" (MSI): 10.60	Precrack Pmax (lbf): 1523.0
Other Specimen ID: CP-405-221	"W" (in): 2.0000	"t <sub>c</sub> " (MSI): 10.60	Precrack Final "a" (in): 1.0256
Operator: Charles Kay	"H" (in): 0.9960	% diff t & t <sub>c</sub> : 0.00	Stress Ratio: 0.10
Test Date: 4/9/2014	"B <sub>n</sub> " (in): 0.7960	"V": 0.30	Kmax (ksi_sqr_in): 8.00
Environment: Air	"B <sub>w</sub> " (in): 0.9570	"YS" (KSI): 37.30	A <sub>op</sub> (in): 1.0256
Temperature (°F): 73	Orientation: L-T	"UTS" (KSI): 55.20	A <sub>eq</sub> (in): 1.0083
Pressure (PSIG): 0	"K <sub>1c</sub> " (ksi): 0.7960	Flow Stress (KSI): 46.26	A <sub>tp</sub> (in): 1.1092
Relative Humidity (%): NA	Hole Span/2 "H" (in): 0.7100	"E"/"YS": 0.28	A <sub>iq</sub> (in): 1.0824
Soak Time (min): 0	COD Span/2 "D" (in): 0.1040		
	Coupon #: M3		

Results	J <sub>q</sub> (in <sup>3</sup> /lb-in <sup>2</sup> ): 117.20	J <sub>e</sub> (in <sup>3</sup> /lb-in <sup>2</sup> ): 102.70	J <sub>p</sub> (in <sup>3</sup> /lb-in <sup>2</sup> ): 14.50	K <sub>Iq</sub> (ksi√in): 36.95	K <sub>Iq</sub> at J <sub>e</sub> (ksi√in): 34.59	K <sub>I</sub> 0.5sec (ksi√in): 29.79	K <sub>I</sub> Req Ligament (in): 1.994	Pmax/Pq: 1.26
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Summary of Test Validities Required for All Tests:

7.4.5 Initial precrack force	P <= Pm for sample type	Valid
7.4.5.1 Initial Kmax	<40% of Precrack YS	Valid
7.4.5.2 Final Kmax	<50% of K result	Valid
9.1.4.1 Precrack straightness	None > 0.050	Valid
7.4.5.3 Precrack length	<0.05B or 0.05inch, wide match	Valid
7.5 Side groove depth	< 0.25B	Valid

Summary of Test Validities Required for J<sub>q</sub>:

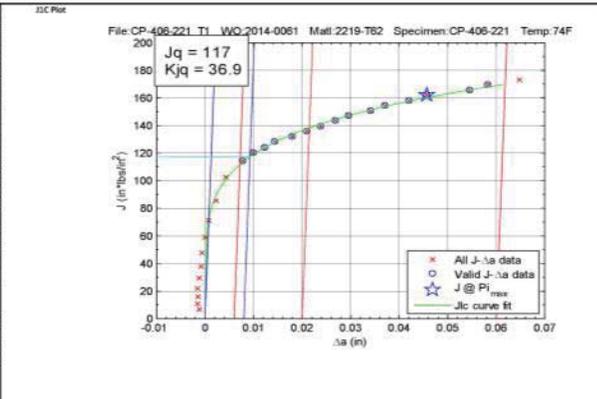
7.4.2 a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1 Even Crack Ext.	None < 50% of avg crk ext.	Valid
9.1.5.2 Accuracy of crk ext. pred.	Diff < 0.15 g ap	Valid
A0.6.4 # pts in region A	# pts = 3 in A	Valid
A0.6.4 # pts in region B	# pts = 3 in B	Valid
A0.6.6 # Valid J-da pts	# pts = 5	Valid
A0.8.1 J-da fit coeff R <sup>2</sup>	R <sup>2</sup> > 0.99	Valid
A0.8.2.1 Accuracy of a <sub>0</sub> eq fit	a <sub>0</sub> eq - a <sub>0</sub> eq  < 0.01W or 0.5mm	Valid
A0.8.2.2 Num pts at a <sub>0</sub> eq fit	# points = 8	Valid
A0.8.2.3 a <sub>0</sub> eq fit slope	# points = 3	Valid
A0.8.2.4 a <sub>0</sub> eq fit R <sup>2</sup>	R <sup>2</sup> > 0.96	Valid
A0.9.1 Thickness requirement	B > 30g/Flow Stress	Valid
A0.9.2 Ligament requirement	B <sub>0</sub> > 30g/Flow Stress	Valid
A0.9.3 Regression line slope	Slope < flow at da <sub>0</sub>	Valid

All validity criteria for J<sub>q</sub> NOT met. J<sub>q</sub> is not fully valid J<sub>q</sub>.  
Non-valid J<sub>q</sub> values may still convey valuable fracture toughness information.

Summary of Test Validities Required for K<sub>Iq</sub>:

7.4.2 a/W Range for K	0.45 <= a/W <= 0.55	Valid
A0.4.2 Ligament length	B <sub>0</sub> > 2.5A/(YS) <sup>2</sup>	NOT valid
A0.4.2 Precr/P <sub>q</sub> ratio	Less than 1.10	NOT valid

All validity criteria for K<sub>Iq</sub> NOT met. K<sub>Iq</sub> is not fully valid K<sub>Iq</sub>.  
Non-valid K<sub>Iq</sub> values may still convey valuable fracture toughness information.

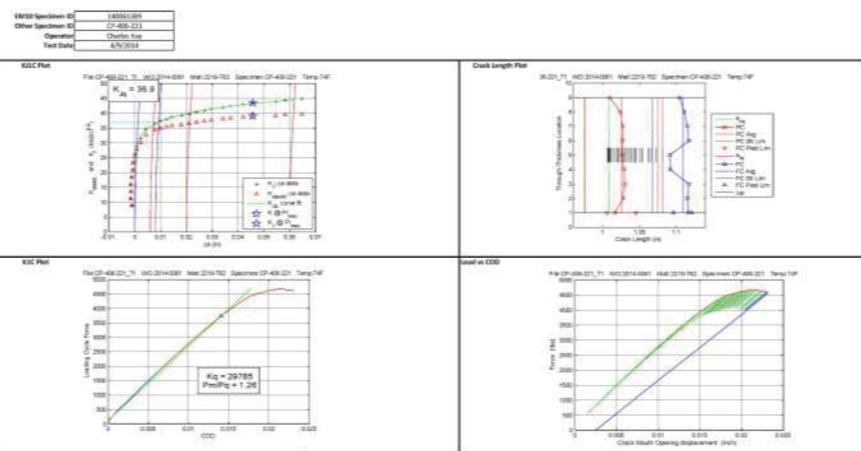


Method File: FTANIT  
Comments: N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.2





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
201 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061391
Other Specimen ID	CP-406-223
Operator	Charles Kay
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

Geometry	(CT)
"W" (in)	2.0000
"B" (in)	1.0000
"Ba" (in)	0.7990
"Bb" (in)	0.9600
Orientation	L-T
"a0" (in)	0.7990
Hole Span/2 "H" (in)	0.7100
COD Span/2 "D" (in)	0.1050
Coupon #	M3

"E" (ksi)	10600000.00
"E <sub>c</sub> " (ksi)	10600000.00
% diff E & E <sub>c</sub>	0.00
"ν"	0.30
"YS" (ksi)	37300.00
"UTS" (ksi)	55200.00
Flow Stress (ksi)	46.25
"E"/"YS"	0.28

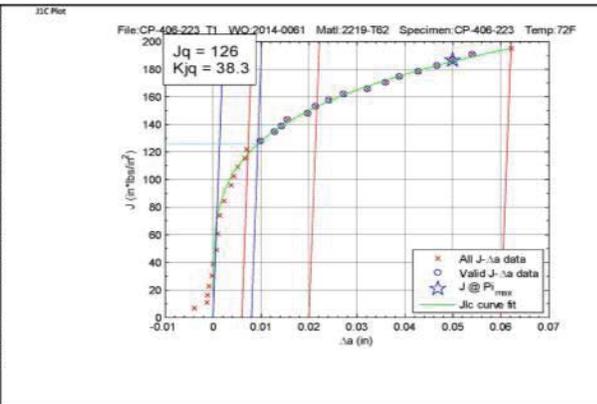
Precrack Pmax (lbf)	1518.0
Precrack Final "a" (in)	1.0391
Stress Ratio	0.20
Kmax (ksi√in)	8.00
A <sub>ap</sub> (in)	1.0391
A <sub>aq</sub> (in)	1.0239
A <sub>ap</sub> (in)	1.1235
A <sub>aq</sub> (in)	1.1022

Results	$J_q$ (in <sup>3</sup> /in <sup>2</sup> )	$J_q$ (in <sup>3</sup> /in <sup>2</sup> )	$J_q$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi√in)	$K_{Ic}$ at $J_q$ (ksi√in)	K (ksi√in)	K Req Ligament (in)	Pmax/Pq
	175.70	109.30	16.40	38.27	35.68	37.51	1.899	1.19

Summary of Test Validity Required for All Tests:			
7.4.5.1	Initial precrack force	P < Pm for sample type	Valid
7.4.5.1	Initial Kmax	< 80% of Precrack YS	Valid
7.4.5.2	Final Kmax	< 50% of K result	Valid
8.1.4.1	Precrack straightness	None > 0.050	Valid
7.4.5.1	Precrack length	< 0.05B or 0.05in, wide match	Valid
7.5	Side groove depth	< 0.25B	Valid

Summary of Test Validity Required for J <sub>Ic</sub> :			
7.4.2.1	a/W Range for J	0.45 < a/W < 0.7	Valid
9.1.5.1	Even Crack Ext.	None < 50% of avg crk ext.	Valid
9.1.5.2	Accuracy of crk ext. pred.	Diff < 0.15 d ap	Valid
A5.4.4	g pos in region A	g pos = 2 in A	Valid
A5.4.4	g pos in region B	g pos = 1 in B	Valid
A5.6.6	Valid J-da pos	g pos = 5	Valid
A5.8.3	J-da fit coeff C2	C2 < 3.0	Valid
A5.8.2.1	Accuracy of a <sub>avg</sub>	a <sub>avg</sub> - a <sub>avg</sub>   < 0.01W or 0.5mm	Valid
A5.8.2.2	Mean pos in a <sub>avg</sub> fit	g points = 8	Valid
A5.8.2.2	0.4a <sub>avg</sub> /B > a <sub>avg</sub> fit	g points = 3	Valid
A5.8.2.2	a <sub>avg</sub> fit R <sup>2</sup>	R <sup>2</sup> > 0.98	Valid
A5.9.1	Thickness requirement	B > 10Jq/flowStress	Valid
A5.9.2	Ligament requirement	b <sub>o</sub> > 10Jq/flowStress	Valid
A5.9.3	Regression line slope	Slope < flow at a <sub>avg</sub>	Valid

All validity criteria for J<sub>Ic</sub> NOT met. J<sub>Ic</sub> is not fully valid J<sub>Ic</sub>.  
Non-valid J<sub>Ic</sub> values may still convey valuable fracture toughness information.



Method File:  
CTA.NJT  
Comments:  
N/A

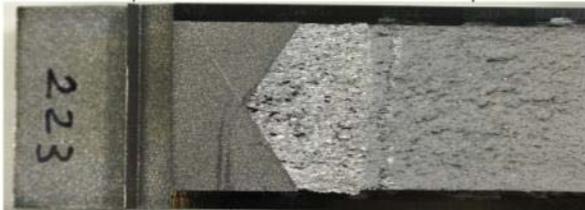
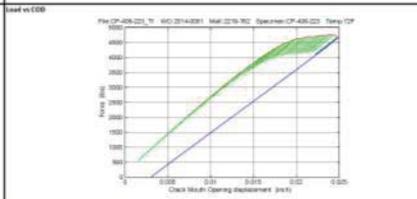
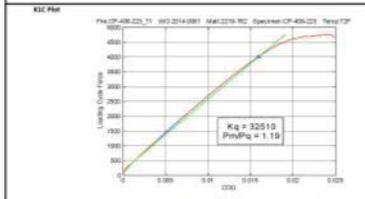
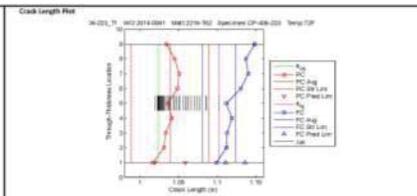
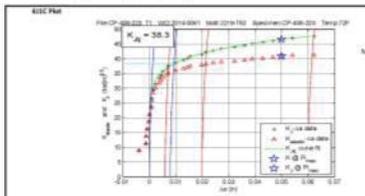


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061391
Other Specimen ID	CP-406-223
Operator	Charles Kay
Test Date	4/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
202 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 160261194	Geometry: (CT)	"E" (MS): 10.00	PreCrack Press (lbf): 1326.0
Other Specimen ID: CP-406-226	"W" (in): 1.9980	"E <sub>c</sub> " (MS): 10.72	PreCrack Final "a" (in): 1.0535
Operator: Charles Kay	"B" (in): 0.9980	% diff E & E <sub>c</sub> : 1.10	Stress Ratio: 0.10
Test Date: 4/10/2014	"B <sub>h</sub> " (in): 0.8010	"r": 0.30	K <sub>max</sub> (ksi <sub>sqrt</sub> in): 8.00
Environment: Air	"B <sub>h</sub> " (in): 0.9980	"V <sub>0</sub> " (MS): 37.10	
Temperature (°F): 73	Orientation: T, L	"V <sub>05</sub> " (MS): 33.90	
Pressure (PSIG): 0	"A <sub>h</sub> " (in): 0.7990	Flow Stress (ksi): 48.10	A <sub>0p</sub> (in): 1.0555
Relative Humidity (%): NA	Hole Span/2 "W" (in): 0.7300	"E"/"V <sub>0</sub> ": 0.29	A <sub>0q</sub> (in): 1.0790
Soak Time (min): 0	CCD Span/2 "D" (in): 0.1050		A <sub>1p</sub> (in): 1.1424
	Crack #:		A <sub>1q</sub> (in): 1.1179

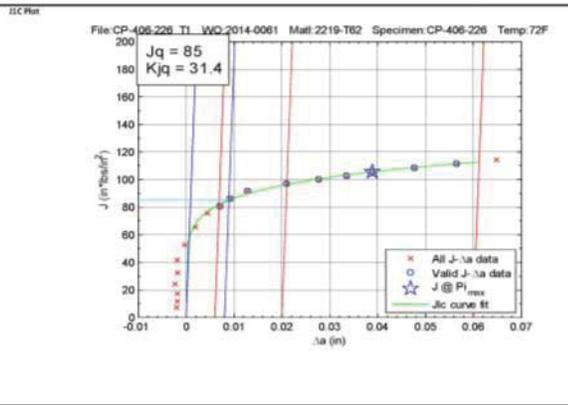
Results	$J_{Ic}$ (in <sup>3</sup> /lbm <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lbm <sup>3/2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lbm <sup>3/2</sup> )	$K_{Ic}$ (ksi <sup>1/2</sup> in <sup>3/2</sup> )	$K_{Ic}$ at $J_{Ic}$ (ksi <sup>1/2</sup> in <sup>3/2</sup> )	$K_{Ic}$ (ksi <sup>1/2</sup> in <sup>3/2</sup> )	# Req Ligament (in)	$P_{max}/P_q$
	84.90	76.70	8.20	31.45	29.88	28.04	1.479	1.12

Summary of Test Validities Required for All Tests:		
7.4.5 Initial precrack force	$P \leq P_{cr}$ for sample type	Valid
7.4.5.1 Initial tension	$\pm 40\%$ of precrack $V_0$	Valid
7.4.5.2 Final tension	$\pm 50\%$ of $K_{max}$	Valid
9.1.4.1 Precrack straightness	None $\pm 0.05\lambda$	Valid
7.4.5.1 Precrack length	$\pm 0.003$ or $0.01$ inch, wide notch	Valid
7.5 Side groove depth	$d \leq 0.25\lambda$	Valid

Summary of Test Validities Required for $J_{Ic}$ :		
7.4.2 $a_0/W$ Range for $J$	$0.45 \leq a_0/W \leq 0.7$	Valid
9.1.5.1 Open Crack Len.	None $\pm 50\%$ of avg. crack len.	Valid
9.1.5.2 Accuracy of crack ext. post.	$\pm 0.01$ in. or $\pm 0.01$ in.	Valid
A9.6.4 # pts in region A	# pts $\geq 3$ in A	Valid
A9.6.4 # pts in region B	# pts $\geq 3$ in B	Valid
A9.6.6 # valid $J$ data pts	# pts $\geq 3$	Valid
A9.8.1.1 $d_0$ fit coeff. C <sub>2</sub>	$C_2 \leq 1.0$	Valid
A9.8.2.1 Accuracy of $a_{0q}$	$ a_{0q} - a_{0p}  \leq 0.01W$ or $0.5$ mm	Valid
A9.8.2.2 Number of $a_{0q}$ fit	# points $\geq 8$	Valid
A9.8.2.3 $d_0$ vs. fit $R^2$	# points $\geq 3$	Valid
A9.8.2.4 $d_0$ vs. fit $R^2$	$R^2 \geq 0.95$	Valid
A9.9.1 Thickness requirement	$B \geq 10(a_0 + \text{flow stress})$	Valid
A9.9.2 Ligament requirement	$B \geq 10(a_0 + \text{flow stress})$	Valid
A9.9.3 Regression line slope	Slope $< \text{flow at } d_{0,q}$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non-valid  $J_{Ic}$  values may still convey valuable fracture toughness information.



Method File: FTA\_M10  
 Comments: N/A

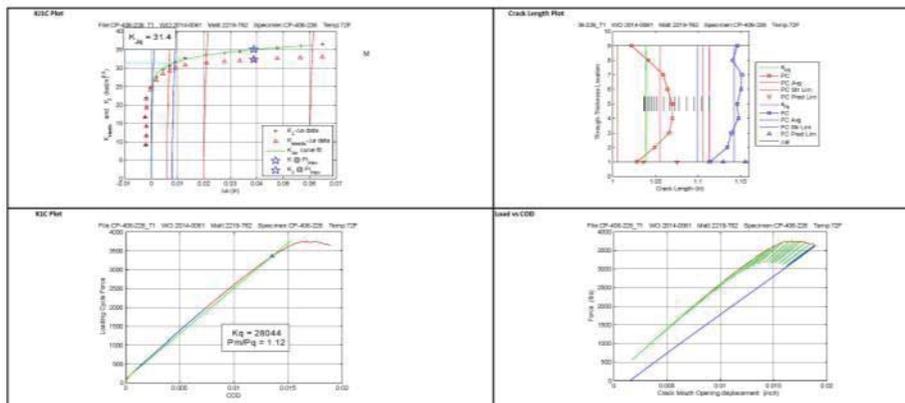


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 160261194
Other Specimen ID: CP-406-226
Operator: Charles Kay
Test Date: 6/25/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
203 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001396
Other Specimen ID	CP-406-228
Operator	Charles Kay
Test Date	4/15/2014
Environment	Air
Temperature (T)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

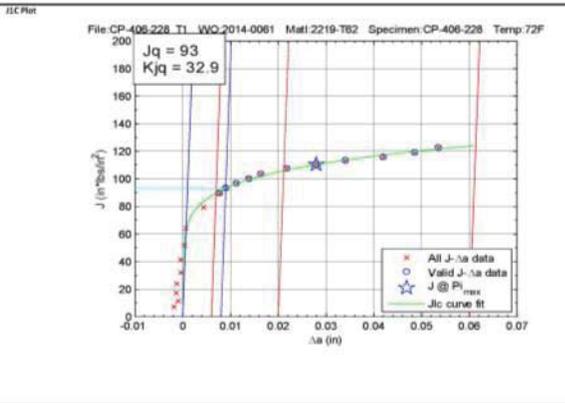
Geometry	CT
"W" (in)	2.0000
"B" (in)	0.9990
"B <sub>0</sub> " (in)	0.7990
"B <sub>1</sub> " (in)	0.9590
Orientation	T-L
"A <sub>0</sub> " (in)	0.7990
Hole Spacing "D" (in)	0.7990
COO Span/2 "D" (in)	0.3995
Coupon #	M1

"E" (Msi)	10.00
"Ec" (Msi)	10.02
% diff E & Ec	0.20
"v <sub>s</sub> " (ksi)	37.10
"v <sub>TS</sub> " (ksi)	55.10
Flow Stress (ksi)	48.10
"E"/"v <sub>s</sub> "	0.29

Precrack Pmax (lbf)	1530.0
Precrack Final "a" (in)	1.0576
Stress Ratio	0.10
Kmax (ksi√in)	8.00
A <sub>0P</sub> (in)	1.0526
A <sub>0Q</sub> (in)	1.0219
A <sub>0R</sub> (in)	1.1417
A <sub>0I</sub> (in)	1.1128

Results	J <sub>Ic</sub> (ksi√in) <sup>2</sup>	J <sub>Q</sub> (ksi√in) <sup>2</sup>	J <sub>P</sub> (ksi√in) <sup>2</sup>	K <sub>Ic</sub> (ksi√in) <sup>2</sup>	K <sub>IQ</sub> (ksi√in) <sup>2</sup>	K <sub>IP</sub> (ksi√in) <sup>2</sup>	K <sub>IQ</sub> Ligament (in)	Pmax/P <sub>Q</sub>
	93.10	91.70	10.49	32.93	31.03	28.37	1.407	1.15

Summary of Test Validities Required for All Tests:			
7.4.0	Initial precrack force	≥ 2σ <sub>TS</sub> for sample edge	Valid
7.4.5.1	Initial Kmax	≥ 40% of Precrack V <sub>S</sub>	Valid
7.4.5.2	Final Kmax	≥ 60% of K result	Valid
8.1.4.1	Precrack straightness	None > 0.05δ	Valid
7.4.5.3	Precrack length	< 0.018 or 0.015inch, wide notch	Valid
7.5	Side groove depth	< 0.25δ	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :			
7.4.2	a <sub>0</sub> /W Range for J	0.45 ≤ a <sub>0</sub> /W ≤ 0.7	Valid
8.1.5.1	Open Crack Ext.	None > 50% of width ext.	Valid
9.1.5.2	Accuracy of ok ext. pred.	Diff = 0.15 δ a <sub>0</sub>	Valid
A9.6.4	P <sub>max</sub> in region A	P <sub>max</sub> ≤ 1 in A	Valid
A9.6.4	P <sub>max</sub> in region B	P <sub>max</sub> ≤ 1 in B	Valid
A9.6.4.1	V <sub>S</sub> da/dN	P <sub>max</sub> ≤ 5	Valid
A9.8.1	da/dN coeff C2	C2 = 1.0	Valid
A9.8.2	Accuracy of a <sub>0Q</sub>	a <sub>0Q</sub> - a <sub>0</sub>   ≤ 0.01W or 0.5mm	Valid
A9.8.2.2	Num pts in a <sub>0Q</sub> fit	4 points = 4	Valid
A9.8.2.2	4-Point Slope a <sub>0Q</sub> fit	4 points = 3	Valid
A9.2.2	a <sub>0Q</sub> fit R <sup>2</sup>	R <sup>2</sup> > 0.98	Valid
A9.9.1	Thickness requirement	B ≥ 1δ a <sub>0Q</sub> /Flow Stress	Valid
A9.9.2	Ligament requirement	B <sub>0</sub> ≥ 3δ a <sub>0Q</sub> /Flow Stress	Valid
A9.9.3	Regression line slope	Slope = 80% of da/dN	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .			
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for K <sub>Ic</sub> :			
7.4.2	a <sub>0</sub> /W Range for K	0.45 ≤ a <sub>0</sub> /W ≤ 0.55	Valid
A5.4.3.1	Ligament length	B <sub>0</sub> ≥ 2.5δ a <sub>0Q</sub> /K <sub>Ic</sub>	NOT Valid
A5.4.2	Pmax/P <sub>Q</sub> ratio	Less than 1.10	NOT Valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .			
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.			



Method File:  
FTA\_NI\_FT  
Comments:  
N/A

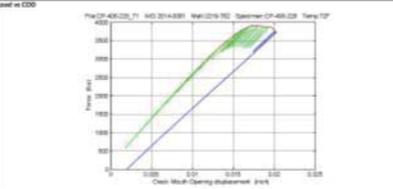
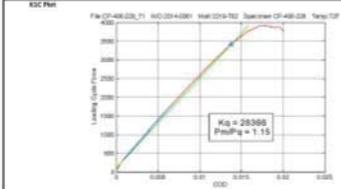
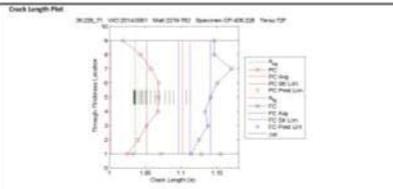
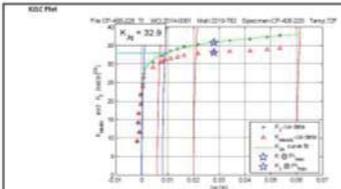


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001396
Other Specimen ID	CP-406-228
Operator	Charles Kay
Test Date	4/15/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
204 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	140031199
Other Specimen ID	CP-406-231
Operator	Charles Kay
Test Date	4/11/2014
Environment	Air
Temperature (T)	73
Pressure (PAC)	0
Relative Humidity (%)	N/A
Soak Time (min)	0

Geometry	CYT
"W" (in)	1.0000
"B" (in)	0.5010
"B <sub>0</sub> " (in)	0.2010
"B <sub>1</sub> " (in)	0.4700
Orientation	S-T
"R <sub>0</sub> " (in)	0.4010
Hole Spans/2 "H" (in)	0.3510
COO Span/2 "O" (in)	0.0900
Coupon #	M3

"E" (ksi)	30.60
"E <sub>c</sub> " (ksi)	30.60
% diff E & E <sub>c</sub>	0.00
"ν"	0.30
"Y <sub>S</sub> " (ksi)	37.30
"UTS" (ksi)	57.30
Flow Stress (ksi)	47.19
"E"/"Y <sub>S</sub> "	0.28

PreCrack Pmax (lbF)	534.0
PreCrack Final "a" (in)	0.1284
Stress Ratio	0.30
Kmax (ksi√in) <sub>app</sub>	0.00
A <sub>10</sub> (in)	0.0284
A <sub>10</sub> (in)	0.0283
A <sub>10</sub> (in)	0.0079
A <sub>10</sub> (in)	0.0045

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (in <sup>3/2</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (in <sup>3/2</sup> /in <sup>2</sup> )	$J_{Ic}$ at $J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ at $J_{Ic}$ (in <sup>3/2</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi√in)	$K_{Ic}$ Req Ligament (in)	Press/Pig
	66.00	58.10	66.00	58.10	27.73	26.02	22.35	0.017	3.20

Summary of Test Validities Required for All Tests:

7.4.5.1 Initial precrack force	$a_0 \leq P_{max}$ for sample type	Valid
7.4.5.1.1 Initial Kmax	$\leq 40\%$ of PreCrack YS	Valid
7.4.5.2 Final Kmax	$\leq 60\%$ of $K_{Ic}$ result	Valid
8.1.1.1 PreCrack straightness	None $\leq 0.05\delta$	Valid
7.4.5.1.2 PreCrack length	$\geq 0.05B$ or $0.05a_{0max}$ wide notch	Valid
7.5.1.1 Side groove depth	$\leq 0.25\delta$	Valid

Summary of Test Validities Required for  $J_{Ic}$ :

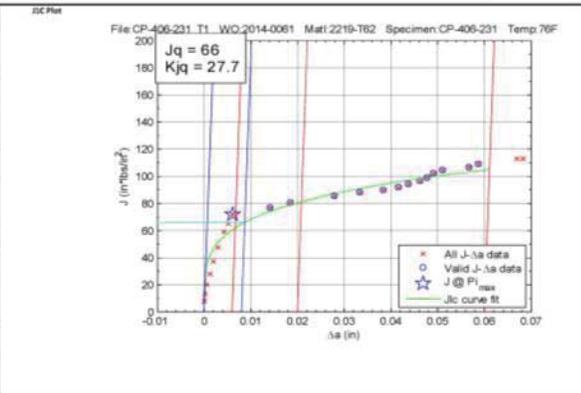
7.4.2.1 $a/W$ Range for $J_{Ic}$	$0.45 \leq a/W \leq 0.7$	Valid
8.1.1.1 Even Crack Fac.	None $\leq 50\%$ of avg crk ext.	Valid
8.1.5.2 Accuracy of crk ext. pred.	$2\%T \leq 0.15 S_{app}$	Valid
AB.4.1 # pts in region A	# pts = 1 in A	Valid
AB.4.2 # pts in region B	# pts = 5 in B	Valid
AB.4.3 # Valid - in pts	# pts = 5	Valid
AB.4.1.1 $a_0/W$ coeff. C2	$C2 \leq 1.0$	Valid
AB.4.2.1 Accuracy of $a_0$ est.	$10 \cdot \sigma_{a_0} \leq a_{0app} \leq 0.05W$ or 0.5mm	Valid
AB.4.2.2 Num. pts in $a_0$ reg. T1	# points = 8	Valid
AB.4.2.3 Acc. of $a_0$ est. $\sigma_{a_0}$	# points = 3	Valid
AB.4.1.1.1 $a_0/W$ coeff. C2	$C2 \leq 1.0$	Valid
AB.4.1.1.2 Thickness requirement	$b_0 \geq 10J_{Ic}/FlowStress$	Valid
AB.4.1.1.3 Ligament requirement	$b_0 \geq 10J_{Ic}/FlowStress$	Valid
AB.4.1.1.4 Regression line slope	Slope $\leq$ flow at $a_0$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-Valid  $J_{Ic}$  values may still convey valuable fracture toughness information.

Summary of Test Validities Required for  $K_{Ic}$ :

7.4.2.1 $a/W$ Range for $K_{Ic}$	$0.45 \leq a/W \leq 0.55$	Valid
AS.4.1 Ligament length	$b_0 \geq 1.5W/75\%T$	NOT Valid
AS.4.2 Press/Pig ratio	Less than 1.10	NOT Valid

All validity criteria for  $K_{Ic}$  NOT met.  $K_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non-Valid  $K_{Ic}$  values may still convey valuable fracture toughness information.



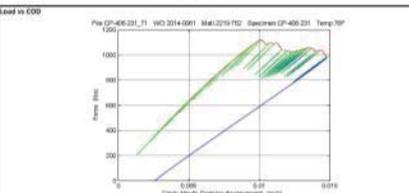
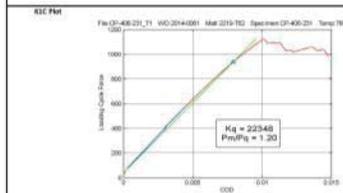
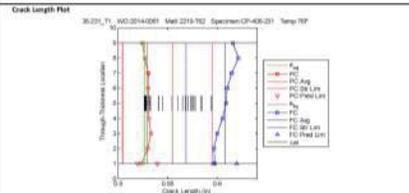
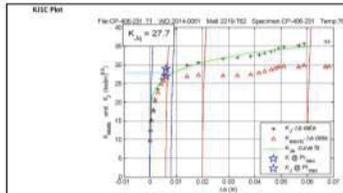
Method File: ITA.NLUT  
Comments:  
N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	140031199
Other Specimen ID	CP-406-231
Operator	Charles Kay
Test Date	4/11/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
205 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	140061403
Other Specimen ID	CP-406-233
Operator	Charles Key
Test Date	4/11/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

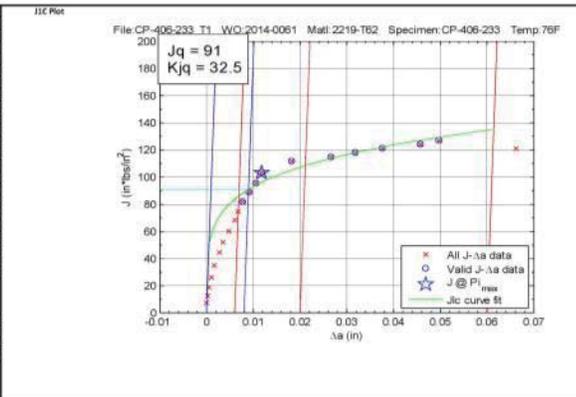
Geometry	CTI
"W" (in)	1.0000
"H" (in)	0.3000
"Bn" (in)	0.3980
"Be" (in)	0.4800
Orientation	S-T
"Wn" (in)	0.4650
Hole Span/2 "H" (in)	0.3550
COO Span/2 "D" (in)	0.3000
Coupon #	M1

"E" (ksi)	10.00
"Er" (ksi)	10.00
%dR @ 8 ft	0.00
"V"	0.30
"YS" (ksi)	37.30
"UTS" (ksi)	57.10
Flow Stress (ksi)	47.19
"E"/"YS"	0.28

PreCrack Pmax (lb/f)	525.0
PreCrack Final "a" (in)	0.5518
Stress Ratio	0.10
Kmax (ksi_sqr_t_in)	8.00
A_w (in)	0.5518
A_w (in)	0.5444
A_fo (in)	0.6175
A_fo (in)	0.6107

Results	$J_0$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_e$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_p$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$K_{Ic}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic}$ at $J_e$ (ksi(in) <sup>3/2</sup> )	$K_{Ic}$ @Sec (ksi(in) <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	90.30	72.40	18.30	32.51	29.04	21.32	0.817	1.43

Summary of Test Validities Required for All Tests:		
7.4.5.1 Initial precrack force	P <= Pm for sample type	Valid
7.4.5.1.1 Initial Kmax	>= 80% of Precrack YS	Valid
7.4.5.1.2 Final Kmax	>= 50% of result	Valid
9.1.4.1 Precrack straightness	Name > 0.05B	Valid
7.4.5.1.3 Precrack length	>= 0.05B or 0.05inch, wide notch	Valid
7.8.1 Side groove depth	< 0.25B	Valid
Summary of Test Validities Required for JIc:		
7.4.2 a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1 Even Crack Ext.	Name < 50% of avg. crk ext.	Valid
9.1.5.2 Accuracy of Crk ext. prod.	20% <= 0.15 of avg.	Valid
A9.6.4 # pts in region A	# pts >= 1 in A	Valid
A9.6.4 # pts in region B	# pts >= 1 in B	Valid
A9.6.4 # pts in region C	# pts >= 5	Valid
A9.8.1.1 da/dN coeff C2	C2 <= 1.0	Valid
A9.8.2.1 Accuracy of a_oq	S_oq - a_oq  < 0.01W or 0.5mm	Valid
A9.8.2.2 Num pts in a_oq fit	# points >= 3	Valid
A9.8.2.2.1 Q24	Q24 >= 0.96	Valid
A9.9.1 Thickness requirement	B > 10tq/Flowstress	Valid
A9.9.2 Ligament requirement	B_o > 10tq/Flowstress	Valid
A9.9.3 Regression line slope	Slope < flow at da/dN	Valid
All validity criteria for JIc NOT met. JIc is not fully valid JIc.		
Non-valid JIc values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for KIc:		
7.4.2 a/W Range for KIc	0.45 <= a/W <= 0.55	Valid
A5.4.1 KIc Ligament length	b_o > 2.5tq/(YS)^2	NOT Valid
A5.4.2 Pmax/Pq ratio	less than 1.10	NOT Valid
All validity criteria for KIc NOT met. KIc is not fully valid KIc.		
Non-valid KIc values may still convey valuable fracture toughness information.		



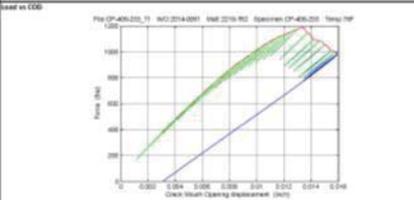
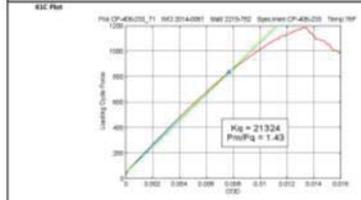
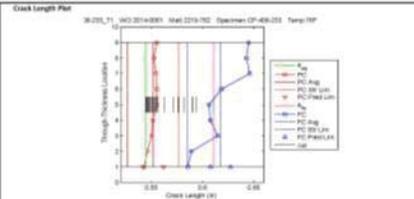
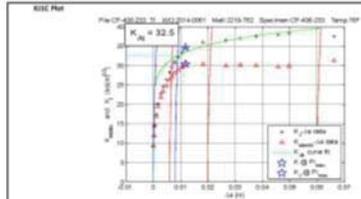
Method File:  
FTA NUT  
Comments:  
N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	180014813
Other Specimen ID	CP-406-233
Operator	Charles Key
Test Date	6/13/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
206 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.1

EM10 Specimen ID	140001404
Other Specimen ID	CP-406-236
Operator	Charles Kay
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

Geometry	CT
"W" (in)	2.0000
"B" (in)	0.9990
"B <sub>0</sub> " (in)	0.7993
"B <sub>e</sub> " (in)	0.9580
Orientation	L-T
"A <sub>0</sub> " (in)	0.9000
Hole Spac/2 "H" (in)	0.7100
COD Spac/2 "D" (in)	0.1050
Coupon #	ME

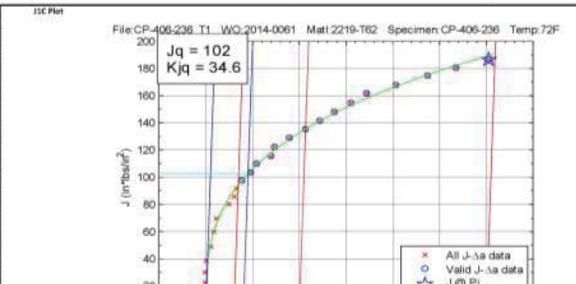
"E" (MPa)	10.60
"E <sub>c</sub> " (MPa)	10.60
% diff E & E <sub>c</sub>	0.00
"ν"	0.30
"ν <sub>s</sub> " (KSI)	39.30
"UTS" (KSI)	59.10
Flow Stress (KSI)	49.20
"E"/"ν <sub>s</sub> "	0.27

Pre-crack Pmax (lbf)	1500.0
Pre-crack Final "a" (in)	1.0226
Stress Ratio	0.10
Kmax (ksi√in)	8.00

A <sub>0p</sub> (in)	1.0270
A <sub>0e</sub> (in)	1.0242
A <sub>0f</sub> (in)	1.1051
A <sub>0t</sub> (in)	1.0791

Results	J <sub>q</sub> (in <sup>2</sup> /lb <sup>2</sup> )	ie <sub>q</sub> (in <sup>2</sup> /lb <sup>2</sup> )	ip <sub>q</sub> (in <sup>2</sup> /lb <sup>2</sup> )	K <sub>Iq</sub> (ksi√in)	K <sub>Iq</sub> at J <sub>q</sub> (ksi√in)	K <sub>I</sub> Slope (ksi√in)	K Req Ligament (in)	Pmax/Pq
	102.50	92.40	10.10	34.55	32.81	29.25	1.885	1.33

Summary of Test Validities Required for All Tests:		
7.4.5.1 Initial precrack force	σ ≤ Pin for sample type	Valid
7.4.5.1.1 Initial Kmax	≤ 40% of Precrack YS	Valid
7.4.5.2 Final Kmax	≤ 50% of K <sub>I</sub> result	Valid
8.1.1.1 Precrack straightness	None > 0.05θ	Valid
7.4.5.1.2 Precrack length	≤ 0.05B or 0.05in, wide notch	Valid
7.5.1.1 Side groove depth	≤ 0.25B	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :		
7.4.2.1 W Range for J	0.45 ≤ a/W ≤ 0.7	Valid
9.1.5.1 Even Crack Fac.	None < 50% of avg crack ext.	Valid
9.1.5.2 Accuracy of crk ext. pred.	Diff < 0.15 δ <sub>ap</sub>	Valid
A5.4.4 # pts in region A	# pts = 1 in A	Valid
A5.4.4 # pts in region B	# pts = 1 in B	Valid
A9.6.6.6 # Valid J-ds pts	# pts = 5	Valid
A9.8.1.1 ds fit coeff C2	C2 < 1.0	Valid
A9.8.2.1 Accuracy of A <sub>0p</sub>	δ <sub>ap</sub> - a <sub>0p</sub>   ≤ 0.01W or 0.5mm	Valid
A9.8.2.2 Norm pts at a <sub>0p</sub> fit	# points = 8	Valid
A9.8.2.3 ds fit slope	# points = 3	Valid
A9.8.2.3.1 ds fit R <sup>2</sup>	R <sup>2</sup> > 0.98	Valid
A5.9.1 Thickness requirement	b <sub>0</sub> ≥ 10t <sub>0</sub> /Flow Stress	Valid
A5.9.2 Ligament requirement	b <sub>0</sub> ≥ 10t <sub>0</sub> /Flow Stress	Valid
A5.9.3 Regression line slope	Slope < flow at ds <sub>0</sub>	Valid



All validity criteria for J <sub>Ic</sub> NOT met. J <sub>q</sub> is not fully valid J <sub>Ic</sub> . Non-valid J <sub>q</sub> values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for K <sub>I</sub> :		
7.4.2.1 W Range for K	0.45 ≤ a/W ≤ 0.55	Valid
A5.4.1 Ligament length	b <sub>0</sub> ≥ 2.5t <sub>0</sub> /YS	NOT Valid
A5.4.2 Pmax/Pq ratio	Less than 1.10	NOT Valid

Method File:  
PTA N1 FT  
Comments:  
N/A

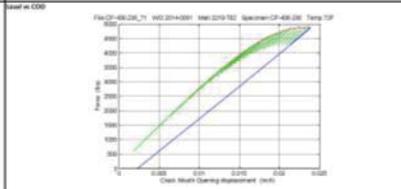
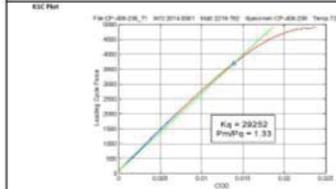
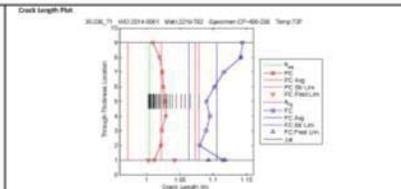
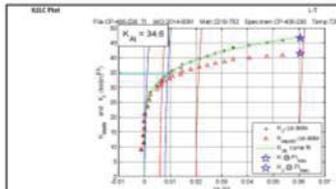


### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.1

EM10 Specimen ID	140001404
Other Specimen ID	CP-406-236
Operator	Charles Kay
Test Date	4/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
207 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001406
Other Specimen ID	CP-406-238
Operator	Charles Kay
Test Date	4/29/2014
Environment	Air
Temperature (T)	72
Pressure (P[SG])	0
Relative Humidity (h)	NA
Soak Time (min)	0

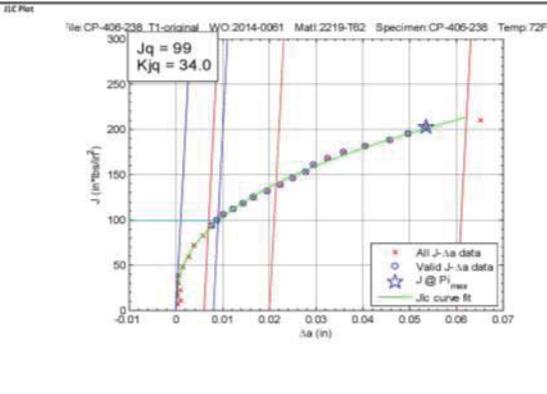
Geometry	CTT
"W" (in)	2.0000
"B" (in)	1.0000
"B <sub>0</sub> " (in)	0.7500
"B <sub>c</sub> " (in)	0.9630
Orientation	L-T
"A <sub>0</sub> " (in)	0.8000
Wide Span/2 "W" (in)	0.7500
COO Span/2 "D" (in)	0.1500
Coupon #	NA

"E" (ksi)	30.00
"E <sub>c</sub> " (ksi)	30.00
%dR F & E <sub>c</sub>	0.00
"ν"	0.30
"ν <sub>s</sub> " (ksi)	39.50
"ν <sub>s</sub> " (ksi)	59.50
Flow Stress (ksi)	48.00
"E"/"ν <sub>s</sub> "	0.27

Precrack Pmax (lbf)	1520.0
Precrack Final "a" (in)	1.0127
Stress Ratio	0.10
Kmax (ksi $\sqrt{in}$ )	8.08
A <sub>avg</sub> (in)	1.0127
A <sub>avg</sub> (in)	1.0127
A <sub>0</sub> (in)	1.1205
A <sub>0</sub> (in)	1.0968

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi $\sqrt{in}$ )	$K_{Ic}$ at $J_{Ic}$ (ksi $\sqrt{in}$ )	$K_{Ic}$ (ksi $\sqrt{in}$ )	$K_{Ic}$ (ksi $\sqrt{in}$ )	$K_{Ic}$ (ksi $\sqrt{in}$ )	Prax/P <sub>0</sub>
	99.50	99.50	103.00	11.97	32.31	12.56	1.715		1.24

Summary of Test Validities Required for All Tests:			
7.4.5	Initial precrack force	≥ 40% of sample type	Valid
7.4.5.1	Initial force	< 40% of Precrack V <sub>0</sub>	Valid
7.4.5.2	Final force	> 50% of K result	Valid
7.4.5.3	Precrack straightness	None + 0.020	Valid
7.4.5.4	Precrack length	< 0.050 or 0.020inch, under match	Valid
7.4.5.5	Side groove depth	< 0.250	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :			
7.4.2.1	Range for K	0.45 <= a/W <= 0.7	Valid
7.4.2.2	Thin Crack Ext.	None + 50% of aug. crk. ext.	Valid
7.4.2.3	Accuracy of crk. ext. grad.	Diff < 0.15 d <sub>ap</sub>	Valid
AS 4.4.1	# pts in region A	# pts = 1 on A	Valid
AS 4.4.2	# pts in region B	# pts = 1 on B	Valid
AS 4.4.3	Valid J <sub>Ic</sub> pts	# pts = 5	Valid
AS 4.4.4	J <sub>Ic</sub> fit coeff. C2	C2 = 1.0	Valid
AS 4.4.5	Accuracy of J <sub>Ic</sub>	1.5, 0.5, 0.1, 0.01 or 0.02W or 0.5mm	Valid
AS 4.4.6	Num. pts in J <sub>Ic</sub> fit	# points = 8	Valid
AS 4.4.7	Exp. (log) a <sub>0</sub> vs J <sub>Ic</sub>	# points = 3	Valid
AS 4.4.8	Exp. fit R <sup>2</sup>	R <sup>2</sup> > 0.96	Valid
AS 4.4.9	Thickness requirements	B = 10g/Thickness	Valid
AS 4.4.10	Alignment requirements	W = 10g/Thickness	Valid
AS 4.4.11	Regression line slope	Slope = flow at d <sub>0</sub> - J <sub>Ic</sub>	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .			
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for K <sub>Ic</sub> :			
7.4.2.1	Range for K	0.45 <= a/W <= 0.55	Valid
AS 4.4.1	Equivalent length	B = 2.5W/Thickness	NOT valid
AS 4.4.2	Prax/P <sub>0</sub> ratio	Prax/P <sub>0</sub> > 1.10	NOT valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .			
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.			



Method File: PTA\_NFT  
Comments: N/A

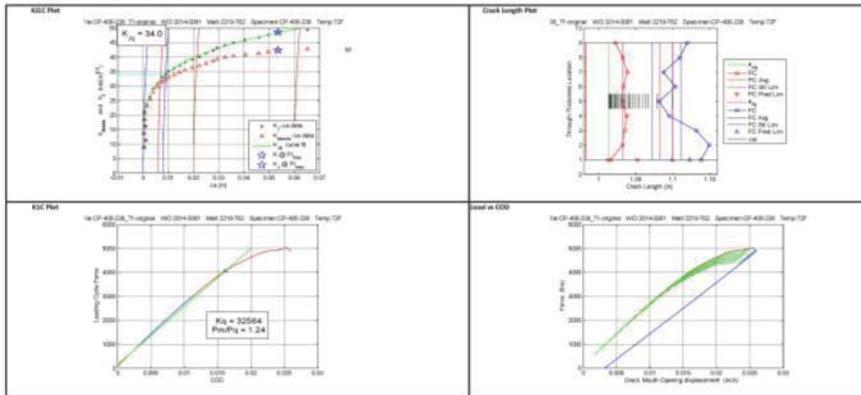


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001407
Other Specimen ID	CP-406-238
Operator	Charles Kay
Test Date	4/29/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
208 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061409	Geometry	CT	"I" (MSI)	10.60	Precrack Pmax (lbf)	1508.0
Other Specimen ID	CP-406-241	"W" (in)	2.0000	"E" (MSI)	10.60	Precrack Final "a" (in)	1.0399
Operator	Charles Kay	"B" (in)	0.9900	% diff E & E1	0.00	Stress Ratio	0.10
Test Date	4/10/2014	"Bn" (in)	0.7960	"V"	0.30	Kmax (kst_sqr_in)	8.00
Environment	Air	"Bw" (in)	0.9570	"YS" (KSI)	39.10		
Temperature (F)	73	Orientation	T-C	"UTS" (KSI)	59.00	A <sub>0p</sub> (in)	1.0399
Pressure (PSIG)	0	"a0" (in)	0.8900	Flow Stress (KSI)	49.06	A <sub>0q</sub> (in)	1.0237
Relative Humidity (%)	NA	Hole Span/2 "H" (in)	0.7100	"E"/"YS"	0.27	A <sub>0p</sub> (in)	1.1128
Soak Time (min)	0	COD Span/2 "D" (in)	0.1050			A <sub>0q</sub> (in)	1.0982
		Coupon #	M4				

Results	J <sub>q</sub> (in <sup>3</sup> /lb-ft <sup>2</sup> )	J <sub>q</sub> (in <sup>3</sup> /lb-ft <sup>2</sup> )	J <sub>q</sub> (in <sup>3</sup> /lb-ft <sup>2</sup> )	K <sub>Iq</sub> (ksi/in <sup>3/2</sup> )	K <sub>Iq,at</sub> (ksi/in <sup>3/2</sup> )	K <sub>Iq,sec</sub> (ksi/in <sup>3/2</sup> )	K <sub>Iq</sub> Req Ligament (in)	Pmax/Pq
	86.00	78.50	7.50	33.65	30.74	28.41	1.320	1.17

Summary of Test Validities Required for All Tests:

7.4.5.1	Initial precrack force	P <= Pm for sample type	Valid
7.4.5.2	Initial Kmax	<40% of Precrack Y3	Valid
7.4.5.2	Final Kmax	<50% of K result	Valid
8.1.4.1	Precrack straightness	None > 0.050	Valid
7.4.5.1	Precrack length	>0.058 or 0.05inch, wide match	Valid
7.5	Side groove depth	< 0.25B	Valid

Summary of Test Validities Required for J<sub>Ic</sub>:

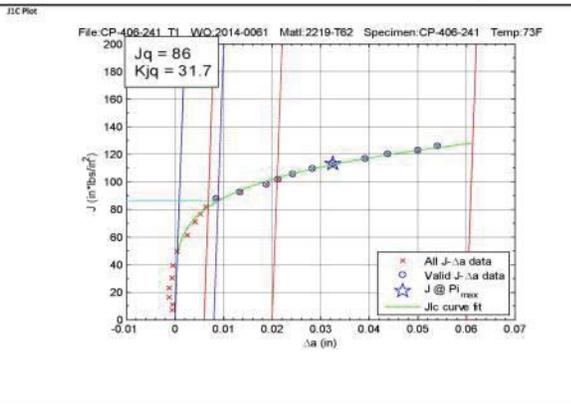
7.4.2	a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1	Even Crack Ext.	None < 50% of avg crk ext.	Valid
9.1.5.2	Accuracy of crk ext. prof.	Diff < 0.15 d ap	Valid
A9.6.4	If p1s in region A	If p1s >= 1 in A	Valid
A9.6.4	If p1s in region B	If p1s >= 1 in B	Valid
A9.6.6	If valid J-da p1s	If p1s >= 5	Valid
A9.8.1	J-da fit coeff C2	C2 < 3.0	Valid
A9.8.2	Accuracy of J-da	J <sub>0</sub> - J <sub>0q</sub> - J <sub>0p</sub>   < 0.01W or 0.5mm	Valid
A9.8.2	Non p1s in J-da fit	If points >= 8	Valid
A9.8.2	0.4a/q1 (B&S) < 0.4q1/c1q	If points >= 3	Valid
A9.8.2	0.4a/q1 R <sup>2</sup>	R <sup>2</sup> > 0.95	Valid
A9.9.1	Thickness requirement	B >= 10J <sub>0q</sub> /flowstress	Valid
A9.9.1	Ligament requirement	B <sub>0</sub> >= 10J <sub>0q</sub> /flowstress	Valid
A9.9.3	Regression line slope	Slope < flow at d <sub>0</sub> q	Valid

All validity criteria for J<sub>Ic</sub> NOT met. J<sub>q</sub> is not fully valid J<sub>Ic</sub>.  
Non-valid J<sub>q</sub> values may still convey valuable fracture toughness information.

Summary of Test Validities Required for K<sub>Ic</sub>:

7.4.2	a/W Range for K <sub>Ic</sub>	0.45 <= a/W <= 0.55	Valid
A5.4.3	Ligament length	B <sub>0</sub> >= 2.5(A/W) <sup>3/2</sup> * 7	NOT valid
A5.4.2	Pmax/P0 ratio	Ratio >= 1.10	NOT valid

All validity criteria for K<sub>Ic</sub> NOT met. K<sub>Iq</sub> is not fully valid K<sub>Ic</sub>.  
Non-valid K<sub>Iq</sub> values may still convey valuable fracture toughness information.

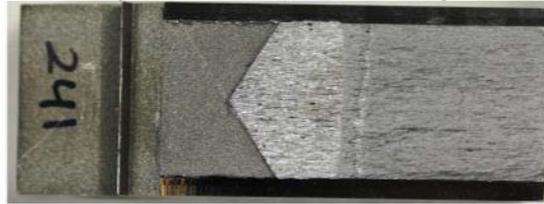
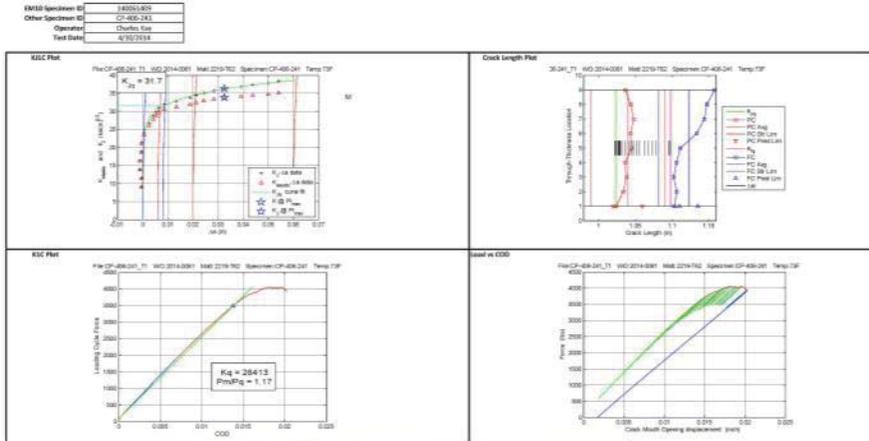


Method File: FTA\_NLT  
Comments: N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
209 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140091411
Other Specimen ID	CP-406-243
Operator	Charles Kay
Test Date	4/30/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

Geometry	CT
"W" (in)	2.0000
"B" (in)	1.0000
"Bc" (in)	0.7500
"Bt" (in)	0.9600
Orientation	T.L.
"Aa" (in)	0.7500
Hole Span/2 "H" (in)	0.7100
COD Span/2 "D" (in)	0.1000
Coupon #	MM

"E" (ksi)	10.60
"Ec" (ksi)	10.60
% diff E & Ec	0.00
"v"	0.30
"YS" (ksi)	39.10
"UTS" (ksi)	99.00
Flow Stress (ksi)	49.06
"E"/"YS"	0.27

Precrack Pmax (lbF)	1919.0
Precrack Pmax "a" (in)	1.0304
Stress Ratio	0.10
Kmax (ksi√in)	9.00
A <sub>avg</sub> (in)	1.0304
A <sub>oq</sub> (in)	1.0148
A <sub>fg</sub> (in)	1.1348
A <sub>tg</sub> (in)	1.0818

Results	J <sub>q</sub> (in <sup>3</sup> /in <sup>2</sup> )	J <sub>e</sub> (in <sup>3</sup> /in <sup>2</sup> )	J <sub>p</sub> (in <sup>3</sup> /in <sup>2</sup> )	K <sub>q</sub> (ksi√in)	K <sub>q,at J<sub>e</sub></sub> (ksi√in)	K <sub>max</sub> (ksi√in)	K <sub>Req</sub> (ksi√in)	Pmax/P <sub>q</sub>
	93.40	84.10	9.30	32.99	31.30	28.66	1.943	1.19

Summary of Test Validities Required for All Tests:

7.4.5 Initial precrack force	P <= P <sub>0</sub> for sample type	Valid
7.4.5.1 Initial Kmax	<= 80% of Precrack Y <sub>0</sub>	Valid
7.4.5.2 Final Kmax	<= 80% of K result	Valid
8.1.4.1 Precrack straightness	None > 0.05%	Valid
7.4.5.1 Precrack length	<= 0.05B or 0.05inch, wide notch	Valid
7.5.5 Side groove depth	< 0.25B	Valid

Summary of Test Validities Required for J<sub>Ic</sub>:

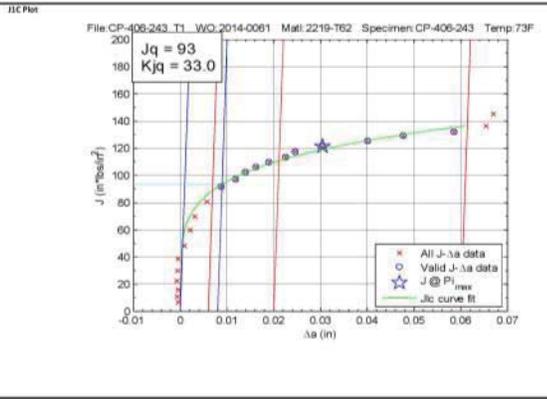
7.4.2 J <sub>Ic</sub> Range for J	0.45 <= a/W <= 0.7	Valid
8.1.5.1 Even Crack Ext.	None > 50% of avg. CR ext.	Valid
8.1.5.2 Accuracy of crack ext. meas.	Diff < 0.15 in. avg	NOT Valid
A9.6.4.1 # pts in region A	# pts >= 1 in A	Valid
A9.6.4.2 # pts in region B	# pts >= 1 in B	Valid
A9.6.4.3 # Valid J da pts	# pts >= 5	Valid
A9.8.1.1 da fit coeff R <sup>2</sup>	R <sup>2</sup> > 1.0	Valid
A9.8.1.2 Accuracy of a <sub>oq</sub>	a <sub>oq</sub> - a <sub>avg</sub>   < 0.01W or 0.5mm	Valid
A9.8.2.1 Numpts in a <sub>oq</sub> fit	# points >= 8	Valid
A9.8.2.2 # daq/fit(a <sub>oq</sub> - a <sub>avg</sub> )	# points >= 3	Valid
A9.8.2.3 a <sub>oq</sub> fit R <sup>2</sup>	R <sup>2</sup> > 0.98	Valid
A9.9.1 Thickness requirement	B >= 10J <sub>Ic</sub> /Flowstress	Valid
A9.9.2 Ligament requirement	B <sub>o</sub> >= 10J <sub>Ic</sub> /Flowstress	Valid
A9.9.3 Regression line slope	Slope > Flow at da <sub>o</sub>	Valid

All validity criteria for J<sub>Ic</sub> NOT met. J<sub>Ic</sub> is not fully valid J<sub>Ic</sub>.  
Non-valid K<sub>q</sub> values may still convey valuable fracture toughness information.

Summary of Test Validities Required for K<sub>Ic</sub>:

7.4.2 J <sub>Ic</sub> Range for K	0.45 <= a/W <= 0.55	Valid
A5.4.3.1 Ligament length	B <sub>o</sub> >= 2.5A/PS <sub>0</sub> <sup>2</sup>	NOT Valid
A5.4.2 Pmax/P <sub>0</sub> ratio	less than 1.10	NOT Valid

All validity criteria for K<sub>Ic</sub> NOT met. K<sub>Ic</sub> is not fully valid K<sub>Ic</sub>.  
Non-valid K<sub>q</sub> values may still convey valuable fracture toughness information.



Method File:  
PTA\_NLFT  
Comments:  
N/A

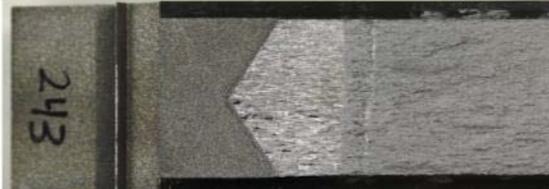
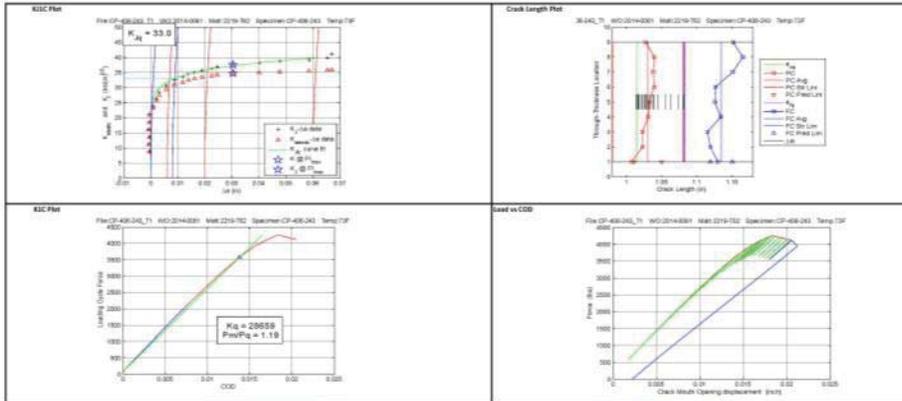


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140091411
Other Specimen ID	CP-406-243
Operator	Charles Kay
Test Date	4/30/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
210 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001414
Other Specimen ID	CP-405-246
Operator	Charles Kay
Test Date	4/11/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

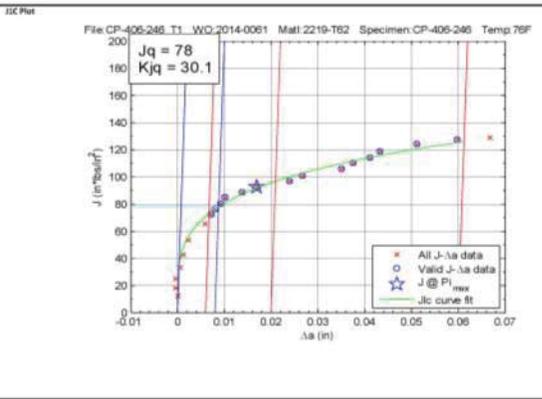
Geometry	CIT
"W" (in)	1.0000
"B" (in)	0.8000
"Bc" (in)	0.3900
"Bp" (in)	0.4800
Orientation	S-T
"R" (in)	0.4000
Hole Span/2 "H" (in)	0.3550
COO Span/2 "D" (in)	0.0900
Coupon #	NA

"E" (ksi)	30.00
"Ec" (ksi)	30.00
% diff E & Ec	0.00
"V"	0.30
"VS" (ksi)	39.20
"UTS" (ksi)	60.10
Flow Stress (ksi)	49.03
"E"/"VS"	0.27

PreCrack Pmax (lbf)	665.0
PreCrack Final "a" (in)	0.1257
Stress Ratio	0.10
Kmax (ksi_sqr_in)	30.00
A_w (in)	0.3257
A_wg (in)	0.5226
A_t0 (in)	0.6169
A_tg (in)	0.6026

Results	$Iq$ (in <sup>3/2</sup> ksi <sup>2</sup> )	$J_c$ (in <sup>3/2</sup> ksi <sup>2</sup> )	$J_{Ic}$ (in <sup>3/2</sup> ksi <sup>2</sup> )	$K_{Ic}$ (ksi_sqr_in)	$K_{Ic}$ at $J_{Ic}$ (ksi_sqr_in)	$K_{Ic}$ Slope (ksi_sqr_in)	$K_{Ic}$ Req Ligament (in)	Pmax/Pq
	78.00	68.30	11.80	30.14	27.76	22.80	0.846	1.24

Summary of Test Validities Required for All Tests:		
7.4.5 Initial precrack force	$P \leq P_m$ for sample type	Valid
7.4.5.1 Initial Kmax	$\leq 80\%$ of Precrack YS	Valid
7.4.5.2 Final Kmax	$\leq 80\%$ of $K_{max}$	Valid
8.1.4.1 Precrack straightness	None $\leq 0.058$	Valid
7.4.5.1 Precrack length	$\leq 0.058$ or 0.075inch, wide notch	Valid
7.5 Side groove depth	$\leq 0.258$	Valid
Summary of Test Validities Required for $J_{Ic}$ :		
7.4.2 $a_0/W$ Range for $J$	$0.45 \leq a_0/W \leq 0.7$	Valid
8.1.5.1 Even Crack Ext.	None $\leq 50\%$ of avg crack ext.	Valid
8.1.5.2 Accuracy of crack ext. meas.	$\pm 0.1 \leq \Delta a$	Valid
A9.4.4 # pts in region A	# pts $\geq 1$ in A	Valid
A9.4.4 # pts in region B	# pts $\geq 1$ in B	Valid
A9.4.4 # Valid $J$ data pts	# pts $\geq 5$	Valid
A9.8.1 Data fit coeff. $C_2$	$C_2 \leq 1.10$	Valid
A9.8.2 Accuracy of $J_c$ req	$ J_c - J_{Ic}  \leq 0.05W$ or 0.5mm	Valid
A9.8.2.1 Num pts in $a_w$ req fit	# points $\geq 8$	Valid
A9.8.2.2 $\Delta a$ req fit $R^2$	$R^2 \geq 0.98$	Valid
A9.8.2.3 $\Delta a$ req fit $R^2$ $J_{Ic}$	# points $\geq 3$	Valid
A9.8.1 Thickness requirement	$B \geq 10J_c/\text{Flow Stress}$	Valid
A9.8.2 Ligament requirement	$B_w \geq 10J_c/\text{Flow Stress}$	Valid
A9.8.3 Regression line slope	$\Delta J_{Ic} = \text{Flow at } \Delta a_w$	Valid
All validity criteria for $J_{Ic}$ NOT met. $J_{Ic}$ is not fully valid fit.		
Non-valid $J_{Ic}$ values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for $K_{Ic}$ :		
7.4.2 $a_0/W$ Range for $K$	$0.45 \leq a_0/W \leq 0.75$	Valid
A5.4.1 Ligament length	$B_w \geq 2.5W/\sqrt{YS}^2$	NOT Valid
A5.4.2 Pmax/Pq ratio	less than 1.10	NOT Valid
All validity criteria for $K_{Ic}$ NOT met. $K_{Ic}$ is not fully valid $K_{Ic}$ .		
Non-valid $K_{Ic}$ values may still convey valuable fracture toughness information.		



Method File:  
FTA\_NIcT  
Comments:  
N/A

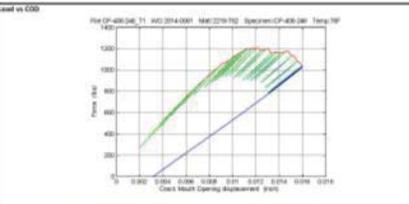
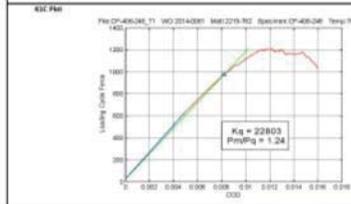
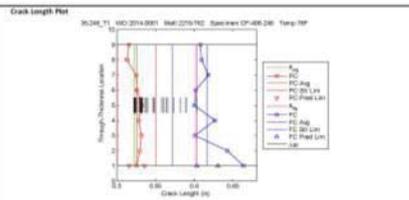
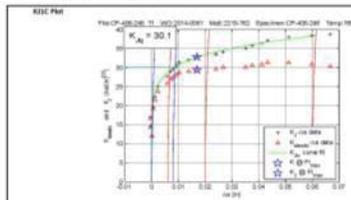


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001414
Other Specimen ID	CP-405-246
Operator	Charles Kay
Test Date	4/11/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
211 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID: 140051410	Geometry: CT7	"E" (MSI): 10.60	PreCrack Pmax (lbF): 528.0
Other Specimen ID: CP-406-248	"W" (in): 1.0000	"E" (MSI): 10.60	PreCrack Pmax "r" (in): 0.5303
Operator: Charles Kay	"T" (in): 0.5000	% del E & B: 0.00	Stress Ratio: 0.10
Test Date: 4/11/2014	"Bn" (in): 0.3970	"v": 0.30	Kmax (ksi_sqr_in): 8.00
Environment: Air	"Be" (in): 0.4800	"VS" (KSI): 39.20	A_op (in): 0.5303
Temperature (F): 73	Orientation: S-T	"UTS" (KSI): 60.10	A_oq (in): 0.5255
Pressure (PSIG): 0	"Be" (in): 0.4030	Flow Stress (KSI): 49.63	A_fm (in): 0.6109
Relative Humidity (%): NA	Hole Span/2 "H" (in): 0.3550	"E"/"YS": 0.27	A_sj (in): 0.6087
Soak Time (min): 0	COD Span/2 "D" (in): 0.0990		
	Coupon #: NA		

Results	$J_I$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_{e,q}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_{p,q}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$K_{Iq}$ (ksi/in) <sup>2</sup>	$K_{Iq,at,J_{e,q}}$ (ksi/in) <sup>2</sup>	$K_{I,5sec}$ (ksi/in) <sup>2</sup>	K Req Ligament (in)	Pmax/Pq
	50.90	44.20	6.70	24.35	22.68	20.72	0.099	1.26

Summary of Test Validities Required for All Tests:

7.4.5 Initial precrack force	$P \ll P_m$ for sample type	Valid
7.4.5.1 Initial Kmax	< 40% of Precrack YS	Valid
7.4.5.2 Final Kmax	< 60% of $K_{max}$	Valid
9.1.4.1 Precrack straightness	None > 0.05B	Valid
7.4.5.1 Precrack length	> 0.05B or 0.05in, wide notch	Valid
7.5 Side groove depth	< 0.35B	Valid

Summary of Test Validities Required for  $J_{Ic}$ :

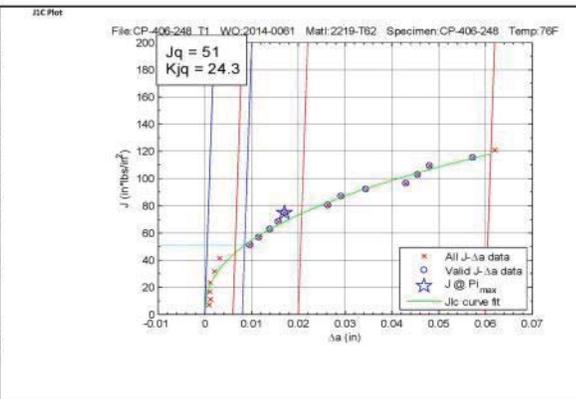
7.4.2 a/W Range for J	$0.45 \leq a/W \leq 0.7$	Valid
8.1.5.1 Even Crack Ext.	None > 50% of avg crk ext.	Valid
9.1.5.2 Accuracy of crk ext. prod.	$20^\circ \leq \theta \leq 30^\circ$	Valid
A9.6.4 # pts in region A	# pts = 1 in A	Valid
A9.6.4 # pts in region B	# pts = 1 in B	Valid
A9.6.4 # valid > 2b pts	# pts = 5	Valid
A9.8.1 J vs $\Delta a$ fit coeff $C_2$	$C_2 \leq 1.0$	Valid
A9.8.2.1 Accuracy of $a_{oq}$	$ a_{oq} - a_{app}  \leq 0.01W$ or 0.5mm	Valid
A9.8.2.2 # pts in $a_{oq}$ fit	# points = 3	Valid
A9.8.2.3 J vs $\Delta a$ fit $R^2$	$R^2 \geq 0.95$	Valid
A9.9.1 Thickness requirement	$B > 10J_q/\text{FlowStress}$	Valid
A9.9.2 Ligament requirement	$b_o > 10J_q/\text{FlowStress}$	Valid
A9.9.3 Regression line slope	Slope = flow at $\Delta a_{oq}$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-valid  $J_{Ic}$  values may still convey valuable fracture toughness information.

Summary of Test Validities Required for  $K_{Iq}$ :

7.4.2 a/W Range for $K_{Iq}$	$0.45 \leq a/W \leq 0.55$	Valid
A5.4.3 Ligament length	$b_o > 2.5W/YS^2$	NOT valid
A5.4.2 Pmax/Pq ratio	Less than 1.10	NOT valid

All validity criteria for  $K_{Iq}$  NOT met.  $K_{Iq}$  is not fully valid  $K_{Iq}$ .  
Non-valid  $K_{Iq}$  values may still convey valuable fracture toughness information.



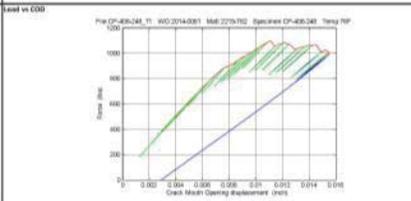
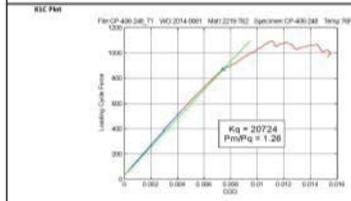
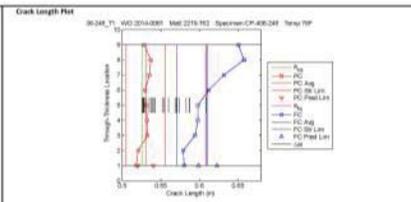
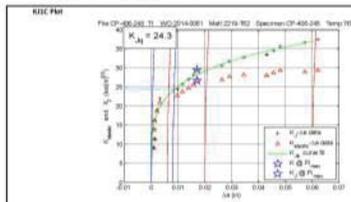
Method File:  
PTA\_NIFT  
Comments:  
N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID: 140051410	Operator: Charles Kay
Other Specimen ID: CP-406-248	Test Date: 4/11/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
212 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.3

EM10 Specimen ID	140061439
Other Specimen ID	CP-406-251
Operator	Charles Kay
Test Date	4/30/2014
Environment	Air
Temperature (T)	73
Pressure (PSIG)	0
Relative Humidity (%)	N/A
Soak Time (min)	0

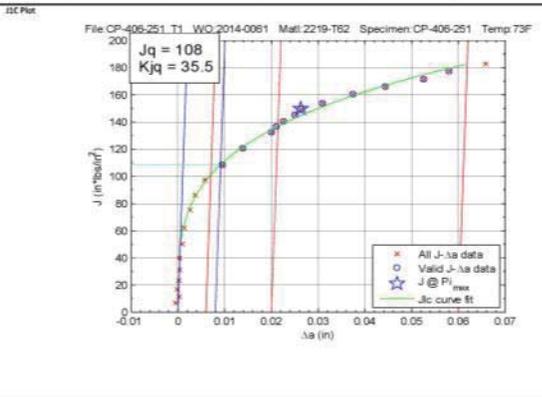
Geometry	CTI
"W" (in)	2.0000
"B" (in)	0.9990
"Bc" (in)	0.7540
"Bt" (in)	0.5570
Orientatation	L-T
"Ae" (in)	0.7980
Hole Spacing "W" (in)	0.7300
COO Span/2 "D" (in)	0.5040
Coupon #	M5

"E" (ksi)	10.00
"Ec" (ksi)	10.00
% diff E & Ec	0.00
"v"	0.30
"VS" (ksi)	38.00
"UTS" (ksi)	57.80
Flow Stress (ksi)	47.94
"E"/"VS"	0.28

Pre-crack Pmax (lb)	1527.0
Pre-crack Final "a" (in)	1.0378
Stress Ratio	0.10
Kmax (ksi_sqr_t_in)	8.90
A_w (in)	1.0378
A_o (in)	1.0383
A_b (in)	1.1008
A_t (in)	1.0978

Results	Jq (in <sup>3</sup> /in <sup>2</sup> )	Jc (in <sup>3</sup> /in <sup>2</sup> )	Jp (in <sup>3</sup> /in <sup>2</sup> )	KIa (ksi√in)	KIa at Jc (ksi√in)	E <sub>Res</sub> (ksi/in <sup>2</sup> )	E Res Ligament (in)	Prms/Pq
	108.40	96.90	22.10	35.53	35.50	29.48	1.504	1.29

Summary of Test Validities Required for All Tests:		
7.4.5.1 Initial precrack finish	R ≤ 0.8 for sample type	Valid
7.4.5.1.1 Initial finish	width of Pre-crack VS	Valid
7.4.5.2 Final finish	±50% of E result	Valid
8.1.4.1 Pre-crack straightness	None > 0.058	Valid
7.4.5.1.2 Pre-crack length	±0.050 or 0.02inch, whatev match	Valid
7.5.1.1 Groove depth	± 0.235	Valid
Summary of Test Validities Required for JIc:		
7.4.2.1 a/W Range for J	0.45 ≤ a/W ≤ 0.7	Valid
9.1.5.1 Even Crack Ext.	None < 50% of avg. crk. ext.	Valid
9.1.5.2 Accuracy of crk. ext. prof.	DIF ≤ 0.15 d <sub>ap</sub>	Valid
A5.6.4 # pits in region A	# pits = 1 in B	Valid
A5.6.4 # pits in region B	# pits = 1 in B	Valid
A5.6.4 # pits in region C	# pits = 5	Valid
A5.8.1.1 da fit coeff. C2	C2 < 1.0	Valid
A5.8.2.1 Accuracy of J <sub>0.05</sub>	15.0% ≤ % diff. < 0.0209 or 0.5mm	Valid
A5.8.2.2 Num. pits in J <sub>0.05</sub> lig	# points = 8	Valid
A5.8.2.3 # pits in J <sub>0.05</sub> lig	# points = 3	Valid
A5.8.2.4 J <sub>0.05</sub> vs J <sub>0.1</sub>	R <sup>2</sup> > 0.96	Valid
A5.9.1 Thickness requirement	B <sub>0.05</sub> > 10g/flow stress	Valid
A5.9.2 Ligament requirement	B <sub>0.1</sub> > 10g/flow stress	Valid
A5.9.3 Regression line slope	Slope < flow at da, q	Valid
All validity criteria for JIc NOT met. Jq is not fully valid JIc. Non-valid Jq values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for KIc:		
7.4.2.1 a/W Range for KI	0.45 ≤ a/W ≤ 0.55	Valid
A5.4.3.1 Ligament length	B <sub>0.1</sub> > 2.5g/√S <sub>YS</sub> <sup>2</sup>	NOT Valid
A5.4.3.2 Prms/Pq ratio	Less than 1.30	NOT Valid
All validity criteria for KIc NOT met. KIc is not fully valid KIc. Non-valid KIc values may still convey valuable fracture toughness information.		



Method File: ITA\_NFT  
Comments:  
N/A

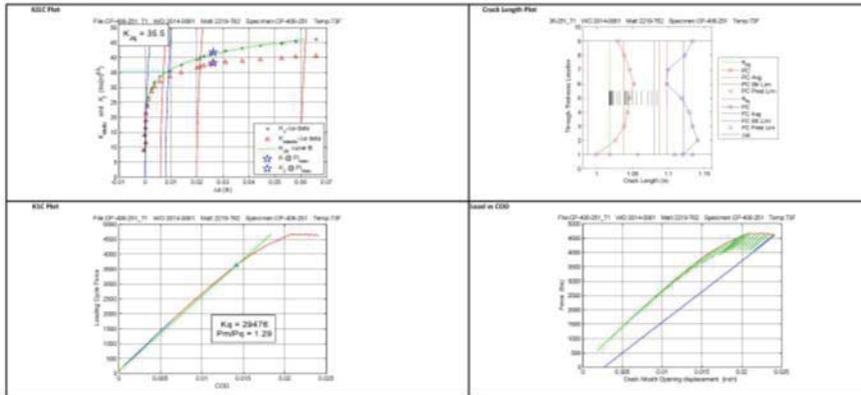


### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.3

EM10 Specimen ID	140061439
Other Specimen ID	CP-406-251
Operator	Charles Kay
Test Date	4/30/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
213 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	180061421
Other Specimen ID	CP-406-253
Operator	Charles Kay
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

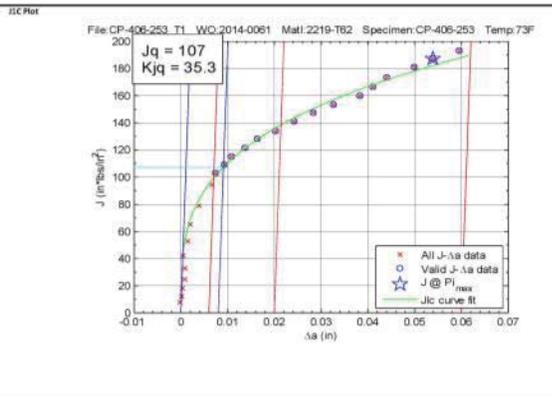
Geometry	CIT
"W" (in)	2.0000
"H" (in)	1.0000
"Bc" (in)	0.7970
"Be" (in)	0.5590
Orientation	L-T
"a" (in)	0.7960
Hole Span/2 "H" (in)	0.7100
COO Span/2 "D" (in)	0.1050
Coupon #	M5

"E" (ksi)	10.00
"E" (ksi)	10.00
"a" (in) @ 0.1 in	0.00
"v" (in)	0.30
"VS" (ksi)	38.00
"UTS" (ksi)	57.30
Flow Stress (ksi)	47.94
"E"/"YS"	0.28

PreCrack Pmax (lbF)	1534.0
PreCrack Final "a" (in)	1.0485
Stress Ratio	0.10
Kmax (ksi_sqr_in)	8.00
A_a0 (in)	1.0485
A_a0 (in)	1.0297
A_f0 (in)	1.1305
A_f0 (in)	1.1138

Results	$J_q$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_{Ic}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_p$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$K_{Ic}$ (ksi/in <sup>3/2</sup> )	$K_{Ic}$ at $J_{Ic}$ (ksi/in <sup>3/2</sup> )	K @50% (ksi/in <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	107.30	95.40	11.90	35.35	33.14	29.74	1.511	1.31

Summary of Test Validities Required for All Tests:		
7.4.5 Initial precrack force	$P < P_m$ for sample type	Valid
7.4.5.1 Initial Kmax	< 80% of PreCrack YS	Valid
7.4.5.2 Final Kmax	< 80% of K reqd	Valid
7.4.4.1 Precrack straightness	None > 0.05B	Valid
7.4.4.1 Precrack length	> 0.05B or 0.05inch, wide notch	Valid
7.5 Side groove depth	< 0.25B	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :		
7.4.2 a/W Range for J	$0.45 < a/W < 0.7$	Valid
8.1.5.1 Even Crack Ext.	None > 50% of avg crk ext.	Valid
8.1.5.2 Accuracy of crk ext. grad.	$20^\circ < \theta < 15^\circ$ @ avg	Valid
A9.6.4 # pts in region A	# pts >= 1 in A	Valid
A9.6.4 # pts in region B	# pts >= 1 in B	Valid
A9.6.4 # pts in region C	# pts >= 5	Valid
A9.8.1 1/8 in. offset C <sub>2</sub>	$C_2 < 1.0$	Valid
A9.8.2.1 Accuracy of a, a <sub>0</sub>	$ a - a_0 - a_{avg}  < 0.01W$ or 0.5mm	Valid
A9.8.2.2 # pts in a, a <sub>0</sub> fit	# points >= 8	Valid
A9.8.2.3 0.4 in/pts a, a <sub>0</sub> fit	# points >= 3	Valid
A9.8.2.4 0.4 in/pts a, a <sub>0</sub> fit	$R^2 > 0.98$	Valid
A9.8.1 Thickness requirement	$B > 10J_q/\text{FlowStress}$	Valid
A9.9.2 Ligament requirement	$b_0 > 10J_q/\text{FlowStress}$	Valid
A9.9.3 Regression line slope	Slope = flow at $a_0, a$	Valid



All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .		
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for K <sub>Ic</sub> :		
7.4.2 a/W Range for K <sub>Ic</sub>	$0.45 < a/W < 0.75$	Valid
A5.4.3 Ligament length	$b_0 > 2.5W/YS^{3/2}$	NOT valid
A5.4.2 Pmax/Pq ratio	less than 1.10	NOT valid

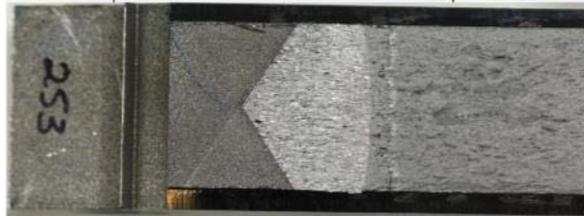
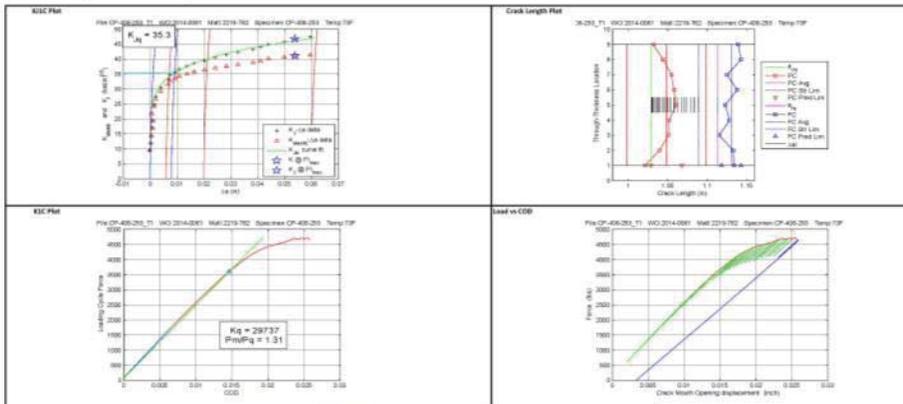
Method File: FTA\_NJ77  
Comments: N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	180061421
Other Specimen ID	CP-406-253
Operator	Charles Kay
Test Date	6/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
214 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.3

EM10 Specimen ID	140091424
Other Specimen ID	CP-406-256
Operator	Charles Kay
Test Date	4/1/2014
Environment	Air
Temperature (F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

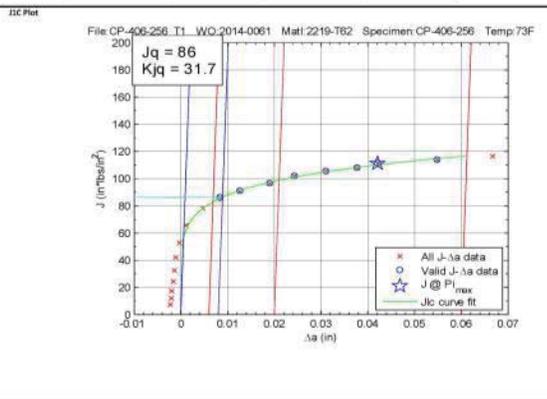
Geometry	CTI
"W" (in)	1.9990
"B" (in)	0.9990
"Bt" (in)	0.7950
"Bc" (in)	0.9580
Orientation	T.S.
"Ap" (in)	0.7990
Hole Spacing "H" (in)	0.7100
COO Span/2 "D" (in)	0.1050
Coupon #	MS

"E" (M50)	10.60
"Ee" (M50)	10.60
% diff E & Ee	0.00
"v" (in)	0.30
"VS" (K50)	37.40
"UTS" (K50)	56.60
Flow Stress (K50)	47.00
"E"/"VS"	0.28

PreCrack Pmax (lbf)	1524.0
PreCrack Final "a" (in)	1.0555
Stress Ratio	0.10
Kmax (ksi_sqr_t_in)	8.00
A <sub>0g</sub> (in)	1.0535
A <sub>0e</sub> (in)	1.0373
A <sub>g</sub> (in)	1.1199
A <sub>e</sub> (in)	1.1107

Results	$J_q$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{e,q}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_p,q$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic,at J_{e,q}}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic,5Sec}$ (ksi(in) <sup>3/2</sup> )	K Res Ligament (in)	Pmax/Pq
	85.50	77.90	9.00	81.71	80.01	27.88	1.389	1.15

Summary of Test Validity Required for All Tests:		
7.4.5 Initial precrack force	$F_p \leq 2a$ for sample type	Valid
7.4.5.1 Initial Kmax	$\leq 60\%$ of PreCrack VS	Valid
7.4.5.2 Final Kmax	$\leq 60\%$ of K result	Valid
8.1.4 Precrack straightness	None $\leq 0.005$	Valid
7.4.5.3 Precrack length	$\geq 0.05B$ or $0.05a$ whichever is greater	Valid
7.5 Side groove depth	$\leq 0.25B$	Valid
Summary of Test Validities Required for $J_{Ic}$ :		
7.4.2 a/W Range for J	$0.45 \leq a/W \leq 0.7$	Valid
9.1.5.1 Even Crack Ext.	None $\leq 50\%$ of auger ext.	Valid
9.1.5.2 Accuracy of crk ext. pred.	$\Delta W \leq 0.15 d_{avg}$	Valid
A9.6.4 # pts in region A	# pts $\geq 1$ in A	Valid
A9.6.4 # pts in region B	# pts $\geq 1$ in B	Valid
A9.6.4 # Valid J - ds pts	# pts $\geq 5$	Valid
A9.8.1 ds fit coeff C2	$C2 \leq 0$	Valid
A9.8.2 Accuracy of a <sub>0g</sub>	$ a_{0g} - a_0  \leq 0.01W$ or $0.5mm$	Valid
A9.8.2.1 Num pts in a <sub>0g</sub> fit	# points $\geq 8$	Valid
A9.8.2.2 Slope of a <sub>0g</sub> fit	# points $\geq 3$	Valid
A9.8.2.3 eq fit R <sup>2</sup>	$R^2 \geq 0.98$	Valid
A9.9.1 Thickness requirement	$B \geq 10J_{max}/FlowStress$	Valid
A9.9.2 Ligament requirement	$B \geq 10J_{max}/FlowStress$	Valid
A9.9.3 Regression line slope	Slope $\leq$ flow at ds, g	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .		
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for K <sub>Ic</sub> :		
7.4.2 a/W Range for K	$0.45 \leq a/W \leq 0.55$	Valid
A5.4.3 Equipment length	$B \geq 2.5 J_{max}/K_{Ic}^2$	NOT Valid
A5.4.2 Pmax/Pq ratio	$\leq 1.10$	NOT Valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .		
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.		



Method File:  
ITA\_NI\_FT  
Comments:  
N/A

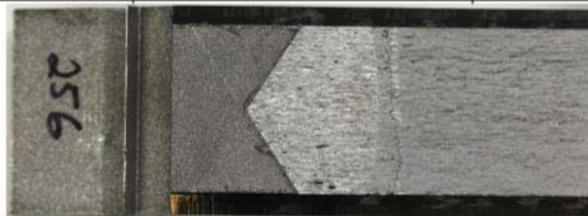
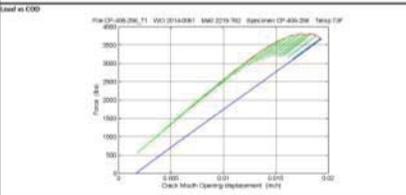
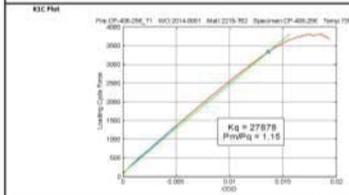
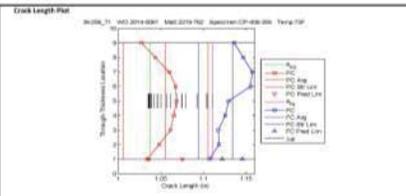
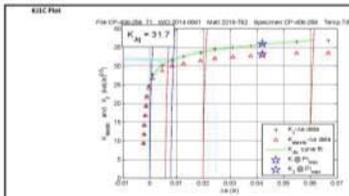


### EM10 Fracture Toughness $J_{Ic}$ Test Results



Version 4.3

EM10 Specimen ID	140091424
Other Specimen ID	CP-406-256
Operator	Charles Kay
Test Date	4/1/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
215 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	140061426
Other Specimen ID	CP-406-258
Operator	Charles Key
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

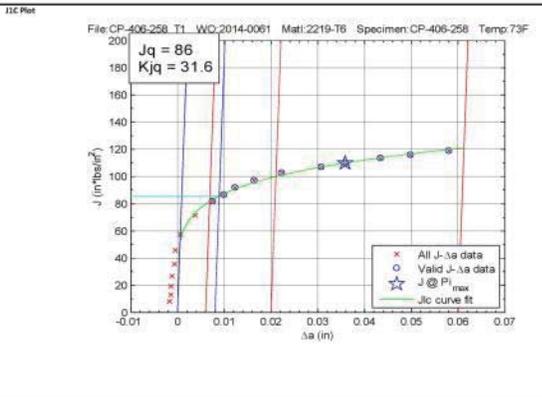
Geometry	CT
"W" (in)	2.0000
"H" (in)	1.0000
"Bn" (in)	0.7880
"Bt" (in)	0.9930
Orientation	T-L
"An" (in)	0.8000
Hole Span/2 "H" (in)	0.7500
COO Span/2 "D" (in)	0.1040
Gougeon #	M5

"E" (ksi)	10.50
"Et" (ksi)	10.50
% diff E & Et	0.00
"v"	0.30
"YS" (ksi)	37.40
"UTS" (ksi)	56.00
Flow Stress (ksi)	47.00
"E"/"YS"	0.28

PreCrack Pmax (lbF)	1537.0
PreCrack Final "a" (in)	1.0568
Stress Ratio	0.10
Kmax (ksi_sqr_t_in)	8.00
A_o6 (in)	1.0666
A_o4 (in)	1.0513
A_o2 (in)	1.1619
A_o1 (in)	1.1349

Results	$J_i$ (in <sup>3</sup> /in <sup>2</sup> )	$J_e$ (in <sup>3</sup> /in <sup>2</sup> )	$J_p$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic\_at\_J_e}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic\_Sec}$ (ksi(in) <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pg
	85.00	77.40	8.30	11.57	30.03	27.91	1.392	1.15

Summary of Test Validities Required for All Tests:		
7.4.5.1 Initial precrack force	P <= Pn for sample type	Valid
7.4.5.1.1 Initial Kmax	<= 40% of Precrack YS	Valid
7.4.5.2 Final force	<= 50% of K result	Valid
9.1.4.1 Precrack straightness	Name > 0.050	Valid
7.4.5.1.1 Precrack length	>= 0.050 or 0.05in, wide notch	Valid
7.5 Side groove depth	< 0.258	Valid
Summary of Test Validities Required for IIc:		
7.4.2 a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1 1mm Crack Init	Name < 50% of avg. ork ext.	Valid
9.1.5.2 Accuracy of ink ext. prod.	2PF < 0.15 <= 3PF	Valid
A9.6.4 # pts in region A	# pts >= 1 in A	Valid
A9.6.4 # pts in region B	# pts >= 1 in B	Valid
A9.6.4 # Valid J-Is pts	# pts >= 5	Valid
A9.8.1.1 Side fit coeff C2	C2 < 1.0	Valid
A9.8.2.1 Accuracy of a_o6	S_o6 - a_o6  < 0.01W or 0.5mm	Valid
A9.8.2.2 Num pts in a_o6 fit	# points >= 8	Valid
A9.8.2.2.1 a_o6 fit R^2	R^2 > 0.99	Valid
A9.9.1 Thickness requirement	b > 10t/FlowStress	Valid
A9.9.2 Ligament requirement	b_o > 10t/FlowStress	Valid
A9.9.3 Regression line slope	Slope < flow at db_o	Valid
All validity criteria for IIc NOT met. JIc is not fully valid IIc.		
Non-valid JIc values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for KIc:		
7.4.2 a/W Range for K	0.45 <= a/W <= 0.55	Valid
A5.4.1.1 Ligament length	b_o > 2.5(K/YS)^2	NOT Valid
A5.4.2 Pmax/Pg ratio	less than 1.10	NOT Valid
All validity criteria for KIc NOT met. KIc is not fully valid KIc.		
Non-valid KIc values may still convey valuable fracture toughness information.		



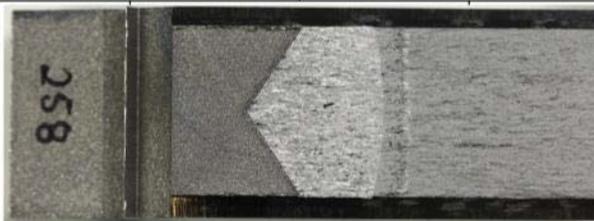
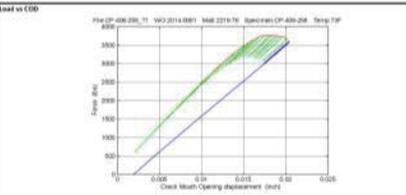
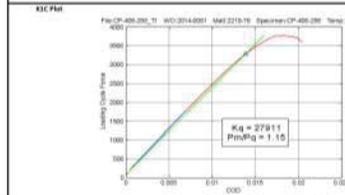
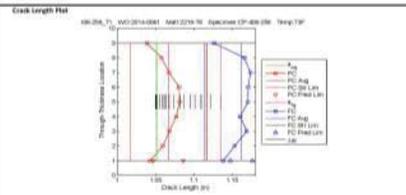
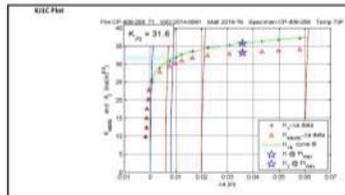
Method File:  
FTA\_NLIT  
Comments:  
N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results



EM10 Specimen ID	140061410
Other Specimen ID	CP-406-258
Operator	Charles Key
Test Date	4/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
216 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001429
Other Specimen ID	CP-406-261
Operator	Charles Kay
Test Date	4/13/2014
Environment	Air
Temperature (°F)	75
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

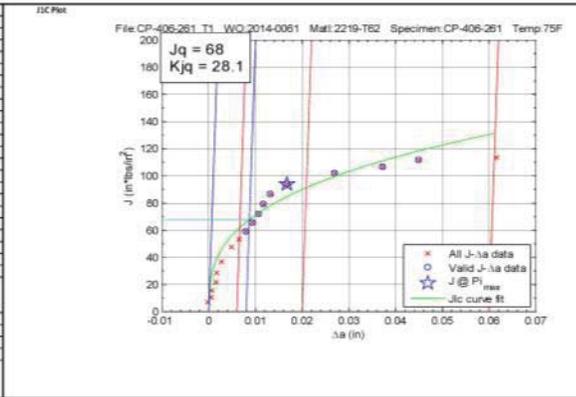
Geometry	CIT
"a" (in)	1.0000
"B" (in)	0.5000
"b" (in)	0.1900
"Bc" (in)	0.4790
Orientation	S-T
"a <sub>0</sub> " (in)	0.4000
Hole Span/2 "H" (in)	0.3500
COO Span/2 "D" (in)	0.0980
Coupon #	NA5

"E" (ksi)	30.60
"E <sub>c</sub> " (ksi)	10.60
% diff E & E <sub>c</sub>	0.00
"ν"	0.30
"ν <sub>s</sub> " (ksi)	38.70
"ν <sub>TS</sub> " (ksi)	59.90
Flow Stress (ksi)	49.25
"E"/"ν <sub>s</sub> "	0.27

Precrack Pmax (lbf)	524.0
Precrack Pload "P" (lbf)	0.5000
Stress Ratio	0.10
Kmax (ksi√in)	0.00
A <sub>0p</sub> (in)	0.5000
A <sub>0q</sub> (in)	0.4958
A <sub>0r</sub> (in)	0.5873
A <sub>0t</sub> (in)	0.5777

Results	Iq (in <sup>3</sup> /lb√in <sup>2</sup> )	Ia, q (in <sup>3</sup> /lb√in <sup>2</sup> )	I <sub>p, q</sub> (in <sup>3</sup> /lb√in <sup>2</sup> )	K <sub>Ic</sub> (ksi√in)	K <sub>Ic, at, Ia, q</sub> (ksi√in)	K <sub>Ic, flow</sub> (ksi√in)	K <sub>Ic, Reg</sub> (ksi√in)	Premax/Pq
	67.80	57.70	50.00	28.10	25.93	20.89	0.729	1.37

Summary of Test Validities Required for All Tests:			
7.4.3	Initial precrack force	P > P <sub>min</sub> for sample type	Valid
7.4.5.1	Initial stress	< 40% of precrack YS	Valid
7.4.5.2	Final stress	< 80% of YS result	Valid
9.1.4.1	Precrack straightness	None > 0.050	Valid
7.4.5.1	Precrack length	> 0.050 in or 0.010 inch, wide notch	Valid
7.5	Side groove depth	< 0.250	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :			
7.4.2	a/W Range for J	0.45 < a/W < 0.7	Valid
9.1.5.1	Open Crack Fac.	None > 50% of aq (in ext.)	Valid
9.1.5.2	Accuracy of crack ext. gage	±0.01 or 0.1% of aq	Valid
A9.4.4	# pts in region A	# pts > 1 in A	Valid
A9.4.4	# pts in region B	# pts > 1 in B	Valid
A9.4.4	# valid J-Ia pts	# pts > 5	Valid
A9.8.1	Id for coeff C2	C2 > 1.0	Valid
A9.8.2.1	Accuracy of a <sub>0p</sub>	Δ a <sub>0p</sub> - a <sub>0p1</sub>   < 0.02W or 0.5mm	Valid
A9.8.2.2	Num pts in a <sub>0p</sub> file	# points > 8	Valid
A9.8.2.3	Δ a <sub>0p</sub> vs a <sub>0p</sub> file	# Δ a <sub>0p</sub> > 0.5mm	Valid
A9.8.2.4	Δ a <sub>0p</sub> vs R <sub>TS</sub>	# Δ a <sub>0p</sub> > 0.5mm	Valid
A9.8.1	Thickness requirement	B > 30a/√flowstress	Valid
A9.9.2	Ligament requirement	b <sub>0</sub> > 30a/√flowstress	Valid
A9.9.3	Regression line slope	Slope = flow at B <sub>0, q</sub>	Valid
All validity criteria for J <sub>Ic</sub> NOT met. J <sub>Ic</sub> is not fully valid J <sub>Ic</sub> .			
Non-valid J <sub>Ic</sub> values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for K <sub>Ic</sub> :			
7.4.2	a/W Range for K <sub>Ic</sub>	0.45 < a/W < 0.55	Valid
A5.4.1	Ligament length	b <sub>0</sub> > 2.5A/√YS <sup>2</sup>	NOT valid
A5.4.2	Premax/Pq ratio	Less than 1.10	NOT valid
All validity criteria for K <sub>Ic</sub> , NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .			
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.			



Method File:  
FTA\_NLFT  
Comments:  
NA

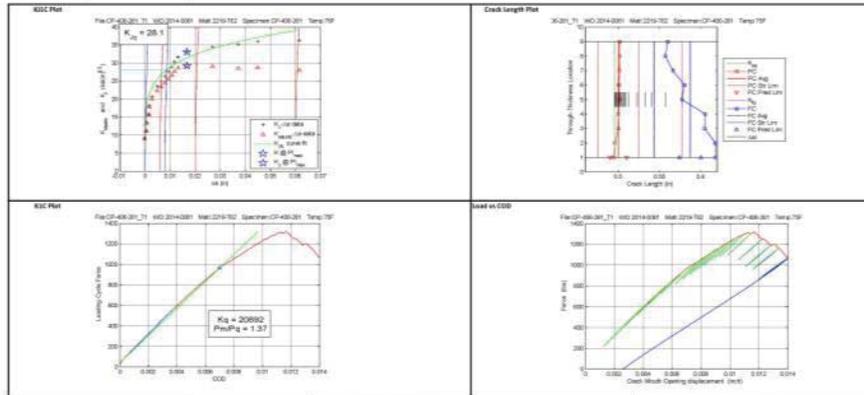


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001429
Other Specimen ID	CP-406-261
Operator	Charles Kay
Test Date	4/13/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
217 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

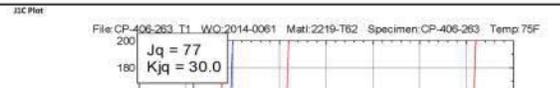
Version 4.3



EM10 Specimen ID: 14001411	Geometry: CTI	"E" (MS): 10.60	Precrack Pmax (lbf): 520.0
Other Specimen ID: CP-406-263	"W" (in): 1.0000	"E" (MS): 10.60	Precrack Final "a" (in): 0.5109
Operator: Charles Key	"W" (in): 0.5000	% del E & E: 0.00	Stress Rate: 8.00
Test Date: 4/12/2014	"Bn" (in): 0.3960	"V": 0.30	Kmax (ksi_sqr_t_in): 8.00
Environment: Air	"Ba" (in): 0.4790	"YS": (KSI): 38.76	A_op (in): 0.5109
Temperature (F): 75	Orientation: S-T	"UTS": (KSI): 59.80	A_oq (in): 0.5100
Pressure (PSIG): 0	"a0" (in): 0.4030	Flow Stress (KSI): 49.35	A_lp (in): 0.5823
Relative Humidity (%): NA	Hole Span/2 "M" (in): 0.3550	"E"/"YS": 0.27	A_q (in): 0.5796
Soak Time (min): 0	COD Span/2 "D" (in): 0.0990		
	Coupon #: MS		

Results	$J_{Ic}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_{E,q}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$J_{p,q}$ (in <sup>3</sup> /lb/in <sup>2</sup> )	$K_{Iq}$ (ksi/in <sup>3/2</sup> )	$K_{Iq,at,J_{E,q}}$ (ksi/in <sup>3/2</sup> )	K_35Sec (ksi/in <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	77.40	65.40	12.00	30.03	27.81	21.86	0.797	1.27

Summary of Test Validities Required for All Tests:		
7.4.5 Initial precrack force	P = Pm for sample type	Valid
7.4.5.1 Initial Kmax	<40% of Precrack VS	Valid
7.4.5.2 Final Kmax	<60% of Kmax	Valid
9.1.4.1 Precrack straightness	None > 0.075	Valid
7.4.5.1.1 Precrack length	<0.05B or 0.05in, wide notch	Valid
7.5 Side groove depth	< 0.25B	Valid



Summary of Test Validities Required for JIc:		
7.4.2 a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1 Open Crack Len	None < 50% of avg crk ext.	Valid
9.1.5.2 Accuracy of crk ext. posnd	Pct < 0.15 Δa_posnd	Valid
A9.6.4 # pts in region A	# pts >= 1 in A	Valid
A9.6.4 # pts in region B	# pts >= 1 in B	Valid
A9.6.4 # Valid J-Ic pts	# pts >= 3	Valid
A9.8.1.1 Δa fit coeff C2	C2 < 1.0	Valid
A9.8.2.1 Accuracy of a_oq	Δa_oq - a_exp  < 0.05W or 0.5mm	Valid
A9.8.2.2 Num pts in a_oq fit	# points >= 8	Valid
A9.8.2.3 Slope/Pts a_oq fit Csq	# points >= 3	Valid
A9.8.2.4 Δa fit R²	R² > 0.96	Valid
A9.9.1 Thickness requirement	B > 10Δa/FlowStress	Valid
A9.9.2 Ligament requirement	b_o > 10Δa/FlowStress	Valid
A9.9.3 Regression line slope	Slope < flow at Δa_o	Valid

All validity criteria for JIc NOT met. JIc is not fully valid JIc. Non-valid JIc values may still convey valuable fracture toughness information.		
7.4.2 a/W Range for K	0.45 <= a/W <= 0.55	Valid
A5.4.3 K Ligament length	b_o > 2.5(K/YS)²	NOT valid
A5.4.2 Pmax/Pq ratio	Less than 1.10	NOT valid

Method File: FTA\_NJFT  
Comments: N/A

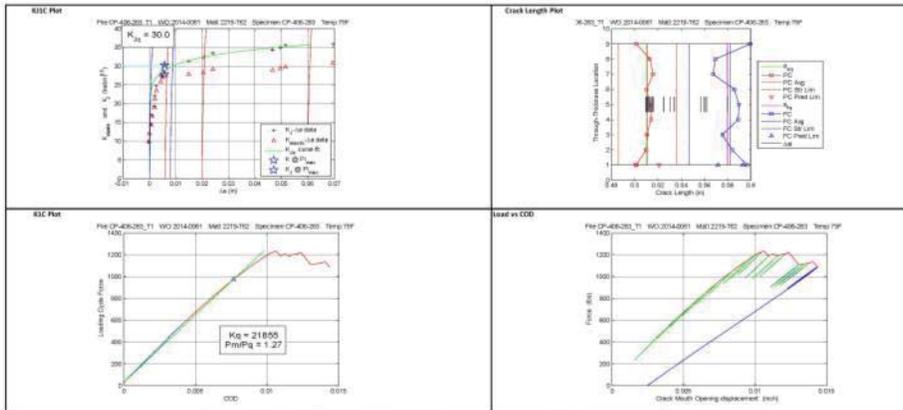


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 14001411	Other Specimen ID: CP-406-263
Operator: Charles Key	Test Date: 6/12/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
218 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061434
Other Specimen ID	CP-406-266
Operator	Charles Kay
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	NA

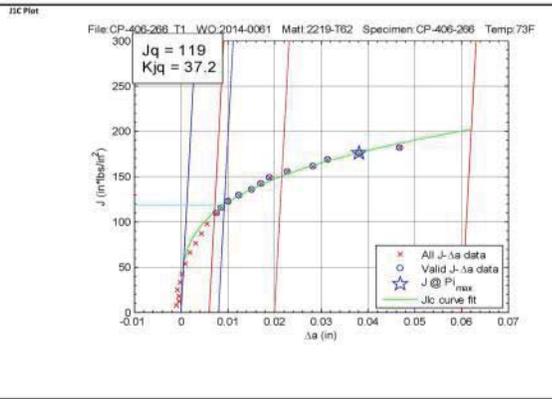
Geometry	CT
"W" (in)	2.000
"B" (in)	1.0000
"Bn" (in)	0.7960
"Bc" (in)	0.9590
Orientation	1.5°
"An" (in)	0.8000
Hole Span/2 "H" (in)	0.7100
COO Span/2 "D" (in)	0.1860
Coupon #	MS

"E" (ksi)	10.60
"E" (MPa)	7.280
% dE/E & E <sub>c</sub>	0.00
"V"	0.30
"VS" (ksi)	38.30
"VTS" (ksi)	57.80
Flow Stress (ksi)	48.04
"E"/"VS"	0.28

Precrack Pmax (lbf)	1520.0
Precrack Final "a" (in)	1.0545
Stress Ratio	0.10
Kmax (ksi $\sqrt{\text{in}}$ )	8.00
A <sub>0a</sub> (in)	1.0545
A <sub>0c</sub> (in)	1.0359
A <sub>0b</sub> (in)	1.1179
A <sub>0g</sub> (in)	1.1055

Results	Iq (in $\sqrt{\text{lb}/\text{in}^2}$ )	Je, q (in $\sqrt{\text{lb}/\text{in}^2}$ )	Jp, q (in $\sqrt{\text{lb}/\text{in}^2}$ )	KIq (ksi $\sqrt{\text{in}}$ )	KIq <sub>at Je, q</sub> (ksi $\sqrt{\text{in}}$ )	K <sub>95sec</sub> (ksi $\sqrt{\text{in}}$ )	K Req Ligament (in)	Pmax/Pq
	118.70	100.50	15.20	97.18	34.72	28.95	1.428	1.36

Summary of Test Validities Required for All Tests:			
7.4.5	Initial precrack force	P <= Pm for sample type	Valid
7.4.5.1	Initial crack test	<=50% of precrack V5	Valid
7.4.5.2	Final stress	<=50% of K result	Valid
9.1.4.3	Precrack straightness	None > 0.05%	Valid
7.4.5.3	Precrack length	>= 0.058 or 0.05in, wide notch	Valid
7.5	Side groove depth	< 0.258	Valid
Summary of Test Validities Required for JIc:			
7.4.2	a/W range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1	Crack Ext. Test	None > 50% of crack ext.	Valid
9.1.5.2	Accuracy of Crk ext. pred.	DPI < 0.15 d <sub>0</sub>	Valid
A6.6.4	# pts in region A	# pts >= 1 in A	Valid
A6.6.4	# pts in region B	# pts >= 1 in B	Valid
A6.6.4	Valid side pts	# pts >= 5	Valid
A6.8	J-1a fit coeff C2	C2 < 1.0	Valid
A6.8.2.1	Accuracy of a <sub>0g</sub>	a <sub>0g</sub> - a <sub>0c</sub>   < 0.03W or 0.5mm	Valid
A6.8.2.2	Num pts in a <sub>0g</sub> fit	# points >= 8	Valid
A6.8.2.3	Regression slope	# points >= 3	Valid
A6.8.2.2	a <sub>0g</sub> in 1/2"	a <sub>0g</sub> > 0.96	Valid
A6.9	Thickness requirement	B > 10Iq/FlowStress	Valid
A6.9	Ligament requirement	B <sub>0</sub> > 10Iq/FlowStress	Valid
A5.9	Regression line slope	Slope = flow at C <sub>0</sub> , a <sub>0</sub>	Valid
All validity criteria for JIc NOT met. JIc is not fully valid.			
Non-valid JIc values may still convey valuable fracture toughness information.			
Summary of Test Validities Required for KIc:			
7.4.2	a/W range for K	0.45 <= a/W <= 0.55	Valid
A5.4.3	Ligament length	B <sub>0</sub> > 2.5(K/V5) <sup>2</sup>	NOT valid
A5.4.2	Pmax/Pq ratio	>= 1.36	NOT valid
All validity criteria for KIc NOT met. KIc is not fully valid.			
Non-valid KIc values may still convey valuable fracture toughness information.			



Method File:  
FTA N17  
Comments:  
N/A

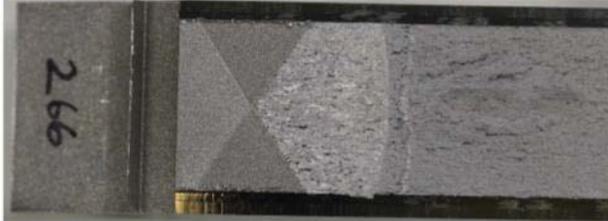
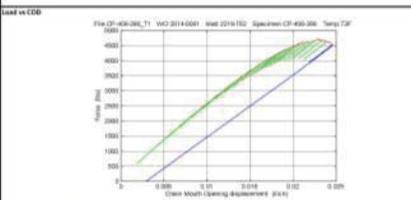
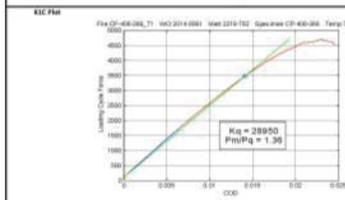
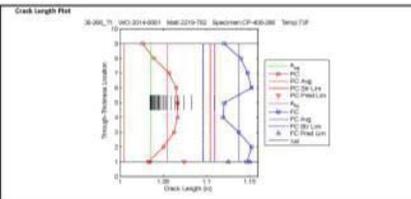
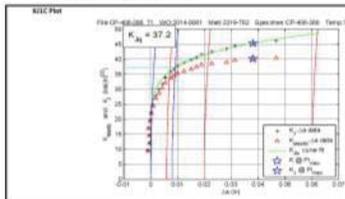


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140061434
Other Specimen ID	CP-406-266
Operator	Charles Kay
Test Date	4/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

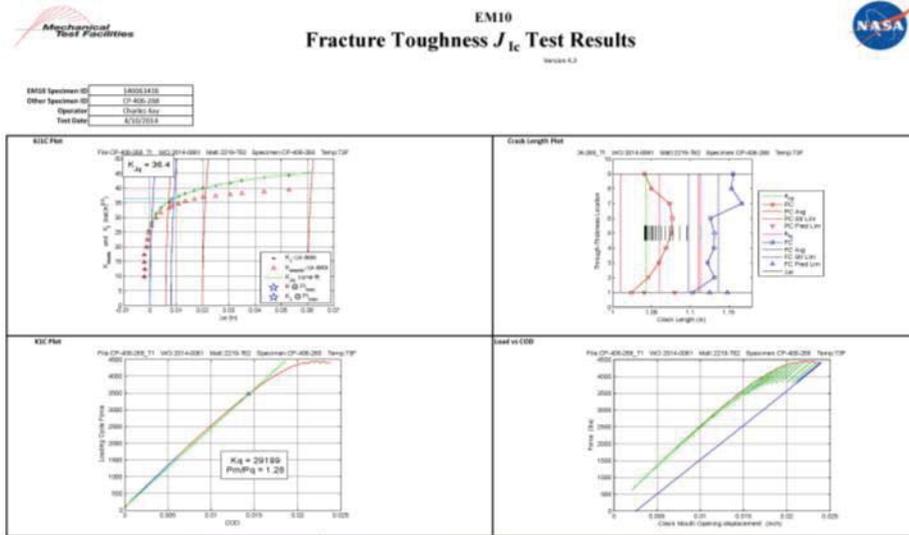
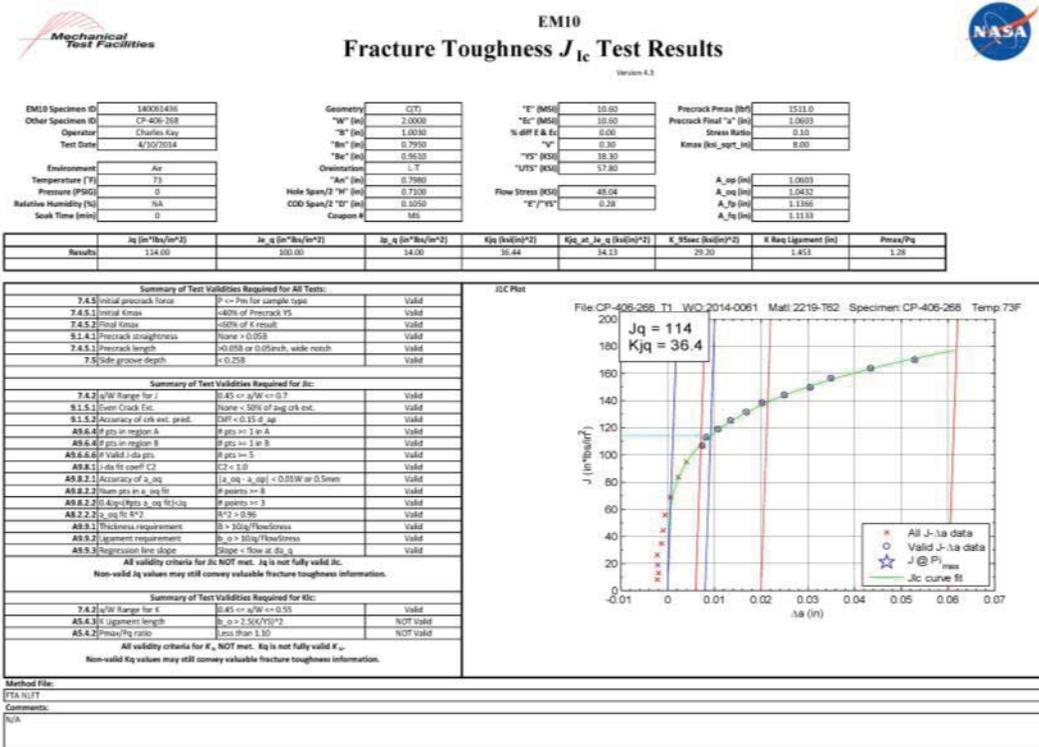
Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
219 of 223





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
220 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001439
Other Specimen ID	CP-406-271
Operator	Charles Key
Test Date	4/10/2014
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

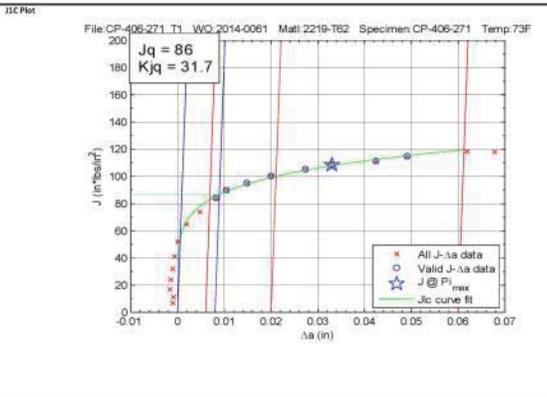
Geometry	CTT
"W" (in)	1.9930
"H" (in)	1.0030
"Bc" (in)	0.7990
"Be" (in)	0.9610
Orientation	T1
"Ae" (in)	0.7990
Hole Span/2 "H" (in)	0.7100
CDD Span/2 "D" (in)	0.1050
Coupon #	NA

"E" (ksi)	10.60
"Ec" (ksi)	10.60
% diff E & Ec	0.00
"v"	0.30
"YS" (ksi)	37.60
"UTS" (ksi)	56.70
Flow Stress (ksi)	47.16
"E"/"YS"	0.28

Pre-crack Pmax (lbf)	1505.0
Pre-crack Pmax "a" (in)	1.0297
Stress Ratio	0.10
Kmax (ksi_sqr_in)	8.00
A_oq (in)	1.0297
A_eq (in)	1.0408
A_fp (in)	1.1341
A_fq (in)	1.1087

Results	$J_{Ic}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{e, q}$ (in <sup>3</sup> /in <sup>2</sup> )	$J_{p, q}$ (in <sup>3</sup> /in <sup>2</sup> )	$K_{Ic}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic, at J_{e, q}}$ (ksi(in) <sup>3/2</sup> )	$K_{Ic, at J_{p, q}}$ (ksi(in) <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	85.90	76.20	8.30	31.74	30.17	28.34	1.420	1.14

Summary of Test Validities Required for All Tests:		
7.4.5.1 Initial precrack force	P <= Pin for sample type	Valid
7.4.5.2 Initial Kmax	<80% of Precrack YS	Valid
7.4.5.3 Final force	>50% of K req	Valid
9.1.4.1 Precrack straightness	None > 0.05B	Valid
7.4.5.3 Precrack length	>0.05B or 0.05inch, wide notch	Valid
7.5 Site groove depth	< 0.25B	Valid
Summary of Test Validities Required for JIC:		
7.4.2 a/W Range for J	0.45 <= a/W <= 0.7	Valid
9.1.5.1 Initial Crack Fat.	None < 50% of avg c/rk ext.	Valid
9.1.5.2 Accuracy of crk ext. prod.	50% < 0.15 a_o	Valid
A9.6.4 # pts in region A	# pts >= 1 in A	Valid
A9.6.4 # pts in region B	# pts >= 1 in B	Valid
A9.6.4 # Valid J-da pts	# pts >= 5	Valid
A9.8.1 J-da to coeff C2	C2 < 1.0	Valid
A9.8.2 Accuracy of a_oq	a_oq - a_opt  < 0.01W or 0.5mm	Valid
A9.8.2.1 Num pts in a_oq fit	# points >= 8	Valid
A9.8.2.2 R^2 of a_oq fit	R^2 > 0.96	Valid
A9.9.1 Thickness requirement	B > 10(a_oq/FlowStress)	Valid
A9.9.2 Ligament requirement	b_o > 10(a_oq/FlowStress)	Valid
A9.9.3 Regression line slope	Slope = flow at da_oq	Valid
All validity criteria for JIC NOT met. Jq is not fully valid Jic.		
Non-valid Jq values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for K <sub>Ic</sub> :		
7.4.2 a/W Range for K <sub>Ic</sub>	0.45 <= a/W <= 0.55	Valid
A5.4.1 Ligament length	b_o > 2.5(a_oq/YS) <sup>2</sup>	NOT Valid
A5.4.2 Pmax/Pq ratio	less than 1.10	NOT Valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .		
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.		



Method File:  
FTA NLT  
Comments:  
N/A

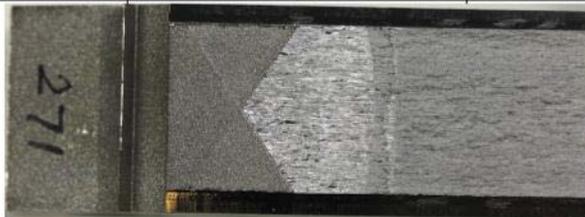
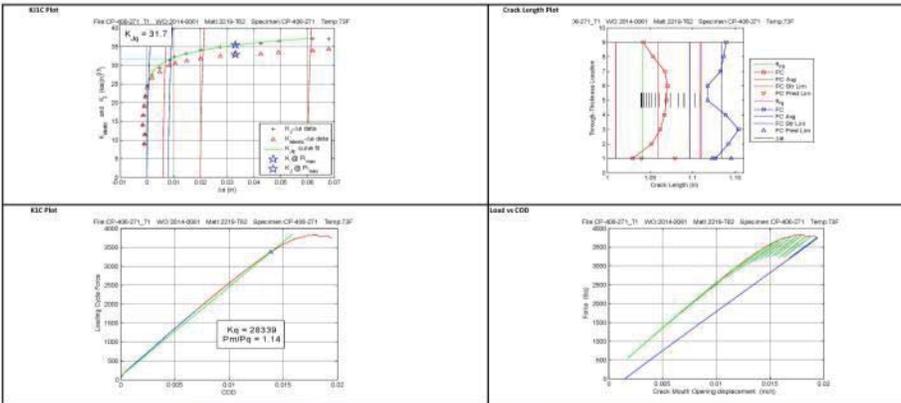


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	140001439
Other Specimen ID	CP-406-271
Operator	Charles Key
Test Date	4/10/2014





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
221 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001441
Other Specimen ID	CP-406-273
Operator	Charles Kay
Test Date	
Environment	Air
Temperature (°F)	73
Pressure (PSIG)	0
Relative Humidity (%)	NA
Soak Time (min)	0

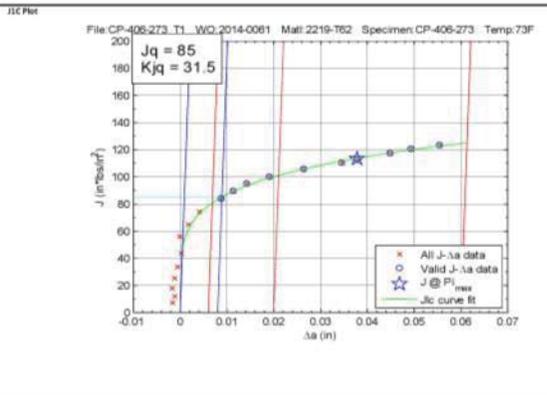
Geometry	CTI
"W" (in)	1.9970
"R" (in)	1.0000
"B <sub>u</sub> " (in)	0.7500
"B <sub>l</sub> " (in)	0.9500
Orientation	T1
"A <sub>u</sub> " (in)	0.7510
Hole Spn/2 "H" (in)	0.7500
COD Spn/2 "D" (in)	0.0500
Coupon #	MS

"E" (ksi)	33.80
"E <sub>r</sub> " (ksi)	35.50
% diff E & E <sub>r</sub>	0.50
"ν"	0.30
"YS" (ksi)	37.60
"UTS" (ksi)	56.70
Flow Stress (ksi)	47.16
"E"/"YS"	0.28

Precrack Pmax (lbF)	1515.0
Precrack Final "a" (in)	1.0810
Stress Ratio	0.10
Kmax (ksi√in)	9.00
A <sub>u,eq</sub> (in)	1.0810
A <sub>u,eq</sub> (in)	1.0650
A <sub>l,eq</sub> (in)	1.1591
A <sub>l,eq</sub> (in)	1.1667

Results	J <sub>q</sub> (in <sup>3</sup> /lb√in <sup>2</sup> )	J <sub>e</sub> (in <sup>3</sup> /lb√in <sup>2</sup> )	J <sub>0.2</sub> (in <sup>3</sup> /lb√in <sup>2</sup> )	K <sub>Ic</sub> (ksi√in)	K <sub>Ic</sub> at J <sub>e</sub> (ksi√in)	E <sub>0.2</sub> (ksi)	E <sub>0.2</sub> Reg. (ksi)	E <sub>0.2</sub> Reg. (ksi)	Pmax/Pq
	85.00	76.10	9.00	11.47	29.76	27.60	1.847	1.17	

Summary of Test Validities Required for All Tests:		
7.4.5 Initial precrack force	P ≤ P <sub>0</sub> for sample type	Valid
7.4.5.1 Initial Pmax	≤ 80% of Precrack YS	Valid
7.4.5.2 Final Pmax	≤ 80% of E result	Valid
8.1.4.1 Precrack straightness	None > 0.05%	Valid
7.4.5.3 Precrack length	±0.008 or 0.05inch, wide notch	Valid
7.5 Wide groove depth	± 0.25%	Valid
Summary of Test Validities Required for J <sub>Ic</sub> :		
7.4.2 J <sub>Ic</sub> Range for J	0.45 ≤ a/W ≤ 0.7	Valid
8.5.1.1 Even Crack Ext.	None > 50% of avg crk ext.	Valid
8.5.1.2 Accuracy of crk ext. grad.	±0.01 ± 0.01 mm	Valid
A9.6.4# pts in region A	# pts ≥ 1 in A	Valid
A9.6.4# pts in region B	# pts ≥ 1 in B	Valid
A9.6.4# Valid J <sub>Ic</sub> pts	# pts = 5	Valid
A9.8.1.1 da/dN over J <sub>Ic</sub>	J <sub>Ic</sub> < 1.0	Valid
A9.8.1.2 Accuracy of a <sub>0</sub> /a <sub>1</sub>	a <sub>0</sub> - a <sub>1</sub> - a <sub>0</sub>   ≤ 0.01W or 0.5mm	Valid
A9.8.2.1 Num. pts in a <sub>0</sub> /a <sub>1</sub>	# points = 8	Valid
A9.8.2.2 J <sub>Ic</sub> (da/dN) vs J <sub>Ic</sub>	# points ≥ 3	Valid
A9.8.2.3 da/dN vs J <sub>Ic</sub>	R <sup>2</sup> ≥ 0.98	Valid
A9.9.1 Thickness requirement	B > 10J <sub>Ic</sub> /flowstress	Valid
A9.9.2 Ligament requirement	B <sub>u</sub> > 10J <sub>Ic</sub> /flowstress	Valid
A9.9.3 Regression line slope	Slope = flow at B <sub>u</sub>	Valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .		
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.		
Summary of Test Validities Required for K <sub>Ic</sub> :		
7.4.2 J <sub>Ic</sub> Range for K	0.45 ≤ a/W ≤ 0.55	Valid
A5.4.3# Ligament length	B <sub>u</sub> > 2.5A <sub>u</sub> /YS <sup>2</sup>	NOT valid
A5.4.2 Pmax/Pa ratio	less than 1.10	NOT valid
All validity criteria for K <sub>Ic</sub> NOT met. K <sub>Ic</sub> is not fully valid K <sub>Ic</sub> .		
Non-valid K <sub>Ic</sub> values may still convey valuable fracture toughness information.		



Method File:  
FTA\_NLJT  
Comments:  
N/A

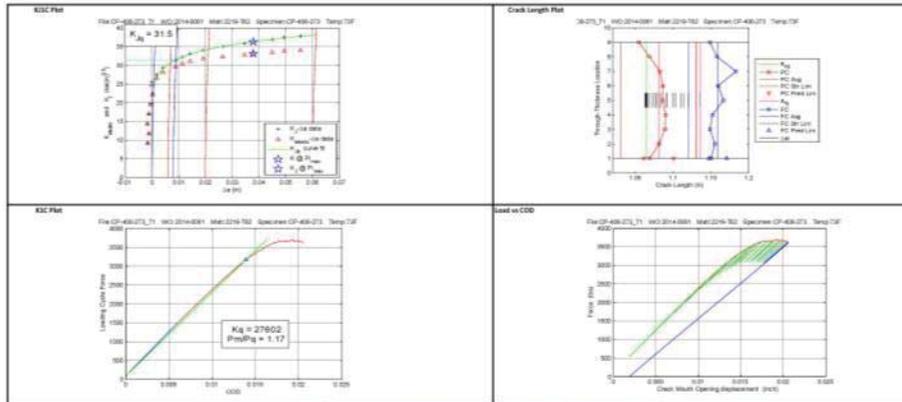


### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID	14001441
Other Specimen ID	CP-406-273
Operator	Charles Kay
Test Date	





# NASA Engineering and Safety Center Technical Assessment Report

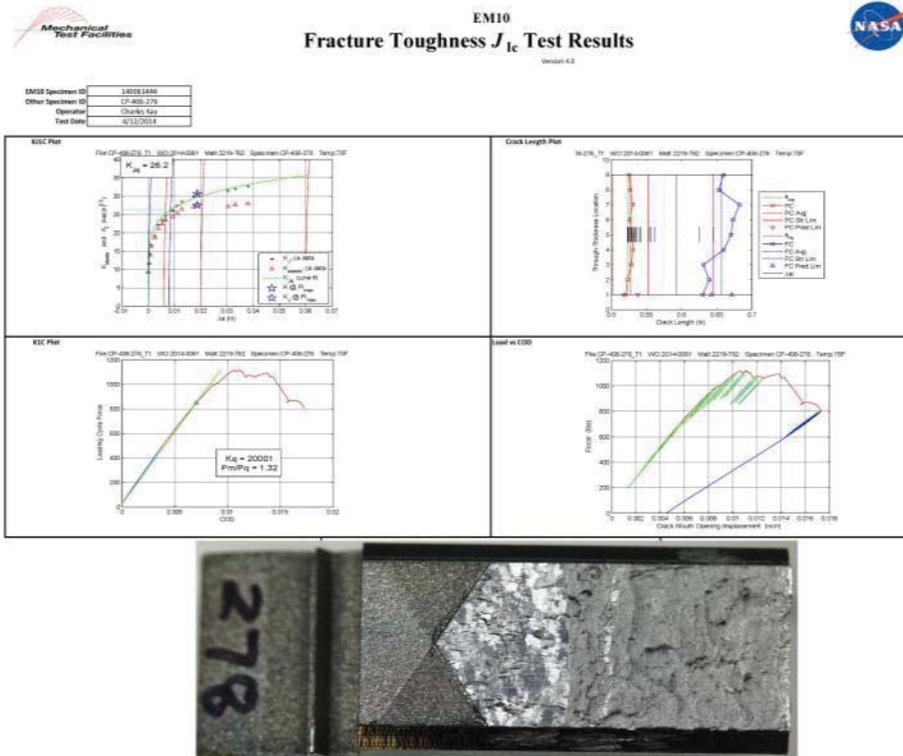
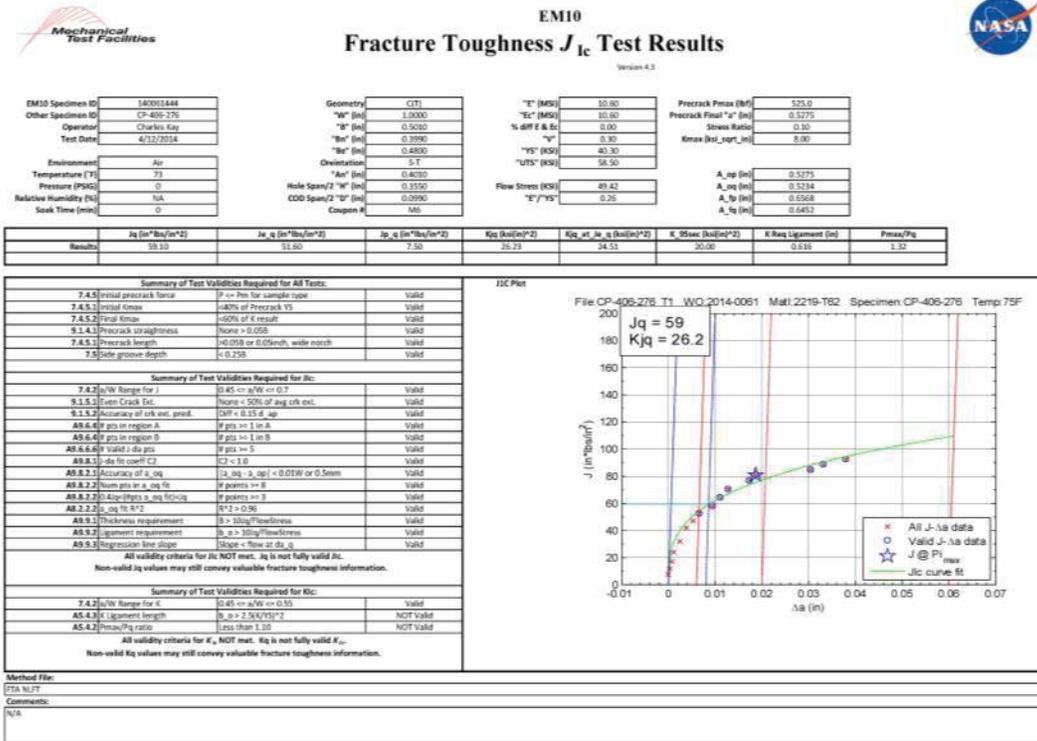
Document #:  
**NESC-RP-  
13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
222 of 223





# NASA Engineering and Safety Center Technical Assessment Report

Document #:  
**NESC-RP-13-00884**

Version:  
**1.0**

Title:

## Spin Forming Al CM Metallic APVBH – Phase II

Page #:  
223 of 223



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



EM10 Specimen ID: 140201440	Geometry: CTI	"E" (MS): 10.00	Pre-crack Pmax (lbf): 542.0
Other Specimen ID: CP-406-278	"W" (in): 0.9990	"W" (MS): 10.00	Pre-crack Final "a" (in): 0.5312
Operator: Charles Kay	"B" (in): 0.5030	"B" (MS): 0.00	Strain Ratio: 0.10
Test Date: 4/11/2014	"B0" (in): 0.3970	"B0" (MS): 0.00	Kmax (ksi_sqt_in): 8.00
Environment: Air	"B1" (in): 0.4790	"UTS" (KSI): 58.50	A_ap (in): 0.5312
Temperature (F): 73	"An" (in): 0.4030	Flow Stress (KSI): 49.43	A_iq (in): 0.5312
Pressure (PSIG): 0	Notch Spacing/2 "H" (in): 0.3550	"Y"/"YS": 0.28	A_3p (in): 0.6170
Relative Humidity (%): 54	COO Spacing/2 "H" (in): 0.0080		A_1q (in): 0.6037
Soak Time (min): 0	Coupon #: 505		

Results	$J_{Ic}$ (in <sup>3</sup> /ft <sup>2</sup> )	$J_{e, JIc}$ (in <sup>3</sup> /ft <sup>2</sup> )	$J_{p, JIc}$ (in <sup>3</sup> /ft <sup>2</sup> )	$K_{Ic}$ (ksi <sup>1/2</sup> /in <sup>3/2</sup> )	$K_{Ic}$ at $J_{e, JIc}$ (ksi <sup>1/2</sup> /in <sup>3/2</sup> )	K (KSI <sup>1/2</sup> /in <sup>3/2</sup> )	K Req Ligament (in)	Pmax/Pq
	57.40	49.90	7.50	25.85	24.10	20.99	0.78	1.18

**Summary of Test Validities Required for All Tests:**

7.4.0 Initial precrack force	$P \leq P_{max}$ for sample type	Valid
7.4.1 Initial Kmax	100% of Precrack K <sub>I</sub>	Valid
7.4.2 Final Kmax	$\leq 60\%$ of K result	Valid
9.1.4.1 Precrack straightness	None $> 0.018$	Valid
7.4.1.1 Precrack length	100% of a or B (Stretch, void notch)	Valid
7.4.1.1.1 Side groove depth	$\leq 0.25a$	Valid

**Summary of Test Validities Required for  $J_{Ic}$ :**

7.4.2.1 $a/W$ range for $J_{Ic}$	$0.45 \leq a/W \leq 0.7$	Valid
9.1.3.1 Even Crack Ext.	None $< 50\%$ of avg. crk. ext.	Valid
9.1.3.2 Accuracy of crk. ext. pred.	$D/E \leq 0.15$ if $a_p$	NOT Valid
AB.6.0.1 pts in region A	# pts = 1 in A	Valid
AB.6.0.2 pts in region B	# pts = 1 in B	Valid
AB.6.0.3 Valid $J_{Ic}$ pts	# pts = 5	Valid
AB.8.1.1 $a_0$ to coeff C2	$C2 = 3.0$	Valid
AB.8.2.1 Accuracy of $a_{0q}$	$ a_{0q} - a_{0p}  \leq 0.01W$ or 0.5mm	Valid
AB.8.2.2 Norm. pts in $a_{0q}$ fit	# points = 8	Valid
AB.8.2.3 4th Order $a_{0q}$ fit $R^2$	# points = 8	Valid
AB.8.2.4 $a_{0q}$ fit $R^2$	$R^2 \geq 0.96$	Valid
AB.8.3 Thickness requirements	$B \geq 10J_{Ic}/FlowStress$	Valid
AB.8.3.1 Ligament requirements	$B_0 \geq 10J_{Ic}/FlowStress$	Valid
AB.8.3.2 Regression line slope	Slope $\leq$ flow at $a_{0q}$	Valid

All validity criteria for  $J_{Ic}$  NOT met.  $J_{Ic}$  is not fully valid  $J_{Ic}$ .  
Non-valid  $J_{Ic}$  values may still convey valuable fracture toughness information.

**Summary of Test Validities Required for  $K_{Ic}$ :**

7.4.2.1 $a/W$ range for K	$0.45 \leq a/W \leq 0.55$	Valid
AB.4.3.1 Ligament length	$B_0 \geq 2.5W/YS^2$	NOT Valid
AB.4.3.2 Pmax/Pq ratio	Ratio $\geq 1.10$	NOT Valid

All validity criteria for  $K_{Ic}$  NOT met.  $K_{Ic}$  is not fully valid  $K_{Ic}$ .  
Non-valid  $K_{Ic}$  values may still convey valuable fracture toughness information.

**JIC Plot**

File: CP-406-278\_T1\_WO\_2014-0061 Mat: 2219-T62 Specimen: CP-406-278 Temp: 75F

Legend:   
 \* All J-A data   
 o Valid J-A data   
 J @ P<sub>max</sub>   
 J<sub>Ic</sub> curve fit

Method file:  
TTA\_NLCT

Comments:  
N/A



### EM10 Fracture Toughness $J_{Ic}$ Test Results

Version 4.3



<p>EM10 Specimen ID: 140201440</p> <p>Other Specimen ID: CP-406-278</p> <p>Operator: Charles Kay</p> <p>Test Date: 4/11/2014</p>	<p><b>JIC Plot</b></p> <p>File: CP-406-278_T1_WO_2014-0061 Mat: 2219-T62 Specimen: CP-406-278 Temp: 75F</p>	<p><b>Crack Length Plot</b></p> <p>File: CP-406-278_T1_WO_2014-0061 Mat: 2219-T62 Specimen: CP-406-278 Temp: 75F</p>
<p><b>JIC Plot</b></p> <p>File: CP-406-278_T1_WO_2014-0061 Mat: 2219-T62 Specimen: CP-406-278 Temp: 75F</p>	<p><b>Load vs COD</b></p> <p>File: CP-406-278_T1_WO_2014-0061 Mat: 2219-T62 Specimen: CP-406-278 Temp: 75F</p>	



**REPORT DOCUMENTATION PAGE**

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				<b>5b. GRANT NUMBER</b>	
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<b>6. AUTHOR(S)</b> Hoffman, Eric K.; Domack, Marcia S.; Torres, Pablo D.; McGill, Preston B.; Tayon, Wesley A.; Bennett, Jay E.; Murphy, Joseph T.				<b>5d. PROJECT NUMBER</b>	
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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> The principal focus of this project was to assist the Multi-Purpose Crew Vehicle (MPCV) program in developing a spin forming fabrication process for manufacture of the Orion crew module (CM) aft pressure vessel bulkhead. The spin forming process would result in a single piece aluminum (Al) alloy 2219 aft bulkhead resulting in the elimination of the current multiple piece welded construction, simplify CM fabrication, and lead to an enhanced design. This report will focus on the aft bulkhead portion of this study only. Phase I (NASA TM-2014-218163, (1)) of this assessment explored spin forming the single-piece CM forward pressure vessel bulkhead.					
<b>15. SUBJECT TERMS</b> Spin Forming; Crew Module; Aft Pressure Vessel Bulkhead; NASA Engineering and Safety Center; Multi-Purpose Crew Vehicle					
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