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The Repair and Return to Flight of Solid Rocket Booster Forward Skirt Serial Number 20022

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June 2008

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LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS

AMS	Aerospace Material Specification
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials International
AWS	American Welding Society
HKN	hardness Knoop number
HR_B	hardness Rockwell B
ICP	inductively coupled plasma
ipm	inches per minute
JE	Jacobs Engineering
M&P	materials and processes
MSFC	Marshall Space Flight Center
MTS	Materials Test Systems Corporation
PEC	Productivity Enhancement Complex
PQR	procedure qualification record
RSRM	redesigned solid rocket motor
SAE	Society of Automotive Engineers International
S/N	serial number
SRB	solid rocket booster
STS	Space Transportation System

LIST OF ACRONYMS, SYMBOLS, AND ABBREVIATIONS (Continued)

TIG	tungsten inert gas
TMC	Technical Micronics Control, Inc.
USA	United Space Alliance
USBI	United Space Boosters, Inc.
UTS	ultimate tensile strength
WPS	weld procedure specification
WQP	welding qualification procedure
YS	yield strength
%El	percent elongation

TECHNICAL MEMORANDUM

THE REPAIR AND RETURN TO FLIGHT OF SOLID ROCKET BOOSTER FORWARD SKIRT SERIAL NUMBER 20022

1. INTRODUCTION

This Technical Memorandum discusses an effort to correct buckling sustained by solid rocket booster (SRB) forward skirts during water impact after Space Transportation System (STS) launches. By early 1991, five skirts—three left-hand and two right-hand flight units—had been damaged in this manner. Three had skin fracture damage and buckling, and one contained a tension failure in the aft clevis. The fifth skirt sustained damage levels that are unknown, as it was lost at sea during retrieval.

This effort involved several initiatives as follows:

- Determine whether damaged flight units might be repaired. The least damaged unit available was SRB forward skirt serial number (S/N) 20022 that buckled after the launch of STS–37. Special hydraulic tooling was used to debuckle S/N 20022. After the debuckling procedure, the aft clevis pinholes were found to be slightly out of alignment with the redesigned solid rocket motor (RSRM) check gauge. This misalignment was corrected using an experimental weld procedure.

- Additional testing and evaluation generated material property data that supported the decision to return S/N 20022 to the flight hardware flow. Postlaunch analysis indicated that S/N 20022 performed nominally after being returned to flight during STS–100.

- United Space Boosters, Inc. (USBI) analytics personnel suggested that the structural integrity of the skirt might be improved by adding stringer reinforcements to its aft bay section. This change was made to S/N 20022 during repairs. It was later recommended as a fleet modification to be implemented on a case-by-case basis for other forward skirts.

2. REPAIR PROCEDURES

2.1 Debuckling Solid Rocket Booster Forward Skirt Serial Number 20022

After the STS–37 launch, S/N 20022 suffered water impact loads in excess of its design strength. The structural alloy (Al 2219) sustained damage that included skin buckling in the aft skin bay area as shown in figure 1. Depressions were observed to a depth of 1.6 cm (0.64 in) in the lower bay.

Figure 1. S/N 20022 buckled forward skirt.

Using a hydraulic press, located at General Products in Huntsville, AL (fig. 2), buckling was removed within 0.5 cm (0.2 in). This operation restored the area contour within the experience base.

2.2 Pinhole Realignment

After the debuckling procedure was complete, the flight direction of S/N 20022's aft clevis pinholes was found to be slightly aft of and misaligned with some RSRM check gauge pinholes. As a result, nominal check gauge aft clevis pins could not be used to mate the two pinhole sets across a circumferential span (≈106-in long) located between aft clevis pinholes 66–96 outside the buckled area. Marshall Space Flight Center (MSFC) recommended that weld heat passes be conducted in an area of the skin adjacent to the misaligned pinholes to shrink the skirt so the pinholes would again match.

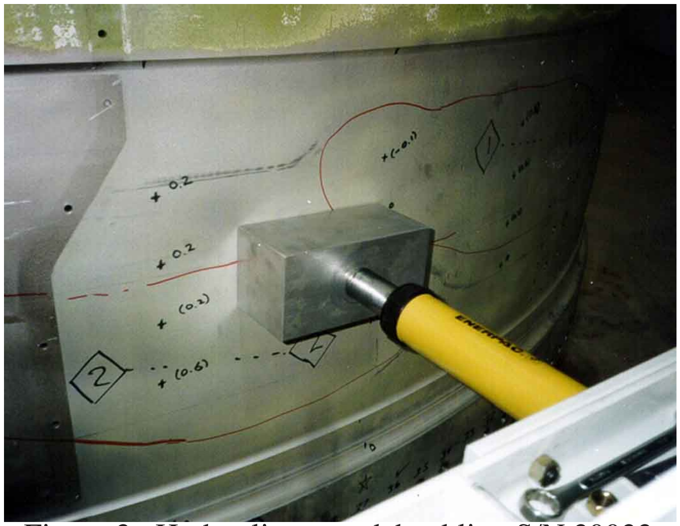


Figure 2. Hydraulic press debuckling S/N 20022.

2.2.1 Marshall Space Flight Center Demonstration Panel Weld

MSFC demonstrated a proposed methodology for a weld heat pass repair using a 2219–T87 test panel (12×24×0.24-in). This demonstration generated shrinkage and strength data to verify the amount of transverse weld shrinkage that would occur with respect to specific weld parameters, as well as subsequent mechanical properties in the weld zones (fig. 3). These data were used to qualify a similar weld schedule at the vendor and effect dimensional changes on S/N 20022.

Tungsten inert gas (TIG) welding was used without filler wire at a current of ≈185 amps and a weld speed of ≈15 ipm in accordance with procedures defined in MSFC–SPEC–504C.[1] Two separate weld passes were made in the geometric center of the panel. Each weld pass was ≈0.25-in wide. The first pass was ≈9-in long. The second was ≈8-in long and overlapped the first weld pass by ≈1 in.

2.2.1.1 Metallography The degree of weld penetration was determined by measuring cross-sections of the weld nugget taken at three locations, with the average measurement indicating a penetration depth of ≈50 percent. Hardness surveys were taken transverse to the welding direction as shown in figure 4.

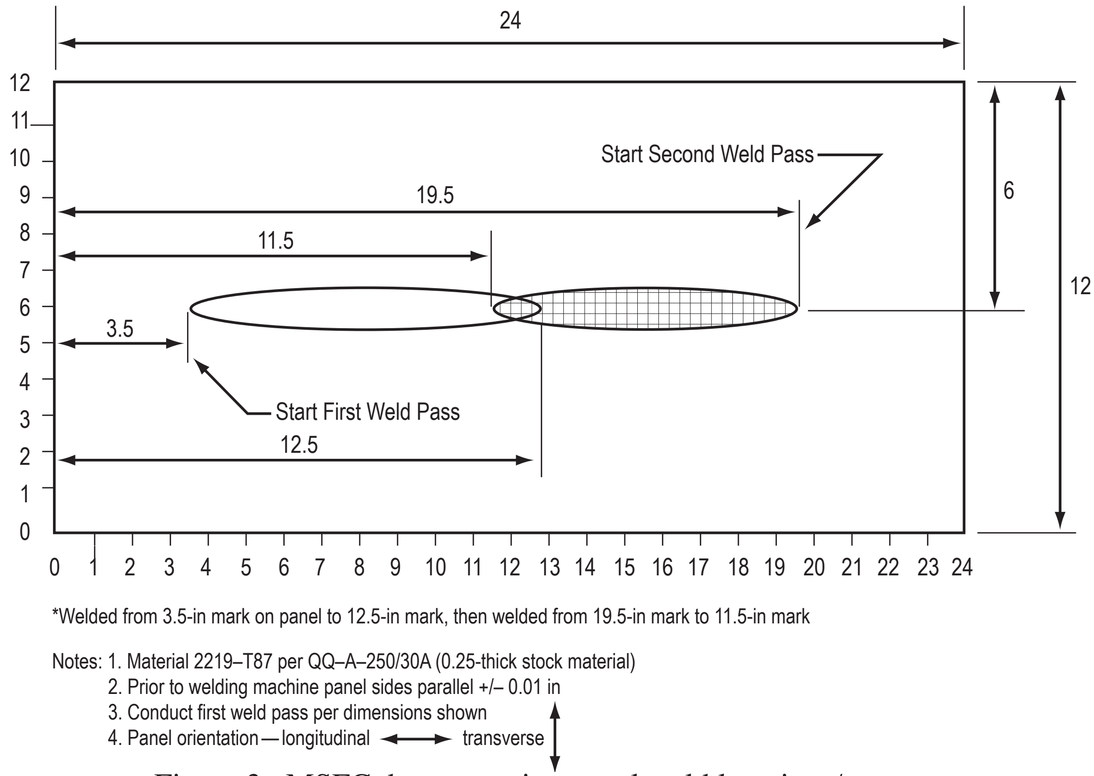


Figure 3. MSFC demonstration panel weld locations/passes.

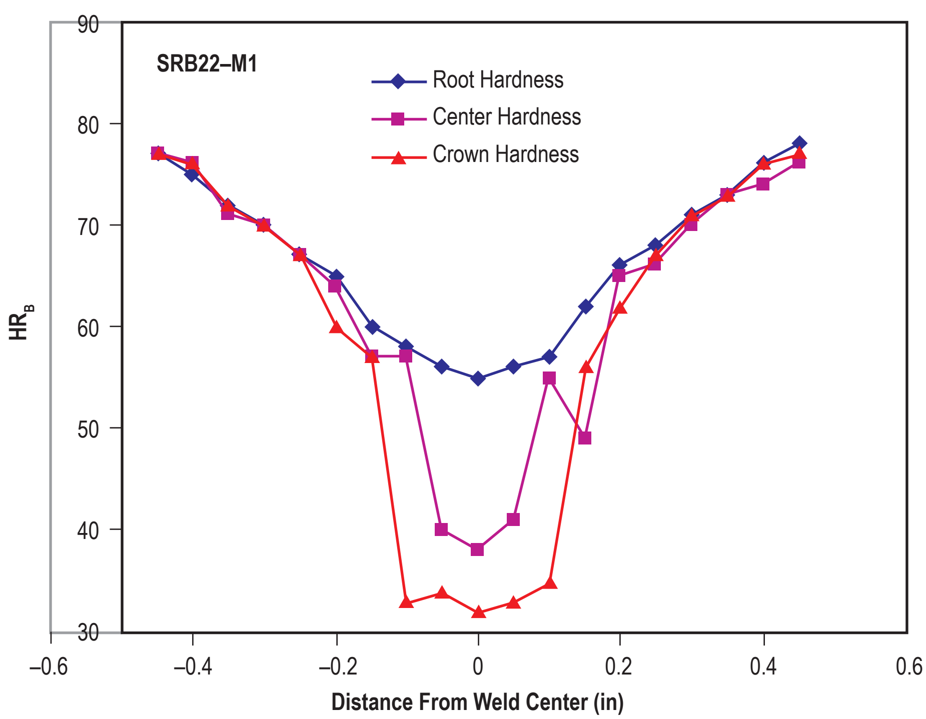


Figure 4. Typical microhardness curve for weld nugget on MSFC demonstration panel.

2.2.1.2 Mechanical Properties Ten tensile specimens with parallel sides were taken at equal intervals transverse to the weld length. Mechanical properties were then determined in accordance with ASTM B 557–84.[2] Data averages included ultimate tensile strength (UTS) of 47.2 ksi, yield strength (YS) at 0.2 percent of 27.1 ksi, percent elongation (%El) using a 2-in gauge length of 4.52 percent, and %El using a 1-in gauge length of 8.93 percent.

2.2.1.3 Shrinkage Two techniques were used to measure the panel before and after welding. Vernier calipers were used to take overall dimensions from the edges of the panel at 1-in intervals in both the transverse and longitudinal directions. Electronic measurements were taken across the weld area at 1-in intervals over a 2-in gauge length in the longitudinal direction using custom equipment developed by MSFC. The following measurements and shrinkage data were generated:

- In the transverse direction, maximum shrinkage (0.03 in) was observed at the midpoint of the panel. Minimum shrinkage (averaging 0.0025 in) occurred at the ends of the panel.

- In the longitudinal direction, maximum shrinkage (0.007 in) was observed at the two outer edges of the panel. Minimum shrinkage was zero at the midpoint of the panel (table 1). These shrinkage data are also presented graphically as curves in figure 5.

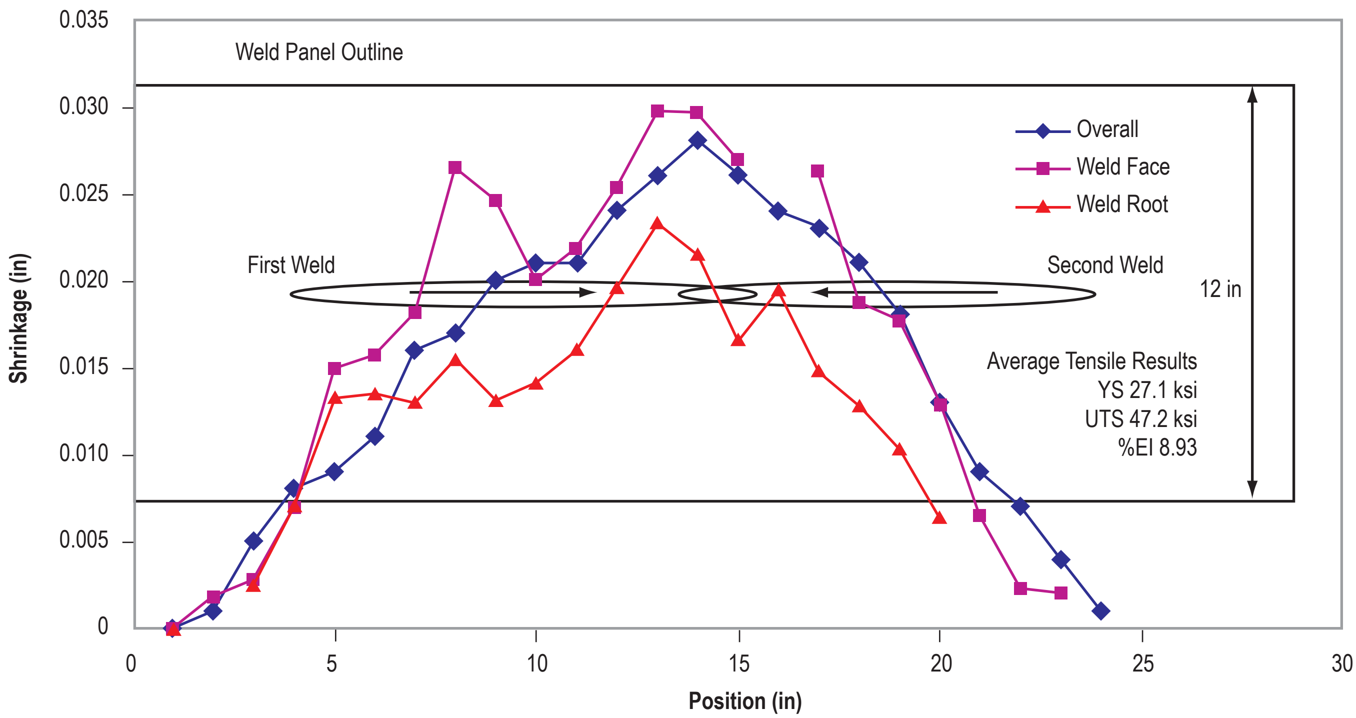


Figure 5. Data curve showing MSFC demonstration panel shrinkage.

Table 1. Shrinkage data for MSFC demonstration panel.

Panel ID: 12×24×0.25 MSFC Demo. Panel
2219–T87 Weld Pass For SRB Skirt Repair

MSFC Demonstration 12×24 Test Panel Shrinkage Data

Date: 10/31/97

	Weld Side, Transverse Shrinkage Measurements **																					
Location	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Overall shrinkage	0.001	0.005	0.008	0.009	0.011	0.016	0.017	0.02	0.021	0.021	0.024	0.026	0.028	0.026	0.024	0.023	0.021	0.018	0.013	0.009	0.007	0.004
Preweld weld side	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013	12.013
Postweld	12.012	12.008	12.005	12.004	12.002	11.997	11.996	11.993	11.992	11.992	11.989	11.987	11.985	11.987	11.989	11.990	11.992	11.995	12	12.004	12.006	12.009

	Weld Side, Longitudinal Shrinkage Measurements **										
Location	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Overall shrinkage	0.008	0.007	0.005	0.003	0.001	0	0.002	0.002	0.004	0.005	0.007
Preweld weld side	23.885	23.888	23.889	23.89	23.891	23.892	23.895	23.895	23.898	23.9	23.902
Postweld	23.877	23.881	23.884	23.887	23.89	23.892	23.893	23.893	23.894	23.895	23.895

		Weld Side Face Measurement Over 2-In Gauge Length																					
	Location	1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3	11.3	12.3	13.3	14.3	15.3	16.3	17.3	18.3	19.3	20.3	21.3	22.3
Weld Face Shrinkage		0.002	0.003	0.007	0.015	0.016	0.018	0.027	0.025	0.02	0.022	0.025	0.03	0.03	0.027	X	0.026	0.019	0.018	0.013	0.006	0.002	0.002
Pass	Preweld weld side	1.987	2.003	2.002	2.004	2.003	2.002	2.005	2.004	2.005	2.004	2.003	2.001	2.002	2.003	1.93	2.003	2.003	2.002	2.004	2.003	2.003	2.004
1	First 9-in pass	1.986	1.998	1.995	1.991	1.984	1.983	1.979	1.980	1.987	1.986	1.987	1.989	1.995	1.999	1.976	1.980	2.002	2.001	2.002	2.003	2.003	2.002
1	Second 8-in pass	1.986	2	1.995	1.989	1.987	1.984	1.979	1.979	1.985	1.983	1.978	1.972	1.972	1.976	1.953	1.977	1.984	1.985	1.991	1.997	2.001	2.002

		Root Side Measurement Over 2-In Gauge Length																					
	Location	1.3	2.3	3.3	4.3	5.3	6.3	7.3	8.3	9.3	10.3	11.3	12.3	13.3	14.3	15.3	16.3	17.3	18.3	19.3	20.3	21.3	22.3
Weld Root Shrinkage		X	0.002	0.007	0.013	0.013	0.013	0.016	0.013	0.014	0.016	0.020	0.023	0.022	0.017	0.019	0.015	0.013	0.01	0.006	X	0.001	X
Pass	Preweld	2.016	2	2.002	1.999	2	2.001	2.002	2.001	2.002	2.002	2.002	2.003	2.002	2.001	2.003	1.999	2.002	2	2.002	1.999	2.003	2.002
1	First 9-in pass	1.998	2	1.998	1.991	1.986	1.987	1.986	1.987	1.988	1.988	1.991	1.994	1.999	2	2.003	1.998	2.001	2	2.001	2.001	2.003	2.002
1	Second 8-in pass	1.999	1.998	1.995	1.986	1.987	1.988	1.987	1.988	1.988	1.986	1.983	1.980	1.981	1.985	1.983	1.984	1.989	1.99	1.996	2.002	2.003	2.003

** Measurements taken with vernier calipers along the outer edge of panel
*** Measurements taken electronically
X Invalid measurements

2.2.2 General Products Additional Test Panels

After the decision was made to shrink S/N 20022 using one or more weld heat passes, a plan was formulated calling for the vendor to develop a welding qualification procedure (WQP) and a procedure qualification record (PQR), in accordance with American National Standards Institute (ANSI)/American Welding Society (AWS) D1.2–90 (part 5C).[3]

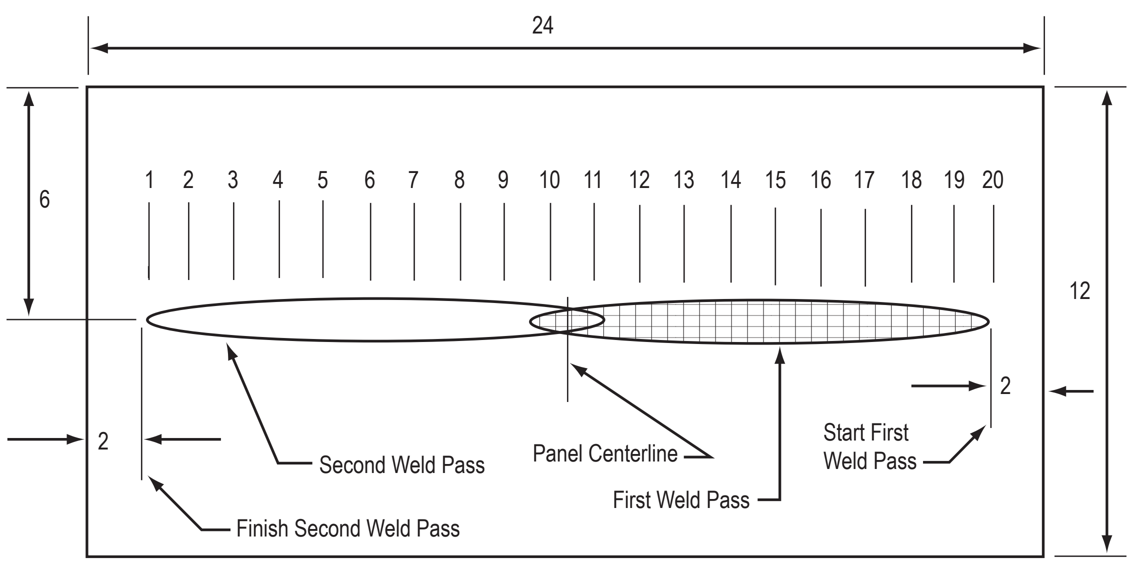
General Products applied this procedure to test panel 1, which was a flat stock panel the same size as the MSFC demonstration panel (12×24×0.25 in). It was machined and welded, as shown in figure 6, generating the following results:

- Before and after measurements showed an average shrinkage of 0.028 in at locations 8–12 near the center of the weld side of the panel.

- Welds were evaluated for defects using visual, penetrant, and radiographic inspections. Technical Micronics Control (TMC), Inc. of Huntsville, AL conducted the radiographic inspections in accordance with MIL–STD–453.[4] No indications were observed.

- Average test data included UTS 44.5 ksi, YS (0.2 percent) 27.2 ksi, and %El (2 in) 5.2 percent.

- Weld nugget penetration averaged 46.9 percent, based upon 10 data points.



Notes: 1. Material 2219–T87 per QQ–A–250/30A (0.25-thick stock material)
2. Prior to welding machine panel sides parallel +/– 0.01 in
3. Conduct first weld pass per dimensions shown
4. Conduct second weld pass to overlap first weld pass by 2 in
5. Conduct second weld pass in the same direction as the first weld pass
6. All dimensions are in inches
7. Specimen locations are at 1-in intervals

Figure 6. General Products test panel 1, specimen locations 1–20.

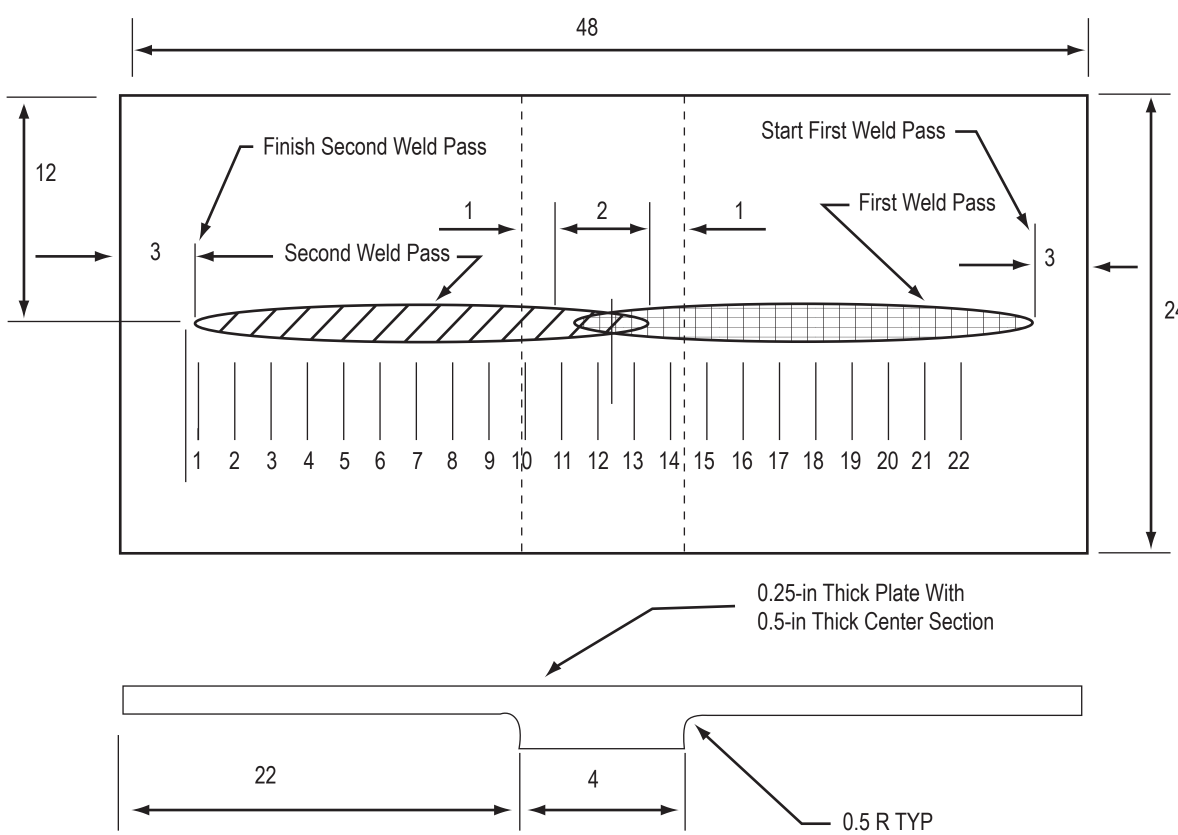
Further qualification was conducted for test panel 2, which was fabricated to simulate the weld heat pass location on the flight hardware. It was machined and welded, as shown in figure 7, with the following results:

- Before and after measurements showed an average shrinkage of 0.017 in at locations 10–14 near the center of the weld side of the panel.

- Welds were evaluated for defects using visual, penetrant, and radiographic inspections conducted by TMC in accordance with MIL–STD–453.[4] No indications were observed.

- Average test data included UTS 48.8 ksi, YS (0.2 percent) 30.7 ksi, and %El (2 in) 5 percent.

- Weld nugget penetration averaged 39 percent, based upon 12 data points. The thick center section (0.5 in) had much lower penetration than the rest of the panel, causing a lower average than for test panel 1.



Flight Hardware Weld Qualification Test Panel Material 2219–T87

Notes: 1. Conduct first weld pass to dimensions shown
2. Conduct second weld pass in the same direction as the first weld pass to dimensions shown
3. Second weld pass to overlap first weld pass by 2 in
4. Before welding machine panel sides parallel +/– 0.01 in
5. All dimensions are in inches
6. Spacing between specimen locations is 2 in

Figure 7. General Products test panel 2, specimen locations 1–22.

A microhardness evaluation was conducted for the weld area on both test panels to define the limit of thermal impact on the parent material, as depicted in figures 8 and 9. These data show a return to the T87 tempered condition (i.e.: ≈76 HR_B) at 0.5–0.6 in from either side of the centerline of the weld nugget.

These test results verified an attainable transverse shrinkage in the Al 2219–T87 panel (test panel 2) that mirrored the predetermined weld location on S/N 20022. When performed in accordance with the WPS and PQR documents, prepared by General Products, these welds contained penetration levels of less than 50 percent and a return to parent metal strength at a distance of 0.5–0.6 in from the centerline. The qualification welded structure (test panel 2) had mechanical properties that included UTS 23.7 ksi, YS 39.8 ksi, and %El 28.6 percent, which were lower than the reported minimum values in accordance with FED QQ–A–250/30.[5] No anomalies were observed when the welds were subjected to nondestructive evaluation by visual, liquid penetrant, and radiographic techniques.

2.2.3 Serial Number 20022 Heat Pass Repair Weld

General Products then performed a weld heat pass repair in accordance to their WPS and PQR documents for the qualification test panel (test panel 2). One weld consisting of two separate passes was made. The second pass was a continuation of the first, but overlapped its end by 2 in. In accordance with written instructions provided by USBI, the welds were conducted on the inboard side of the skirt between aft clevis holes 66 to 96, ≈11 $^1/_8$-in from the bottom of the aft clevis. The combined length of the two weld passes was ≈75 in. Allowances were made for determining additional welds/locations after completion of the first weld and any subsequent dimensional and/or pin-check evaluations, if required.

The area was measured before and after welding. It showed maximum shrinkages of 0.02 in across the weld nugget side (inboard) and 0.017 in across the root side (outboard). The weld pass area was allowed to stabilize to ambient temperature for ≈20 hr. Measurements were then made using a theodolite instrument that showed the aft clevis had shrunk ≈0.035 in. As a result, all RSRM check gauge pinholes were able to admit nominal, rather than reduced, diameter clevis pins. Afterwards, the skirt was installed with stringer reinforcements. Upon its arrival at Kennedy Space Center, a planarity check showed that all dimensions fell within the experience base.

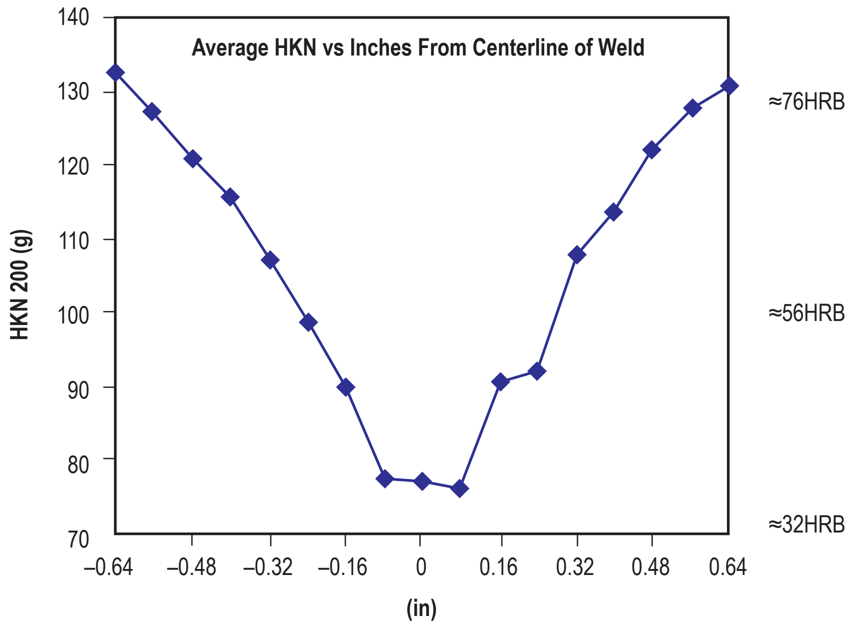


Figure 8. General Products test panel 1 hardness values, from weld centerline into parent material.

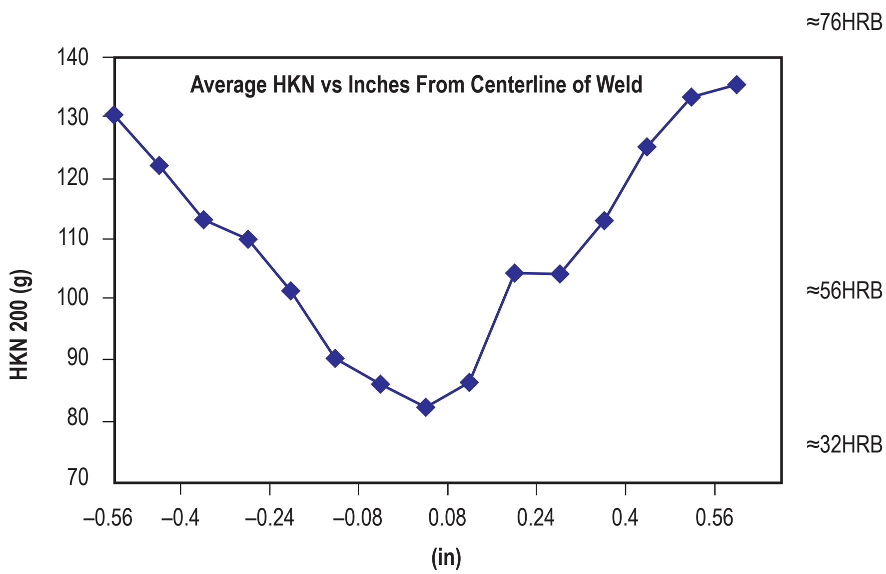


Figure 9. General Products test panel 2 hardness values, from weld centerline into parent material.

3. MATERIAL EVALUATIONS

Additional studies included material property testing and evaluation of buckled and debuckled Al 2219, as well as Al 2219 that was removed from long-term storage and reprocessed to fabricate stringer reinforcements.

3.1 Buckled and Debuckled Al 2219

To show the soundness of S/N 20022 as repaired, USBI analytics requested design values for similar materials that had been buckled and then debuckled. These values were used during an analysis that indicated the repair was acceptable for return to flight based, in part, on a strength reduction factor of 25 percent of the original design values. This knockdown factor was suggested by a consortium of M&P personnel from MSFC and United Space Alliance (USA) based on prior experience with the material rather than specific data. However, an independent assessment review required MSFC and USA to conduct mechanical testing to validate the knockdown factor.

In May 2000, a section of similarly buckled material from another damaged forward skirt, S/N 007, was selected for testing. This section was the same material (Al 2219–T87) and thickness (0.63 cm or 0.25 in) as the area in question on S/N 20022, with a maximum deflection or buckle of ≈7.1 cm (2.8 in). The buckled panel was photographed as received (figs. 10 and 11). Following the removal of all coatings using a hydrolaser, radiographic and dye penetrant inspections were conducted. A 1¾-in long crack was found and trimmed away. No other anomalies were detected.

S/N 007 was debuckled and restored to within 0.5 cm (0.2 in) of the original surface by General Products, using the same tooling and expertise as for S/N 20022. Actual postdebuckling measurements indicated a flatness of 0.25–0.38 cm (0.1–0.15 in). The panel was photographed again after debuckling, as shown in figures 12 and 13. No indications were reported during another round of nondestructive evaluation. Tensile specimens were then fabricated from the repaired section, figure 14, per ASTM E 8, “Standard Test Method for Tension Testing of Metallic Materials.”[6]

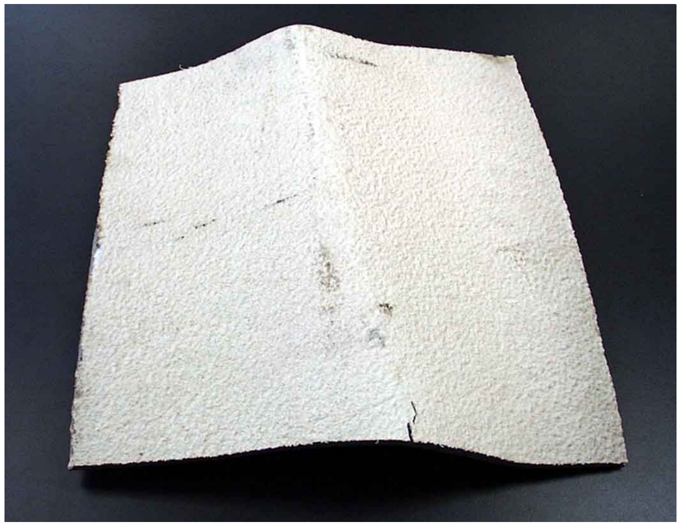


Figure 10. As-received, S/N 007 test section.

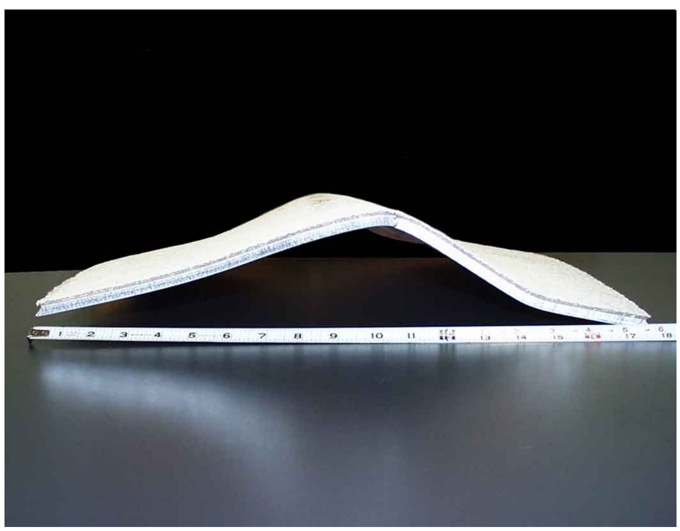


Figure 11. As-received, S/N 007 test section, side view.

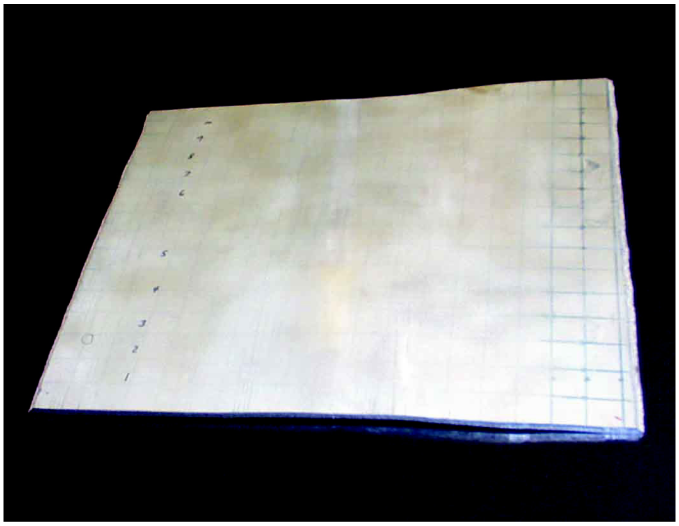


Figure 12. S/N 007 debuckled test section.

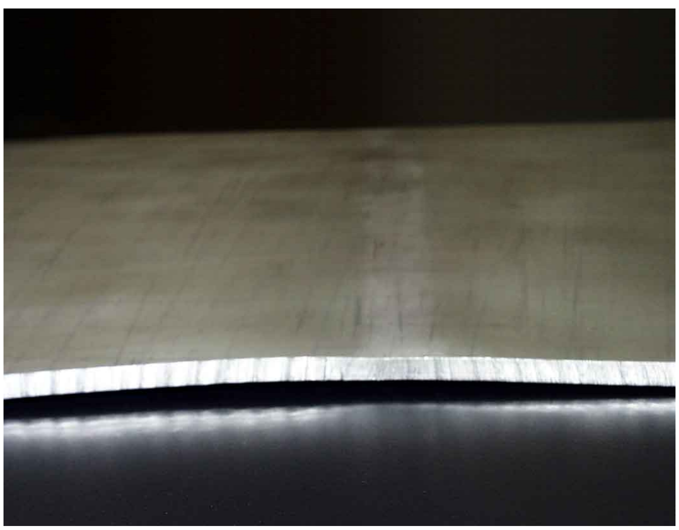


Figure 13. S/N 007 debuckled test section, side view.

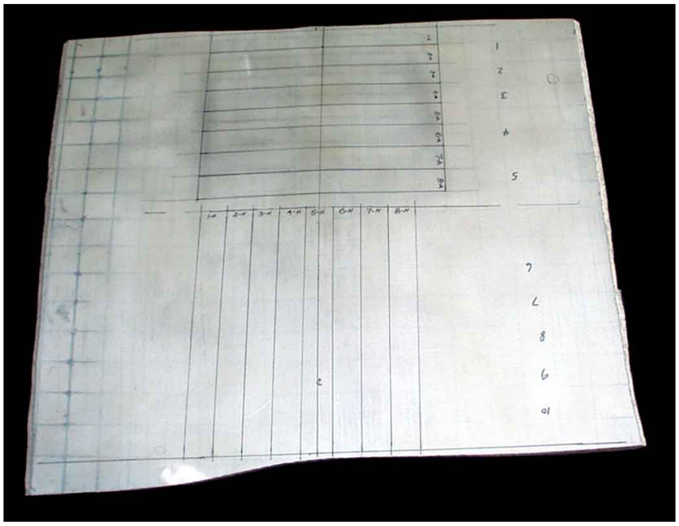


Figure 14. Specimen locations on S/N 007 debuckled test section.

Tensile specimens were mechanically tested using an Instron series IX automated materials test system on a 100-kN (20-kip) Mechanical Test Systems Corporation servohydraulic load frame. Test results are provided in table 2.

Table 2. S/N 007 debuckled section mechanical test results.

Mechanical Property	Minimum Required MIL–HDBK–5[8]	Using 25% Knockdown Factor	Axial Tests (8-Specimen Average)	Hoop Tests (8-Specimen Average)
UTS (ksi)	64	48	71.7	71.7
YS (ksi)	51	38.2	57	57.9
%El (2 in)	7	5.2	7.9	8.3

Hardness was measured in accordance with ASTM E 18, "Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials."[7] A New Age Indentron unit was used to take HR_B measurements on the grip end of several tensile test specimens and at various locations on the residual test material. A total of 12 measurements yielded an average hardness value of 79 HR_B, well within the material acceptance requirements for Al 2219 given in the Society of Automotive Engineers International (SAE)/Aerospace Material Specification (AMS) 2658, "Hardness and Conductivity Inspection of Wrought Aluminum Alloy Parts (table 1)," which indicates a minimum acceptance value of 75 HR_B.[9]

A chemical analysis was conducted (table 3) to certify that the material was, in fact, Al 2219 as stated in the drawing requirement. X-ray fluorescence spectroscopy revealed that all elements were within the acceptable ranges for Al 2219 as specified by FED QQ–A–250/30.[5]

Table 3. Chemical composition of S/N 007 debuckled section.

Element	Sample (Weight %)	Al 2219 (AMS 2658)
Al	(Balance)	
Cr	0.005	–
Cu	6.39	5.8 to 6.8
Fe	0.23	0.3 (maximum)
Mg	0.02	0.02 (maximum)
Mn	0.25	0.2 to 0.4
Ni	0.01	–
Si	0.15	0.2 (maximum)
Ti	0.07	0.02 to 0.1
V	0.1	0.05 to 0.15
Zn	0.01	0.1 (maximum)
Zr	0.14	0.1 to 0.25

3.2 Al 2219 Stringer Reinforcements

This incident prompted a study by USA to reduce the risk of buckling SRB forward skirts during water impact after launch. As a result, Al 2219 stringers were installed in the aft bay area of S/N 20022 during the repair procedure. Although skirt buckling had never been predicted analytically, a relative level of improvement was shown over the buckling strength of the current configuration. Therefore a fleet modification was recommended.

In recent years, it has become difficult to obtain Al 2219–T87 in sufficiently small quantities to fulfill needs as they arise, and material was not commercially available to meet this requirement. However, a substantial amount of Al 2219–T37 had been stored by the MSFC SRB Program Office for over 30 years. Unfortunately, the natural process of ambient temperature aging had left it in a condition that was not easy to recover.

USA took on the challenge of recovering this material to use in fabricating the forming stringers to reinforce the skirt structure. Three pieces of Al 2219–T37 measuring 122×244 cm (48×96 in) and 0.63-cm (0.25-in) thick were obtained from NASA program stock for S/N 20022 stringer fabrication. Mechanical properties and chemical analysis needed verification since no supporting documentation was supplied with the material. It was also necessary to confirm that the recovered material met the requirements for T87 temper.

3.2.1 Chemical Analysis

A bulk chemical analysis was conducted using x-ray fluorescence spectroscopy that indicated two elements—copper and magnesium—were out of tolerance. A quantitative analysis was then conducted using inductively coupled plasma (ICP) emission spectrometry, a method with detection limits in the parts-per-million range, that indicated the material met specification requirements (table 4).

3.2.2 Mechanical Properties

Thirty specimens were machined from three pieces of Al 2219–T37 plate that was 0.63-cm (0.25-in) thick, to evaluate natural aging properties that had developed during 30+ years of storage (table 5). The raw data and calculated minimum both exceeded the minimum requirements specified. These results indicated that a standard aging treatment would probably overage the material, which would then fail to meet the minimum requirements for T87.

Table 4. Bulk chemical analysis for stored Al 2219.

X-Ray Fluorescence	1D	2D	3D	Al 2219 Specification
Al	(Balance)			
Cr	0.01	0.01	0.01	0.05 max
Cu	6.95	6.95	6.94	5.8 to 6.8
Fe	0.16	0.16	0.17	0.3 max
Mg	0.025	0.029	0.026	0.02 max
Mn	0.25	0.26	0.26	0.2 to 0.4
Si	0.13	0.16	0.18	0.2 max
Ti	0.03	0.03	0.03	0.02 to 0.1
V	0.07	0.07	0.07	0.05 to 0.15
Zn	0.01	0.01	0.01	0.1 max
Zr	0.1	0.1	0.1	0.1 to 0.25

ICP Emission Spectrometry	1D	2D	3D	Al 2219 Specification
Cu	6.41	6.51	6.52	5.8–6.8
Mg	0.011	0.01	0.012	0.02 max

Note: All values in weight%

Table 5. Mechanical properties for stored Al 2219.

Specimen No.	Date Tested	YS (ksi)	UTS (ksi)	Modulus (Msi)	%El (1 in)
008–1C–1	04/10/1998	43.64	60.27	10.2	16.3
008–1C–2	04/10/1998	42.49	59.26	10.3	18.9
008–1C–3	04/10/1998	43.13	59.91	10.4	17.9
008–1C–4	04/10/1998	43.86	59.88	10.4	17.7
008–1C–5	04/10/1998	44.23	60.31	10.5	16.5
008–1C–6	04/10/1998	43.91	59.95	10.4	17.8
008–1C–7	04/10/1998	43.87	60.01	10.3	18.2
008–1C–8	04/10/1998	44.13	60.17	10.5	18
008–1C–9	04/10/1998	44.58	60.68	10.5	17.1
008–1C–10	04/10/1998	43.78	60.27	10.8	17.3
008–1C–19	04/10/1998	42.99	59.36	10.3	17.7
008–2C–2	04/10/1998	44.09	61.05	10.9	19.5
008–2C–3	04/10/1998	43.08	60.05	10.7	18.5
008–2C–4	04/13/1998	43.04	59.97	10.6	16.3
008–2C–5	04/13/1998	43.34	59.94	10.4	17.7
008–2C–6	04/13/1998	42.95	59.87	10.6	17.6
008–2C–7	04/13/1998	42.77	60.17	10.4	14.5
008–2C–8	04/13/1998	43.57	60.65	10.3	18.7
008–2C–9	04/13/1998	44.07	60.79	10.6	18.2
008–2C–10	04/13/1998	43.6	60.77	10.8	18.8
008–3C–1	04/09/1998	44.35	60.45	10.1	17.6
008–3C–2	04/09/1998	43.93	60.21	10.2	16.5
008–3C–3	04/09/1998	43.3	60.16	10	17.3
008–3C–4	04/09/1998	43.59	60.06	10.3	18.4
008–3C–5	04/09/1998	43.64	60.34	10.1	12
008–3C–6	04/09/1998	43.05	60.05	10.4	19.5
008–3C–7	04/09/1998	43.08	59.85	10.1	16.5
008–3C–8	04/09/1998	43.63	59.86	10.3	18.3
008–3C–9	04/09/1998	43.99	59.96	10.3	18.5
008–3C–10	04/09/1998	43.78	59.94	10.4	18.3

	YS (ksi)	UTS (ksi)	Modulus (Msi)	%El (1 in)
Mean	43.58	60.14	10.4	17.54
Standard Deviation	0.51	0.39	0.22	1.49
Direct Calculated A-Basis Value	42	59	–	–
Minimum Required by FED QQ–A–250/30	37	49	–	6

General Products Inc. fabricated two stringers according to the design requirements as shown in figure 15. They were heat-treated in accordance with MIL–H–6088, "Heat-Treatment of Aluminum Alloys" that requires aging at 177 °C (350 °F) for 18 hr to achieve a T87 temper.[10]

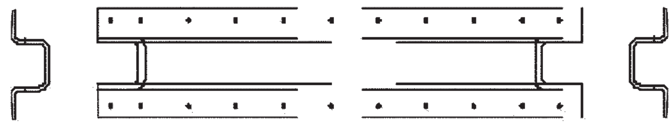


Figure 15. Two stringers fabricated by General Products.

Five tensile coupons were sectioned from one stringer and tensile tested in accordance with ASTM B 557–84, "Tensile Testing."[2] These test results (table 6) clearly show the need for a modified heat-treatment to produce acceptable properties.

Table 6. Mechanical property data for stored Al 2219, heat-treated at 177 °C (350 °F) for 18 hr, first set of test samples.

Specimen No.	Date Tested	YS (ksi)	UTS (ksi)	Modulus (Msi)	Elongation (1 in)
SRB HT1	04/09/1998	45.4	60.7	10.1	9.8
SRB HT2	04/09/1998	44.7	60.7	10.5	9.5
SRB HT3	04/09/1998	45.5	61.1	10.5	10.4
SRB HT4	04/09/1998	45	60.4	10.6	11.6
SRB HT5	04/09/1998	45.4	60.9	10.7	10.8
Mean		45.2	60.76	10.48	10.42
Standard Deviation		0.34	0.26	0.23	0.83
FED QQ–A–250/30		51	64		6

Three additional specimens were sectioned from a plate originally intended for stringer fabrication to support the development of a longer aging treatment. These were aged in a modified Blue-M oven, programmed to ramp to an aging temperature of 177 °C (350 °F) at ≈2.5°C (5 ºF) per min, hold at temperature for 24 hr, and then cool to 65 °C (150 °F). The samples were then removed and allowed to cool to ambient temperature. Mechanical testing, conducted in accordance with ASTM B 557–84, showed this process produced material that met the minimum requirements (table 7).[2]

Table 7. Mechanical property data for stored Al 2219, heat-treated at 177 °C (350 °F) for 24 hr, second set of test samples.

Specimen No.	YS (ksi)	UTS (ksi)	Elongation (1 in)
008–1c–11	51.87	66.03	10.8
008–1c–12	51.78	65.92	12.4
008–1c–13	51.51	65.84	10.5
Mean	51.72	65.93	11.23
Standard Deviation	0.187	0.095	1.021
Minimum Required by FED QQ–A–250/30	51	64	6

Once the treatment cycle was established, 23 more samples were extracted from the panels and tested to verify the minimum requirement (table 8). The values were sufficiently close to the minimum requirement that USA recommended the modified heat treatment for this material.

Table 8. Mechanical property data for stored Al 2219, heat-treated at 177 °C (350 °F) for 24 hr, third set of test samples.

Specimen No.	UTS (ksi)	YS (ksi)	Elongation (1 in)
008–1c–11	66.03	51.87	10.8
008–1c–12	65.92	51.78	12.4
008–1c–13	65.84	51.51	10.5
008–1c–17	64.2	50.3	10.5
008–1c–18	65.2	50.8	10.7
008–1c–09	65.7	51	10.6
008–1c–20	65.9	51.5	10.9
008–2c–11	65.9	51.2	10.4
008–2c–12	65.8	51	10.6
008–2c–13	66.1	51.3	10.5
008–2c–14	66.3	51.6	10.4
008–2c–15	65.7	51	10.5
008–2c–16	65.9	51.3	10.5
008–2c–17	66.1	51.1	10.7
008–2c–18	66.3	51.5	10.6
008–2c–20	66	51.4	10.6
008–3c–11	67	52.1	10.5
008–3c–12	67.3	52.4	10.3
008–3c–13	66.9	52.2	10.5
008–3c–14	67	52	10.6
008–3c–15	66.5	51.6	10.7
008–3c–16	66.8	51.8	10.5
008–3c–17	66.5	52.1	10.3
008–3c–18	65.8	51.4	10.5
008–3c–19	66.1	51.6	10.3
008–3c–20	65.8	51.1	10.8
Mean	66.1	51.479	10.623
Standard Deviation	0.627	0.481	0.393
Minimum Required by FED QQ–A–250/30	64	51	6

As a result of these evaluations, stringers were fabricated and installed on S/N 20022 (fig. 16) in preparation for its return to flight.

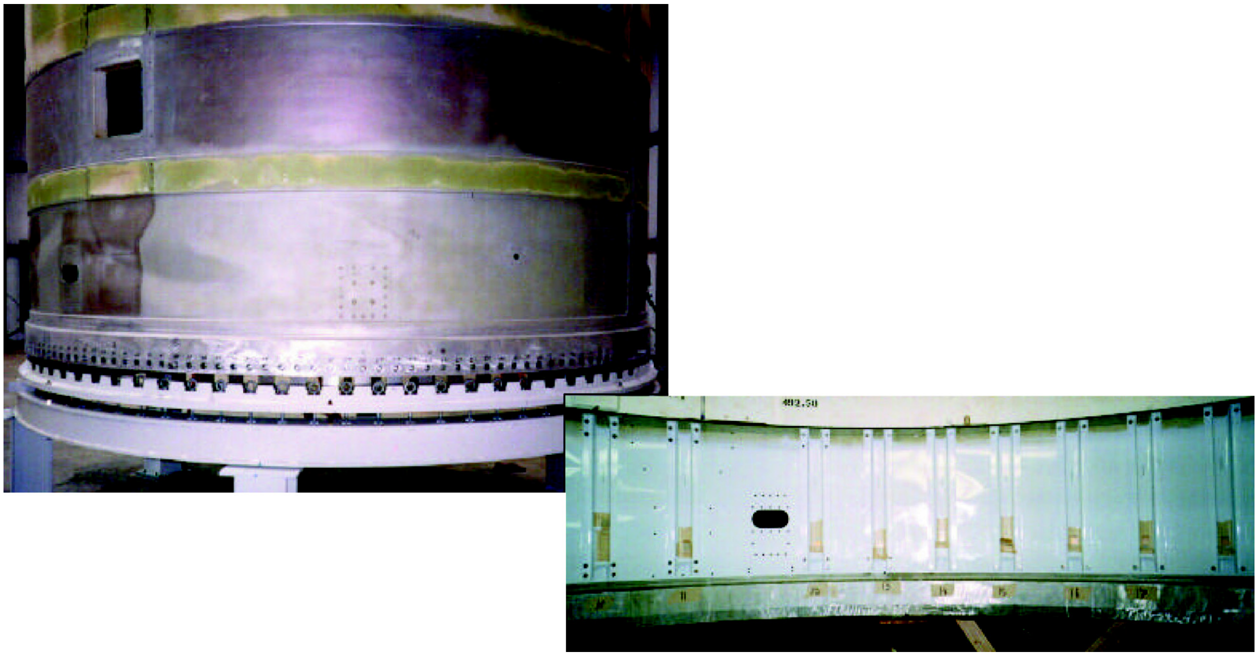


Figure 16. Exterior of S/N 20022 with callout of installed stringers.

4. CONCLUSIONS

Valuable methodologies were developed from this effort including the following:

- Using a hydraulic press to repair a damaged forward skirt.

- Correcting minor distortion that occurred during the debuckling procedure.

- Verifying material properties afterwards.

All mechanical properties were found to either meet or exceed minimum design requirements, which supported the idea that a 25-percent strength reduction factor would provide a conservative estimate of the structure's strength after repairs. S/N 20022 successfully returned to flight on April 19, 2001 during STS–100. Plans call for it to continue in the SRB flight hardware flow.

Note: The original buckling problem was resolved at a later date by using saltwater-activated release mechanisms to keep the SRB parachutes attached until after splashdown.

APPENDIX A—TEST PLANS/REPORTS

During the course of this work, the following test plans/reports were generated by USBI:

JHH–002–97MP	"Test Plan to Demonstrate Methodology for Locally Shrinking Forward Skirt S/N 20022 by Conducting Weld Passes," USBI, 1997.
JHH–002–98MP	"Results of Test Plan to Demonstrate Methodology for Locally Shrinking Forward Skirt S/N 20022 by Conducting Weld Passes," USBI, 1998.
JHH–003–98MP	"Vendor Qualification Requirements to Shrink Forward Skirt S/N 20022 by Conducting Weld Passes," USBI, 1998.
JHH–005–98MP	"Vendor Qualification Test Results for Shrinking Forward Skirt S/N 20022 by Conducting Weld Passes," USBI, 1998.
JHH–005–99MP	"Verification of 2219 Aluminum Material Properties After Long-Term Storage," USBI, 1999.
JHH–002–00MP	"Validation of the 25% Reduction in Material Properties for Forward Skirt S/N 20022," Final Report, USA, MSFC–PEC Operations, August 11, 2000.

REFERENCES

1. "Welding Aluminum Alloys," MSFC–SPEC–504C.

2. "Standard Methods of Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products," ASTM B 557–84.

3. "Structural Welding Code, Aluminum," ANSI/AWS–D1.2–90.

4. "Radiographic Inspection," MIL–STD–453 (now superseded by "Standard Practice for Radiographic Examination," ASTM E 1742).

5. "2219 Aluminum Alloy Plate and Sheet," FED QQ–A–250/30.

6. "Standard Test Method for Tension Testing of Metallic Materials," ASTM E 8.

7. "Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials," ASTM E 18.

8. Military Handbook, "Metallic Materials and Elements for Aerospace Vehicle Structures," MIL–HDBK–5 (now superseded by "Metallic Materials Properties Development of Standardization Handbook." MMPDS–03).

9. "Hardness and Conductivity Inspection of Wrought Aluminum Alloy Parts," AMS 2658.

10. "Heat Treatment of Aluminum Alloys," MIL–H–6088.

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13. ABSTRACT *(Maximum 200 words)*

On April 5, 1991, a solid rocket booster (SRB) forward skirt serial number (S/N) 20022 sustained buckling damage during water impact after the launch of Space Transportation System Flight 37 (STS–37). As of that date, five forward skirts had been lost during water impact. Repair attempts began with the least damaged skirt available (S/N 20022). Special hydraulic tooling was used to remove buckled areas of the skirt. Afterwards, its aft clevis pinholes were found to be out of alignment with the redesigned solid rocket motor (RSRM) check gauge, but weld passes were used to correct this condition. Meanwhile, USA Analytics generated mechanical property data for buckled and subsequently debuckled material. Their analysis suggested that structural integrity might be improved by adding stringer reinforcements, stiffeners, to the aft bay section of the skirt. This improvement was recommended as a fleet modification to be implemented on a case-by-case basis.

14. SUBJECT TERMS

flight vehicles, Space Shuttle boosters, skirts, welded structures, stringers, aluminum alloys, aging (metallurgy), heat-treatment, mechanical properties, tensile properties, materials tests, and materials science.

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