LFPS-RPT-316

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National Aeronautics and
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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Lunar Flashlight Propulsion System
Fracture Control Report
Revision B

MARSHALL SPACE FLIGHT CENTER ADVANCED EXPLORATION SYSTEM

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1.0 SCOPE

This document describes how the Lunar Flashlight Propulsion System (LFPS) meets the requirements listed in the LFPS Fracture Control Plan (FCP) (LFPS-PLAN-111). This document lists all the specific analyses and justifications to show that fracture control is satisfied for this program. The provisions of this plan shall be met to demonstrate that the parts are in compliance with NASA's fracture control requirements for space flight hardware.

1.1 Revision Log

1.1.1 Revision A

This document is released as part of memorandum ER41 (20-027). The changes to this document are listed below:

- The pre and post proof tank leak checks have been removed from the weld alternate approach rationale to align with the new procedure. A leak check is still performed at the assembly level.
- The alternate approaches in sections 6.1.5, 6.2, and 6.5 have been rewritten to match those in the Fracture Control Plan.

1.1.2 Revision B

This document is released as part of memorandum ER41 (20-027). The changes to this document are listed below:

- Added the Material Usage Agreement (MUA), Additive Manufacturing Control Plan (AMCP), and Certificates of Conformance (CoC) to the applicable documents (section 2.2).

2.0 APPLICABLE DOCUMENTS

The following documents form a part of this document to the extent noted. Unless otherwise specified, the referenced documents are to be the latest issue date. In the event of a conflict between a referenced document and this document, NASA-STD-5019 will take precedence, over all documents as it is the governing fracture control document for the SLS Secondary Payloads.

2.1 NASA Documents

MMPDS-13	Metallic Material Properties Development and Standardization Handbook
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-5009	Non-destructive Evaluation Requirements for Fracture Control
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware
AIAA-S-080	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

2.2 MSFC Documents

5074913 (XP5-X-150PA)	Purchase Order - Certificate of Conformance, Measurement Specialties Inc.
5074913 (XP5-X-750PA)	Purchase Order - Certificate of Conformance, Measurement Specialties Inc.
AMS 2680C	Electron Beam Weld Procedure
C-LFPS-001	Lunar Flashlight Certification Material Usage Agreement (MUA)
D-98572	LFPS Safety Data Package (10/10/2019 version)
LFPS-PLAN-111	Fracture Control Plan for Lunar Flashlight Propulsion System
LFPS-PLAN-112	LFPS Additive Manufacturing Control Plan
LFPS-RPT-303	Structural Analysis Report for Lunar Flashlight Propulsion System Also part of Memorandum ER41 (20-027)
Memorandum ER41 (18-028)	Structural Analysis of the Cubesat Fill Valve Assembly
Memorandum ER41 (20-009)	Lunar Flashlight Propulsion System Critical Design Review Detailed Structural Assessments - Draft, For Record
SPIE-SP-LFPS-0001	MUA - AF-M315E Fluid Compatibility
SPIE-SP-LFPS-0002	MUA - Stress Corrosion Cracking

3.0 INTRODUCTION

3.1 Hardware Description

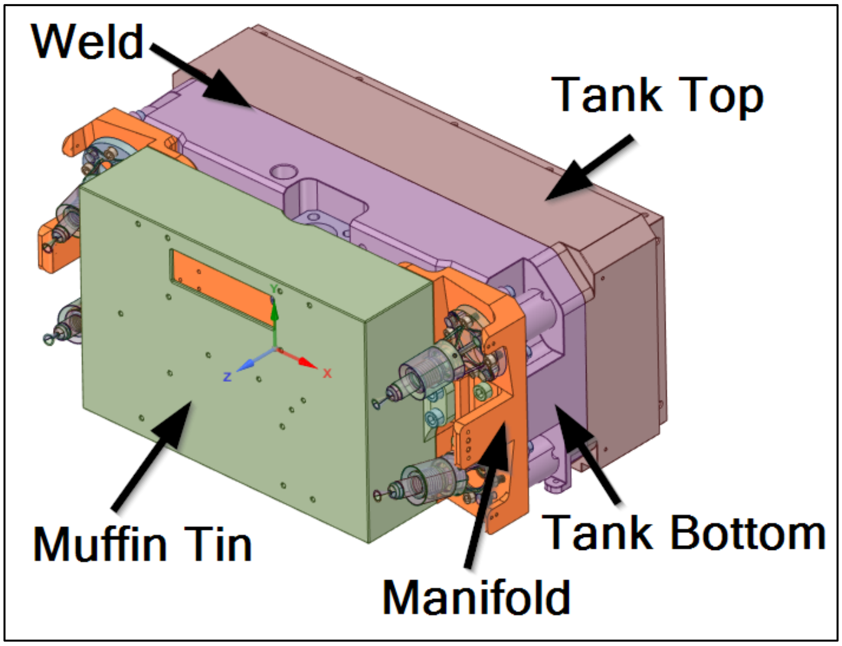


Figure 1 LFPS Primary Structural Components

The LFPS is comprised of four primary structural components (tank top, tank bottom, manifold, and muffin tin). These components support other smaller components within LFPS and are fastened to the rest of the Lunar Flashlight CubeSat.

3.1.1 Tank

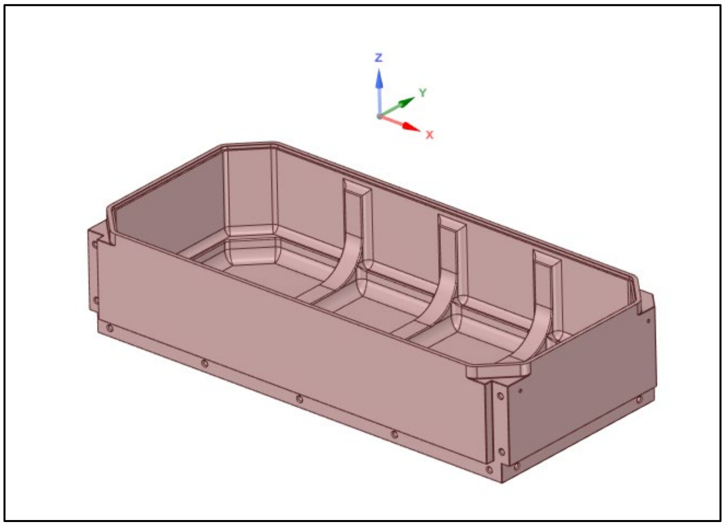


Figure 2 Tank Top

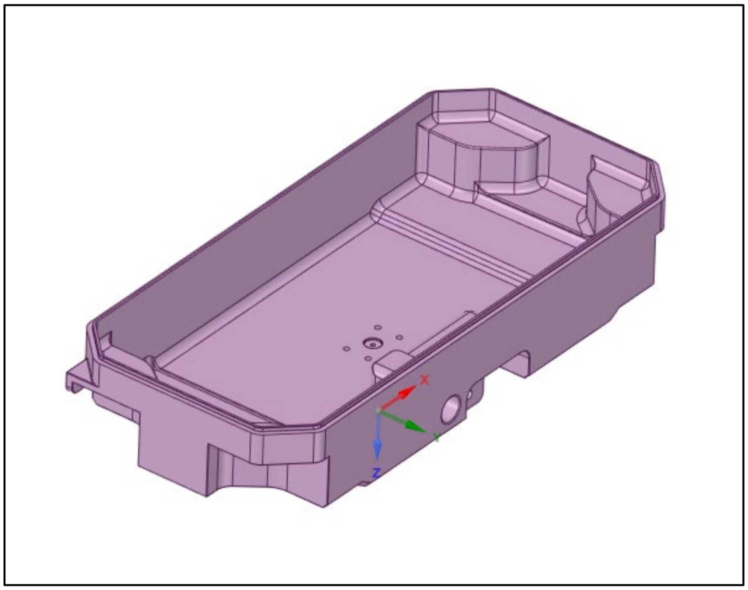


Figure 3 Tank Bottom

The tank top and bottom are traditionally manufactured and are EB welded together circumferentially. The tank is filled and pressurized prior to launch with AF-M315E propellant. The tank is fracture critical and contains the Propellant Management Device (PMD). Everything downstream of the tank is only pressurized with propellant following separation from SLS. There are three devices leading from the pressurized volume:

1. Pressure Transducer
2. Service Valve

3. Isolation Valve

Note that there is a tube within the tank bottom that is downstream of the isolation valve, this does not contain any hazardous fluid while fracture control is enforced.

3.1.2 Manifold

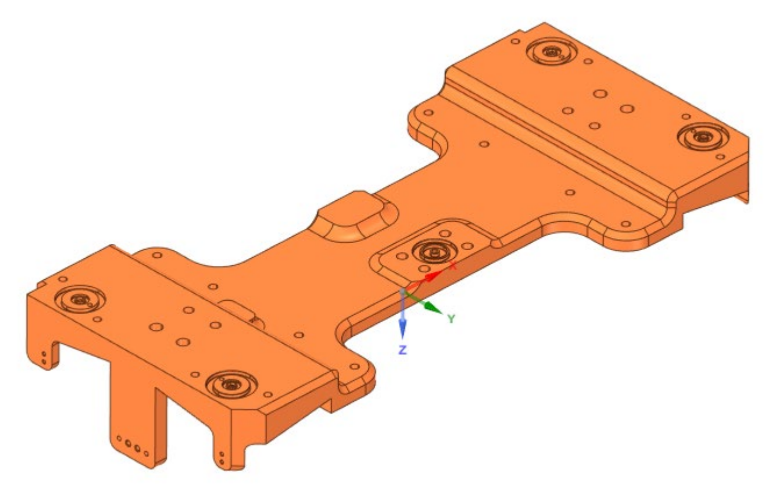


Figure 4 Manifold (11/29/2019 Design)

The Manifold is an additively manufactured part. It is not filled with a hazardous fluid while fracture control is enforced. The primary purpose of the Manifold is to support parts and route fluids using embedded channels. The fluid is routed through the pump, recirculation block, pressure transducer, valves, and thrusters. This component also supports the thrusters, valves (excluding the isolation and service valves), electronics, muffin tin, pump, and solar panels for the experiment.

3.1.3 Muffin Tin

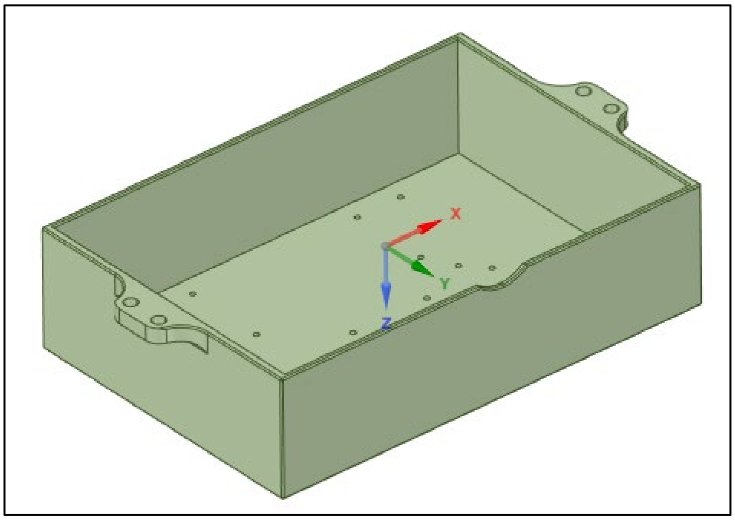


Figure 5 Muffin Tin (11/29/2019 Design)

The muffin tin shrouds some of the smaller components (electronics and pump) of the LFPS from direct sunlight and the thrusters. It also supports various experiment components (not a part of LFPS).

3.1.4 Isolation Valve

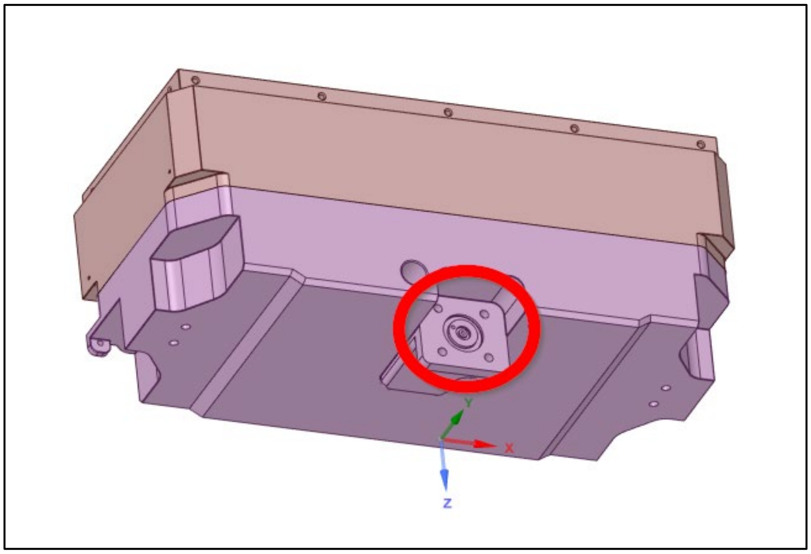


Figure 6 Isolation Valve Location

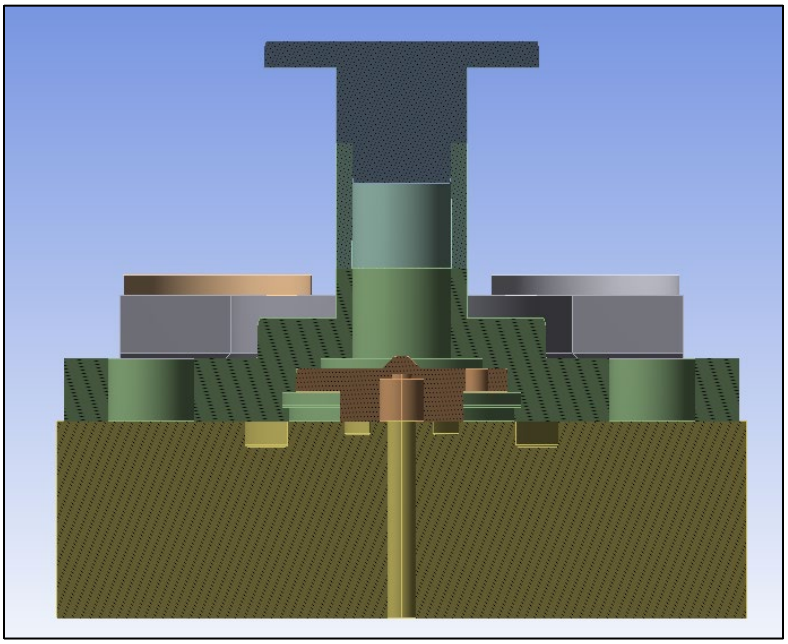


Figure 7 Isolation Valve Cross Section

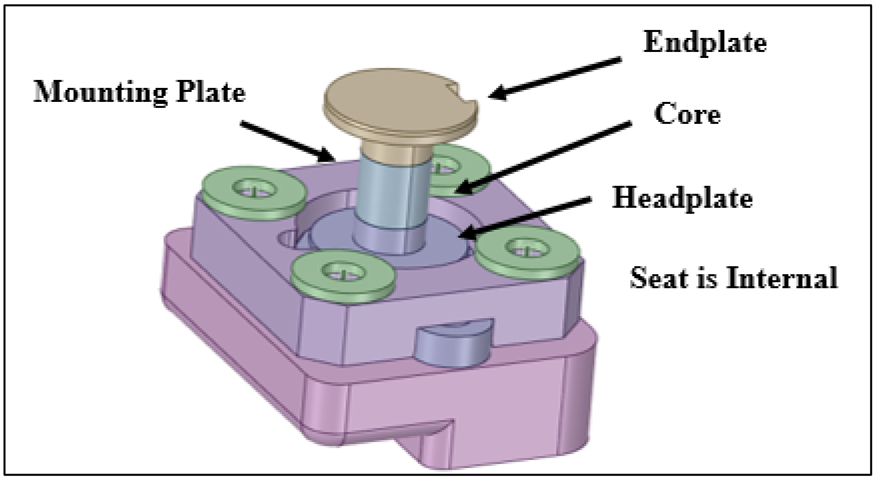


Figure 8 Isolation Valve Subcomponents (Including the Mounting Plate)

The isolation valve is mounted on the tank and isolates the hazardous fluid within the tank from the rest of the LFPS while on board SLS. After Lunar Flashlight is launched from SLS, the valve is commanded open for the duration of the mission. The micro-valve part used on the tank is the same as the four used on the manifold for thruster control.

3.1.5 Isolation Valve Mounting Plate

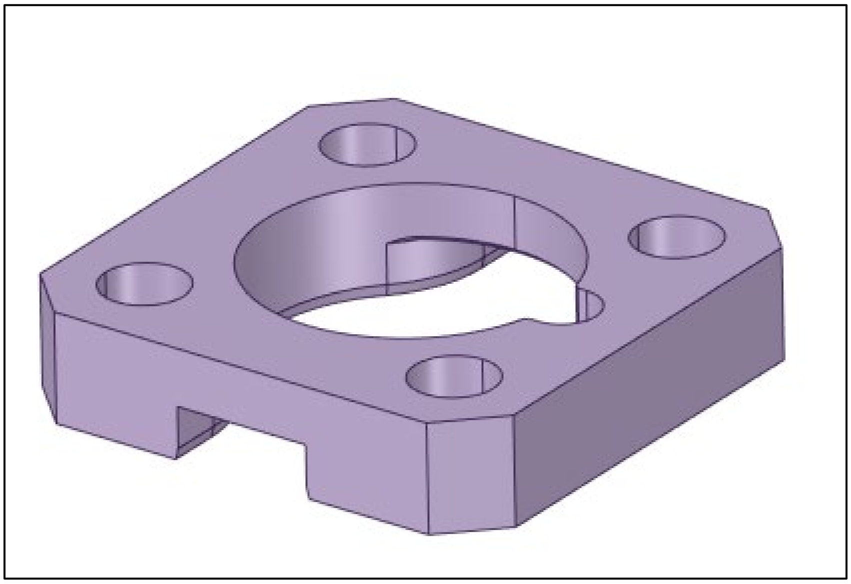


Figure 9 Isolation Valve Mounting Plate

The isolation valve is clamped to the tank underneath the isolation valve mounting plate. The two bolt fastener pattern of the micro-valve prevents the bolts from being designated as fail safe. The mounting plate allows for more fasteners and is used to prevent the bolts from being deemed fracture critical. The mounting plate does not see significant loads following installation.

3.1.6 Service Valve

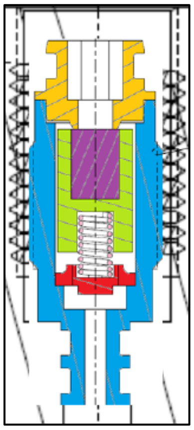


Figure 10 Service Valve Cross Section

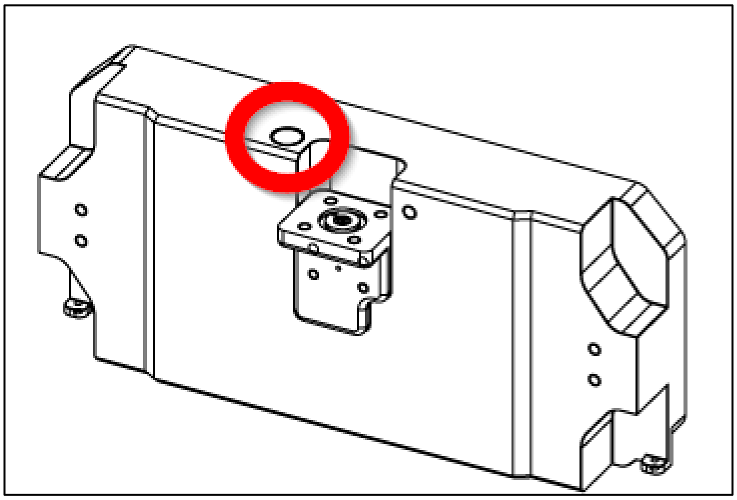


Figure 11 Service Valve Location

The service valve is used to fill, drain, and pressurize the tank. The service valve is a previously qualified part that was assessed to higher pressures for another program. This component is in a different configuration on the ground compared to flight. The ground support half is removed and the opening is plugged prior to launch. See memo ER41 (18-028) for structural analysis.

3.1.7 Pressure Transducer

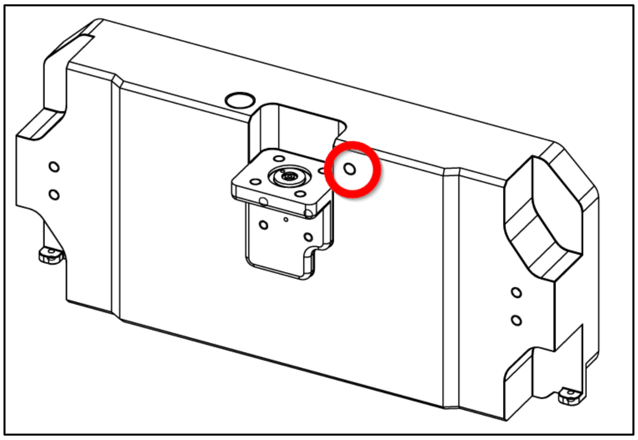


Figure 12 Pressure Transducer Location

The pressure transducer is a commercial off the shelf component that is installed into the tank bottom. It is qualified to a much higher pressure than that of the tank. The stress analysis for this part is discussed in the LFPS Structural Analysis Report.

3.1.8 Other Components

The other components are of less importance for the fracture analysis, as these components are to be designated as NFC-Contained or Exempt. None of these components are used to contain the hazardous fluid during launch. These components include:

1. Controller
2. Pump
3. Recirculation block
4. Propellant management device (PMD)
5. Thrusters
6. Thruster valves
7. Seals
8. All fasteners other than those on the isolation valve

3.2 Fracture Disposition and Summary

Table 1 Fracture Summary

Part Name	Part Numbers	Materials	Heat Treatment	Fracture Disposition	Ult. MS
Tank Top	GT-PN 1111-001 B	Ti 6Al-4V	AMS 4928	FC – Pressurized Vessel – Safe-Life Analysis	+0.06
Tank Bottom	GT-PN 1111-001 E	Ti 6Al-4V	AMS 4928		
Tank Weld	N/A	Ti 6Al-4V	Stress Relieved		+0.77
Manifold	GT-PN 1210-001 C	DMLS Ti 6Al-4V	AMS 2801B	NFC – Contained	+1.92
Muffin Tin	GT-PN 1261-001 C	Ti 6Al-4V	AMS 4967	NFC – Contained	+9.17
Isolation Micro-Valve	GT-PN 1121-001 A	CRES 304L CRES 430	Annealed	FC – Pressurized Component	+0.09
Isolation Valve Mounting Plate	GT-PN 1122-001 A	CRES 304L	Annealed	NFC – Failsafe	+0.23
Isolation Valve Fasteners	NAS1352N08L8	A286	N/A	NFC – Failsafe	+0.00
Service Valve	GT-PN 1134-001 A	15-5PH	H900	FC – Pressurized Component	N/A
Pressure Transducer	GT-PN 1131-001 A TE XP5-X-150PA-/V05/L3M/Z02	COTS – N/A	N/A	FC – Pressurized Component	N/A
Pump	GT-PN 1241/4-001 A	Various	N/A	NFC – Contained	N/A
Recirculation Block	GT-PN 1234-001 C	DMLS Ti 6Al-4V	AMS 2801B	NFC – Contained	+0.67
PMD Vanes	GLRG-LFPS-903	Ti 6Al-4V	ASTM B265 Grade 5	NFC-Contained	+8.37
PMD Sponge	GLRG-LFPS-902	DMLS Ti 6Al-4V	AMS 2801B	NFC-Contained	+0.62
Thrusters	GT-PN 1221/4-001 A	Various	N/A	NFC – Contained	N/A
Thruster Micro-Valve	GT-PN 1241/4-001 A	CRES 304L CRES 430	Annealed	NFC – Contained	+0.09
All fasteners except those on isolation valve	NAS1352	A286	N/A	NFC – Contained	+0.00
Controller	GT-PN 1250-001 C	N/A	N/A	Exempt	N/A

3.3 Geometry

3.3.1 Tank Top/Bottom

The tank geometry used in the finite element model (FEM) accounts for worst case GD&T on the wall thicknesses. The tolerances and nominal CAD model are based on the 11/22/2019 design freeze. The geometry provided was held to a general tolerance of ±0.014", so the wall thicknesses were reduced by 0.028" everywhere but at the weld. Fillet radii, bolt hole locations, and feature locations were not geometrically changed in the model to account for tolerances. These features should not impact the stress results significantly. The tank geometry was reviewed on 4/1/2020 and was determined that the final tolerances are better than those used in the 11/22/2019 FEM, therefore a rerun is not necessary.

The damage tolerance analysis assumes a minimum thickness based on the worst location in the entire tank. The ER41 Design assisted and interrogated the 4/1/2020 model to check 6 locations for minimum thicknesses. Tolerance stackups were developed at these locations to find the minimum dimension between the pressurized space and the exterior of the tank. Each location of interest is described here:

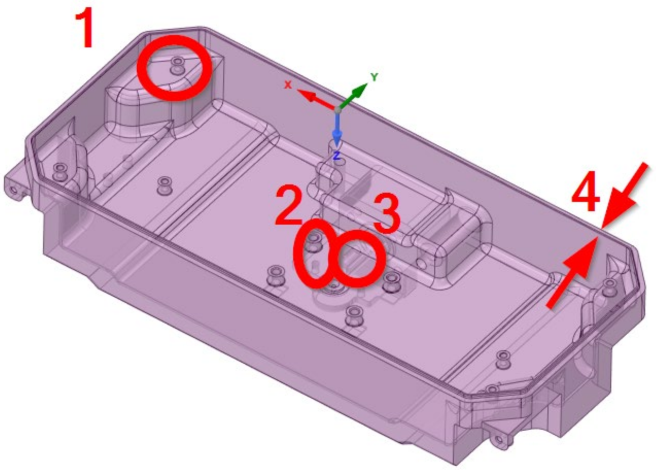


Figure 13 Tank Top Critical Dimension Locations

1. The minimum thickness locations are in the tank bottom, located at the outermost standoffs for the PMD Vanes. The worst case distance between the bottom of the bolt holes and the tank exterior is 0.087".
2. Bolt holes are close to each other in the bottom of the tank. On one side are the PMD standoffs and the other is the manifold connection. The minimum distance between these holes is 0.123".

3. The two fluid lines drilled into the bottom of the tank are 0.113” apart worst case. One tube is under pressure during launch, while the other is unpressurized, realistically, a flaw that propagates here would not necessarily result in a catastrophic hazard, but it is assumed that this is the case. This location will be inspected with eddy current, as dye penetrant inspection is impossible in this enclosed space.
4. The tank walls are 0.118” thick nominally, with a minimum thickness of 0.108”. These tank walls will only be inspected with dye penetrant NDE.

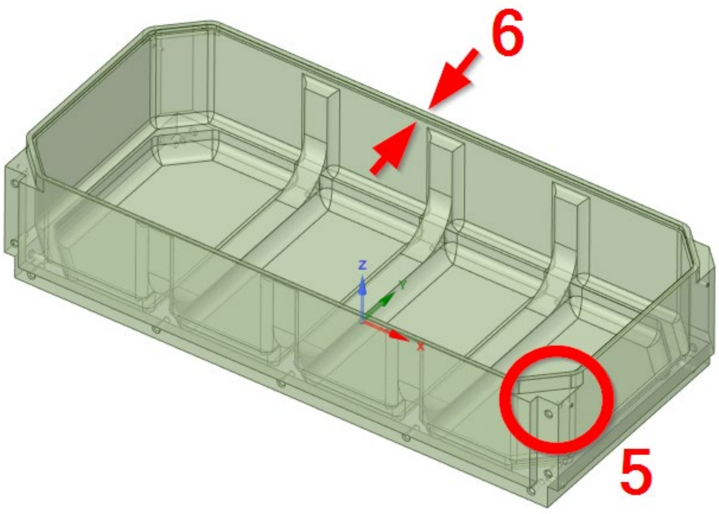
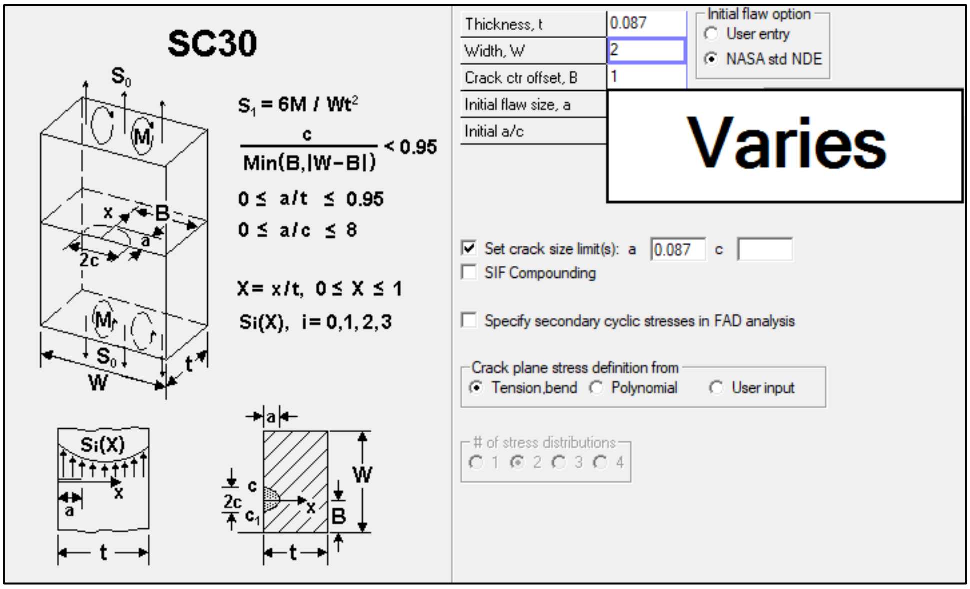


Figure 14 Tank Top Critical Dimension Locations

5. Holes are drilled into the tank exterior for connecting LFPS to the remainder of the Lunar Flashlight. The minimum dimension between these holes and the tank interior is 0.108”.
6. The tank walls are 0.118” thick nominally, with a minimum thickness of 0.108”. These tank walls will only be inspected with dye penetrant NDE.

- Note that the isolation valve interface has seal grooves that are thinner (0.050”) than the flaws that eddy current can inspect for (0.1”). Flaws at this location are screened using leak checks during testing. Additionally, this location is not expected to see significant stresses during flight (<2 ksi during MDP pressures) so flaws are not expected to grow.

The above geometry is used in the finite element analysis and the NASGRO analysis. The specific dimensions used in the NASGRO analysis are shown in the figure below:



Thickness, t	0.087
Width, W	2
Crack ctr offset, B	1
Initial flaw size, a	Varies
Initial a/c	Varies

Initial flaw option
○ User entry
● NASA std NDE

☑ Set crack size limit(s): a 0.087 c
☐ SIF Compounding

☐ Specify secondary cyclic stresses in FAD analysis

Crack plane stress definition from
● Tension,bend ○ Polynomial ○ User input

# of stress distributions
○ 1 ● 2 ○ 3 ○ 4

Figure 15 NASGRO Tank Top/Bottom Dimensions

3.3.2 Weld Dimensions

The weld dimensions used in the analysis are from the 11/22/2019 geometry design freeze, but align with tolerances from the 4/1/2020 design. The weld is held to AMS 2680C, which allows a 10% reduction in depth; this is not accounted for in the FEM analysis, but is accounted for in the damage tolerance analysis. The worst case weld depth is 0.067”, accounting for AMS 2680C. The worst case geometry used in the FEM can be seen in the following figures:

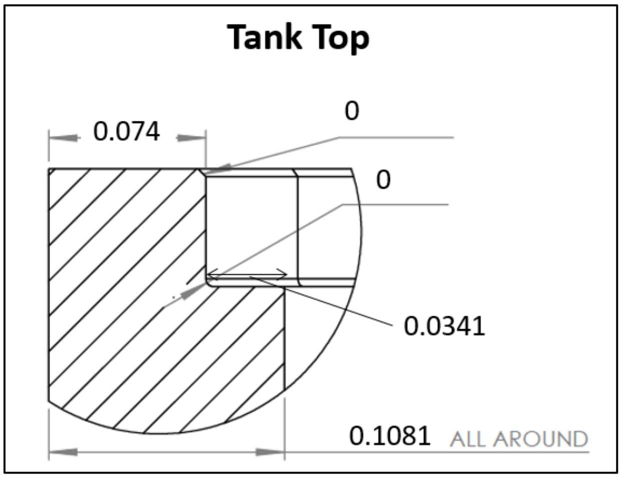


Figure 16 Worst case Weld Geometry – Tank Top

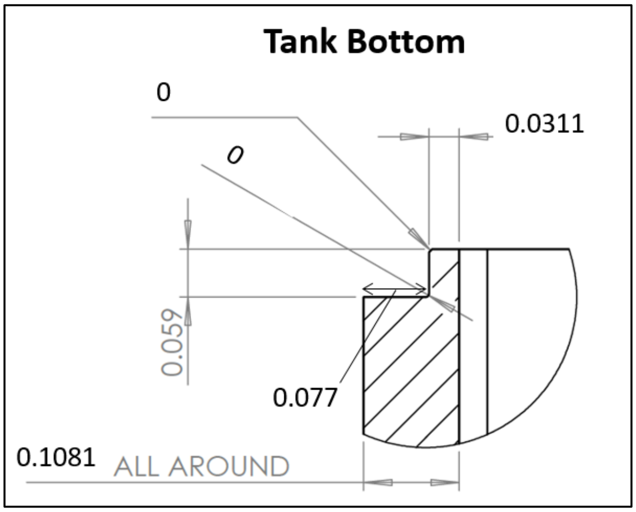
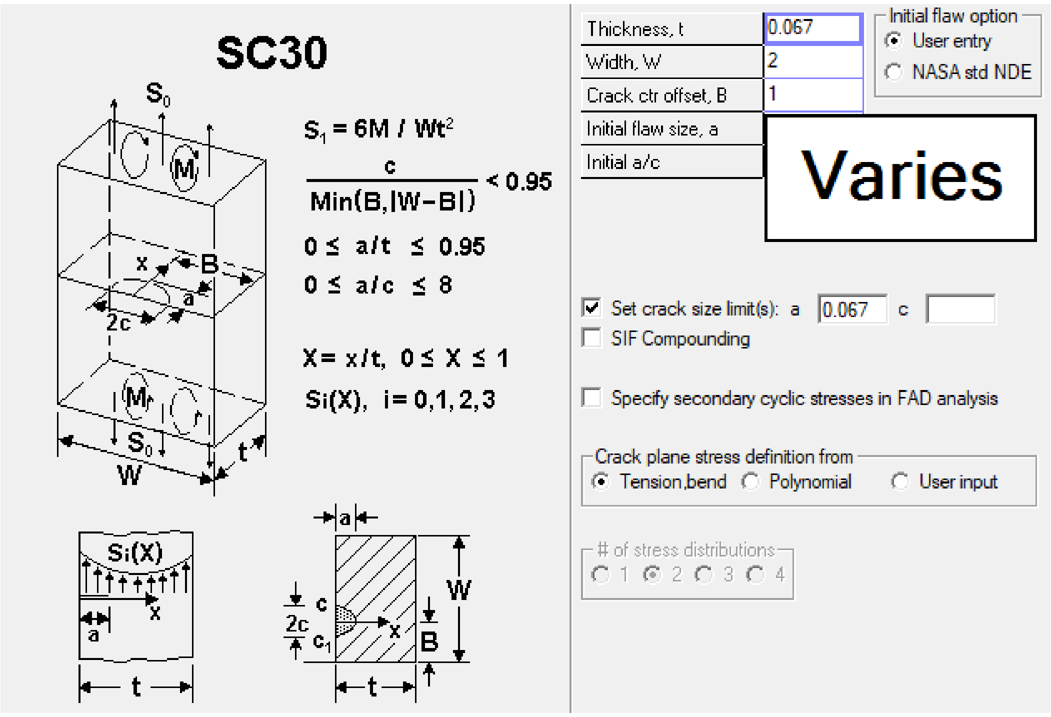


Figure 17 Worst Case Weld Geometry – Tank Bottom

The above geometry is used in the finite element analysis and the NASGRO analysis. The specific dimensions used in the NASGRO analysis are shown in the figure below:



Thickness, t: 0.067
Width, W: 2
Crack ctr offset, B: 1
Initial flaw size, a
Initial a/c
Varies

Initial flaw option: ● User entry ○ NASA std NDE

☑ Set crack size limit(s): a 0.067 c

☐ SIF Compounding

☐ Specify secondary cyclic stresses in FAD analysis

Crack plane stress definition from: ● Tension,bend ○ Polynomial ○ User input

# of stress distributions: ○ 1 ● 2 ○ 3 ○ 4

Figure 18 NASGRO Weld Dimensions

3.3.3 NDE Inspection Methods

Various NDE methods are used on lunar flashlight:

- Tank Top and Bottom pre-machining – Ultrasonic inspection of the raw stock per NASA-STD-5009B.
- Tank Top and Bottom post-machining – dye penetrant inspection where possible, eddy current inspection everywhere else. Flaw detection criteria & dimensions are per NASA-STD-5009B. The damage tolerance analysis conservatively uses dye penetrant flaw sizes in all locations.
- Tank Weld – Dye penetrant inspection, before and after tank proof test. Flaw size used will be 90% of the thickness, as noted in the alternative approaches section of the Fracture Control Plan.
- Isolation Valve – the valve will be inspected on the exterior using dye penetrant per NASA-STD-5009B. 2

3.3.4 Isolation Valve Mounting Plate

The isolation mounting plate model is run with nominal dimensions. The part has sufficient margin that this is not a concern.

3.3.5 Isolation Valve Mounting Plate Fasteners

The fastener information is listed below:

- Bolt: NAS1352N08L6
- 0.164-32 Threads
- 15 in*lbf max locking torque
- 8-10 in*lbf installation torque (above running torque)
- 0.97 Thermal knockdown (140°F, MMPDS13, see LFPS Structural Analysis Report)
- Plate 2: Mounting Plate & Valve (0.25" thick)
- Plate 3: Tank (0.125" thread engagement)

3.4 Factors of Safety

Factors of Safety are referenced per LFPS-SPEC-201, Safety document “LF-04 Pressure System Rupture 20191010”, AIAA S-080-1998, NASA-STD-5019, and NASA-STD-5001.

Table 2 Factors of Safety

Load Case		**Proof / Yield Factor of Safety**	**Burst / Ultimate Factor of Safety**
Ground / Launch / On-Orbit / Proof / Burst / Buckling	Inertia	1.25[3]	1.4[3]
	Pressure	1.5[2]	2.5[1]

Notes:

1. Burst/ultimate pressure test includes safety factor (2.5) (per LFPS-SPEC-201 & AIAA S-080-1998), and an ECF of 1.06 (required by NASA-STD-5019). This aligns/exceeds the factors listed in “LF-04 Pressure System Rupture 20191010.doc §1.1.
2. Proof/yield pressure test includes a 1.5x safety factor (LFPS-SPEC-201) and an ECF of 1.06 (required by NASA-STD-5019). This aligns with “LF-04 Pressure System Rupture 20191010.doc §1.1.
3. From NASA-STD-5001 Table 1

4.0 MATERIAL PROPERTIES

Material properties are used in a variety of analyses and descriptions will be sorted by material type. This data includes material properties used in all analyses, as some non-fracture critical parts are included in analysis of fracture critical components. Additionally, some of these properties are only used in the LFPS Structural Analysis Report.

4.1 Ti-6Al-4V Bar (AMS 4928)

Used on:

- Tank top
- Tank bottom
- Muffin tin

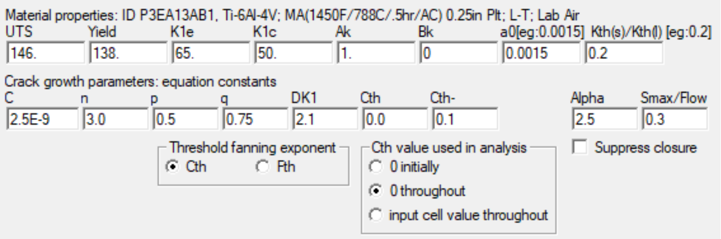
Material Stock Information:

- Formerly AMS 4967
- Condition: Annealed, stress relieved after weld (tank only)
- Form: Bar
- Stock: 6-10” T (conservative)

Static MS Calculations:

- These properties are used to determine static margins of safety for the parts, fastener static analyses, fastener thermal analysis, factor of safety for proof testing, and fatigue analyses
- F_{tu}=130 ksi (MMPDS13)
- F_{ty} = 119 ksi (MMPDS13)
- E=16.9 x10^6 psi (MMPDS13)
- $\alpha_{300°F}$= 5.1*10^{-6} in/in/°F (MMPDS13 F5.4.1.0(a2))
- ECF_{NonOp} = 0.94 (F_{tu} & F_{ty} - 140°F - MMPDS13 F5.4.1.2.1)

NASGRO Properties:

- These properties are used exclusively in the NASGRO/NASFLA analyses. The material is based on the data in the NASGRO material library with some modifications.
- Material ID: P3EA13AB1
- Material description: Ti-6Al-4V; MA(1450F/788C/0.5hr/AC) 0.25in Plt; L-T; Lab Air
- Modifications:
    - BK=0 – This change is required by NASA-STD-5019
    - 

Material properties: ID P3EA13AB1, Ti-6Al-4V; MA(1450F/788C/.5hr/AC) 0.25in Plt; L-T; Lab Air

UTS	Yield	K1e	K1c	Ak	Bk	a0[eg:0.0015]	Kth(s)/Kth(l) [eg:0.2]
146.	138.	65.	50.	1.	0	0.0015	0.2

Crack growth parameters: equation constants

C	n	p	q	DK1	Cth	Cth-	Alpha	Smax/Flow
2.5E-9	3.0	0.5	0.75	2.1	0.0	0.1	2.5	0.3

Threshold fanning exponent
● Cth ○ Rth

Cth value used in analysis
○ 0 initially
● 0 throughout
○ input cell value throughout

☐ Suppress closure

FEM Properties:

- ER41 Material Library – 1.37
- Ti-6Al-4V STA, Bar, AMS 4967, 3”>t>4”, 4”>W>8” (Acceptable because model is within elastic range)

Fatigue properties:

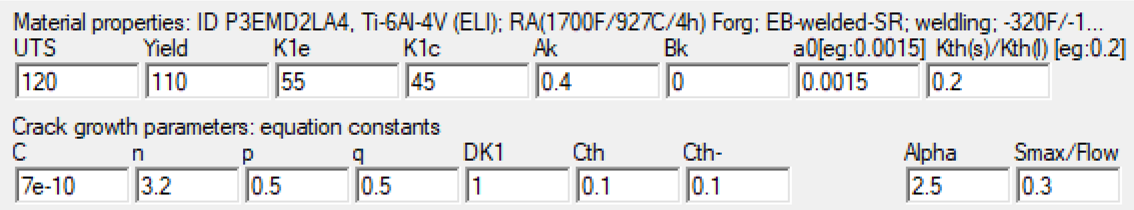
- S-N curve from MMPDS13, Figure 5.4.1.1.8(a)
- S-N curve is read at 10^7 cycles, unnotched, R=-1: S_{eq}=45 ksi

4.2 Ti-6Al-4V Weld

Used on:
- Tank weld

Material information:
- Same material as tank, but EB welded and heat treated

Static MS Calculations:
- These properties are used to determine static margins of safety for the parts and fatigue analyses
- Based on fatigue data from the “Atlas of Fatigue Curves,” the yield and ultimate stress allowables can be assumed to be greater than 100 ksi
- ECF_{NonOp}, ECF_{Op} are assumed to be the same as the tank

NASGRO Properties:
- These properties are used exclusively in the NASGRO/NASFLA analyses. The material is based on the data in the NASGRO material library with some modifications.
- Properties have been coordinated with EM21 (Doug Wells)
- Material ID: P3EMD2LA4
- Material Description: Ti-6Al-4V (ELI); RA(1700F/927C/4h); EB – Electron Beam’ weld/paralled/stress relieved; LG; -320F/-196C Liq. N2
- Modifications per EM21/ Doug Wells: UTS=120, YS=110, Kie=55.0, K1c=45.0, DK1=1.0, BK=0
- 

Material properties: ID P3EMD2LA4, Ti-6Al-4V (ELI); RA(1700F/927C/4h) Forg; EB-welded-SR; weldling; -320F/-1...

UTS	Yield	K1e	K1c	Ak	Bk	a0[eg:0.0015]	Kth(s)/Kth(l) [eg:0.2]
120	110	55	45	0.4	0	0.0015	0.2

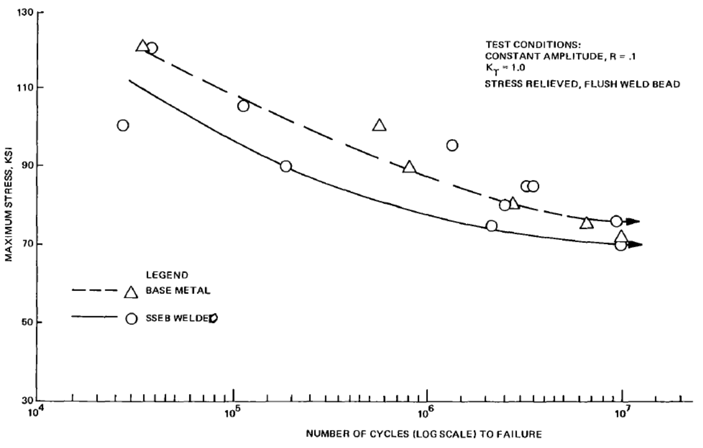
Crack growth parameters: equation constants

C	n	p	q	DK1	Cth	Cth-	Alpha	Smax/Flow
7e-10	3.2	0.5	0.5	1	0.1	0.1	2.5	0.3

FEM Properties:
- ER41 Material Library – 1.37
- Ti-6Al-4V STA, Bar, AMS 4967, 3”>t>4”, 4”>W>8”

Fatigue properties:
- S-N curve from Atlas of Fatigue Curves, ASM International (1986), Page 457
- S-N curve is read at 10^7 cycles, unnotched, and R=0.1: S_{eq}=70 ksi

17-44. Ti-6Al-4V: Base Metal vs SSEB-Welded Material for Cycles to Failure **457**



S-N curve for titanium alloy plate—base metal versus SSEB-welded. Results show that the constant-amplitude fatigue life of SSEB weldments in 0.440-in.-thick plate equals that of the base metal.

4.3 AM Ti-6Al-4V

Used On:

- Manifold
- Pump Block
- PMD Sponge

Material Information

- Additively Manufactured DMLS Titanium

Static MS Calculations:

- These properties are used to determine static margins of safety for the parts, fastener static analyses, fastener thermal analysis, factor of safety for proof testing, and fatigue analyses
- Source: "Metal Additive Manufacturing. A Review of Mechanical Properties" – Lewandowski Seifi – 2016 – Provided by Omar Rodriguez / EM31
- F_{ty} = 111.4 ksi
- F_{tu} = 117.6 ksi
- ECF_{NonOp}, ECF_{Op} are assumed to be similar to the tank

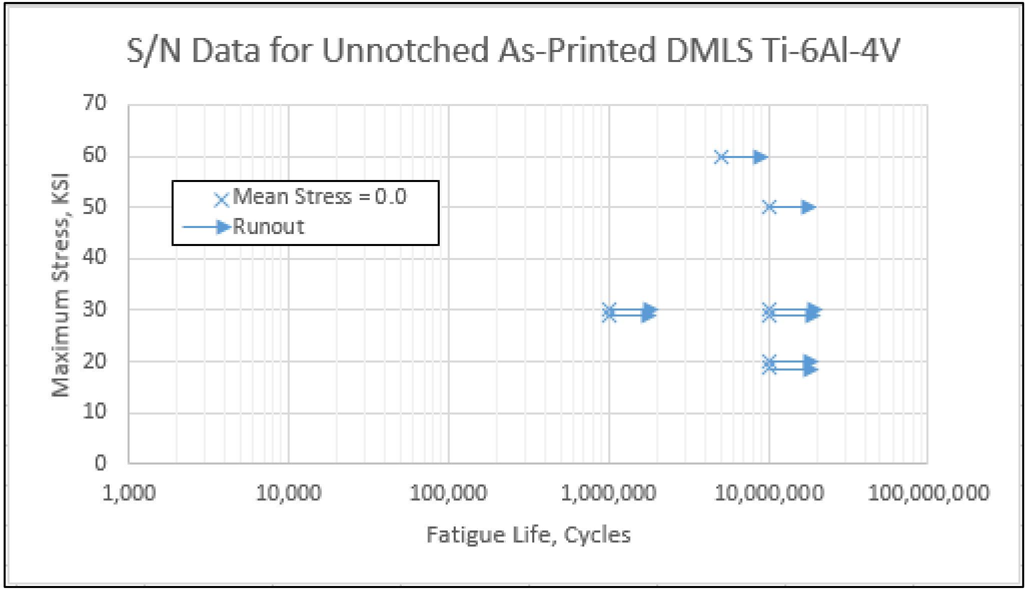
NASGRO Properties:

- N/A (no damage tolerance analysis performed)

FEM Properties:

- ER41 Material Library – 1.37
- Ti-6Al-4V STA, Bar, AMS 4967, 3">t>4", 4">W>8"

Fatigue Properties

- All 8 tests ran out at different stresses and cycles
- Data shown in the figure on the right
- Samples are from the same print as the flight manifold
- Conservatively use 106 cycles, R=-1, Seq=30 ksi for the fatigue analysis
- 

4.4 Aluminum 7075-T7351

Used On:
- Lunar Flashlight Spaceframe

Material Information:
- Aluminum 7075-T7351

FEM Properties:
- ER41 Material Library – 9.17
- Al 7075-T7351, Plate, AMS 4078, 0.5” > t > 1.0”

NASGRO Properties:
- N/A (no damage tolerance analysis performed)

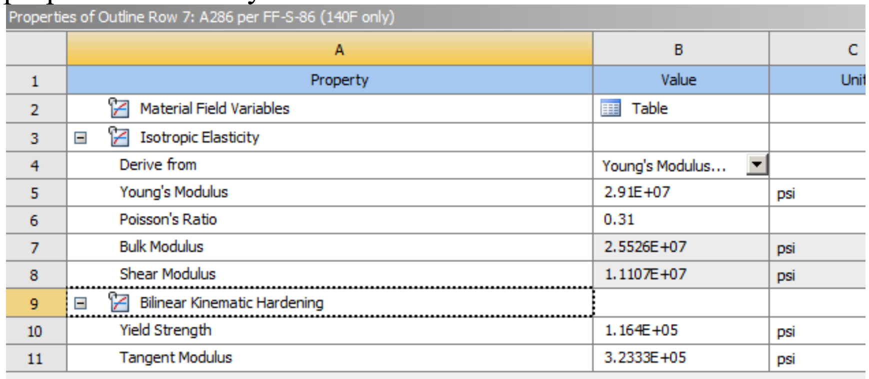
4.5 A286 Bolts:

Used on:
- All Fasteners

Material Information
- A286 Per FF-S-86E

Static MS Calculations:
- These properties are used to determine fastener static analyses, fastener thermal analysis, factor of safety for proof testing, and fatigue analyses
- F_{tu} = 160 ksi per FF-S-86E
- F_{ty} = 120 ksi per FF-S-86E
- $E=29.1 \times 10^{6}$ psi (MMPDS13)
- $\alpha_{300°F} = 9.3*10^{-6}$ in/in/°F (MMPDS13 F6.2.1.0(b))
- $ECF_{NonOp} = 0.97$ (F_{tu} & F_{ty} - 140°F - MMPDS13 F6.2.1.1.1)

FEM Properties:
- ER41 Material Library – 10.1
- A286 STA, sheet/strip/plate, AMS 5525
- Plastic properties used only in the isolation valve FEM:



Properties of Outline Row 7: A286 per FF-S-86 (140F only)

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	⊟ Isotropic Elasticity		
4	Derive from	Young's Modulus...	
5	Young's Modulus	2.91E+07	psi
6	Poisson's Ratio	0.31	
7	Bulk Modulus	2.5526E+07	psi
8	Shear Modulus	1.1107E+07	psi
9	⊟ Bilinear Kinematic Hardening		
10	Yield Strength	1.164E+05	psi
11	Tangent Modulus	3.2333E+05	psi

NASGRO Properties:
- N/A (no damage tolerance analysis performed)

Fatigue Properties:
- Heritage shuttle data used
- S-N curve is read at 106 cycles, unnotched, and R=-1: Seq=50 ksi

4.6 CRES 304L

Used On:

- Isolation Valve Core and Mounting Plate
- Thruster Valve Core

Material Information:

- CRES 304L

Static MS Calculations:

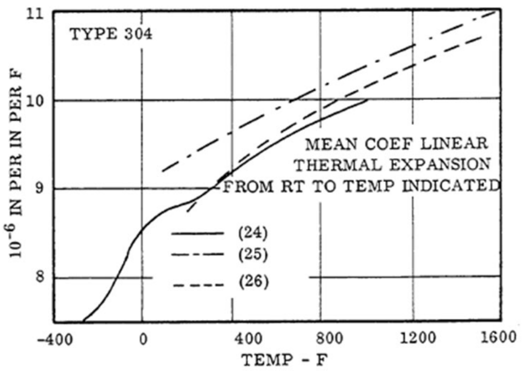
- These properties are used to determine static margins of safety for the parts, fastener static analyses, fastener thermal analysis, and fatigue analyses
- F_{tu} = 70 ksi per ASTM A276
- F_{ty} = 25 ksi per ASTM A276
- ECF_{NonOp} = 0.94 (Ftu & Fty - 140°F - MMPDS13 F2.7.1.1.1(a)&(b))
- E=29 x10^6 psi per MMPDS13
- e=0.30 in/in (MMPDS-13 T2.7.1.0(b3)) (Used in point strain calculations)
- Coefficient of thermal expansion properties are from ASMH Figure 2.014
- 

  FIG 2.014 THERMAL EXPANSION

  (21, p. 22)(24)(25, p. 6)(26)

FEM Properties:

- ER41 Material Library – 8.1
- AISI 304 Stainless Steel – Solution Treated – AMS 5513

NASGRO Properties:

- N/A (no damage tolerance analysis performed)

Fatigue Properties:

- Sourced from heritage shuttle data
- S-N curve is read at 10^6 cycles, unnotched, and R=-1: S_{eq}=24 ksi

4.7 430 CRES (ASTM A276)

Used On:

- Isolation Valve Headplate and Endplate
- Thruster Valve Headplate and Endplate

Material Information:

- 430 CRES per ASTM A276

Static MS Calculations:

- These properties are used to determine static margins of safety for the parts, fastener static analyses, fastener thermal analysis, and fatigue analyses
- F_{tu} = 60 ksi per ASTM A276
- F_{ty} = 30 ksi per ASTM A276
- Modulus of elasticity and coefficient of thermal expansion provided by EM31
- Assume ECF is the same as CRES 304L
- e=0.20 in/in (MMPDS-13 T2.7.1.0(b3)) (Used in point strain calculations)
- E=29000 ksi (Assume same as 304L) (Used in point strain calculations)

FEM Properties:

- ER41 Material Library – 16.1
- AISI 430 – Annealed – ASTM A276

NASGRO Properties:

- N/A (no damage tolerance analysis performed)

Fatigue Properties:

- Sourced from heritage shuttle data
- S-N curve is read at 10^6 cycles, unnotched, and R=-1: S_{eq}=42 ksi

4.8 CRES 304L to ASTM A276 Weld

Used on:
- Welds for the isolation and thruster valves. Specifically between the core and the adjacent components.

Static Properties:
- Based on historical ER41 documentation and processes for EB weld knockdown factors (60%) and the worst properties of the two welded materials
- Ftu = 36 ksi
- Fty = 15 ksi
- Assume ECF is the same as CRES 304L

Fatigue Properties:
- Sourced from heritage shuttle data
- S-N curve is read at 10^6 cycles, unnotched, and R=-1: Seq=21 ksi

NASGRO Properties:
- N/A (no damage tolerance analysis performed)

4.9 15-5 PH Service Valve

Used On:
- Service Valve

Fatigue Properties:
- Ftu = 185.9 ksi (Memo ER41(18-028))
- S-N curve from MMPDS13 Fig. 2.6.7.2.8(b)
- S-N curve is read at 10^6 cycles, unnotched, and R=0.1: Seq=166 ksi

NASGRO Properties:
- N/A (no damage tolerance analysis performed)

5.0 LOADS AND ENVIRONMENTS

5.1 Mission Profile

The Lunar Flashlight undergoes a single mission launched from SLS during Artemis-1. Following testing and launch, it is jettisoned from SLS at “Bus Stop 1” and will make passes around the moon using LFPS multiple times to change its orbit. Some components see testing prior to system integration.

Table 3 Mission Profile

Event	Cycles	Operational Load
Micro Valve Proof 1	1 cycle[3] (valves only)	600 psi[3]
Micro Valve Proof 2	1 cycle[3] (valves only)	1307 psi[3]
Tank Fill Events	10 cycles[4] (tank & valves)	-1 atmosphere to 1x MDP[14]
Pressure Tests	50 cycles[4] (tank, lines, & valves)	1x MDP[1]
Tank Proof Test	1 cycle[4] (tank & valves)	159 psi[12]
System Proof Test	1 cycle[4] (tank, lines, & valves)	1.1x MDP[4]
System Proto-Qual RV Test	3 events	Unpressurized Various Inertia Loads
Launch	1 event	1x MDP Various Inertia Loads
Mission Pressure	<200 events[5] (lines and valves)	1x MDP

References

1. LFPS-SPEC-201
2. Tank proof test has been increased 6% (NASA-STD-5019 required environmental correction factor, with MMPDS-13 data)
3. Brad Addona / ER14
4. Carlos Diaz & Hunter Williams / ER11
5. The pump output pressures will vary insignificantly during each thruster event.

Notes

- Tank fill and pressure cycles are increased as the test plan isn’t finalized
- Inertial cycles have been derived from available data and are discussed later
- LFPS-SPEC-205 §3.2.7.3 requires 50,000 operation cycles of the micro-valve

- Thermal cycles are assumed to be insignificant due to low cycle counts and a benign thermal environment. The total number of thermal cycles is estimated as the number of days LFPS sits in SLS (365 days per LFPS-SPEC-201) plus the number of firing events (<200 per ER12 on 7/21/2020).

5.2 Pressure

The tank is designed such that the pressure will not exceed MDP of 100 psi. The lines downstream of the pump have an MDP of 500 psi. The analysis assumes that MDP is achieved in all pressurized events (assembly, test, launch, and operation). Additionally, 1 atmosphere crush pressure is assumed for tank fill events as a vacuum is pulled prior to fluid loading. It is worth noting that the service, isolation, and thruster valves are tested to a proof pressure greater than what is necessary on LFPS. The MDP pressures, burst factors, and proof factors are derived from requirements in LFPS-SPEC-201, specifically LFPS-REQ-011, LFPS-REQ-012, and LFPS-REQ-013.

5.3 Thermal

The thermal environment is benign. The analysis assumes non-operational temperatures will occur at the same time as worst case loads. Material thermal degradation factors are used on all static margins. Thermal expansion is ignored for all analyses except for fasteners. The below temperatures were obtained from LFPS-SPEC-201 requirement LFPS-REQ-061 (converted from Celsius):

1. Non-operational: 5°-140°F
2. Operational: 41°-104°F

5.4 Inertial

The LFPS undergoes five inertial events: handling, ground transportation, system level RV testing, launch, and thruster firings. Handling, ground transportation and thruster firings are ignored. Thruster firings generate 0.0034 g's (per ER11), which is negligible.

The load factors on the LFPS are sourced from LFPS-SPEC-201 requirements LFPS-REQ-059 and LFPS-REQ-060. The low frequency and RV load factors are combined in the below table and are listed in the SLS dispenser local coordinate system.

Table 4 LFPS Load Factors

	Axial		Lateral		Radial	
LC1	31.02	-32.64	3.00	-3.00	4.58	-2.18
LC2	2.82	-4.44	18.60	-18.60	4.58	-2.18
LC3	2.82	-4.44	3.00	-3.00	22.58	-20.18

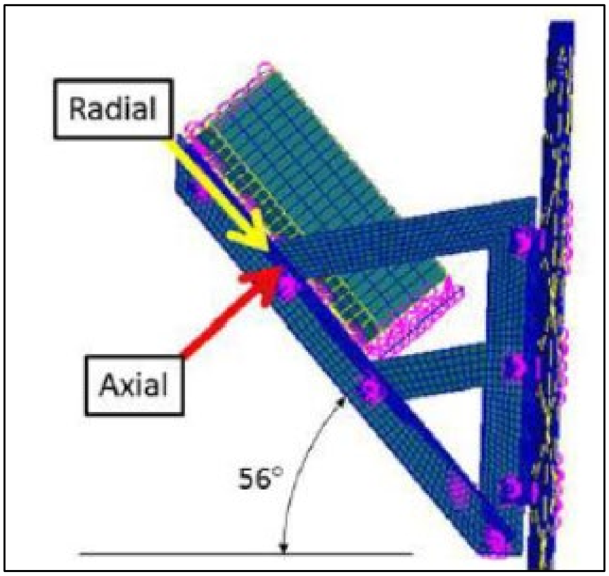
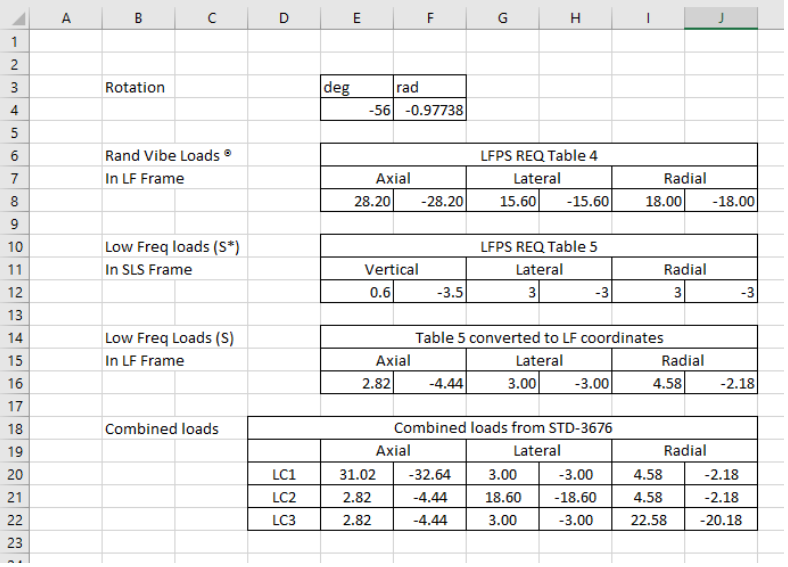
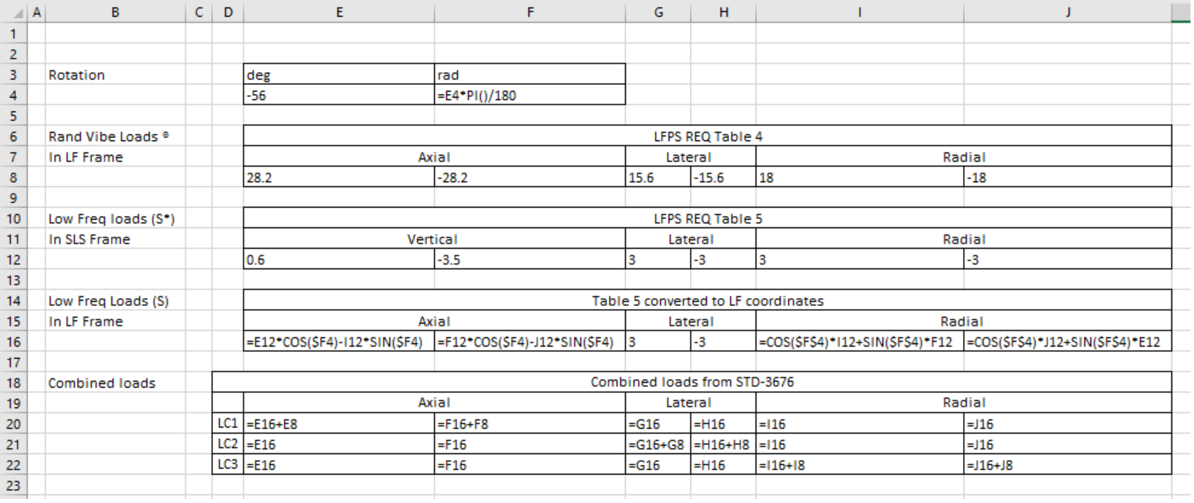


Figure 19 SLS Dispenser Local Coordinate System



	A	B	C	D	E	F	G	H	I	J
1										
2										
3		Rotation			deg	rad				
4					-56	-0.97738				
5										
6		Rand Vibe Loads ®			LFPS REQ Table 4					
7		In LF Frame			Axial		Lateral		Radial	
8					28.20	-28.20	15.60	-15.60	18.00	-18.00
9										
10		Low Freq loads (S*)			LFPS REQ Table 5					
11		In SLS Frame			Vertical		Lateral		Radial	
12					0.6	-3.5	3	-3	3	-3
13										
14		Low Freq Loads (S)			Table 5 converted to LF coordinates					
15		In LF Frame			Axial		Lateral		Radial	
16					2.82	-4.44	3.00	-3.00	4.58	-2.18
17										
18		Combined loads		Combined loads from STD-3676						
19					Axial		Lateral		Radial	
20				LC1	31.02	-32.64	3.00	-3.00	4.58	-2.18
21				LC2	2.82	-4.44	18.60	-18.60	4.58	-2.18
22				LC3	2.82	-4.44	3.00	-3.00	22.58	-20.18
23										

Figure 20 Load Combination Spreadsheet Results



	A	B	C	D	E	F	G	H	I	J
1										
2										
3		Rotation			deg	rad				
4					-56	=E4*PI()/180				
5										
6		Rand Vibe Loads ®			LFPS REQ Table 4					
7		In LF Frame			Axial		Lateral		Radial	
8					28.2	-28.2	15.6	-15.6	18	-18
9										
10		Low Freq loads (S*)			LFPS REQ Table 5					
11		In SLS Frame			Vertical		Lateral		Radial	
12					0.6	-3.5	3	-3	3	-3
13										
14		Low Freq Loads (S)			Table 5 converted to LF coordinates					
15		In LF Frame			Axial		Lateral		Radial	
16					=E12*COS($F4)-I12*SIN($F4)	=F12*COS($F4)-J12*SIN($F4)	3	-3	=COS(F4)*I12+SIN(F4)*F12	=COS(F4)*J12+SIN(F4)*E12
17										
18		Combined loads		Combined loads from STD-3676						
19					Axial		Lateral		Radial	
20				LC1	=E16+E8	=F16+F8	=G16	=H16	=I16	=J16
21				LC2	=E16	=F16	=G16+G8	=H16+H8	=I16	=J16
22				LC3	=E16	=F16	=G16	=H16	=I16+I8	=J16+J8
23										

Figure 21 Load Combination Spreadsheet Calculations

5.4.1 RV Cycle Spectra Creation

The RV spectra isn't defined in the parent specifications for the LFPS. A conservative spectra has been generated using information from test plans, SLS, and the structural analysis FEM.

A conservative modal analysis was run to determine the fundamental frequencies of the LFPS. The structural analysis FEM was used (see LFPS Structural Analysis Report for more details on the model). The boundary conditions in the structural FEM should be much stiffer than those of the launch environment, which is conservative. Mass participations were extracted to help identify which modes excited the tank. Note that the modes that excited other components (e.g. the muffin tin) are ignored. The fluid, thruster, valve, PMD, pump, and controller masses are conservatively ignored. The mass participation results and the three fundamental modal shapes can be seen below.

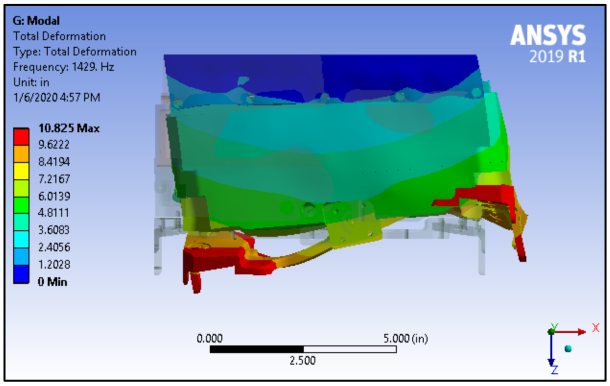


Figure 22 Primary Tank Y Mode Shape (Mode 58, 1429Hz)

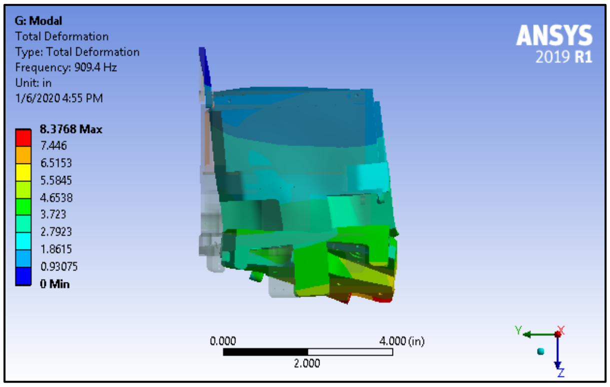


Figure 23 Primary Tank Y Mode Shape (Mode 22, 909Hz)

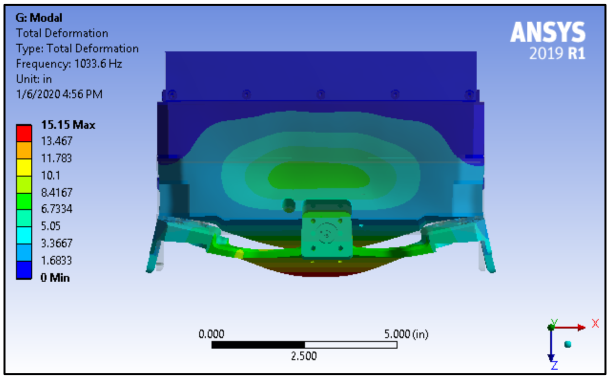


Figure 24 Primary Tank Z Mode Shape (Mode 41, 1034Hz)

Table 5 Modal Analysis: Mass Participation Results

Mode	Freq. (Hz)	Mass Participation Percentage		
		X%	Y%	Z%
1	234	0%	1%	0%
2	495	0%	0%	0%
3	581	0%	25%	0%
4	588	0%	0%	0%
5	590	0%	0%	0%
6	590	0%	0%	0%
7	590	0%	0%	0%
8	659	1%	0%	0%
9	670	0%	0%	0%
10	674	0%	0%	0%
11	693	18%	0%	0%
12	702	0%	0%	0%
13	703	1%	0%	0%
14	791	0%	0%	6%
15	796	0%	0%	0%
16	800	1%	0%	0%
17	818	0%	0%	0%
18	818	0%	0%	0%
19	865	0%	0%	0%
20	874	0%	0%	0%
21	906	0%	0%	0%
22	909	0%	10%	2%
23	929	0%	0%	0%
24	933	0%	0%	0%
25	934	0%	0%	0%
26	934	0%	0%	0%
27	934	0%	0%	0%
28	937	0%	0%	0%
29	938	0%	0%	0%
30	938	0%	1%	0%
31	939	0%	0%	0%
32	939	0%	0%	0%
33	939	0%	0%	0%
34	940	0%	0%	0%
35	940	0%	0%	0%
36	940	0%	0%	0%
37	941	0%	0%	0%
38	942	0%	0%	0%
39	966	0%	32%	1%
40	1026	1%	0%	0%
41	1034	0%	1%	13%
42	1043	0%	0%	0%
43	1054	0%	1%	1%
44	1059	0%	0%	0%
45	1065	0%	0%	0%
46	1065	0%	0%	0%
47	1079	0%	8%	8%
48	1179	0%	0%	0%
49	1180	0%	0%	0%
50	1181	0%	0%	0%
51	1181	0%	0%	0%
52	1194	0%	0%	3%
53	1302	0%	0%	0%
54	1349	0%	0%	0%
55	1351	0%	0%	0%
56	1405	0%	0%	0%
57	1405	0%	0%	0%
58	1429	28%	0%	0%
59	1446	1%	0%	0%
60	1515	0%	0%	0%
61	1521	0%	0%	0%
62	1551	1%	0%	0%
63	1649	6%	0%	13%
64	1660	12%	0%	8%

It is assumed that the random vibration events will occur at these fundamental frequencies. The random vibration tests are performed once in each direction, each directional test will excite the corresponding mode shape. It is conservatively assumed that the launch event will excite the direction with the highest frequency.

The RV test durations are listed in LFPS-SPEC-201 requirement LFPS-REQ-059 to be 60 seconds in each direction. The effective RV duration for the CubeSat on SLS launch was determined to be 13 seconds (Lowery Duvall/ER41). Both of these factors are conservatively multiplied by a 4.0 scatter factor. This results in 240 seconds of RV in each direction during test and 52 seconds during launch. Assuming that each event occurs at the fundamental frequencies determined in the modal analysis: 240*(1429 + 909 + 1034) = 809,280 cycles are expected during RV testing and 52*1429 = 74,308 cycles are expected during launch.

These cycles are spread across a Rayleigh distribution based on methods from NASA-TM-X-64669. An upward bound of 3σ is used to align with the assumptions made to develop the RV load factors. The curve is approximated using discretization at midpoints with a 10% interval, as seen in the below figure and table.

Table 6 Rayleigh Distribution Discretization

Rayleigh Approximation		
Max	**Min**	**Cycles**
10%	-10%	4.48%
20%	-20%	12.29%
30%	-30%	17.10%
40%	-40%	18.28%
50%	-50%	16.40%
60%	-60%	12.78%
70%	-70%	8.80%
80%	-80%	5.41%
90%	-90%	2.98%
100%	-100%	1.48%

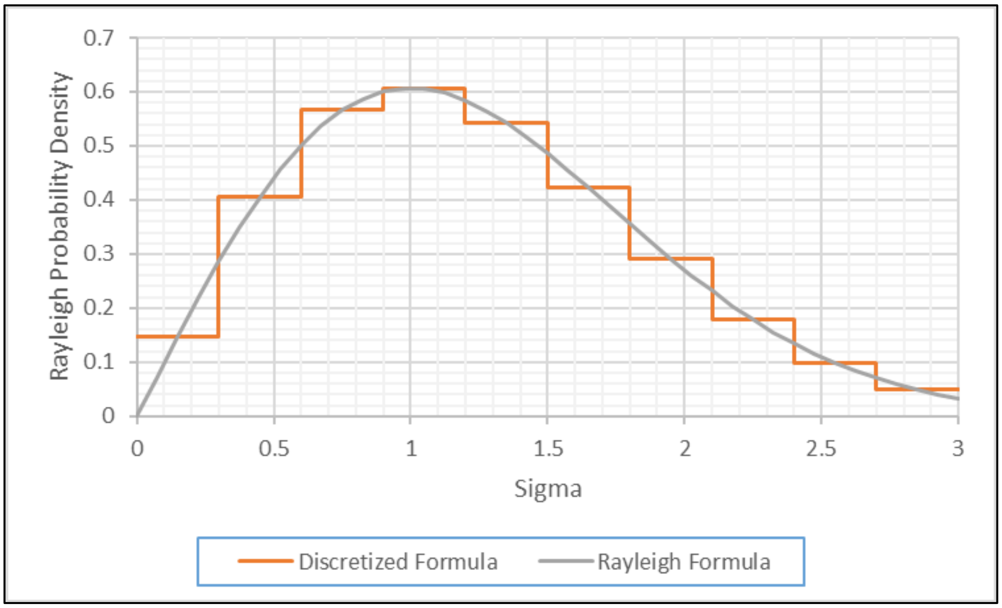


Figure 25 Rayleigh Distribution Discretization

The cycle counts are spread across this distribution for the flight and RV test cycles. The resulting spectra can be seen in the table below.

Table 7 RV Spectra Approximation

Max	Min	Test Cycles	Flight Cycles
10%	-10%	36,256	3,329
20%	-20%	99,461	9,132
30%	-30%	138,387	12,707
40%	-40%	147,936	13,584
50%	-50%	132,722	12,187
60%	-60%	103,426	9,497
70%	-70%	71,217	6,539
80%	-80%	43,782	4,020
90%	-90%	24,117	2,214
100%	-100%	11,977	1,100

6.0 COMPONENT DETAILS

6.1 Tank Top, Tank Bottom, and Tank Weld

The tank is classified as a fracture critical pressure vessel as it contains a hazardous fluid. The tank meets NASA-STD-5019 and AIAA-S-080-1998 requirements by verifying the safe life analysis and testing requirements are met.

6.1.1 Stress Analysis Results

A FEM was used to find the data needed to develop the stress spectra for the NASGRO damage tolerance analysis. The stress model and results are described in detail within the LFPS Structural Analysis Report. The models used are listed below:

1. Inertial model with 1.0x load factor and fluid modeled in the tank. 9 directions are checked to ensure the worst case load direction is assessed.
    - Submodels are used to obtain values at stress concentrations in the tank top/bottom
2. Inertial model with 1.0x load factor and no fluid modeled in the tank. Submodels are not used as the stress concentrations are in artificial sharp corner locations on the tank top/bottom.
3. Pressure model with 1.0x load factor on MDP
    - Submodels are used to obtain values at stress concentrations on the tank top/bottom
    - Submodels are used at three critical locations along the weld. The weld submodel stress results are recorded at the interior and exterior of the weld surface. These locations have been selected to envelope the worst cases. Locations A and B were chosen because they have the highest stresses. Location C was selected because the weld stress field had bending stress acting in the opposite direction from A and B.

Max principle stresses are used in the tank top/bottom and in the weld (pressure model only). Inertial weld stresses are taken at the weld surface by combining the peak tension and shear stresses together using the Von Mises equivalent stress equation:

$$\sigma_{Eq} = \sqrt{\sigma_T^2 + 3 * \tau^2}$$

Stresses in the weld are recorded at the interior and exterior of the weld surface for the pressure load case. Note that some inertial cases used magnitudes that were greater than the expected environments, so these results are scaled down. The stress results shown with load magnitudes of 56.5 g's are scaled down linearly to 32.6 g's. Results and critical stress contours are shown below.

Table 8 Limit Stress Results – Tank Fluid Included

#	Load Case	Load Magnitude (g)	Weld Stress (ksi) (tension, shear, combined)	Tank Stress (ksi)	Weld Stress (adjusted) (ksi)	Tank Stress (adjusted) (ksi)
N/A	Pressure Only	N/A	N/A	51.6	N/A	**51.6**
1	Inertia +/-/+	56.5	3.5, 1.6, 4.5	10.0	**2.6**	5.8
2	Inertia +/+/+	56.5	2.7, 1.1, 3.3	11.8	1.9	**6.8**
3	Inertia +/-/-	56.5	3.1, 1.4, 3.9	8.8	2.3	5.1
4	Inertia +/+/-	56.5	2.4, 0.8, 2.8	10.8	1.6	6.2
5	Inertia +/ /	32.6	1.7, 0.8, 2.2	6.0	2.2	6.0
6	Inertia /+/	32.6	0.9, 0.3, 1.0	4.1	1.0	4.1
7	Inertia / /+	32.6	0.8, 0.3, 1.0	5.4	1.0	5.4
8	Inertia /-/	32.6	1.4, 0.6, 1.7	3.4	1.7	3.4
9	Inertia / /-	32.6	0.4, 0.2, 0.5	6.5	0.5	6.5
N/A	Inertia -/any/any	Assumed to be enveloped by the other inertial cases				

Table 9 Limit Stress Results – Tank Fluid Excluded

#	Load Case	Load Magnitude (g)	Weld Stress (psi) (tension, shear, combined)	Tank Stress (psi)	Weld Stress (adjusted) (psi)	Tank Stress (adjusted) (psi)
1	Inertia +/-/+	56.5	570, 727, 1382	1197	798	691
2	Inertia +/+/+	56.5	608, 754, 1441	1341	831	773
3	Inertia +/-/-	56.5	901, 787, 1634	1824	943	1052
4	Inertia +/+/-	56.5	1034, 780, 1701	1897	982	1094
5	Inertia +/ /	32.6	212, 237, 462	681	462	681
6	Inertia /+/	32.6	667, 576, 1200	1464	**1200**	**1464**
7	Inertia / /+	32.6	108, 188, 343	677	343	677
8	Inertia /-/	32.6	534, 576, 1132	1260	1132	1260
9	Inertia / /-	32.6	363, 188, 488	774	488	774
N/A	Inertia -/any/any	Assumed to be enveloped by the other inertial cases				

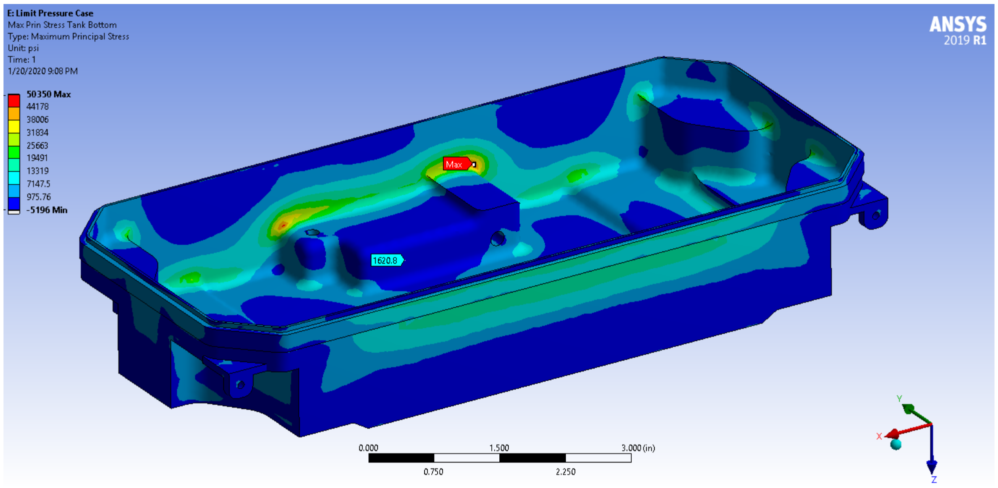


Figure 26 Max Principle Stress Location Due to MDP in Tank Top/Bottom

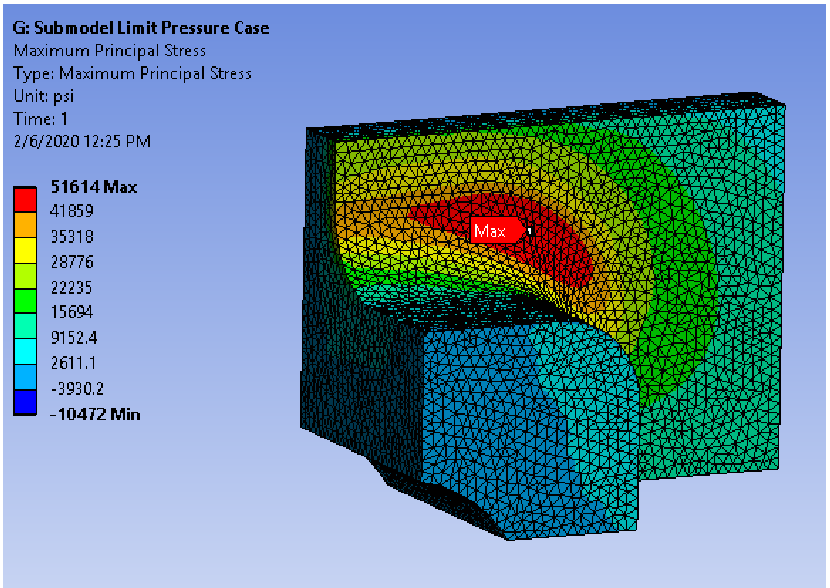


Figure 27 Max Principle Stress Location Due to MDP in Tank Top/Bottom – Submodel

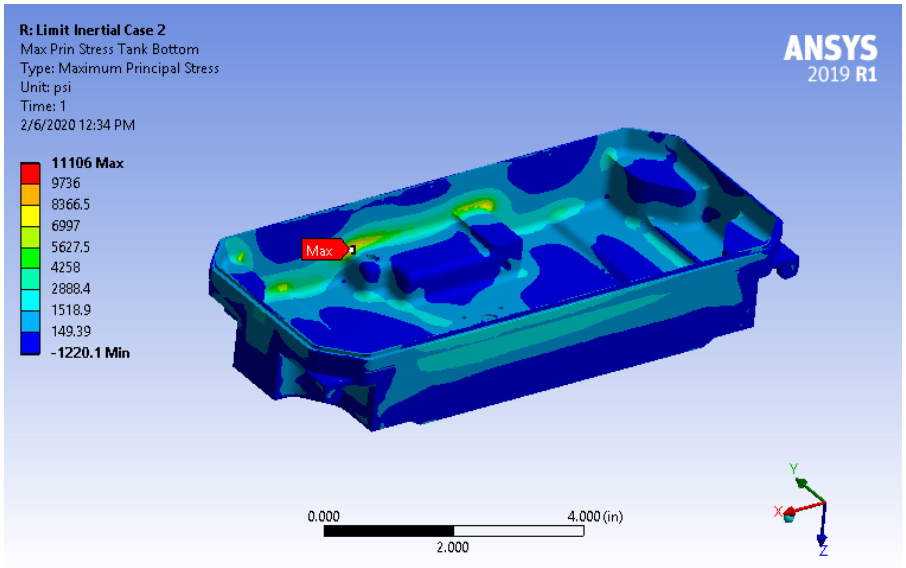


Figure 28 Max Principle Stress Location Due to Inertia (Full Tank) in Tank Top/Bottom (56.5 g Load Factor, Correction Factor: 32.6/56.5)

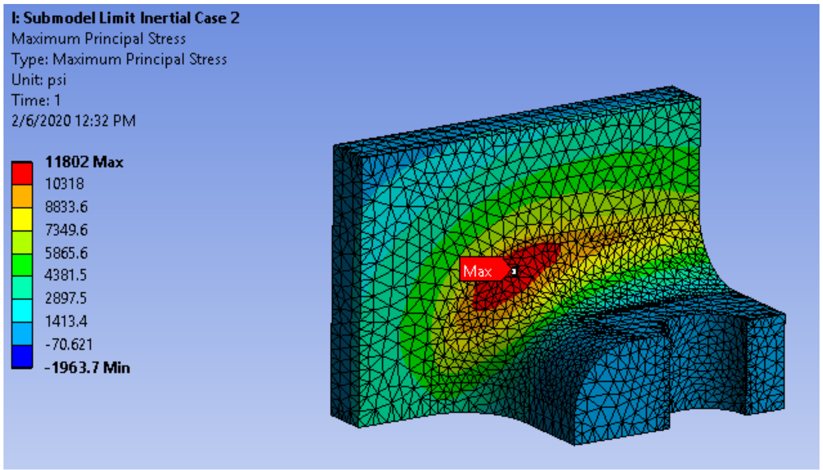


Figure 29 Max Principle Stress Location Due to Inertia (Full Tank) in Tank Top/Bottom – Submodel (56.5 g Load Factor, Correction Factor: 32.6/56.5)

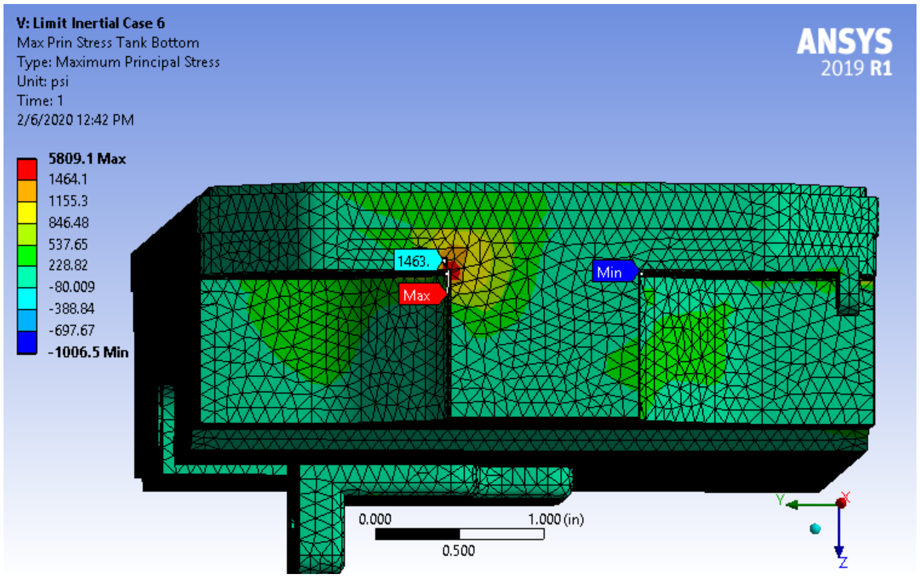


Figure 30 Max Principle Stress Location Due to Inertia (Empty Tank) in Tank Top/Bottom (32.6 g Load Factor)

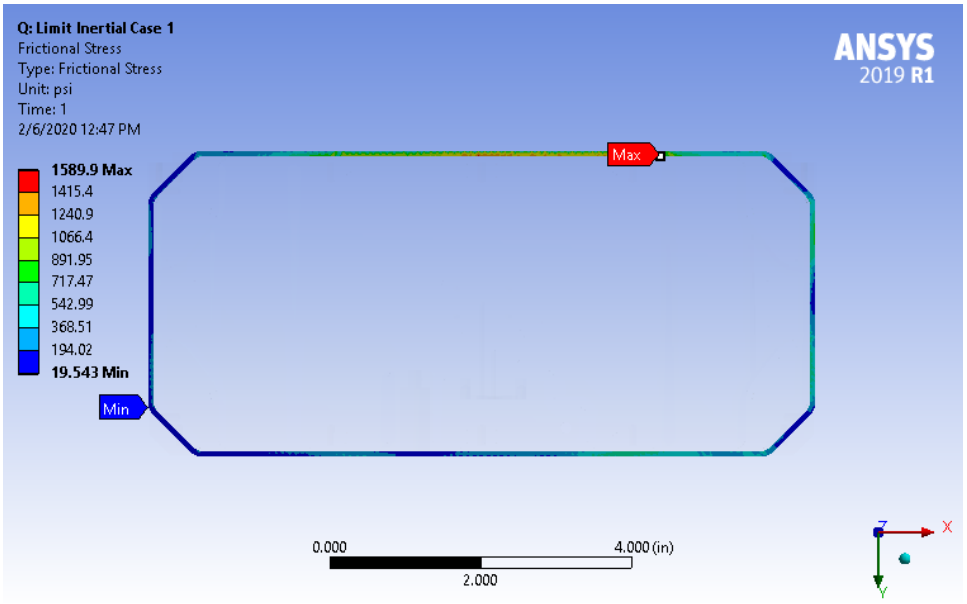


Figure 31 Maximum Shear Stress Due to Inertia (Full Tank) in Weld (56.5 g Load Factor, Correction Factor: 32.6/56.5)

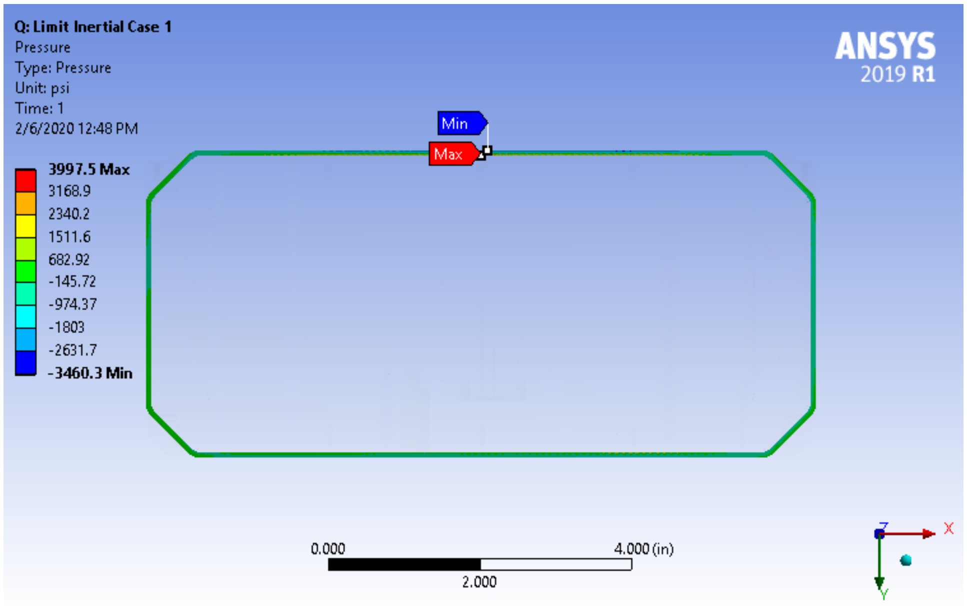


Figure 32 Maximum Tensile Stress Due to Inertia (Full Tank) in Weld (56.5 g Load Factor, Correction Factor: 32.6/56.5)

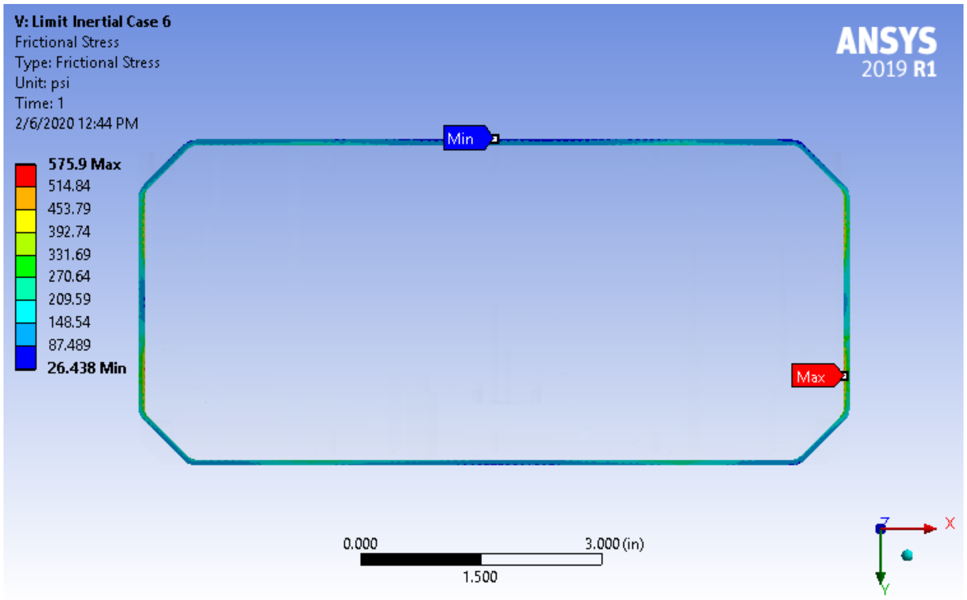


Figure 33 Maximum Shear Stress Due to Inertia (Empty Tank) in Weld (32.6 g Load Factor)

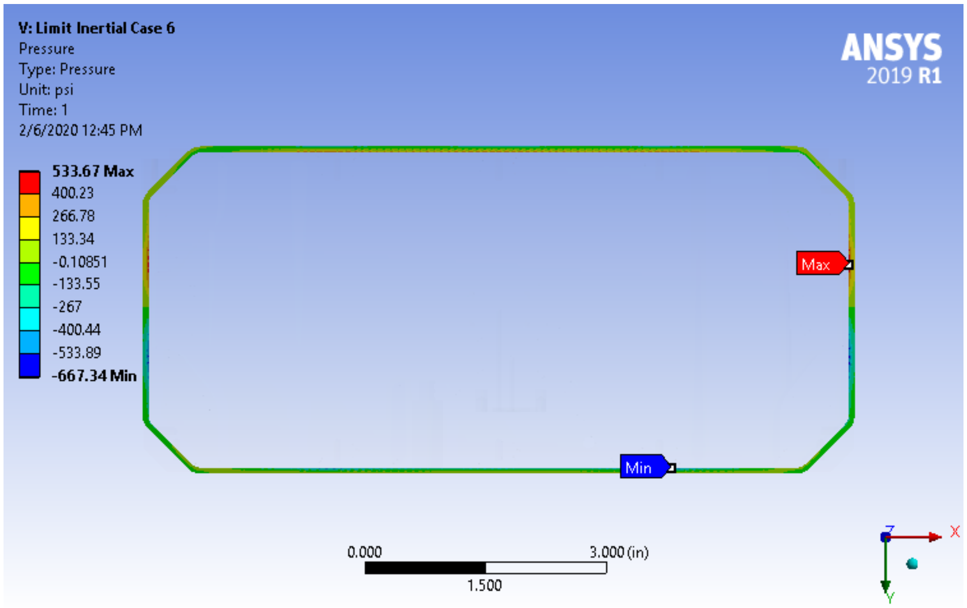


Figure 34 Maximum Tensile Stress Due to Inertia (Empty Tank) in Weld (32.6 g Load Factor)

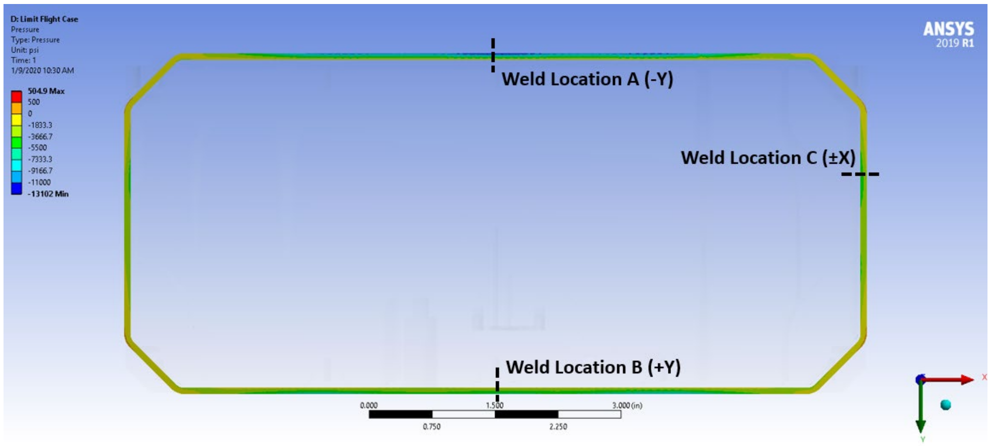


Figure 35 Weld Submodel Locations

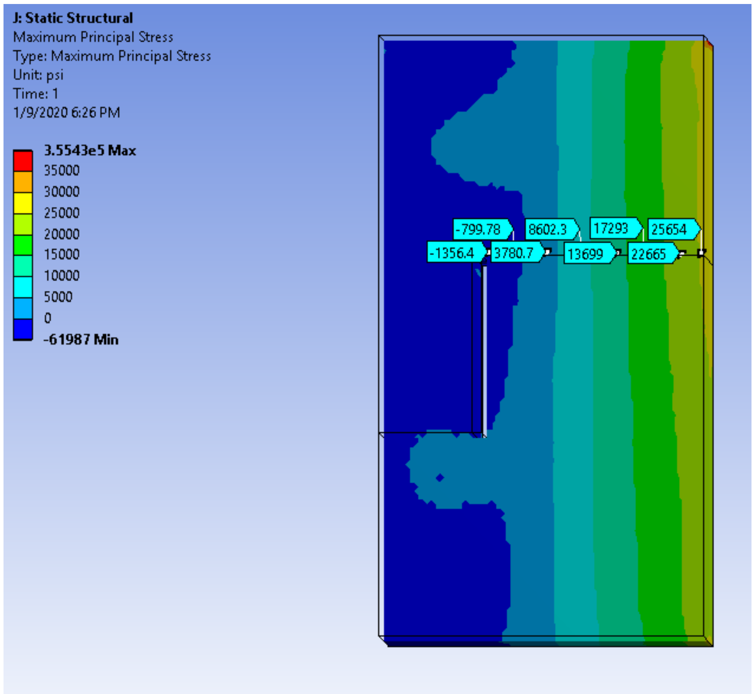


Figure 36 Maximum Principle Stress Due to MDP at Weld Location A (-Y)

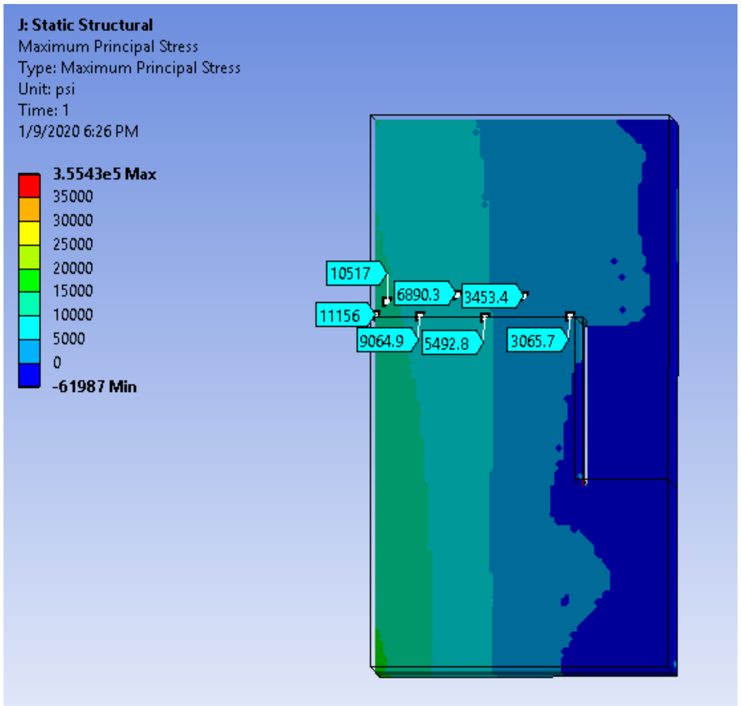


Figure 37 Maximum Principle Stress Due to MDP at Weld Location B (+Y)

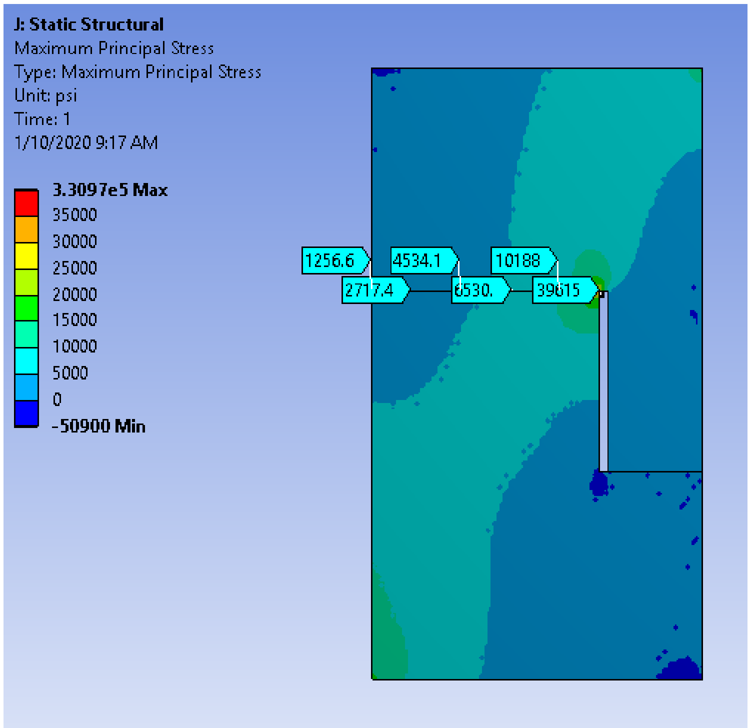


Figure 38 Maximum Principle Stress Due to MDP at Weld Location C (±X)

6.1.2 Stress Assumptions

The tank top/bottom stresses are combined within NASGRO SC30 analyses assuming they are split evenly between S0 and S1. This is reasonable as all peak stress locations on the interior of the tank have compressive max principle stresses on the exterior. The assumed stress fields from interior to exterior (or vice versa) are conservative as the peak stresses are nonlinear concentrations but are assumed to be linear. The idealized stresses are listed in the table below, showing the split between S0 (tension in NASGRO) and S1 (bending in NASGRO).

Table 10 Tank Top/Bottom Stress Results

Inertia Stress (Empty Tank)		Inertia Stress (Full Tank)		MDP Stress	
S0 (ksi)	S1 (ksi)	S0 (ksi)	S1 (ksi)	S0 (ksi)	S1 (ksi)
0.7	0.7	3.4	3.4	25.8	25.8

The tank weld stresses are modeled differently. Inertial stresses are assumed to be pure tension using peak values across the entire weld. The stresses due to pressure are modeled at three locations, with a linear distribution from interior to exterior. The idealized stresses are listed in the table below, showing the split between S0 (tension in NASGRO) and S1 (bending in NASGRO).

Table 11 Tank Weld Stress Results

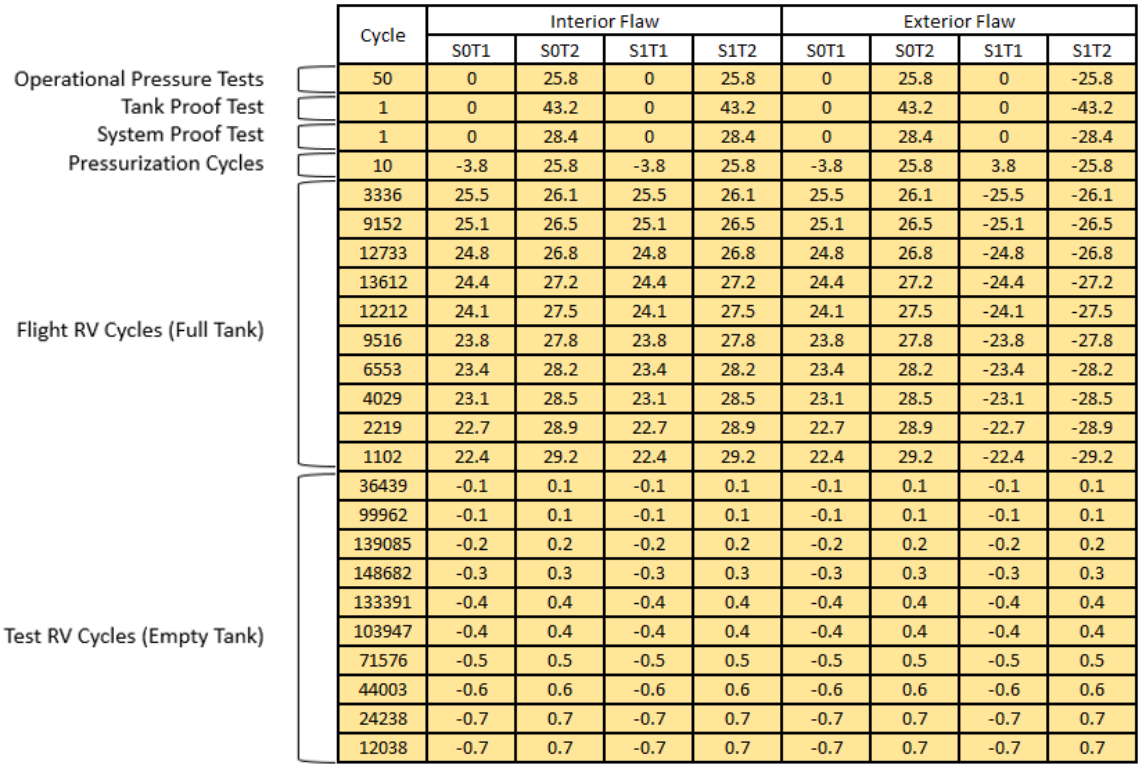
Location	Inertia Stress (Empty Tank)		Inertia Stress (Full Tank)		MDP Stress	
	S0 (ksi)	S1 (ksi)	S0 (ksi)	S1 (ksi)	S0 (ksi)	S1 (ksi)
Weld A	1.2	0	2.6	0	12.2	13.6
Weld B	1.2	0	2.6	0	7.2	4.1
Weld C	1.2	0	2.6	0	5.7	-4.4

6.1.3 Load Combinations

RV test cycles have a mean stress of 0 because they are unpressurized. Flight RV cycles use MDP results as the mean stress. Pressure events (proof tests, pressure tests, and pressurization cycles) are assumed to occur without inertial loads. It's important to note that the pressurization cycles have a vacuum pulled on the tank prior to propellant loading, seen in the following tables as a non-zero initial state. The proof pressure test includes factors on top of MDP: 1.5x according to system requirements (LFPS-SPEC-201), 1.06 environmental correction factor (corresponding to the tank Ftu ECF) as required by NASA-STD-5019, and an inadvertent 1.05 factor (conservative). Note that cases are run for flaws on the both the interior and exterior of the tank. This is done by reversing the bending stresses (S1 in NASGRO).

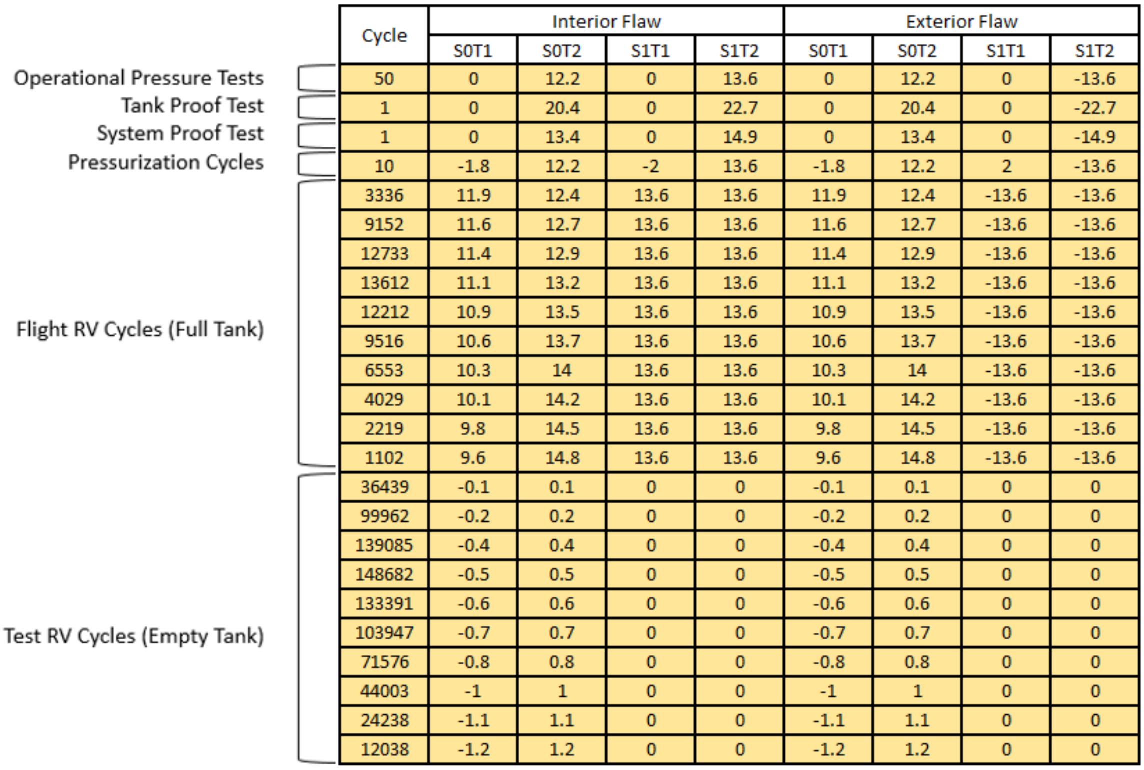
The combined stresses, cycles, and events can be seen in the following tables. These are used as direct inputs into NASGRO using longblock files.

Table 12 NASGRO Longblock Data – Tank Top/Bottom Interior/Exterior Flaw



	Cycle	Interior Flaw				Exterior Flaw			
		S0T1	S0T2	S1T1	S1T2	S0T1	S0T2	S1T1	S1T2
Operational Pressure Tests	50	0	25.8	0	25.8	0	25.8	0	-25.8
Tank Proof Test	1	0	43.2	0	43.2	0	43.2	0	-43.2
System Proof Test	1	0	28.4	0	28.4	0	28.4	0	-28.4
Pressurization Cycles	10	-3.8	25.8	-3.8	25.8	-3.8	25.8	3.8	-25.8
Flight RV Cycles (Full Tank)	3336	25.5	26.1	25.5	26.1	25.5	26.1	-25.5	-26.1
	9152	25.1	26.5	25.1	26.5	25.1	26.5	-25.1	-26.5
	12733	24.8	26.8	24.8	26.8	24.8	26.8	-24.8	-26.8
	13612	24.4	27.2	24.4	27.2	24.4	27.2	-24.4	-27.2
	12212	24.1	27.5	24.1	27.5	24.1	27.5	-24.1	-27.5
	9516	23.8	27.8	23.8	27.8	23.8	27.8	-23.8	-27.8
	6553	23.4	28.2	23.4	28.2	23.4	28.2	-23.4	-28.2
	4029	23.1	28.5	23.1	28.5	23.1	28.5	-23.1	-28.5
	2219	22.7	28.9	22.7	28.9	22.7	28.9	-22.7	-28.9
	1102	22.4	29.2	22.4	29.2	22.4	29.2	-22.4	-29.2
Test RV Cycles (Empty Tank)	36439	-0.1	0.1	-0.1	0.1	-0.1	0.1	-0.1	0.1
	99962	-0.1	0.1	-0.1	0.1	-0.1	0.1	-0.1	0.1
	139085	-0.2	0.2	-0.2	0.2	-0.2	0.2	-0.2	0.2
	148682	-0.3	0.3	-0.3	0.3	-0.3	0.3	-0.3	0.3
	133391	-0.4	0.4	-0.4	0.4	-0.4	0.4	-0.4	0.4
	103947	-0.4	0.4	-0.4	0.4	-0.4	0.4	-0.4	0.4
	71576	-0.5	0.5	-0.5	0.5	-0.5	0.5	-0.5	0.5
	44003	-0.6	0.6	-0.6	0.6	-0.6	0.6	-0.6	0.6
	24238	-0.7	0.7	-0.7	0.7	-0.7	0.7	-0.7	0.7
	12038	-0.7	0.7	-0.7	0.7	-0.7	0.7	-0.7	0.7

Table 13 NASGRO Longblock Data – Tank Weld – Location A (-Y) Interior/Exterior Flaw



	Cycle	Interior Flaw				Exterior Flaw			
		S0T1	S0T2	S1T1	S1T2	S0T1	S0T2	S1T1	S1T2
Operational Pressure Tests	50	0	12.2	0	13.6	0	12.2	0	-13.6
Tank Proof Test	1	0	20.4	0	22.7	0	20.4	0	-22.7
System Proof Test	1	0	13.4	0	14.9	0	13.4	0	-14.9
Pressurization Cycles	10	-1.8	12.2	-2	13.6	-1.8	12.2	2	-13.6
Flight RV Cycles (Full Tank)	3336	11.9	12.4	13.6	13.6	11.9	12.4	-13.6	-13.6
	9152	11.6	12.7	13.6	13.6	11.6	12.7	-13.6	-13.6
	12733	11.4	12.9	13.6	13.6	11.4	12.9	-13.6	-13.6
	13612	11.1	13.2	13.6	13.6	11.1	13.2	-13.6	-13.6
	12212	10.9	13.5	13.6	13.6	10.9	13.5	-13.6	-13.6
	9516	10.6	13.7	13.6	13.6	10.6	13.7	-13.6	-13.6
	6553	10.3	14	13.6	13.6	10.3	14	-13.6	-13.6
	4029	10.1	14.2	13.6	13.6	10.1	14.2	-13.6	-13.6
	2219	9.8	14.5	13.6	13.6	9.8	14.5	-13.6	-13.6
	1102	9.6	14.8	13.6	13.6	9.6	14.8	-13.6	-13.6
Test RV Cycles (Empty Tank)	36439	-0.1	0.1	0	0	-0.1	0.1	0	0
	99962	-0.2	0.2	0	0	-0.2	0.2	0	0
	139085	-0.4	0.4	0	0	-0.4	0.4	0	0
	148682	-0.5	0.5	0	0	-0.5	0.5	0	0
	133391	-0.6	0.6	0	0	-0.6	0.6	0	0
	103947	-0.7	0.7	0	0	-0.7	0.7	0	0
	71576	-0.8	0.8	0	0	-0.8	0.8	0	0
	44003	-1	1	0	0	-1	1	0	0
	24238	-1.1	1.1	0	0	-1.1	1.1	0	0
	12038	-1.2	1.2	0	0	-1.2	1.2	0	0

Table 14 NASGRO Longblock Data – Tank Weld – Location B (+Y) Interior/Exterior Flaw

	Cycle	Interior Flaw				Exterior Flaw			
		S0T1	S0T2	S1T1	S1T2	S0T1	S0T2	S1T1	S1T2
Operational Pressure Tests	50	0	7.2	0	4.1	0	7.2	0	-4.1
Tank Proof Test	1	0	12	0	6.8	0	12	0	-6.8
System Proof Test	1	0	7.9	0	4.5	0	7.9	0	-4.5
Pressurization Cycles	10	-1.1	7.2	-0.6	4.1	-1.1	7.2	0.6	-4.1
Flight RV Cycles (Full Tank)	3336	6.9	7.4	4.1	4.1	6.9	7.4	-4.1	-4.1
	9152	6.6	7.7	4.1	4.1	6.6	7.7	-4.1	-4.1
	12733	6.4	7.9	4.1	4.1	6.4	7.9	-4.1	-4.1
	13612	6.1	8.2	4.1	4.1	6.1	8.2	-4.1	-4.1
	12212	5.9	8.5	4.1	4.1	5.9	8.5	-4.1	-4.1
	9516	5.6	8.7	4.1	4.1	5.6	8.7	-4.1	-4.1
	6553	5.3	9	4.1	4.1	5.3	9	-4.1	-4.1
	4029	5.1	9.2	4.1	4.1	5.1	9.2	-4.1	-4.1
	2219	4.8	9.5	4.1	4.1	4.8	9.5	-4.1	-4.1
	1102	4.6	9.8	4.1	4.1	4.6	9.8	-4.1	-4.1
Test RV Cycles (Empty Tank)	36439	-0.1	0.1	0	0	-0.1	0.1	0	0
	99962	-0.2	0.2	0	0	-0.2	0.2	0	0
	139085	-0.4	0.4	0	0	-0.4	0.4	0	0
	148682	-0.5	0.5	0	0	-0.5	0.5	0	0
	133391	-0.6	0.6	0	0	-0.6	0.6	0	0
	103947	-0.7	0.7	0	0	-0.7	0.7	0	0
	71576	-0.8	0.8	0	0	-0.8	0.8	0	0
	44003	-1	1	0	0	-1	1	0	0
	24238	-1.1	1.1	0	0	-1.1	1.1	0	0
	12038	-1.2	1.2	0	0	-1.2	1.2	0	0

Table 15 NASGRO Longblock Data – Tank Weld – Location C (±X) Interior/Exterior Flaw

	Cycle	Interior Flaw				Exterior Flaw			
		S0T1	S0T2	S1T1	S1T2	S0T1	S0T2	S1T1	S1T2
Operational Pressure Tests	50	0	5.7	0	-4.4	0	5.7	0	4.4
Tank Proof Test	1	0	9.5	0	-7.3	0	9.5	0	7.3
System Proof Test	1	0	6.2	0	-4.8	0	6.2	0	4.8
Pressurization Cycles	10	-0.8	5.7	0.6	-4.4	-0.8	5.7	-0.6	4.4
Flight RV Cycles (Full Tank)	3336	5.4	5.9	-4.4	-4.4	5.4	5.9	4.4	4.4
	9152	5.1	6.2	-4.4	-4.4	5.1	6.2	4.4	4.4
	12733	4.9	6.4	-4.4	-4.4	4.9	6.4	4.4	4.4
	13612	4.6	6.7	-4.4	-4.4	4.6	6.7	4.4	4.4
	12212	4.4	7	-4.4	-4.4	4.4	7	4.4	4.4
	9516	4.1	7.2	-4.4	-4.4	4.1	7.2	4.4	4.4
	6553	3.8	7.5	-4.4	-4.4	3.8	7.5	4.4	4.4
	4029	3.6	7.7	-4.4	-4.4	3.6	7.7	4.4	4.4
	2219	3.3	8	-4.4	-4.4	3.3	8	4.4	4.4
	1102	3.1	8.3	-4.4	-4.4	3.1	8.3	4.4	4.4
Test RV Cycles (Empty Tank)	36439	-0.1	0.1	0	0	-0.1	0.1	0	0
	99962	-0.2	0.2	0	0	-0.2	0.2	0	0
	139085	-0.4	0.4	0	0	-0.4	0.4	0	0
	148682	-0.5	0.5	0	0	-0.5	0.5	0	0
	133391	-0.6	0.6	0	0	-0.6	0.6	0	0
	103947	-0.7	0.7	0	0	-0.7	0.7	0	0
	71576	-0.8	0.8	0	0	-0.8	0.8	0	0
	44003	-1	1	0	0	-1	1	0	0
	24238	-1.1	1.1	0	0	-1.1	1.1	0	0
	12038	-1.2	1.2	0	0	-1.2	1.2	0	0

6.1.4 Tank Top/Bottom Safe-Life / Damage Tolerance Analysis

A safe life analysis was carried out in NASGRO to check that sufficient life exists with worst case loads, flaw, materials, dimensions, and environments. The material properties used in this analysis can be seen in §4.1. The mission and associated spectra used in the DT analysis are described in §5.0 and are combined with stresses in §6.1.3. The flaw sizes and cross sections used in the NASGRO analyses are described in §3.3.1 and §3.3.3. The flaws are assumed to be surface cracks using NASGRO SC30 formulation.

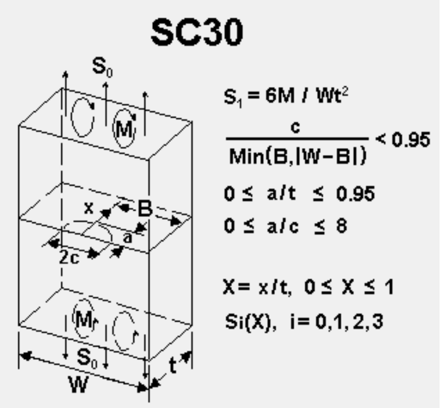


Figure 39 NASGRO SC30 Formulation

Failure criteria include unstable crack growth, net section failure, and surface cracks transitioning to through cracks (fluid leakage is unacceptable). Four lives are required by NASA-STD-5019 and AIAA S-080-1998. The tank top and bottom have sufficient life, with a minimum prediction of 20 lives before failure. The NASGRO analyses are summarized in the table below.

Table 16 NASGRO Results – Tank Top/Bottom

	Initiated on Interior	Initiated on Exterior
Deep Flaw a=0.075” a/c=1	23 lives completed	20 lives completed
Shallow Flaw a=0.025” a/c=0.2	>100 lives completed	36 lives completed

6.1.5 Tank Weld Alternative Approach / Safe-Life / Damage Tolerance Analysis

The tank weld is classified as a fracture critical as it contains a hazardous fluid. The weld meets NASA-STD-5019 and AIAA-S-080-1998 requirements through an alternative approach.

Alternative Approach Justification:

- Due to tank weld geometry, radiographic inspection of the propellant tank weld joint will not be performed. In lieu of this inspection, the following activities will be performed:

    - A damage tolerance analysis will be performed to demonstrate that the weld is capable of withstanding significant damage. This analysis will show that failure doesn’t occur using a starting flaw size that exceeds 90% of the thickness.
    - Qualification unit will undergo burst testing to verify maximum design pressure.
    - Pre- and post-weld coupons will be cross-sectioned to verify weld process. Coupons will also be inspected via radiography and surface dye penetrant.
    - Post-weld dye penetrant inspection of tank and weld.
    - Proof test performed to 1.5X MDP.
    - Post-proof dye penetrant inspection of tank and weld.
    - Leak test at next higher assembly level

A safe-life analysis was carried out in NASGRO to check that the weld is capable of withstanding significant damage. The analysis assumes worst case loads, flaw, materials, dimensions, and environments. The material properties used in this analysis can be seen in §4.1. The mission and associated spectra used in the DT analysis are described in §5.0 and are combined with stresses in §6.1.3. The flaw sizes and cross sections used in the NASGRO analyses are described in §3.3.2 and §3.3.3. The flaws are assumed to be surface cracks with 90% depth using NASGRO SC30 formulation.

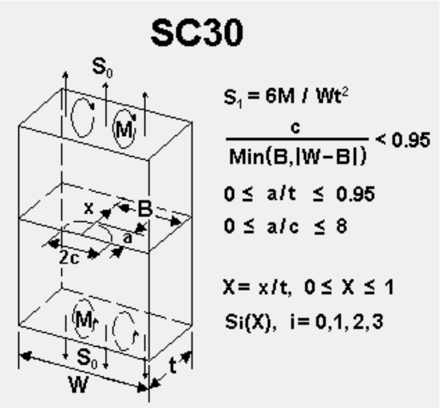


Figure 40 NASGRO SC30 Formulation

Failure criteria include unstable crack growth, net section failure, and surface cracks transitioning to through cracks (fluid leakage is unacceptable). Four lives are required by NASA-STD-5019 and AIAA S-080-1998. The critical flaw size hasn't been reached after 4 lives for those originating on the weld exterior and interior, so there is sufficient life. The NASGRO analyses are summarized in the table below.

Table 17 NASGRO Results – Tank Weld Life

Flaw Shape	Flaw Location	Weld Location A	Weld Location B	Weld Location C
Deep Flaw a=0.0603" a/c=1	Interior Flaw	>100 lives completed	>100 lives completed	>100 lives completed
	Exterior Flaw	>100 lives completed	>100 lives completed	>100 lives completed
Wide Flaw a=0.0603" a/c=0.2	Interior Flaw	5 lives completed	6 lives completed	7 lives completed
	Exterior Flaw	5 lives completed	6 lives completed	7 lives completed

6.2 Isolation Valve

The isolation valve is classified as a fracture critical pressurized component as it contains a hazardous fluid. The valve meets NASA-STD-5019 and AIAA-S-080-1998 requirements through an alternative approach.

Alternative Approach Justification:

- Due to the isolation valve geometry, radiographic inspection of the weld joint will not be performed. In lieu of this inspection, the following activities will be performed:
    - Qualification unit will undergo burst testing to verify maximum design pressure.
    - Pre- and post-weld coupons will be cross-sectioned to verify weld process.
    - Pre-proof pressure testing dye penetrant inspection of weld joint.
    - Proof test performed at 1.5x MDP
    - Post-proof dye penetrant inspection of weld.
    - Component-level leak test.

6.3 Isolation Valve Mounting Plate

The isolation valve mounting plate is classified as "NFC-Fail Safe" as it contains a hazardous fluid, but can withstand a single failure without creating a hazard. The plate meets NASA-STD-5019 and AIAA-S-080-1998 requirements by verifying the remaining damaged system meets strength, life, and functional (leak) requirements.

6.3.1 Finite Element Model

The finite element model used and described in the memo ER41 (20-005) was used to develop the failsafe case. Two changes were made to the model:

- The mounting plate is assumed to fail along the section shown in the figure below. This simulates a failure along the highest stressed/loaded section, which meets NASA-STD-5019 requirements for fail safety.
- The bolts are preloaded differently from the nominal model to account for the new geometry and are preloaded by adjusting length instead of by prescribing a load. The original model (described in the LFPS Structural Analysis Report Rev. A) was interrogated and the average bolt lengths at the end of the preload step were used in this analysis. The overall effect should be acceptable and will properly imitate a preload prior to failing the mounting plate.

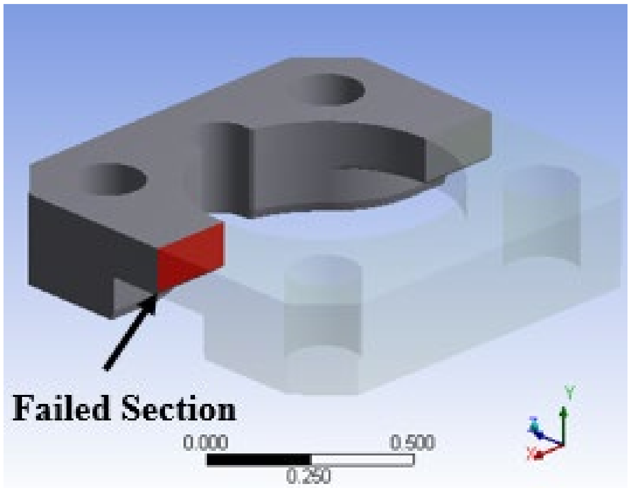


Figure 41 Isolation Valve Mounting Plate Failsafe Plate Condition

6.3.2 Static Strength Assessment

The static strength assessment of the damaged mounting plate is discussed in the ER41 Structural Analysis Report Rev. A. The critical strength margin is +0.23 for the failsafe condition.

6.3.3 Fastener Check

The fasteners are assessed for strength and life in the failsafe condition in the ER41 Structural Analysis Report Rev. A. The minimum margin of safety is +0.00 due to fastener yield failure.

6.3.4 Fatigue Check

The fatigue checks performed as part of the LFPS Structural Analysis Report Rev. A account for the failsafe load case described in this analysis. The fatigue analysis described in that memo confirms that the fasteners and the plate have sufficient life (>4 lives).

6.3.5 Seal Check

The resulting seal gap underneath the isolation valve is $4.7*10^{-5}$ inches and can be seen in the figure below. There is no hard allowable associated with this valve design, but this value was determined to be acceptable per ER14 on 1/27/2020, see §6.3.5.1.

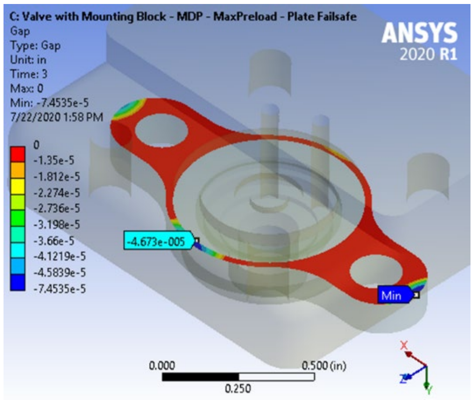


Figure 42 Isolation Valve Seal Performance Following Mounting Plate Failure

6.3.5.1 Seal Performance Email from MSFC ER14

From: Addona, Brad M. (MSFC-ER14) <brad.m.addona@nasa.gov>
Sent: Monday, January 27, 2020 1:21 PM
To: Dyment, Samuel R. (MSFC-ER41) <samuel.r.dyment@nasa.gov>
Subject: RE: Micro Valve Allowable Gap

There isn't a hard limit. That number is very small and seems just fine.

Brad

From: Dyment, Samuel R. (MSFC-ER41) <samuel.r.dyment@nasa.gov>
Sent: Saturday, January 25, 2020 2:37 PM
To: Addona, Brad M. (MSFC-ER14) <brad.m.addona@nasa.gov>
Subject: Micro Valve Allowable Gap

Hey Brad,

What's the acceptable gap for the isolation valve? I'm seeing 1.3 x 10-4 inches as a maximum during a failsafe condition and am wondering if that's acceptable.

Thanks,

Sam Dyment
ER41
Work: 256-544-6462

6.4 Isolation Valve Mounting Plate Fasteners

The isolation valve mounting plate fasteners are classified as "NFC-Fail Safe" as they contain a hazardous fluid, but can withstand a single failure without creating a hazard. The fasteners meet NASA-STD-5019 and AIAA-S-080-1998 requirements by verifying the remaining damaged system meets strength, life, and functional (leak) requirements.

6.4.1 Finite Element Model

The finite element model used and described in the ER41 Structural Analysis Report Rev. A was used to develop the failsafe case. The nominal model was only changed to remove the highest loaded bolt, which is shown in the figure below:

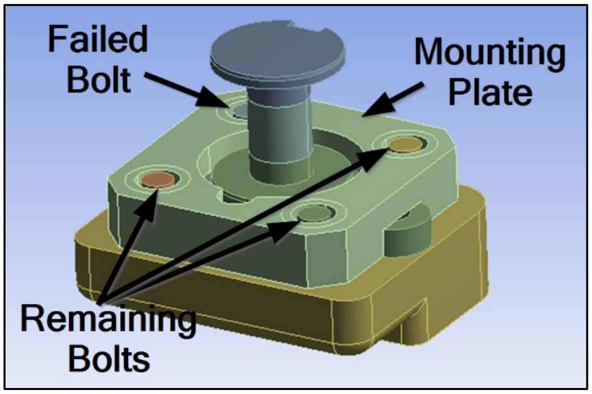


Figure 43 Isolation Valve Mounting Plate Failsafe Bolt Condition

6.4.2 Static Strength Assessment

The static strength assessment of the damaged mounting plate is discussed in the ER41 Structural Analysis Report Rev. A. The critical strength margin is +0.23 for the failsafe condition.

6.4.3 Fastener Check

The fasteners are assessed for strength and life in the failsafe condition in the ER41 Structural Analysis Report Rev. A.. The minimum margin of safety is +0.00 due to fastener yield failure.

6.4.4 Fatigue Check

The fatigue checks performed as part of the LFPS Structural Analysis Report account for the failsafe load case described in this analysis. The fatigue analysis described in that memo confirms that the fasteners and the plate have sufficient life (>4 lives).

6.4.5 Seal Check

The resulting seal gap underneath the isolation valve is $8.4*10^{-5}$ inches and can be seen in the figure below. There is no hard allowable associated with this valve design, but this value was determined to be acceptable per ER14 on 1/27/2020, see §6.3.5.1.

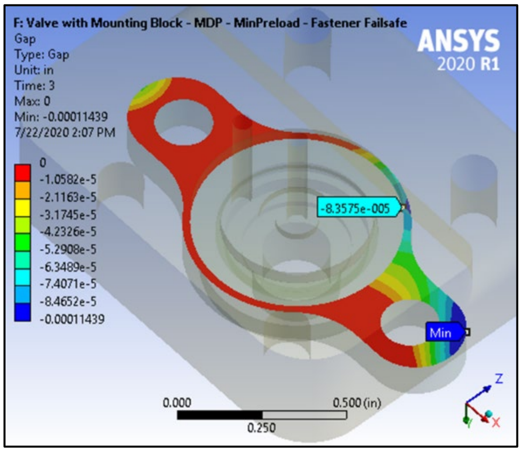


Figure 44 Isolation Valve Seal Performance Following Bolt Failure

6.5 Service Valve

The service valve is classified as a fracture critical pressurized component as it contains a hazardous fluid. The valve meets NASA-STD-5019 and AIAA-S-080-1998 requirements through an alternative approach.

Alternative Approach Justification:

- Due to its size and the risk of contamination, the service valve will forego dye penetrant inspection of its single circumferential weld. In order to alleviate concerns with bypassing this inspection, the following activities will be performed during qualification and acceptance:
    - Valve design employs high factors of safety on system maximum expected operating pressure (>6X MEOP, see ER41 Memorandum (18-028)).
    - Qualification unit will undergo burst testing to verify maximum design pressure.
    - Pre- and post-weld coupons will be cross-sectioned to verify weld process.
    - Leak test performed at component level.
    - Proof test performed after installation into system.
    - Leak test performed after system-level proof testing.
    - Service valve cap, once installed, will keep weld in compression.

6.6 Pressure Transducer

The pressure transducer is classified as a fracture critical pressurized component as it contains a hazardous fluid. The transducer meets NASA-STD-5019 and AIAA-S-080-1998 requirements through an alternative approach.

Alternative Approach Justification:

- Due to its size and the risk of contamination, the transducer will forgo flaw inspection and analysis. In order to alleviate concerns with bypassing this inspection, the following activities will be performed during qualification and acceptance:
  - Transducer design employs high factors of safety on system maximum design pressure (components are rated to 3X LFPS MDP for proof and 7.5x LFPS MDP for burst (TE Connectivity part number is TE XP5-X-150PA-/V05/L3M/Z02)).
  - 1.1X LFPS MDP Proof test performed after installation into system.
  - Leak check performed after system-level proof testing.

6.7 NFC – Contained Components

All other LFPS components that are not explicitly described above or as "Exempt" are considered "NFC-Contained". These components do not pose a hazard to SLS because they are isolated from the hazardous fluid and are contained by the CubeSat launcher. These components are listed below:

- Manifold
- Muffin tin
- Controller
- Pump
- Pump interface block
- Propellant management device (PMD)
- Thrusters
- Thruster valves
- Seals
- All fasteners other than those on the isolation valve

6.8 Exempt Components

The controller and all cables on the LFPS are considered exempt.

7.0 ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Definition
α	Coefficient of thermal expansion
§	Section
a	Surface crack depth
AIAA	American Institute of Aeronautics and Astronautics
AM	Additively manufactured
AMS	Aerospace material specification
ANSYS	Engineering simulation and 3D design software
AMCP	Additive Manufacturing Control Plan
ASMH	Aerospace Structural Metals Handbook
c	Surface half crack width
CAD	Computer aided design
COTS	Commercial off the shelf
CRES	Corrosion resistant steel
DMLS	Direct metal laser sintering
DT	Damage tolerance
E	Young’s Modulus
EB	Electron Beam
ECF	Environmental Correction Factor
ER11	MSFC Spacecraft and Vehicle Propulsion Branch
ER14	MSFC Valves, Actuators, Ducts Design & Development Branch
ER41	MSFC Propulsion Structures and Design Branch
F	Fahrenheit
FC	Fracture Critical
FCB	Fracture Control Board
FCP	Fracture Control Plan
FEM	Finite element model
FSU	Ultimate factor of safety
FSY	Yield factor of safety
F_{tu}	Tensile ultimate stress
F_{ty}	Tensile yield stress
GD&T	Geometric dimensioning and tolerancing
GT	Georgia Institute of Technology
HDBK	Handbook
in	Inches

Acronym / Abbreviation	Definition
ksi	Thousand pounds-force per square inch
lbf	Pounds-force
LC	Load case
LFPS	Lunar Flashlight Propulsion System
MDP	Maximum Design Pressure
Memo	Memorandum
MEOP	Maximum expected operating pressure
MMPDS	Metallic Materials Properties Development and Standardization
MS	Margin of safety
MSFC	Marshall Space Flight Center
MUA	Material Usage Agreement
NASA	National Aeronautics and Space Administration
NASGRO	NASA Crack Growth Computer Program
NDE	Non-destructive evaluation
NDY	Non-detrimental yielding
NFC	Non-fracture critical
PMD	Propellant management device
psi	Pounds-force per square inch
Rev.	Revision
RV	Random vibration
S-N	Stress-life curve
S0	Tensile stress in NASGRO SC30
S1	Bending stress in NASGRO SC30
S_{Alt}	Alternating stress
SC30	Surface crack formulation in NASGRO
SLS	Space Launch System
STA	Solution Treated and Aged
Ult.	Ultimate
Yld.	Yield