

Advanced Material Options for the *Portable Life Support System (PLSS)*

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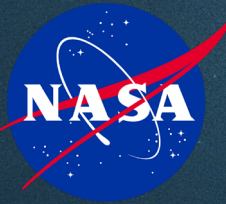
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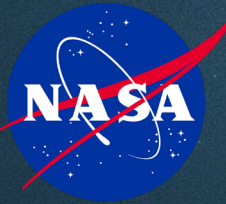
Introduction



- The Government Reference Design for the Exploration Extravehicular Mobility Unit (xEMU) Portable Life Support System (PLSS) has challenging mass requirements to meet
- Titanium selected as primary metal for the backplate and thermal loop, although galvanic compatibility concerns add design complexities
- Lunar Artemis and potential future Mars missions make mass a more critical driver going forward
 - Mars will more than double the apparent gravity compared to the Moon.
 - Insertion mass cost to orbit can also be a large driver
- This will outline a potential roadmap for lowering the weight of the PLSS with material considerations alone
 - Includes preliminary testing and feasibility studies done focusing on thermoplastics and Additive Manufacturing (AM) (I.E., 3D printing)



Considerations



- **Strength and Mechanical Properties**

- Key starting property – this factor alone will likely lead to using aluminum or titanium, although manufacturing considerations and compatibility may not make them the best choice

- **Service Life**

- Next generation PLSS has a 15-year operating life
- May drive use of protective features like coatings

- **Galvanic Compatibility**

- Electrical potential between two metals not recommended above 0.25Volts
- Coatings may be required otherwise

- **Thermal Properties and Heat Dissipation**

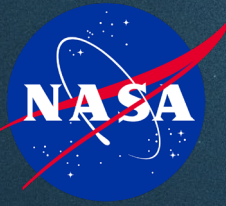
- Some materials may be exposed to the extreme hot and cold of space
- For components (e.g. avionics) that produce heat, the box must be able to expel the heat

- **Electromagnetic Interference (EMI) and Grounding**

- 1ohm grounding requirement between all components in the PLSS
- Galvanic compatibility coatings may run counter requiring special considerations



Considerations – Continued



- **On-destination Maintainability**

- Removability of key systems is required, forgoing the possibility for permanent bonding methods

- **Oxygen Compatibility**

- Suit operates at 100% oxygen including a 3000psia supply, and 4.3psia vent loop
- Each material must be scrutinized for flammability at high oxygen concentration
 - Apollo 1, EMU 1980 Fire

- **Water Compatibility**

- For thermal loop components, components must minimize water absorption to avoid unintended failures due to expansion or material performance degradation
- Depending on the biocide used (silver/iodine) materials selected must be compatible

- **Off-gassing**

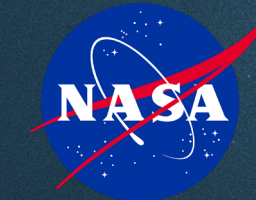
- Materials in the vent loop or inside the suit volume must be assessed for odors and chemical off gassing at suit pressure to ensure there is nothing that may affect the crewmember over suit life

- **Vacuum Outgassing**

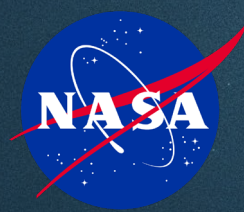
- Components exposed to vacuum may release volatiles, affecting performance of the material and could deposit on other sensitive equipment
- Max 1% total mass and 0.1% collectable condensable material



EMU Material History



- EMU has been operating over 40 years and seen many material failures to learn from – some key examples:
 - **1980 EMU fire**
 - Oxygen Compatibility – Changed regulator from aluminum to Monel
 - **Coated aluminum vent loop flaking during service and corroding**
 - Service Life/Galvanic Compatibility – Replaced with stainless steel (SS) where possible
 - **Pressure gauge aluminum corrosion**
 - Service Life/Galvanic Compatibility – Replaced with SS
 - **Corrosion in aluminum and SS water loop**
 - Service Life/Galvanic Compatibility – Replaced with Nitronic 60
 - **Neoprene water bladder leak and leaching**
 - Service Life/Water Compatibility – Replaced with Flourel
 - **Rotor seize due to epoxy expansion from water loop**
 - Water Compatibility – Replaced with a weld



State of the Art (xEMU xPLSS)

- The xEMU exploration PLSS (xPLSS) primarily used metals for most components
- **Aluminum** was selected for most components because it is light and easy to manufacture
 - Also acceptable for low-pressure oxygen applications in the vent loop
- **Titanium** was selected for the thermal loop because of its high strength and compatibility with iodine biocide
 - Material for structural backplate with embedded water channels
 - Incompatible and unsafe for contact with pure oxygen
- **Monel** was selected for the high pressure oxygen recharge loop for oxygen compatibility
- **Inconel** was selected for materials interacting with both vent and thermal loop for compatibility

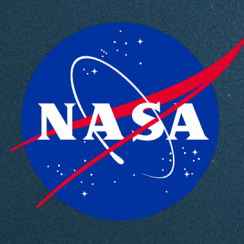
Materials used in the xEMU

* = materials with galvanic compatibility pair

Material	Strength/ Density Ratio (ksi/(lb/in ³))	Density (lb/in ³)	Ultimate Tensile Strength (ksi)
Aluminum 6061-T6	429	0.098	42
Aluminum 7075-T73	713	0.101	68
Titanium 6Al-4V*	969	0.160	155
316 Stainless*	255	0.286	73
Inconel 625*	390	0.305	119
Inconel 718*	606	0.297	180
Monel K500*	295	0.305	90
Monel 400*	235	0.318	75
Hastelloy*	354	0.297	105



xEMU Space Suit

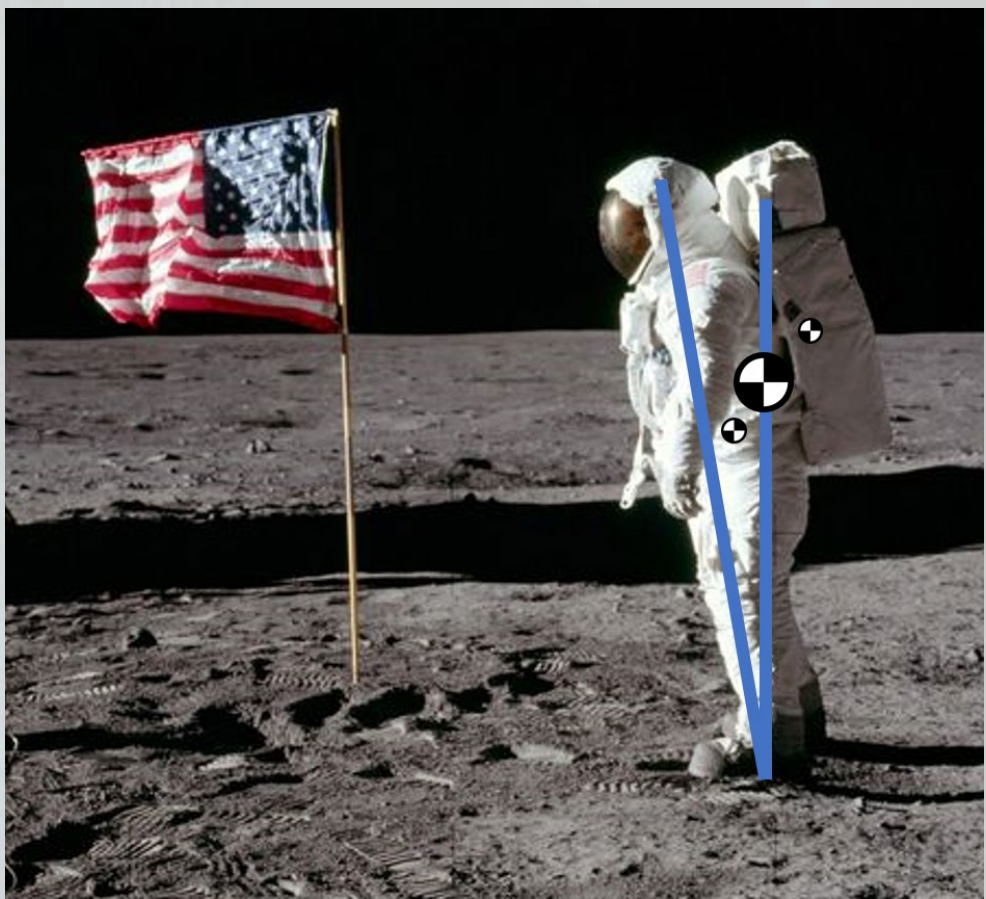


xEMU Weight Breakdown

- Weight of xEMU: **334lbs (151 kg)**
 - xPLSS: **215lbs (98 kg)**
 - Pressure Garment System (PGS): **119lbs (54 kg)**
- Relative Weight
 - Assumes 180lb (82kg) crewmember
 - Earth: **514lbs (233 kg)**
 - Moon: **85lbs (39 kg)***
 - Mars: **194lb (89 kg)***
- Mars missions would require weight reduction to stand and work well. Long duration microgravity may lead to crew strength degradation, even with exercise
- Center of gravity is pulled upwards and towards the back, requiring a hunched over position to balance

xEMU Mass Breakdown

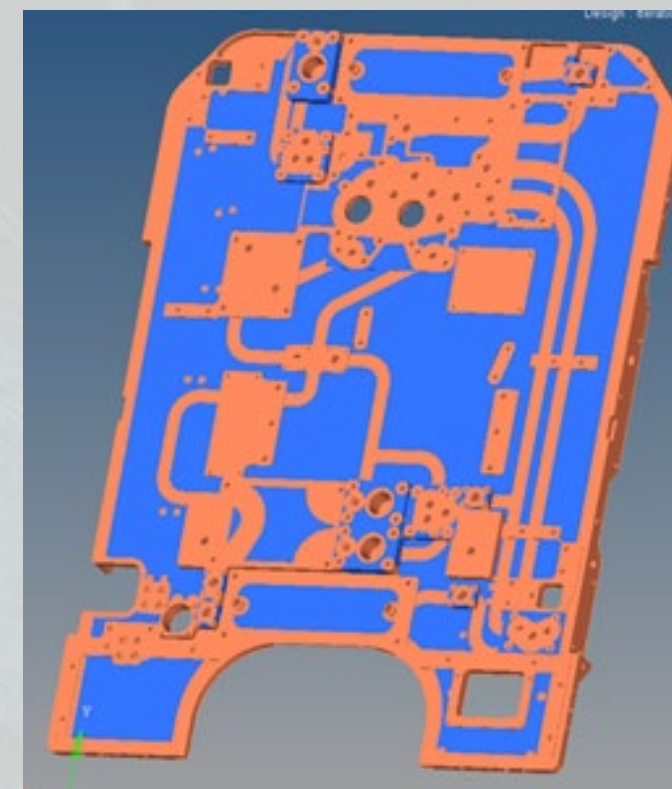
Category	Weight lb (kg)
Backplate	46.9 (21.2)
Cover	23.2 (10.5)
Oxygen Supply	29.2 (12.2)
Vent Loop	26.3 (11.9)
Thermal Loop	14.4 (6.5)
Avionics	32.6 (14.8)
Sensor	11.4 (5.2)
Power	28.0 (12.7)



Center of gravity balance - Apollo

*Kg would be same as a measure of mass – estimate assumes earth relative difference

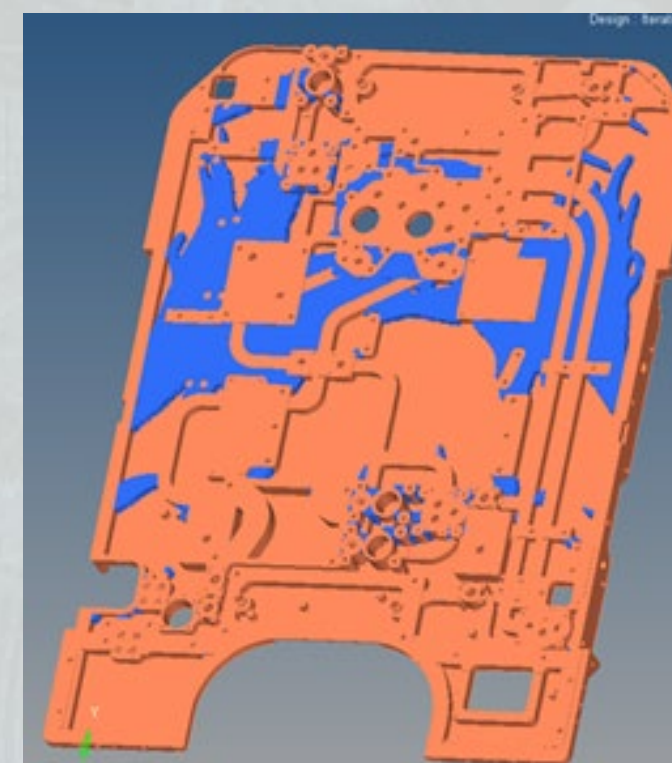
- Mass optimization: removes material in un-needed locations
 - Drawback: time intensive for design, analysis and machining
 - Generative design method: start with key functional elements only and add material back/between elements to meet stress margins
 - xEMU used this method on the backplate as shown
- New additive methods for metals
 - Powder Based Fusion (PBF) processes:
 - Direct Metal Laser Sintering (DMLS) or Electron Beam Melting (EBM)
 - Direct Energy Deposition (DED) deposits metal onto stock material
 - All processes require post-print machining operations to achieve required surface finishes, tolerances, etc
 - Can combine parts into one monolithic part optimizing volume, overall part count, and weight
 - Complex fluid paths can be embedded within component, eliminating fittings, cross-drilled



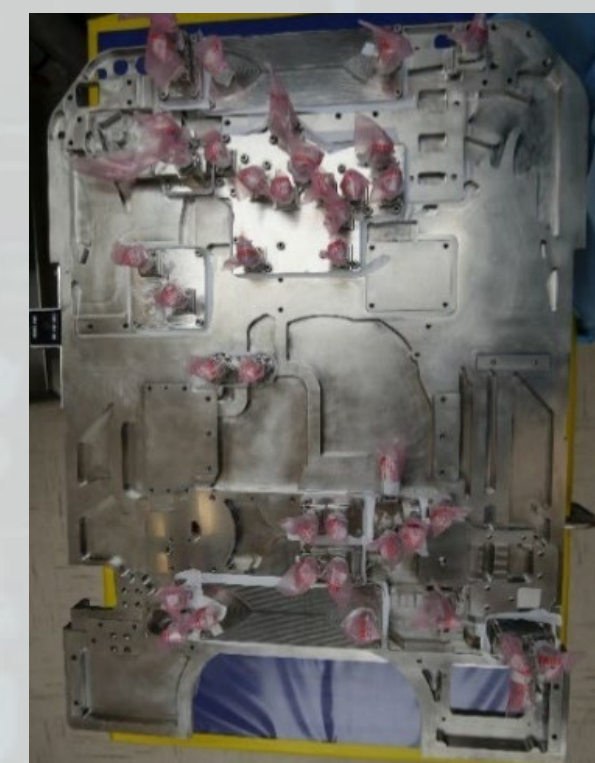
Initial Topology



Before Machining



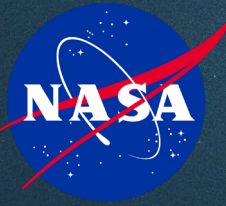
Optimal Topology



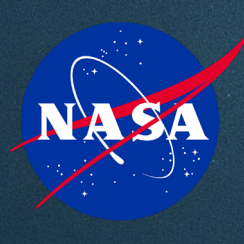
After Machining + Cleaning



Plastics



- Machined Plastics
 - For machined metals, extra mass may be caused by machine tool limitations, tolerances, or wall thickness, leading to thicker sections with high stress margins
 - Many plastics may be substituted to reduce weight by half or more
 - Ultem and Peek each with 30% glass fill (GF) have some of the highest strengths in thermoplastics and meet outgassing requirements ideal for non-structural replacements
- Additive Manufactured (AM) Plastics
 - Similar to AM metals, they offer complex geometry options and reduced complexity in assemblies
 - Ultem 9085 is one of the strongest Fused Deposition Modeling (FDM) based AM plastics
 - Windform is a newer Selective Laser Sintering (SLS) material that is water impermeable and stronger, with good off gassing properties
- Considerations:
 - Plating and insert install methods need to be evaluated and standardized
 - NASA views current plastic AM processes as relatively immature and difficult to fully inspect. This lack of guaranteed reliability limits their use to non-critical applications
 - Industry-wide improvements to processes and inspection, as well as wider use, will help advance state of the art



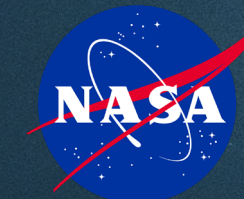
Advanced Material Options

Material	Material Category	Process	Strength/ Density Ratio (ksi/(lb/in ³))	Density (lb/in ³)	Ultimate Tensile Strength (ksi)
Titanium 6Al-4V	Metal	Machine	969	0.160	155
EOS Titanium Ti64	Metal	PBF	956	0.160	153
Aluminum 7075-T73	Metal	Machine	713	0.101	68
EOS Aluminum AlSi10Mg	Metal	PBF	673	0.098	66
PEEK 30% GF	Plastic	Machine	581	0.0520	30
Ultem 2300 30% GF	Plastic	Machine	449	0.0544	24.4
Aluminum 6061-T651	Metal	Machine	429	0.0980	42
Ultem 1000 Black	Plastic	Machine	332	0.0458	15.2
Windform XT 2.0	Plastic	SLS	307	0.0394	12.1
Windform SP	Plastic	SLS	274	0.0400	11.0
Polycarbonate 20% GF	Plastic	Machine	268	0.0487	13.1
PEEK	Plastic	Machine	261	0.0470	12.3
Vespel SP-1	Plastic	Machine	242	0.0517	12.5
Ultem 9085	Plastic	FDM	180	0.0483	8.6
Teflon (PTFE)	Plastic	Machine	46	0.078	3.6

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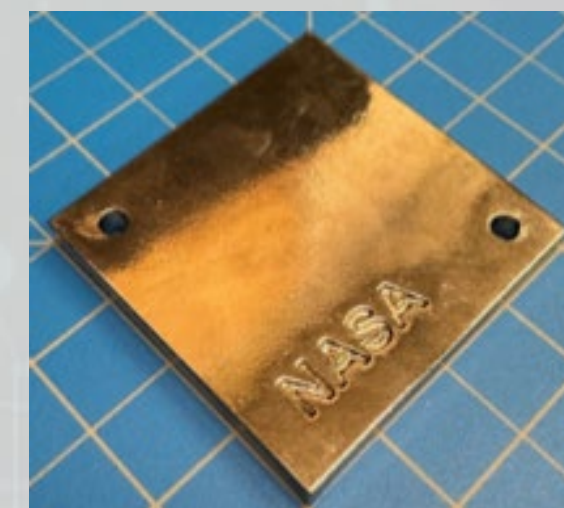
Plastics Plating



- Plating originally done on metals for corrosion prevention
 - Plating plastics can improve thermal conduction heat transfer, EMI, and strength
- Electroless methods are used to plate plastics because electroplating requires conduction
- For electroless nickel, an underlayer of copper is often used for adhesion before applying the top nickel surface
 - Thickness ranges from 0.001" – 0.005" (0.0254 - 0.127 mm)
- Thermal vias could be added to facilitate thermal conduction through the material
- Windform SP (AM plastic) was selected to test a several different vendor plating process; there are wide ranges in results still being evaluated



Windform SP Un-plated



Plated – Company A



Plated – Company B

Inserts testing with more testing words

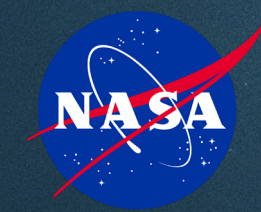
- Metallic inserts are required to add strength to a bolted joint to increase pull out strength
 - Typically made from brass, though SS are available and used here
- Developing a method and procedure for installing inserts in plastic
 - Varying installation force, temperatures, hole geometry, and surrounding thickness
- Preliminary Results:
 - Installation temperature and thickness do not affect results if the insert is installed fully
 - Windform SP:
 - Helical insert pull out strength: 366lb (12lb std. dev.)
 - Note: Manufacturer recommended geometry in this material causes beading over - requiring sanding before usage
 - Heat insert pull out strength: 348lb (23lb std. dev.)
 - Ultem 2300:
 - Heat inserts: Failed installation at hottest temp. (800F, 426C)
 - Helical insert pull out strength: 746lb (22lb std. dev.)



Windform SP Inserts – Before Sanding

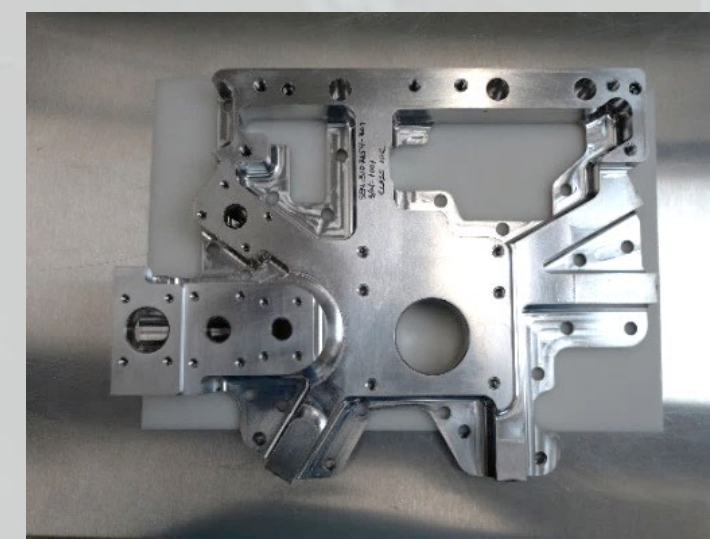


Windform SP Inserts – After Sanding

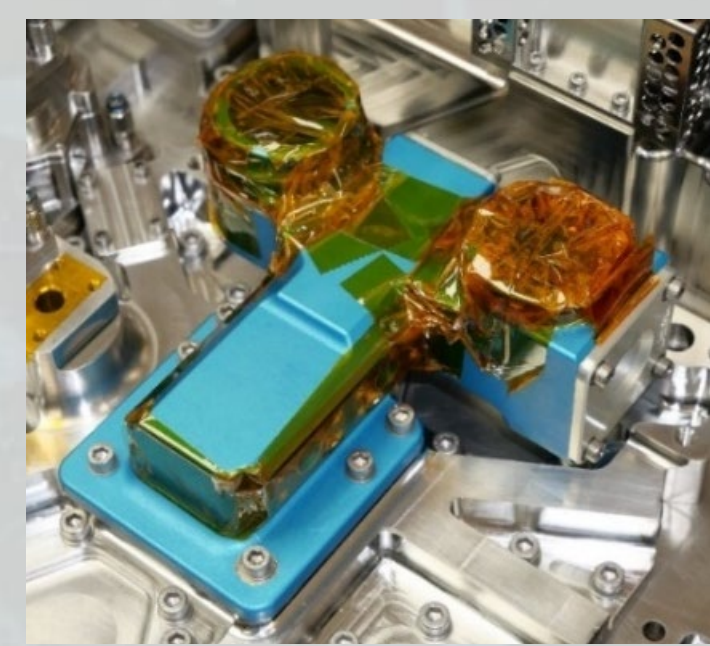


Candidates for Weight Reduction

- Several PLSS components are ready candidates for mass reduction with alternate materials and processes - some examples below:
 - Looking at all similar components, weight reduction could be around 35 lbs for replacing materials alone
- **Interface Pad Weldment (Inconel 625)**
 - Handles vent and thermal loop, Inconel could be replaced with an AM plastic, reducing weight from 6.2 lbs to 1.0 lbs
- **Fan Inlet Manifold (Al 7075)**
 - Aluminum could be replaced with an AM plastic, reducing weight from 1.4 lbs to 0.6 lbs
- **Avionics Boxes (Al 6061)**
 - Aluminum could be replaced with a plated machinable thermoplastic to reduce weight from 2.0 lbs to 1.1 lbs



Interface Pad Weldment



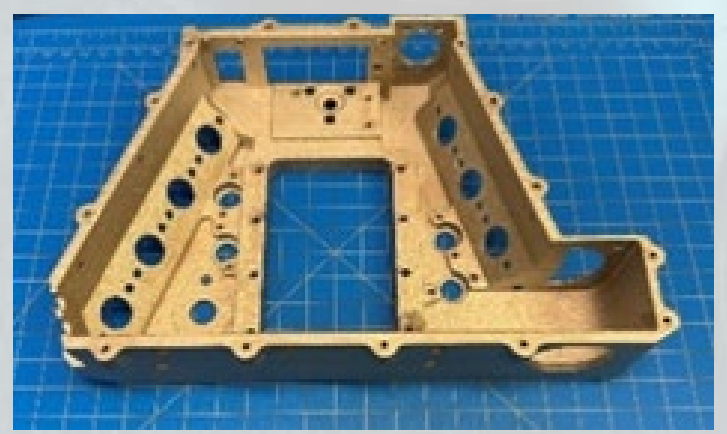
Fan Inlet Manifold



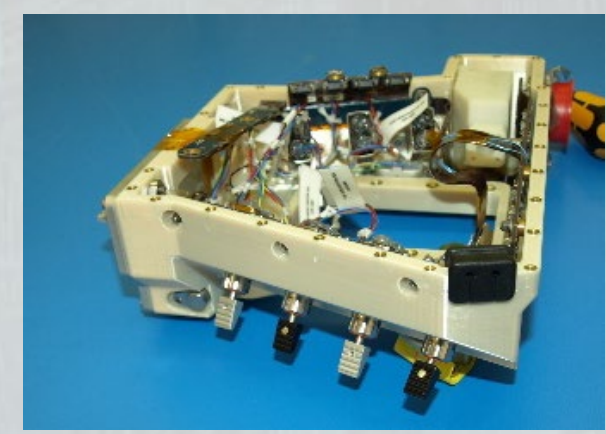
Aluminum 6061



Windform SP



Windform SP – Electroless Nickel Plate

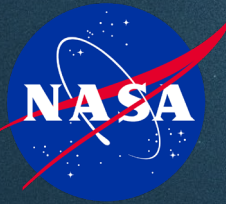


Ultem 9085

Display and Control Unit (DCU)

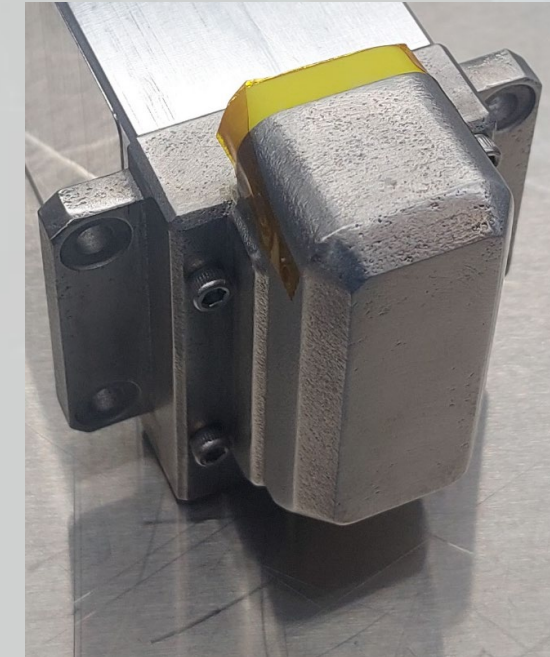
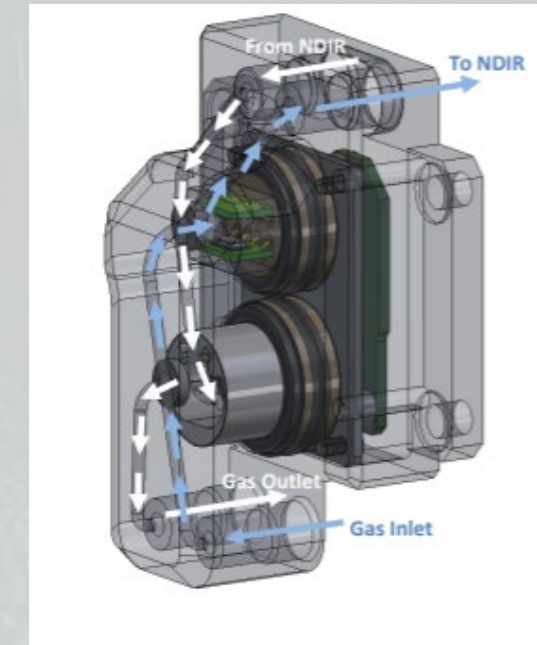


Future Work - Plastics

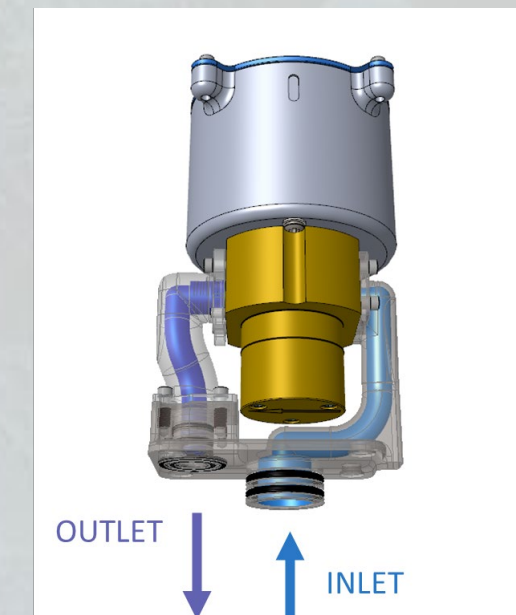


- Advanced Methods and Properties to Explore
 - Plating vendors and options
 - Insert installation methods
 - Thermal vias for heat transfer
 - Compatibility tests for degradation, leach, corrosion, offgas, etc.
- Material Testing Options
 - Gather all data on new advanced materials
 - Determine necessary data for each application
 - Fill in data gaps of testing using ASTM/NASA standards
- Specialized Testing
 - Specific application tests which do not fall under ASTM/NASA standards may need to be explored for plating, inserts, heat transfer, creep, compression set, cold flow, EMI, and radiation

- Metal AM reduces overall part count and can optimize fluid paths
 - Designs can be further tailored for mass reduction
- Increase design and integration experience
 - Pilot projects following NASA-STD-6030 for implementation in flight or human integrated testing hardware
 - Use as alternative for prototyping high-complexity machined parts
 - Implement in developmental and lab hardware
- Establish common practices for post-print operations
 - Machining and fixturing best practices
 - Internal surface finish improvements (i.e. electropolish, extrude hone, etc.)



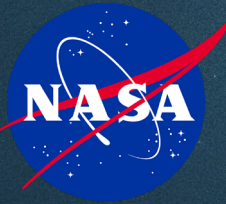
Gas Sensor Manifold



SERFE Pump with AM Inlet/Outlet



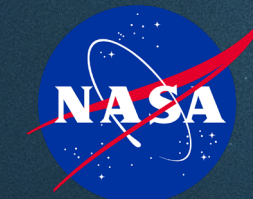
Conclusion



- Space suit weight is becoming an increasingly key factor for human exploration to the Moon, Mars, and beyond
- Advanced AM or machinable thermoplastics may need to be considered
 - Despite lower strength-to-density properties, they may still meet stress margins where materials were originally chosen for compatibility or other considerations over strength
- Further testing of these materials and processes will be required
 - These tests will provide designers and stress engineers the necessary values to use before using in their designs
 - Plating and insert installation may be key processes to explore on thermoplastics before adoption
 - With more maturity these should be able to be adopted in flight cases and eventually into critical applications
- There are many existing components on the xEMU xPLSS which could be modified to use these advanced materials, reducing weight by around 35 lbs



Thank You!



Questions?

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