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Advanced Material Options for the Portable Life Support System

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Meeting an aggressive mass requirement is a challenge for new space suit development efforts, including that of the Exploration Extravehicular Mobility Unit Portable Life Support System (PLSS) government reference design. To reduce overall system mass, titanium was selected as the primary metal for the PLSS backplate and thermal loop. However, galvanically compatible metals (Hastelloy, Inconel, Monel) have relatively high densities and require further design complexities such as coatings and more challenging manufacturing. Efforts to reduce the mass of the government reference design for an International Space Station (ISS) or lunar mission were halted due to the government's transition to a commercial Extravehicular Activity (EVA) services approach, but research was conducted into methodologies for mass savings using advanced materials. With the advent of a lunar Artemis mission and potential for future Mars missions, mass becomes a more critical driver going forward. Therefore, alternative materials and processes must be considered to fully close the mass requirement. There are many new materials and processes that can be considered; however, considerations must be made to ensure galvanic compatibility, radiation concerns for sensitive electronics, vacuum compatibility, tight tolerances, fluid compatibility with oxygen and water, and thread insert options. Individual PLSS components may have different requirements and need to be considered separately for reducing overall mass. This report will touch on comparisons between advanced materials, focusing on composites, additive manufacturing, and plastics. It will also address the different processes that may need to be applied when using these materials in the harsh environment of space. Lastly, it will look at specific components and make recommendations for options to reduce the mass of each one.

Nomenclature

AM = Additive Manufacturing
DCU = Display and Control Unit
DED = Direct Energy Deposition
DMLS = Direct Metal Laser Sintering
DVT = Design Verification and Test
EBM = Electron Beam Melting
EMI = Electromagnetic Interference
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
FDM = Fused Deposition Modeling
FOD = Foreign Object Debris
GF = Glass filled
lb/in^3 = Pounds per cubic inch (density)
O_2 = Oxygen

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ORU = On-Orbit Replacement Units
PEEK = Polyetheretherketone
PLSS = Portable Life Support System
PGS = Pressure Garment System
SLS = Selective Laser Sintering
SOP = Secondary Oxygen Pack
xPLSS = Exploration Portable Life Support System (next generation)
xEMU = Exploration Extravehicular Mobility Unit (next generation)

I. Introduction

When designing a space suit, several main driving requirements are: Extravehicular Activity (EVA) time, two-fault tolerance (safety), and mass. In the current design space, mass is mostly driven by cost to orbit and to the Moon; however, looking at Mars' higher gravity, this requirement becomes more important so astronauts can still traverse on the surface. Furthermore, with constraints to budget and the increased commercialization of space, cost to orbit may become a higher driving factor. Therefore, the mass of the suit becomes increasingly important. To decrease mass, alternative materials may be considered instead of trading other requirements. In this case, many emerging materials and processes may be considered as replacements for heritage materials that have been driving up mass for decades. However, it is important to consider the implications of these materials and ensure they are still compatible in each location. Therefore, studies must be conducted to weigh each material and process option for each location and ideally settle on a handful of recommended replacements for different systems and structures. This paper lays out a roadmap for considering new materials, including some preliminary testing completed to guide the development and adoption of new materials and processes for the space suits.

II. Considerations

The following are key general requirements that drive the materials selection for space suits.

A. Strength and Mechanical Properties

Strength and mechanical properties are typically the first set of properties to consider for material selection. The density and tensile strength are key, driving many spaceflight materials to either be aluminum (Al) or titanium. This is only a start; there are many cases in which lower-density and lighter materials can easily be used. There can be cases in which aluminum or titanium may be incompatible or unmachinable. Furthermore, special coatings may be required to avoid corrosion or to correct for other inadequacies. It is important to consider each part separately to choose the best material for the job.

B. Service Life

As an exploration suit, the Portable Life Support System (PLSS) must be able to operate over extended periods, with significant lengths of storage in between missions. The next generation PLSS is designed for a 15-year operating life, with up to two or three years of quiescent storage between EVAs to account for mission tempo.[1] Both of these requirements mandate materials that are not only individually acceptable for long-term storage, but for long-term storage in contact with dissimilar materials in the presence of electrolytes such as the thermal loop's water.

Similarly, robustness of design is paramount to extensive maintenance or repair capability which may have limited availability at lunar or low earth orbit destinations. This drives selections of materials and protective features (like coatings) that will not deteriorate or require replacement during the relatively long service life.

C. Galvanic Compatibility

Dissimilar metals in contact in the presence of an electrolyte (such as ambient humidity or wetted materials in a water loop) will corrode. In general, it is best practice to avoid pairing two metals if the electrical potential between them exceeds 0.25 Volts.[2]

In situations where two dissimilar metals must be in contact and their electrical potential is too high, measures must be taken to prevent the anodic material from corroding. These can include permanent solutions at the interface, such as primers, adhesives, or pastes; separable solutions, such as gaskets or shims; or permanent coatings applied to the anodic material. Aluminum, while an extremely common material, is typically the anodic member of a galvanic pair. Typically, anodizing the material is used to protect the material, but coatings are susceptible to failure over time. Other protective solutions include chemical conversion coating (also known as Alodine) or electroless nickel plating. Conversion coating offers negligible corrosion protection on its own and is generally preferred as a primer before applying other coatings.[3] Where possible, a permanent sealant, such as Koropon, is preferred at the joint between two dissimilar metals, but this prevents component removal and maintenance.

D. Thermal Properties & Heat Dissipation

A second key factor considers the thermal environment in which the material will be used. Some may be exposed directly to space and extreme hot and cold temperatures, while others may be kept within a more controlled environment. It is important to review thermal ranges of the material and ensure they fall within the environment ranges.

In cases where items produce heat, it is important to consider thermal conductivity of the material. Since there is no convective heat transfer in vacuum, heat transfer occurs only via radiation and conduction. This becomes incredibly important for items like enclosed avionics boxes that produce heat internally. Without standard methods to allow convective heat transfer using fans, the internal temperature can build up and damage electronics. Considerations must be made to transfer heat outside. For a plastic such as Polyetheretherketone (PEEK) (thermal conductivity of 0.24-0.26 W/m/K) and aluminum (76-240 W/m/k), there is a 3-4 order of magnitude difference between PEEK and aluminum.[4] This is similar across most metals and plastic combinations. This could make it exceedingly difficult to adopt plastics for some systems like avionics in space; however, some additional post-processing methods may allow the use of plastics. For instance, plating the plastic with metal could allow the heat transfer to occur across the box. This may still cause the heat to translate across the skin of the surface and pass through the edges of the box where pieces mate. Pass-through holes may be required so the high-thermal-conductivity metal plating the plastic can coat a path between the inside and outside of the box.

E. Electromagnetic Interference (EMI) and Grounding

To provide the entire PLSS with a single ground, all components in contact with one another must maintain a resistance of 1 Ohm or less. This also prevents electrostatic accumulation. This low-resistance connection is also necessary to prevent EMI from affecting electrical components.

Often, this requirement runs counter to galvanic compatibility. The best way to prevent galvanic corrosion is to have dissimilar metals completely isolated from one another, but the conductivity requirement necessitates electrical contact. The result is an application of interfacing materials, such as specific electrochemical coatings, conductive gaskets, or pastes.

F. On-destination Maintainability

On-destination (low earth orbit or lunar) maintenance is sometimes necessary. To reduce the complexity of maintenance or component repair on orbit, key subsystem components such as heat exchangers, pumps, or valves are packaged as On Orbit Replacement Units (ORUs) that are easily separable from the larger PLSS assembly. These components are normally attached by captive screws and electrical harnesses so that unfastening these features enables complete removal of the component without having to further break component connections.

In addition to the considerations above, any solutions to these challenges must also meet the maintainability requirement. Permanent adhesives, pastes, or frangible coatings at the ORU interface are all unacceptable, as they would prevent component separation or generate Foreign Object Debris (FOD) as components separate.

G. Oxygen Compatibility

The space suit operates at 4.3 psia at 100% oxygen (O_2) concentration to allow for easier mobility of the pressurized suit.[5] A 100% O_2 environment poses a high fire risk. When possible, materials that will burn at 100% O_2 are avoided or controlled. At the 3000psia high pressures where the O_2 bottles and regulator operate, material selection becomes critical, as multiple potential ignition sources (e.g. particle impact, flow friction, mechanical impact) can cause a fire to ignite, causing catastrophic effects. Many metals, including aluminum, are often avoided at these high pressures since they can ignite and burn. Generally, the lower the absolute pressure of pure O2, the more inflammable materials there are to choose from. For the 100% O_2 ventilation loop at low partial pressure, more materials may be used since fewer materials are flammable, , but there must still be scrutiny for the whole system and controls on potential ignition mechanisms. The Extravehicular Mobility Unit (EMU) fire in 1980 that destroyed an EMU being tested at high pressure and the Apollo 1 fire at low pressure were both caused by an ignition in a pure O_2 environment where a fire began and propagated with disastrous effects.[5] Therefore, material selection and compatibility with O_2 for the ventilation loop and the high-pressure O_2 loop are critical to avoid future failures.

H. Water Compatibility

For components within the water loop, it is important to consider water compatibility. It is necessary to ensure the absorption, if any, is low and material strength is maintained after soaking the material in water and then pull testing it. For instance, with the International Space Station (ISS) EMU in 2003, a rotor seized after the epoxy in the rotor expanded due to water absorption. This epoxy was later replaced with a welded solution.[7] Additionally, in critical water valve sealing locations, it is important to choose a material that is good at sealing and is insensitive to contamination.

The materials also need to be compatible with the biocide in the water. On the ISS, the U.S. segment uses iodine, whereas the Russians use silver as a biocide. There are also teams at NASA considering silver as a biocide; therefore, an attempt was made to choose materials that would be compatible with both biocides. However, it was found that the silver biocide has compatibility issues, especially with stainless steel and titanium metals tested, which end up allowing the silver to deposit on the surface.[6] This causes two problems. First, the biocide may no longer be in solution, meaning that for long periods of quiescence, organisms could grow. Second, the plated silver can plate onto moving parts, like the pump, and stall them. Currently, the materials are chosen to only be compatible with iodine. Iodine has fewer restrictions on materials. Most metallics and composites are compatible with iodine; however, some polymers may still absorb the iodine. For instance, when testing the feedwater supply assembly, the outer layer changed color which is believed to be due to iodine absorption.

I. Off-gassing

There are several materials that, if used, could off-gas odors or chemicals that may affect the crewmember. At a lower pressure or vacuum, this could be increased. With time, sitting un-used volatile organic compounds could build up to become untenable or unpleasant for the crewmember. Therefore, it is important to consider and test materials for off-gassing and ensure that if they do off-gas, it is minimal and controlled to not create problems given the service life of the suit.

J. Vacuum Outgassing

Many non-metallic materials will release volatile constituent material in a vacuum. This can affect the mechanical performance of the material, and the emitted material could be deposited on sensitive equipment, such as cameras, solar panels, or sensors, and affect their performance. Deposited materials can also alter the optical properties of multi-layer insulation, compromising its performance. NASA evaluates a material's outgassing performance based on the total mass loss and collected volatile condensable materials (the amount of outgassed matter that condenses on a collector during the test) in a vacuum environment. Materials that lose less than 1% of their total mass, and only 0.1% collected volatile condensable material, are considered acceptable for vacuum application.

III. History (EMU) and State of the Art (xEMU)

A. EMU History[7]

Over the course of its development and 40 years of subsequent use in orbit, the EMU has seen an evolution of its design and constituent materials, reflecting lessons learned and corrective actions. Most notably, the valve and regulator body of the Secondary Oxygen Pack (SOP) was changed from aluminum to Monel as a corrective action following the 1980 EMU fire at Johnson Space Center. In a pure O_2 operating environment, the aluminum body's design was susceptible to particle impact ignition. Monel, however, will not ignite at the SOP's operating condition. This is an excellent example of material choice mitigating or eliminating a hazard entirely.

The EMU ventilation loop was initially composed entirely of coated aluminum to reduce mass and improve heat exchanger performance. Aluminum tubes connected aluminum castings, allowing the production of complex geometries to fit within the confines of the PLSS volume. Epoxy coatings were used to protect against corrosion. As components were disassembled for maintenance, these coatings would chip, allowing the aluminum to corrode. Coating systems were found to be difficult, if not impossible, to repair in the field. Where possible, coated aluminum parts were replaced with stainless steel to remove the corrosion risk, at the cost of higher system mass. Similarly, condensation caused corrosion in aluminum components of pressure gauges. Changing materials to stainless steel resolved these problems.

The water loop is predominantly stainless steel. As the design evolved, aluminum and plated stainless steel components were replaced with Nitronic 60, which has better corrosion and galling properties. The nonmetallic water bladder was originally made from Neoprenene. Over time, this material would leak water and leach unreacted components in the water stream, causing corrosion and contamination of sensitive heat exchangers. Changing the bladder material to Fluorel mitigated this problem, as it was half as permeable to water as neoprene, and any effluent was significantly less corrosive.

B. xEMU

The next generation Exploration Extravehicular Mobility Unit (xEMU) shown in Figure 1 includes the next generation exploration PLSS (xPLSS). Metallic materials were primarily chosen for the xPLSS due to their robust strength, well-defined material properties, spaceflight heritage, ready availability, and ease and repeatability of manufacturing. Typically, properties other than material strength, such as O_2 compatibility or electrical potential, drove material selection. A summary of the metals used, as well as their mass and strength properties, are shown in Table 1.

Table 1. Metals Used in the xEMU

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

*Properties derived from MMPDS: Values selected are the lowest values for A-basis material[8]
**Annealed Properties[9]
*** Annealed Properties[10]

The first metal of choice for use in the xPLSS vent loop was aluminum 6061-T6, because of its material properties, and it is a readily available and manufacturable material. It is also one of the lightest metals, with a density of 0.098 lb/in^3. Structural components were made from Al7075-T73, an alloy and temper that is 60% stronger than Al6061-T6 with a negligible increase in density (0.101 lb/in^3). Though Al7075 can be susceptible to stress corrosion cracking, the T73 temper exhibits the highest resistance to stress corrosion cracking while offering significantly higher strength than Al6061-T6.

As a standard precaution against corrosion, all aluminum components are anodized. When metal-to-metal contact between aluminum components is required for conductivity, the mating surfaces are protected by a Class 1A Alodine coating per MIL-DTL-5541. This provides less corrosion protection than anodizing while meeting conductivity requirements. An Alodine coating is not sufficient protection against galvanic corrosion when aluminum is paired with a dissimilar metal. To avoid the use of FOD-generating conductive pastes or gaskets, the aluminum in such interfaces is protected with an electroless nickel coating. The nickel of the coating is compatible with the other materials used in the xPLSS, and the nickel/aluminum joint is protected from corrosion, absent the presence of water (such as a leak or spillage during maintenance). Electroless nickel coatings can crack, and inadvertent water contact can exacerbate the problem. As the coating cracks, it can flake off, creating FOD. In the xPLSS, this was mitigated by designing the electroless nickel joint so that it was entirely covered by the mating material (preventing cracked material from becoming liberated). Sealing the interface between the aluminum and electroless nickel around the perimeter of the coated area can protect the aluminum and nickel joint from water intrusion.


Figure 1. xEMU suit assembly.

Materials in the water loop were selected first for compatibility with the iodine biocide, then for galvanic compatibility with other wetted metals, starting with the backplate. Titanium 6Al-4V, with a density of 0.190 lb/in^3, is the preferred metal due to its biocide compatibility and significantly lower density while still having relatively high strength. Metals are considered galvanically compatible if the galvanic couple does not exceed 0.25V. Other compatible materials include nickel alloys (such as Inconel or Hastelloy), Monel, and austenitic stainless steels (such as 316 Stainless). These materials typically have much higher densities (0.280 - 0.320 lb/in^3). In galvanic contact with any of these materials, aluminum will corrode and dissolve.

To reduce the overall front-to-back dimension of the xPLSS, the structural backplate and thermal loop plumbing were combined into a single large, welded, titanium assembly. While this successfully reduced the overall front-to-back of the xPLSS assembly, adding the titanium assembly to a traditional, structural aluminum backplate added significant mass.

Anodized Al6061 was the primary material for the 10.6 psid ventilation loop. Several components require simultaneous wetting from both ventilation O_2 and thermal loop water. These components were made from Inconel 625 for compatibility and the ability to be welded without heat treat. High-pressure O_2 in the xPLSS is stored at 3,000 psi. The xPLSS design philosophy for O_2 compatibility and fire prevention is to select materials that will not burn at these pressures. Monel alloys offer exceptional strength and will not burn, at the cost of being the heaviest materials in the xPLSS, with densities of 0.320 lb/in^3.

C. xEMU Mass Breakdown

The xEMU consists of both the Pressure Garment System (PGS) in the front to hold the astronaut and the xPLSS in the back to supply life support. The xEMU as built is estimated to weigh 334 lb (151kg), made up of 119 lb (54 kg) PGS and 215 lb (98 kg) xPLSS. There are two concerns with this mass: one being the significant resources to launch, and the other being mobility on the lunar, Mars, or other partial gravity environment.

This weight can become problematic for surface mobility, especially for Mars suit architectures. Assuming an average 180-lb crewmember, the total mass of the suit and crewmember would be 514 lb (233 kg). On the Moon (~1/6th relative Earth gravity), that would be about 85 lb (39 kg). The Moon weight of the suit is less critical, though the center of gravity will be pulled upwards and toward the xPLSS and will likely require the astronaut to stay in a hunched over position to balance. On Mars (~3/8th relative earth gravity), the mass would be about 194 lb (89 kg). Though this only slightly exceeds the weight of the human on Earth, and backpackers could easily handle the weight, there are still multiple concerns with this. First, the mobility of the suit provides significantly higher resistance. Secondly, the suit's center of gravity is going to be much higher and farther back than a standard backpacking backpack. Lastly, the extended journey through space to get to Mars, which could take many months, coupled with the lower gravity on the surface of Mars, may make the crewmember ill equipped to handle their own weight regardless of physical fitness. Exercise and/or artificial gravity on this long journey could help with this concern. Concurrently, there can also be research into ways to reduce the suit mass. The suit mass can be reduced either by reducing capability such as EVA time, forgoing two-fault tolerance in some areas, or ideally by reducing component mass. Reducing component mass would require either making the component more efficient and smaller or using lighter weight materials.

For the xPLSS, the detailed breakdown by subsystem and section is shown in Table 2. These weights were either estimated using computer modeling or measured on a scale before installation into the prototype xPLSS. While this is helpful to understand the current subsystem breakdown, individual components should still be looked at on a case-by-case basis to consider reduction in weight.

Table 2. Detailed Weight Breakdown of xPLSS

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)

IV. Advanced Material Options and Methods

A. Overview

For each type of material, there is a set of manufacturing methods and processes that can be applied to it successfully.

Manufacturing processes can be categorized into additive or subtractive manufacturing. Subtractive has been a key machining method for centuries, with certain additive categories being relatively new. With the advent of computer control systems, Additive Manufacturing (AM) has been able to take on a new role, such as machines able to precisely melt, cure, and/or deposit material exactly where desired in a repetitive and precise way that no human could easily replicate. In some applications, this may be beneficial to consider reducing complexity of a part or make parts that were never possible before. There are still many instances in which more traditional machining methods are more practical and less complex. There are several key process subtypes to cover. There is traditional subtractive machining or milling; and additive molding, casting, melting, deposition, or chemical cure methods,. A few specific processes are discussed here. Fused Deposition Modeling (FDM) melts the material and deposits it at a precise location on a build table, fusing it with the previously placed material in its vicinity. Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) use a laser to melt composites or metals, respectively, on a bed of powder to fuse the material with adjacent material. Stereolithography works similarly to fuse adjacent material, but instead uses an ultraviolet light to chemically cure resin that is placed in layers.

There are several broad material groups that describe most, if not all, materials available: metals, plastics, and composites. Table 3 shows a potential list of advanced materials to consider, which will be covered in more detail. Some of them are already in use with the xEMU (like aluminum and titanium), while others are newer materials in consideration for spaceflight (like Ultem or Windform). These materials are ordered by their strength-to-density ratio as a resource for selecting the best one for a particular application. However, this is only a starting point. Many materials may be lightweight, but other properties and considerations make them unusable or drive-up overall weight in other ways. For instance, titanium has some galvanic compatibility concerns, meaning materials bolted to it may need to be a heavier material type that is compatible, or extra process controls need to be considered to protect the coupling.

Table 3. Advanced Materials for Consideration

Material	**Material Category**	**Process**	**Strength/ Density Ratio (ksi/(lb/in^3))**	**Density (lb/in^3)**	**Ultimate Tensile Strength (ksi)**
Titanium 6Al-4V[8]	Metal	Machine	969	0.160	155
Aluminum 7075-T73[8]	Metal	Machine	713	0.101	68
PEEK 30% GF[11]	Plastic	Machine	581	0.0520	30
Ultem 2300 30% GF[12]	Plastic	Machine	449	0.0544	24.4
Aluminum 6061-T651[8]	Metal	Machine	429	0.0980	42
Ultem 1000 Black[12]	Plastic	Machine	332	0.0458	15.2
Windform XT 2.0[13*]	Plastic	SLS	307	0.0394	12.1
Windform SP[12*]	Plastic	SLS	274	0.0400	11.0
Polycarbonate 20% GF[14]	Plastic	Machine	268	0.0487	13.1
PEEK[15]	Plastic	Machine	261	0.0470	12.3
Vespel SP-1[16]	Plastic	Machine	242	0.0517	12.5
Ultem 9085[17*]	Plastic	FDM	180	0.0483	8.6
Teflon (PTFE)[15]	Plastic	Machine	46	0.078	3.6

*These materials may be anisotropic due to the additive manufacturing process, and have different values based on axial direction. The values from the axial direction with the lowest properties are conservatively reported here.

B. Metal Options

1. Mass Optimization

The metals currently used in the xPLSS are already optimized for key performance characteristics, and they typically offer significantly higher strength than required. Limitations in how much material can be economically and safely removed from critical geometry during machining leaves an extremely robust product. The welds of the titanium backplate, for example, would not burst at 20,000 psid during testing, when the pressure during actual operation is only ~22 psid. In many cases, lighter metals simply cannot be used without compromising on other key characteristics, such as O_2 or galvanic compatibility. In these instances, the best opportunity to reduce mass is by optimizing the component to have the smallest mass while meeting strength requirements. Traditionally, this is achieved by machining as much additional material as possible from the initial design. These machining solutions are limited in the thinnest walls and materials they can leave behind without the part warping or breaking under tool stresses. Typically, this is done after a design has been proven to meet other design requirements.

In the xPLSS, complex components such as the backplate were not fully mass optimized when initially manufactured. Later, the plates were further machined from their "ideal" state in Figure 2. With an original manufactured mass of 51 lb (23 kg), secondary machining operations reduced the overall backplate mass to 39 lb (18 kg) while still maintaining conservative strength margins.

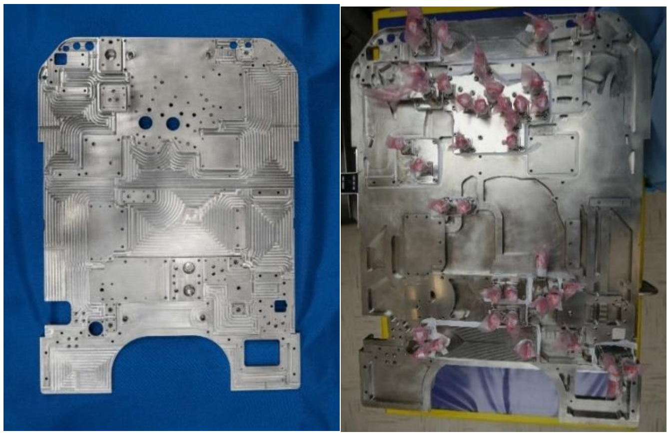
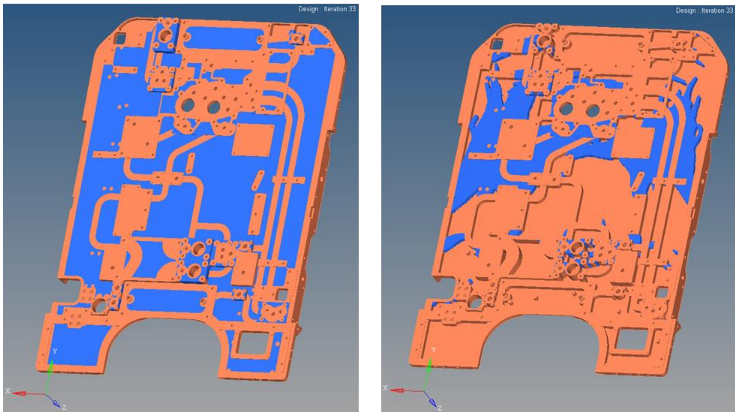

A) Before **B) After**

Figure 2. xPLSS backplate mass optimization machining.

The typical design process for mass optimization involves several iterations of design change and stress analysis. For large parts with complex interfaces, this can be an extremely time-intensive process. Recent new tools and analyses, such as topology optimization and generative design, can shorten these design cycles by automating the initial design iterations. The final design must always be verified with traditional, approved methods. These tools still leave room for improvement; the tools do not often result in machinable designs without significant designer simplifications. Further, these tools typically still leave a design with excess strength margin. The DVT xPLSS mass optimization was achieved using a generative design approach, where the analysis program "added" material to a skeletonized backplate to meet the combined load cases of a fully built space suit under launch and landing loads in Figure 3. The blue areas were open for the analysis to remove material.



A) Initial Topology **B) Optimal Topology**

Figure 3. Graphical representation of backplate mass optimization process.

2. New Manufacturing Methods

Additive manufacturing of metals offers several opportunities to produce equivalent-material parts with significantly more mass optimization. Most powder-based DMLS or Electron Beam Melting (EBM) processes create thinner-walled geometries than those made by traditional machining. Complex, pocketed shapes can be created more quickly and economically than from machining from billets of material. Other processes, such as Direct Energy Deposition (DED) can enable the production of "hybrid" machined and printed components. This can allow primary fabrication from traditional billets, with the after-machining application of material to reinforce stressed areas.

Additive manufacturing also enables the combination of multiple components into one single part. Complex manifolds that typically required additional fasteners, welding, or seals (and the mass added by these features) can be printed as a single component with weight reduction features built in.

DMLS, EBM, DED, and other metal additive processes also offer an opportunity that is beginning to be employed in industry: combining multiple metals into a single, monolithic part. An aluminum avionics box could have a titanium-compatible layer at its base, removing the need for coatings. A water loop component, such as a pump housing, could have a water-compatible titanium internal cavity with a lighter aluminum exterior providing strength.

Any additive manufactured process would require extensive characterization and process control for flight hardware production. These controls would include configuration control and management of all machine and software parameters, material lot control, and witness specimens made concurrently with each component.

C. Plastics

1. Machined Plastics

If overall strength is not a primary concern, there are many plastics that can be substituted and can reduce weight by half or more. In many cases of designing a machined part, there is a lot of unnecessary mass driven by machining rules, tolerances, or thinness of walls. Just increasing thickness helps compensate for these requirements. This usually makes it such that strength of material is a secondary concern since the margins are so high to account for these other requirements. In these cases, a plastic or composite material replacement could be substituted without compromising part integrity, thus reducing overall weight. This method could be a great first option to optimize materials, especially if a lot of machined parts are already designed.

PEEK with 30% Glass Fill (GF) and Ultem have some of the highest strengths available in thermoplastics. Additionally, it has an “A” out-gassing rating, meaning it has a total mass loss less than 1% in vacuum. This makes these materials ideally suited as replacements for non-structural aluminum components such as electronics and battery housings. Additionally, 30% GF PEEK offers superior water absorption relative to Ultem.

2. Additive Manufactured Plastics

Additive manufacturing processes in plastics offer similar benefits to additively manufacturing metals. Parts can be created with thinner walls and complex geometry that would be comparatively difficult to fabricate with traditional methods.

Strength of additive manufactured parts is highly geometry dependent. In general, Ultem 9085 is recognized as one of the strongest-available additive plastics. This material also has excellent off-gassing and outgassing properties, making it acceptable for use in vacuum. Parts from Ultem 9085 are made via FDM. This extrusion-type process does not lend itself to parts that require impermeability (i.e., parts that hold pressure). The creation of walls, layers, and infills can leave voids and gaps that allow fluid penetration and absorption. In cases where an additive manufactured part is intended to hold (even minor) pressures, SLS creates higher-density parts that are more likely to be fully waterproof. Nylon-based powders such as Windform are ideal candidates for these applications. Like Ultem, it also has excellent off-gassing properties but lower strength. Currently, vacuum outgassing data is not available.

NASA has created a baseline requirement document, NASA-STD-6030, for “Additive Manufacturing Requirements for Spaceflight Systems.”[18] The current state of the art for additive manufacturing polymers is not considered mature enough for Class A parts that, should they fail, would lead to a catastrophic, critical, or safety hazard.[18] For example, the difficulty in performing nondestructive evaluation of AM plastics with current technologies and the lack of standardized fracture toughness testing make these materials extremely unlikely to meet the requirements for Class A parts. Accordingly, NASA will not approve any use of additive manufacturing polymers in high consequence of failure parts. In a PLSS, this limits the current acceptable use of additive manufacturing polymer parts to non-structural, non-critical applications, such as electronics enclosures. As industry material characterization and alternative nondestructive inspection methods improve, there will be opportunities to integrate these materials into increasingly demanding applications.

3. Plating

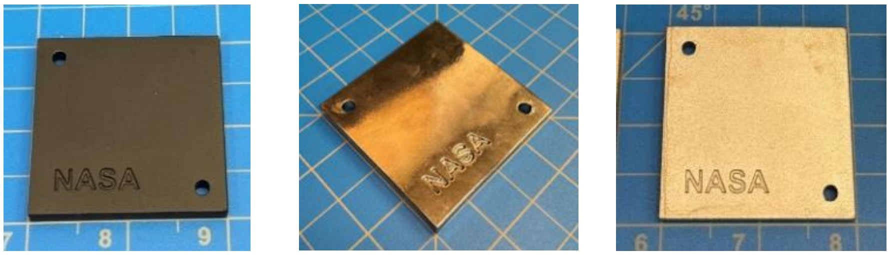
Plating has typically been done in the past as a means of corrosion prevention; however, with the introduction of composites and plastics, the concerns of radiation, heat transfer, and EMI may be benefited by plating. Since plastics and composites are typically non- or minimally electrically or thermally conductive, there is little to no protection from radiation or EMI. Additionally, heat transfer becomes an issue, especially if the component is a housing for avionics that must expel waste heat. Therefore, many of them must be plated to address these issues.

A challenge for plating plastics or composites is that many existing processes require the piece to be electrically conductive where plastic is not. Instead, electroless methods are used to plate the materials with a conductive layer. Electroless nickel is a standard plating process that is being considered by the PLSS team for plating plastics. Testing and talking with various vendors showed that an underlayer of copper is used to plate the surface before deposition of the nickel layer. After this initial copper layer has been plated, further layers of different or specialty materials could potentially be electroplated if desired, although this has yet to have been thoroughly tested. Total layer deposition and thickness tends to run from 0.001 in. - 0.005 in. (0.0254 - 0.127 mm) and can be set to a specific thickness to vary by application and need. For thicker layers, designers may need to consider the thickness of the plating job if there are critical tolerances.

The exact thickness requirements may be driven by radiation, thermal, and EMI requirements, to protect internal components. If thermal conduction requirements are a concern, the plate may need to be modified to allow thermal heat transfer. Small holes throughout the surface which would get plated with the rest of the job could act as thermal vias and allow a path for the heat to travel, although this method needs further investigation. Furthermore, to increase emissivity, a black final layer is ideal to help radiate heat away from the part. For space background radiation and EMI, the coating must be just thick enough to protect the internal components well, although the exact thickness is still a matter for future research.

To verify that the plating job is acceptable, a few things must be considered. First, it is desirable to have a smooth, continuous thickness free of imperfections that may cause detriments to usage. Second, the plating must have good adhesion such that adhesion of the material would be able to pass a plating pull test. Lastly, the plating material should be corrosion resistant.

As part of this research, samples were made to test electroless nickel plating, as shown in Figure 4. Windform, an additively manufactured carbon doped plastic, was selected as a test material in line with the advanced materials being considered. A sample was sent to two companies, A & B. Company A came back with one sample that had a good visual surface finish, but said they were not able to complete the others. Company B came back with a good sample, which, although very grainy in texture, appears to have good adhesion and could work well. They also stated that they have more labor-intensive processes available to give a better finish. A more complex model was sent to Company B of our Display and Control Unit (DCU) housing, which they also were able to plate well. A test plating job of the DCU is shown below in the avionics box section V.B. These plating processes and companies are still under evaluation.



A) Windform SP (Un-plated) **B) Company A Plating** **C) Company B Plating**

Figure 4. Plating samples.

Much of the existing research for these materials is still in the early stages for spacesuit development and will need further research, development, and testing to verify plating. Most of the current verification has been visual inspections. However, visual inspections sometimes reveal discoloration, blistering, adhesion issues, or other problems that still may need to be resolved. Further samples could be sent to other vendors to test different methods of plating and explore different layering options to get a better overall finish. Lastly, once samples start coming back with good visual inspection results, further tests will need to be conducted to numerically compare adhesion, shielding, thermal properties, and other parameters to make the best choice for each application.

4. Inserts

To make new plastic components compatible with bolted joints, metallic inserts are necessary to increase pull out strength. Traditionally, helical inserts have been known to pull out or break free from tapped threads in plastics, although this may be less of a concern using high performance plastics. Also, industry-standard thread locking compounds may need to be avoided because they attack thermoplastics[19].

Heat set inserts have been explored as an alternative for plastic components in the PLSS. While these inserts are typically made from brass, stainless steel versions are offered commercially, and these offer better material combability with stainless steel screws.

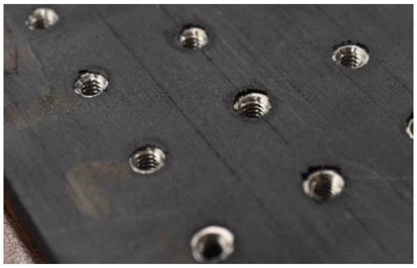


Figure 5. Inserts in Windform SP material.

Installation of heat set inserts is highly equipment dependent. The NASA PLSS team began preliminary efforts to create a detailed technical procedure for the installation of heat set inserts into plastics using equipment common to several team facilities. Insert vendors allow a wide range of installation force and temperatures for a given insert size, and it was found that any variations within these recommended bands did not significantly change the performance or pull-out strength of the insert.

Based on the limited heat set insert testing done, it was also found that the Windform SP carbon composite in Figure 5 was able to accept inserts. The glass filled Ultem 2300 test did not allow installation up to the highest force able to be imparted and temperatures up to 800 °F (426 °C), despite having similar thermal melting and conductivity properties, which could mean other glass-filled composites may have difficulty accepting inserts, though more material tests are needed.

In another limited test series at JSC, standard helical inserts were tested for Ultem 2300 and Windform SP with just one 6-32 bolt size to start to start comparing methods. In Windform SP, 6-32 x 0.207" (MS122118) helical inserts had a pull-out strength of 366 lb average (12 lb std dev.) which was a ~5% increase in pull out strength compared to the IUC-632-2 heat set inserts at 348 lb (23 lb std. dev.). Helical inserts also decreased the standard deviation in pull out strength from the Windform SP heat set inserts by approximately 50%. These same helical inserts were also able to be installed successfully in the Ultem 2300 with a 746 lb (22 lb std. dev.) pull out strength where the heat set inserts could not be installed in previous tests. This may indicate that for these high-performance plastics, helical inserts may be the better option compared to heat set inserts, though more testing will be needed to confirm.

Testing is still ongoing to qualify this process for flight hardware and standardize the method of parameter development for future fastener sizes. Further testing may include different materials, different hole sizes and geometries, different size inserts, comparisons to standard hole tapping, and comparisons to helical inserts.

D. Composites

Composites are materials fibers, such as carbon or glass, layered into an epoxy resin to provide extra strength corresponding to the fiber alignment. These materials require significant design and analytical consideration. Many components within the PLSS are relatively small, with highly complex geometries that do not lend themselves to ready fabrication with composites methods. While composites are worth considering for oxygen pressure vessels or structural components and covers, and the xPLSS features a composite impact cover, methods involving additive manufactured or machinable may have more potential to be adopted in the space suit at this time.

V. Component Candidates for Weight Reduction

There is opportunity to reduce weight for components across the xPLSS. Many of these parts in Table 4 are machined metals which have available stress margins which could allow weight reduction, though manufacturing, sealing, and bolting standards require materials to be thicker where stress is not a driving factor. Additionally, stresses may be able to be managed using slightly thicker walls and sections if needed, with the assumption that the overall body reduces significantly in weight with the advanced, lighter weight material chosen.

Table 4. xPLSS Parts Considered for Weight Reduction[12]

Part	Current Material	Current Weight (lb)	Reduction Method	New Weight (lb)	Weight Reduction (lb, (%))
Interface Pad Weldment	Inconel 625	6.15	AM Plastic	0.99	5.16 (84%)
Thermal Loop Jumper	Inconel 625	0.23	Machinable Plastic	0.03	0.2 (87%)
Avionics Mounting Brackets	Aluminum 7075	0.81	Machinable Plastic	0.44	0.37 (46%)
Antenna Mounting Bracket	Aluminum 7075	0.92	Machinable Plastic	0.49	0.43 (46%)
Connector Bracket	Aluminum 7075	0.59	Machinable Plastic	0.32	0.27 (46%)
Controller Housing - 150	Aluminum 6061	1.20	Machinable Plastic	0.65	0.56 (46%)
Controller Housing - 250	Aluminum 6061	1.20	Machinable Plastic	0.65	0.56 (46%)
Controller Housing - 350	Aluminum 6061	1.07	Machinable Plastic	0.58	0.49 (46%)
Controller Housing - 450	Aluminum 6061	1.04	Machinable Plastic	0.56	0.48 (46%)
Controller Housing - 550	Aluminum 6061	2.00	Machinable Plastic	1.08	0.92 (46%)
Controller Housing - 650	Aluminum 6061	2.20	Machinable Plastic	1.18	1.01 (46%)
Controller Housing - 659	Aluminum 6061	0.60	Machinable Plastic	0.32	0.27 (46%)
Controller Housing - 701	Aluminum 6061	0.98	Machinable Plastic	0.53	0.45 (46%)
Controller Housing - 702	Aluminum 6061	1.54	Machinable Plastic	0.83	0.71 (46%)
Gas Sensors Mounting Bracket	Aluminum 7075	0.76	Machinable Plastic	0.41	0.35 (46%)
Ventilation Heat Exchanger Body	Inconel 625	2.39	Machinable Plastic	0.44	1.95 (82%)

Thermal Control Valve Body	Titanium 6-4	0.51	Machinable Plastic	0.17	0.33 (66%)
Water Membrane Evap. Housing	Titanium 6-4	3.63	Machinable Plastic	1.23	2.4 (66%)
Battery Housing (x12)	Aluminum 6061	7.56	Machinable Plastic	4.07	3.49 (46%)
Fan Inlet Manifold	Aluminum 6061	1.40	AM Plastic	0.55	0.85 (60%)
Fan Outlet Manifold	Aluminum 7075	1.43	AM Plastic	0.57	0.86 (60%)
Vacuum Access Manifold	Aluminum 6061	1.26	AM Plastic	0.50	0.76 (60%)
Display Control Unit Housing	Aluminum 6061	2.02	Machinable Plastic	1.09	0.93 (46%)
				Total	**35.53 (47%)**

For most of these parts, either a machinable plastic or an additively manufactured plastic could replace the part material. Some example material candidates used in Table 4 for estimating the reduction in weight include Ultem 2300 as a machinable plastic replacement and Windform SP as additive manufactured replacement. These are just notional examples and starting points, and an engineer should review other materials in Table 3 before selecting. For most cases, machinable plastics are recommended because they are still easier and more reliable to manufacture with better properties than an additively manufactured version. However, in cases where a manifold or part requires cross drills creating extra plugs, an additively manufactured option could be considered. Using an additively manufactured option could reduce complexity and failure mechanisms due to the extra pieces, bolts, and sealing mechanisms required to drill and plug holes. There are also some parts for which the original material is still recommended due to stress concerns or other concerns, however lightening methods could be considered.

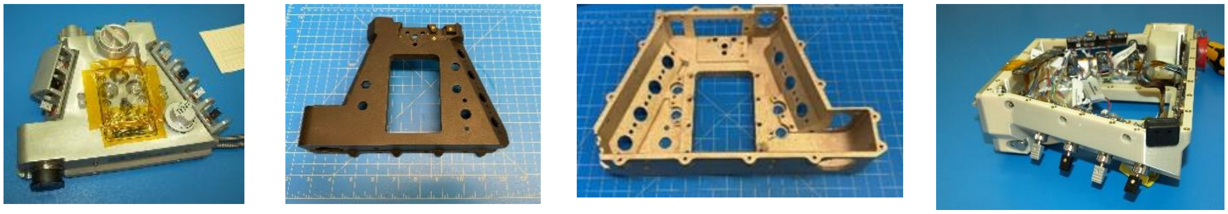
A. Backplate

The current xEMU architecture requires a material that is both electrically and thermally conductive and compatible with water and biocide. Additionally, it is the key structural component of the xPLSS. Without significant xPLSS repackaging or changes to the thermal loops' operating fluids and design, titanium is still the ideal material for this application. Additionally, typical powder-based additive manufacturing processes such as DMLS or EBM were not found to have sufficient manufacturing volume when the design was first explored. Even if the processes could be scaled to fit the form factor required, the thermal gradient resulting from the heat source acting on unheated titanium would lead to significant warping and cracking.[20]

Traditionally, mass reduction through material removal remains the best option to reduce the mass of this component. As mentioned previously, this allowed a mass reduction of 24% in the DVT xEMU unit. These results can be further improved through more aggressive machining, more stringent material sourcing (to allow the use of a tighter, higher range of material properties), and reduced external loads by lightening other components.

B. Avionics Boxes

Avionics boxes are unique in that they house the microprocessors that generate heat and are susceptible to radiation such as the DCU in Figure 6. However, the box strength is not very critical at all. Therefore, there is opportunity to reduce weight substantially. The entire avionics weighs about 32.6 lb (14.8 kg), including cabling, 28.6 lb (13.0 kg) of which are the controllers. The O_2 regulator controller (CON-150/250), for example, weighed 1.68 lb (0.762 kg). The casing was calculated to weigh 0.905 lb (0.411 kg) or approximately 54% of the box weight. Assuming this is similar for all boxes, then there are 15.4lb (6.99 kg) for just the casing holding the avionics. These are currently all made with aluminum 6061. If the material was swapped with Ultem 1000 Black (46% as dense as the aluminum), it would save 8.3 lb (3.8kg) on the xPLSS, which is significant. Considerations such as radiation, EMI, grounding, and heat dissipation and inserts may need to be considered with this new material, such that plating, increased material thickness, and heat inserts may need to be added to the final design. This may cause the savings to be slightly less, but even if it only saves half the potential amount, it is still worth considering. Furthermore, successful implementation of a new material and process could change avionic box manufacturing across the agency for other programs.



A) Aluminum 6061 **B) Windform SP** **C) Windform SP Electroless Nickel Plate** **D) Ultem 9085**

Figure 6. DCU materials comparison.

C. Ventilation Loop Components

All ventilation loop components must withstand a delta pressure of up to 10.6 psid of pure O_2. The part must be compatible with O_2 and provide no significant concerns to fire safety. Additionally, for O_2 fire safety, the ventilation loop is cleaned to 150A and maintained to level 150, so the part must be able to be cleaned, verified, and maintained to these levels. Non-structural manifolds in the xEMU were previously made from aluminum or, in one case, Inconel 625. A one-for-one material replacement of these metals for plastics can result in significant mass savings without any changes to the interfacing components.

The most ideal candidate is the xPLSS interface adapter in Figure 7. This manifold uniquely interfaces with both the xEMU ventilation and thermal loops, connecting various fluid paths to their terminating locations at the xPLSS/PGS interface. Because of the requirement to be compatible with both O_2 and water, Inconel 625 was chosen. The strength of this material was drastically higher than needed in this application. A PEEK or Vespel replacement component could reduce the mass of the interface adapter from 6.05 lb (2.74 kg) to 0.99 lb (.45 kg), an 83% reduction in mass, before any additional mass optimization by additional material removal.

Another option is a typical aluminum manifold, such as the fan inlet manifold, in Figure 8. This manifold has mass reductions of 60% in a one-for-one replacement. This part's complex geometry (taking flow from one source and diverting it to two fans with six total "turns") is relatively difficult to traditionally machine in a space-saving manner requiring multiple cross drills and plugs. A design optimized for minimum line length would be ideal for additive manufacturing and would allow a smaller and a less complex overall part as well. However, maturity of additive manufacturing may need to improve because NASA-STD-6030 does not currently consider polymeric additive manufacturing mature enough for high consequence part like this.

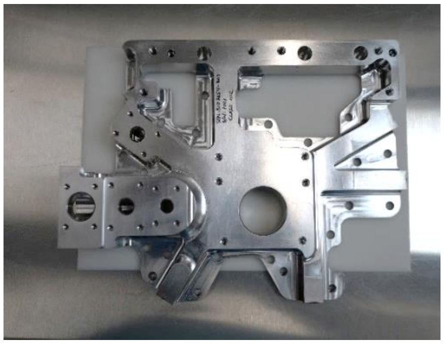


Figure 7. xPLSS interface pad adapter.

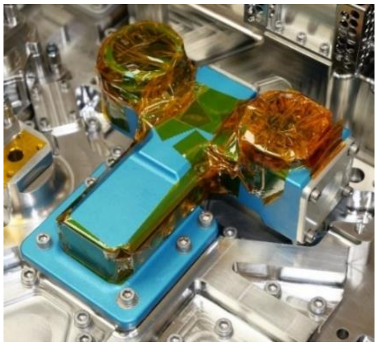


Figure 8. xPLSS fan inlet manifold.

D. Thermal Loop Components

For thermal components, the main differing requirement from ventilation components is pressurized water compatibility. The material must not absorb (or only minimally absorb) water, and if it does, not significantly change material properties. Additionally, the materials chosen must not leach trace elements when exposed to the water loop as this can clog filters or contaminate sensitive hardware and cause the thermal loop to fail. The sublimation heat exchanger on the EMU is sensitive to contamination that can cause it to fail. The water loop must be maintained to a precision clean level of 150A.[1] For pressure, it must be able to withstand 30 psid. Most of these components have only light loads and are ideal candidates for weight reduction, although they must be compatible with deionized water.

VI. Future Work

A. Advanced Methods and Properties to Explore

Most materials being recommended as a lighter-weight option are non-metallic and lower strength, which sacrifices some critical properties for bolt pull-out strength, EMI tolerance, thermal heat transfer, and compatibility concerns. Further testing is necessary to test plating that could improve EMI and thermal heat transfer. The PLSS team plans to explore methods of plating as well as methods to create thermal vias, which are plated through holes, through the material to allow heat flow through the low thermal conductivity material. Furthermore, materials with lower strength may have issues tapping the material, and even if they do tap well, the pull-out strength is low. This leads to a need to test heat inserts designed for thermoplastics and certify them for flight. Lastly, based on the specific application, tests need to be developed to ensure compatibility with materials to ensure they do not degrade, leach, corrode, off-gas, or harm the suit in other unintended ways.

B. Materials Testing Options

To determine the most appropriate materials, data on properties of selected materials must be gathered. For most materials, these properties are readily available; however, if modifications are made such as plating or adding inserts, many of these tests may need to be repeated. Additionally, in cases where vendor data is available, it may be useful to verify critical properties like tensile strength. Furthermore, there may be tests not available from the vendor or elsewhere; therefore, tests may need to be run. Table 5 lists a set of tests for consideration. It attempts to provide a starting point for researching materials, but it may not be all inclusive or may have more than needed, depending on the application. It is important to critically review the new material being considered for both the intended location and the required tests to ensure the material is fully compatible for spaceflight. A list of American Society for Testing and Materials (ASTM), NASA, and other standards are listed as a potential method to verify each property, although there may be others that are more relevant to specific applications. These were sourced and compiled from NASA documents, similar vendor documents, and online review of available standards. To certify additively manufactured materials for flight, it is recommended that NASA-STD-6030 be reviewed for compliance.

Table 5. Potential Tests for Consideration[12]

Type	**Property**	**Standard**
Physical/General	Density	ASTM D792
Physical/General	Water Absorption	ASTM D570
Physical/General	Vacuum Outgassing	ASTM E595
Physical/General	Off Gassing	NASA-STD-6001
Physical/General	UV Sensitivity	ASTM D4329
Physical/General	Surface Finish	ASTM D7127 / ASME B46.1
Mechanical	Tensile Properties	ASTM D638
Mechanical	Flexural Properties	ASTM D790 / ASTM D7774
Mechanical	Charpy Impact	ASTM D6110
Mechanical	Izod Impact	ASTM D256 / ASTM D4812
Mechanical	Gardner Impact	ASTM D5420
Mechanical	Bulk Modulus	ASTM D4065
Mechanical	Poisson's Ratio	ASTM E132
Mechanical	Rockwell Hardness	ASTM D785
Mechanical	Hardness	ASTM D2583 / ASTM D785
Mechanical	Compressive Properties	ASTM D695
Mechanical	Torsional Modulus	ASTM E143
Mechanical	Shear Testing	ASTM D732 / ASTM B769
Mechanical	Fatigue	ASTM E606 / ASTM D7991
Mechanical	Fatigue Crack Growth	ASTM E647
Mechanical	Fracture Toughness	ASTM E399 / ASTM E561
Mechanical	Creep	ASTM E139
Temperatures of Deformation	Melting	ASTM D7426 / ASTM D3418
Temperatures of Deformation	Vicat Softening Temp	ASTM D1525
Temperatures of Deformation	Deflection Temp under load	ASTM D648
Temperatures of Deformation	Glass Transition Temp	ASTM D3418 / ASTM 7028
Temperatures of Deformation	Polymer Degradation Temp	ASTM D3835 / ASTM E2550
Temperatures of Deformation	Coef. of Linear Therm. Expan. (CTE)	ASTM D696
Thermal	Specific Heat Capacity	ASTM E1269 / ASTM E2716
Thermal	Thermal Conductivity	ASTM C177 / ASTM E1530
Thermal	Emissivity and Absorptivity	ASTM E1862
Flammability	Flammability of Plastic	UL94
Flammability	Oxygen Index	ASTM D2863
Flammability	Autogenous Ignition Temperature	ASTM G72
Flammability	Flash Point	ASTM E502
Flammability	Ignition of non-metallics	ASTM G74
Flammability	Heat of Combustion	ASTM G86
Electrical	Class S/R Bond Eval	NASA-STD-4003 / ASTM B571

Electrical	EMI Testing	CTSD-ADV-1763 / ASTM D4935
Electrical	Resistivity	ASTM D257
Electrical	Dielectric Strength	ASTM D149
Electrical	Dielectric Constant	ASTM D150
Specialized Testing	Inserts Pull out Strength	ASTM D7332
Specialized Testing	Plating	SAE AMS2404J
Specialized Testing	Atomic oxygen	ASTM E2089
Specialized Testing	Soak Testing & Pull Test	CTSD-ADV-1763 / ASTM D638

Based on available data and selected items for material transfer, a testing plan should be created to fill in the gaps and ensure the materials will meet requirements for each application. Some testing methods may need to be modified or developed for different materials or processes. In many cases, there may be multiple materials or processes being considered. In which case, as much relevant data based on the application should be gathered from this list of tests to down select the best option.

C. Specialized Testing and Forward Work

While tests like tensile are well known, understood, and standardized, other tests to verify advanced properties may need to be developed and performed. In this case, there is further work to define test plans for plating, inserts, thermal, creep, compression set, cold flow, EMI, and radiation requirements and verification for each part and material chosen. For plating, tests need to be designed to verify quality by testing adhesion, smoothness, and quality of job, deposition thickness, and corrosion resistance. In many cases, plating could be layered to provide the best external facing properties and adhesion. Heat inserts are still relatively new and are often used when prototyping with additive manufacturing; however, when it comes to critical life safety equipment, heat inserts need to be better understood and an expected test and range for pull-out strength must be determined. Some preliminary research has set out some methods; however, many variables such as insert hole size and cross-sectional parameters have barely been explored beyond manufacturer recommendations. Therefore, more research will be needed to verify these parameters. For thermal, tests will need to be conducted after an analysis is run for plating materials. Lastly, creep, compression set, cold flow, EMI, and radiation testing methods will need to be determined and run.

VII. Conclusion

Reducing space suit weight is a key factor in future human exploration to the Moon, Mars, and beyond, both to save cost and make it possible to traverse on the surface of Mars. To reduce mass of the xPLSS, advanced and emerging additively manufactured or machinable plastics may need to be considered. These materials have lower strength-to-density properties, but may be able to meet stress margins, especially in locations where existing heavier materials are chosen for compatibility over strength. However, testing to verify these materials and properties may still need to be done, or standards need to be developed to provide a method for comparison against the current heritage materials. Furthermore, new processes may need to be developed or verified to accept hardware, such as inserts for bolts, and plating to provide EMI shielding and heat dissipation. Some preliminary efforts have shown good results on tested materials, although more testing is needed before adoption. In the short term, existing materials can be analyzed for potential replacement in existing designs. Additionally, testing can be performed concurrently to fill in gaps of testing for items like insert pull out strength and material plating. Given emphasis on materials research & testing, plastics may be able to be adopted in flight cases in the upcoming years for space suits or other flight projects. Additive manufacturing may require continued development with more base material testing and usage in low-risk scenarios to increase maturity of the process before adoption in critical flight parts as a longer-term goal. All these tests will provide stress analysts with appropriate properties to verify operation and validate their models in addition to providing designers with recommended methods and processes for using these new materials.

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