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Advanced Materials Testing Plan for the Space Suit Portable Life Support System

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Introduction

- Advanced Materials are important to reducing weight and maintaining suit capability for all mission profiles
  - Current government reference design, the exploration Extravehicular Mobility Unit (xEMU) suit is 391lbs (177kg)
  - Mars suit maximum mass is currently estimated at 229lbs (104kg), requiring a 44% reduction in mass from the xEMU design
- Machined thermoplastics and additively manufactured (AM) parts are considered for infusion
  - Glass or carbon filled thermoplastics provide some of the highest performing properties on the market after metals
  - Augmentation such as plating could be used to improve strength properties
  - Inserts may be used to improve bolt pull out strength
- A series of testing is required to ensure advanced materials meet all stringent spaceflight requirements

Considerations, Usage, and Safety

- Spaceflight has many environmental considerations that materials must meet
  - Ultimate tensile strength (UTS) and other mechanical properties
  - Galvanic compatibility
  - Thermal properties including operation at cryogenic temperatures, heat dissipation
  - Electromagnetic interference (EMI) protection and grounding
  - Oxygen compatibility
  - Off gassing, and vacuum outgassing
- Thermoplastics are not new, but usage in criticality 1 space suit life support applications in space is new
  - Prior systems have only considered metallics to be mature enough for critical applications
  - NASAs AM handbook does not consider thermoplastic AM mature enough for critical applications, but metallic AM can be considered now
  - Machined thermoplastics could be used with sufficient testing
  - A set of tests to verify advanced materials starting with machined thermoplastics would build confidence to integrate these materials in critical applications

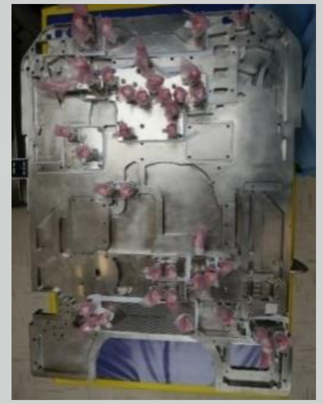
Advanced Material Options

Material	Material Category	Process	UTS/ Density Ratio ksi/(lb/in^3) (MPa/(g/cm^3))	Density Average lb/in^3 (g/cm^3)	UTS ksi (MPa)
Titanium 6Al-4V	Metal	Machine	969 (241)	0.16 (4.43)	155 (1069)
EOS Titanium Ti64	Metal	PBF (AM)	956 (238)	0.16 (4.43)	153 (1055)
Aluminum 7075-T73	Metal	Machine	713 (168)	0.101 (2.8)	68 (469)
EOS Aluminum AlSi10Mg	Metal	PBF (AM)	673 (168)	0.098 (2.71)	66 (455)
PEEK 30% CF	Plastic	Machine	529 (132)	0.051 (1.41)	27 (186)
PEI 30% GF (Ultem 2300)	Plastic	Machine	466 (116)	0.0545 (1.51)	25.4 (175)
Aluminum 6061-T651	Metal	Machine	429 (107)	0.098 (2.71)	42 (290)
PEEK 30% GF	Plastic	Machine	407 (101)	0.054 (1.49)	22 (152)
PEI (Ultem 1000)	Plastic	Machine	359 (89)	0.046 (1.27)	16.5 (114)
PEEK	Plastic	Machine	340 (85)	0.047 (1.3)	16 (110)
Nylon 12 + CF / Windform XT 2.0	Plastic	SLS (AM)	307 (76)	0.0394 (1.09)	12.1 (83)
Nylon 11 + CF / Windform SP	Plastic	SLS (AM)	274 (68)	0.04 (1.11)	11 (76)
Polycarbonate 20% GF	Plastic	Machine	268 (67)	0.0487 (1.35)	13.1 (90)
Vespel SP-1	Plastic	Machine	242 (60)	0.0517 (1.43)	12.5 (86)
Ultem 9085	Plastic	FDM (AM)	180 (44)	0.0483 (1.34)	8.6 (59)
DuraForm PA / Nylon 12	Plastic	SLS (AM)	171 (43)	0.0361 (1)	6.2 (43)
PerFORM	Plastic	SLA (AM)	161 (40)	0.0582 (1.61)	9.4 (65)

Current Applications

TRL	Source	Description
7	NASA JSC	SERFE flew to test a next generation thermal loop for the space suit. It included a prototype pump that utilized AM titanium with post process machining. This system was tested at vacuum on the ISS and functioned adequately.
7	NASA JSC	This backplate was developed by NASA JSC with Langley research center using traditional machining methods but augmented with generative design for mass removal and Electron Beam Welded (EBM) Channels. Generative design has simplified the design iteration process to come to an optimized solution using automated systems and then verified using traditional methods. The EBM channels have helped reduce complexity by creating a single monolithic part. Additionally, a version of this method was also used and flown on the SERFE project in the vacuum of space and functioned without issue.
5	NASA JSC	Ultem 9085 has been implemented in the Display and Control Unit (DCU) housing for the space suit government reference design. This was tested in the “Suit 2,” a full PGS build, during thermal vacuum testing. It performed without any issues. Another prototype of the DCU housing was explored using Windform SP that was plated with nickel as a proof of concept shown here.
3	Makel Engineering	A multi-gas sensor primarily intended to measure carbon dioxide is being developed for NASA by Makel Engineering. Makel has explored metal AM as a method to create complex internal geometries for the sensor. They looked at mechanical and electrical polishing the sensor to improve the finish and sealing at first, though they are now looking at machining post processing to improve sealing surfaces.
4	Hamilton Sundstrand	A prototype AM heat exchanger for the space suit PLSS was fabricated out of titanium and Inconel using PBF. The sealing surfaces were machined before testing and the heat exchanger functioned adequately. It even had a bit higher effectiveness of heat transfer, thought to be due to the increased surface roughness. This demonstration shows the viability of using PBF in the space suit for complex articles such as these.
3	University of Maryland	An AM elbow assembly from the University of Maryland made from DuraForm PA has been tested at 4.3 psia relative pressure differential. It tested well overall, but there were leaks at the seals. They explored epoxy coating and sanding to improve sealing, but that did not work. Future work is to address some leaks due to surface roughness and to investigate traditional machining for post processing to improve sealing.


Pump Manifold


Backplate


Display and Control Unit Body


Gas Sensor Body


Heat Exchanger


Elbow Assembly

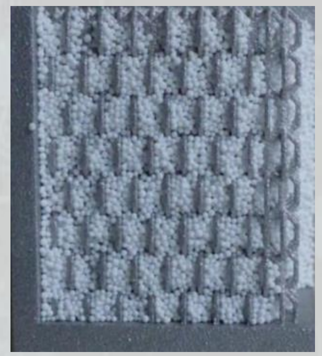
Current Applications

TRL	Source	Description
3	David Clark	Prototype AM for PGS solid portions has been studied by David Clark Company focusing on boots and helmets. These demonstrations indicate the ability for AM to meet the complex shapes needed for the PGS and can meet basic functional requirements through mechanical testing. The research notes this could be expanded to the large Hard Upper Torso (HUT) assembly, though indicates the need for continued materials testing.
9	CRP/ Windform, G.A.U.S.S. Srl, Tetonsys, and others	A Tubesat-POD was developed to launch cube satellites from the ISS. It utilized Windform XT 2.0 as the primary external structure. Two Tubesats were launched with this: Tancredo-1 and OSNSAT. While this is not space suit related, this demonstrates the ability of AM thermoplastics to successfully function for critical deployments in space.
4	Repliform, Pennsylvania State & Formlabs	Repliform in conjunction with Pennsylvania state has been exploring a method of plating AM with a copper/nickel coating to increase the strength of the overall structure. This method uses topology optimization combined with SLA AM to create complex forms, then plated and tested in bending with good results that rival AM PBF aluminum. Future work is needed to develop predictive models using this method and integrate it into hardware.
4	Reaction Systems	Reaction Systems has been exploring a method to create a lattice for the Rapid Cycle Amine (RCA) swing bed using AM. The figure shows a cross section of the amine beads in the AM lattice.
9	SpaceX	SpaceX conducted their Polaris Dawn mission with their suits that used polycarbonate AM as the base material for their helmet.

Spacesuit Helmet – David Clark

CubeSat Deployment

Plating AM Thermoplastic

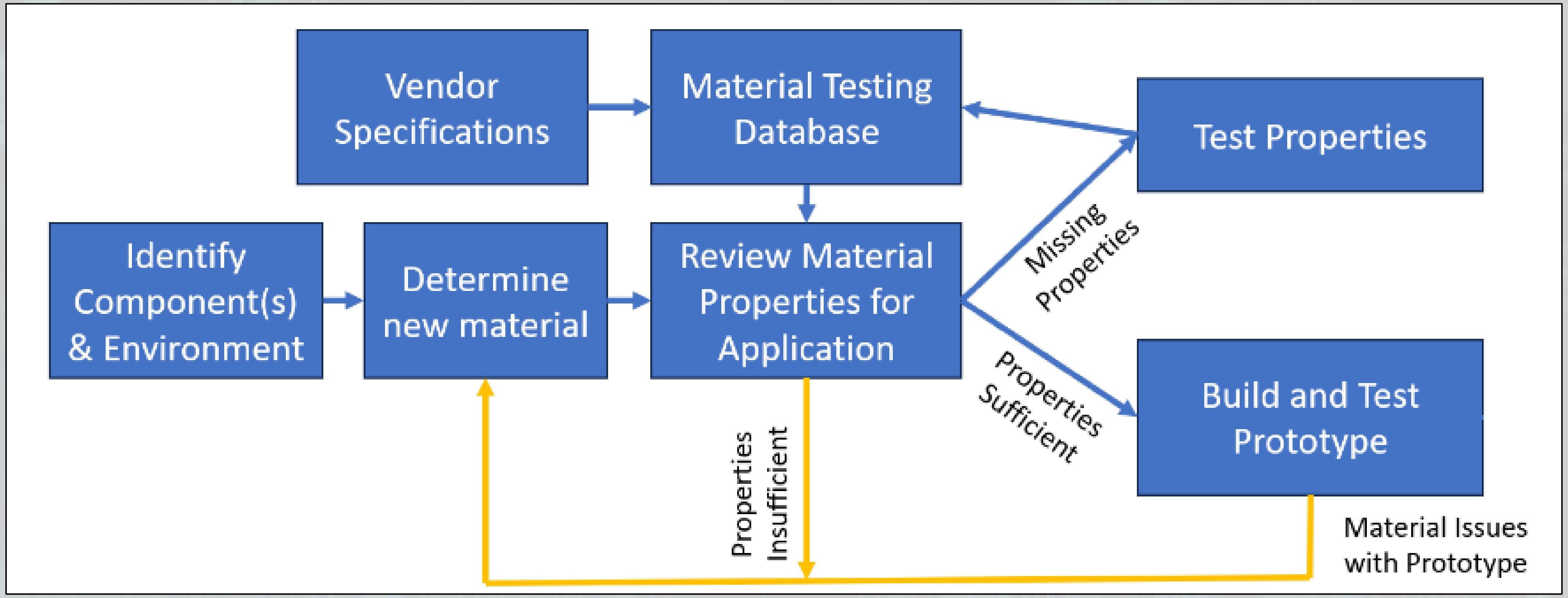


Lattice Sorbent Bed

Spacesuit Helmet – SpaceX

Testing Plan

- To raise the TRL of the materials considered, an infusion path is defined
  - Identify environment
  - Consider new materials for infusion
  - Review existing materials properties from material database and vendor specifications
  - Identify material testing gaps
  - Test materials and update database
  - Build and test prototypes



Testing Plan and Infusion Path

Applications

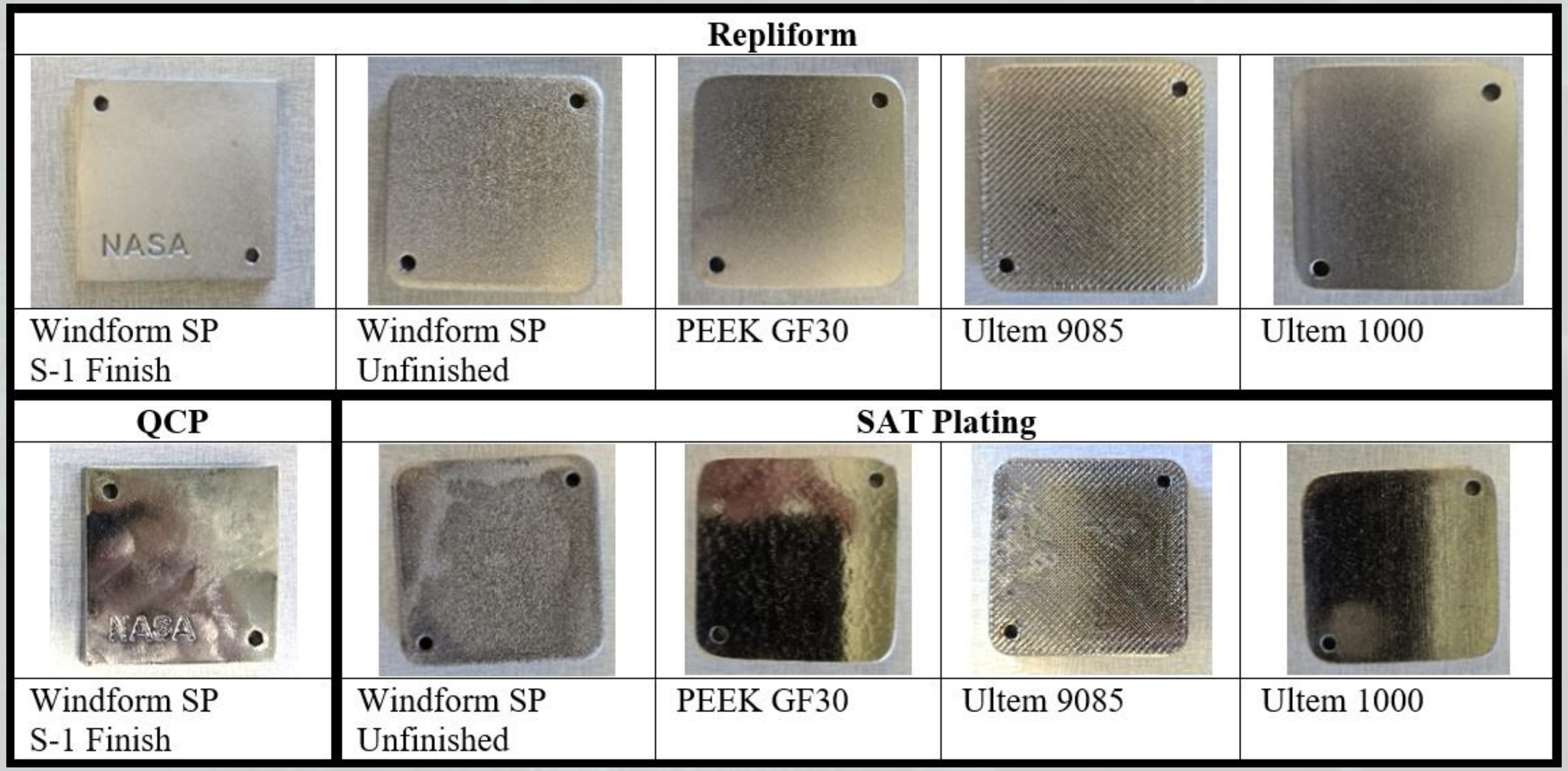
- **Ventilation System**
  - Consists of manifolds, fans, CO_2 removal systems and associated housings, and heat exchangers.
  - Thermoplastics could be integrated to replace the pressure-holding elements
  - Special attention should be paid to the 100% oxygen requirement
- **Thermal Loop System**
  - Consists of pumps, housings, water evaporator, heat exchanger, check valves, and associated tubing.
  - Thermoplastics could be used to replace any non-active, pressure holding elements in the water loop.
  - Special attention and testing should be conducted to verify the iodinated water is compatible with the material chosen and the material does not leach into the water loop
- **Avionics and Power**
  - Consists of multiple avionics boxes and battery housings
  - Could be replaced with thermoplastics as they do not hold a lot of stress
  - Special attention should be paid to EMI, thermal, and bonding requirements
- **Structure**
  - Holds all the other components of the PLSS together
  - Brackets could be switched to thermoplastics
  - Special attention should be paid to galvanic compatibility between the primary structure and the associated brackets

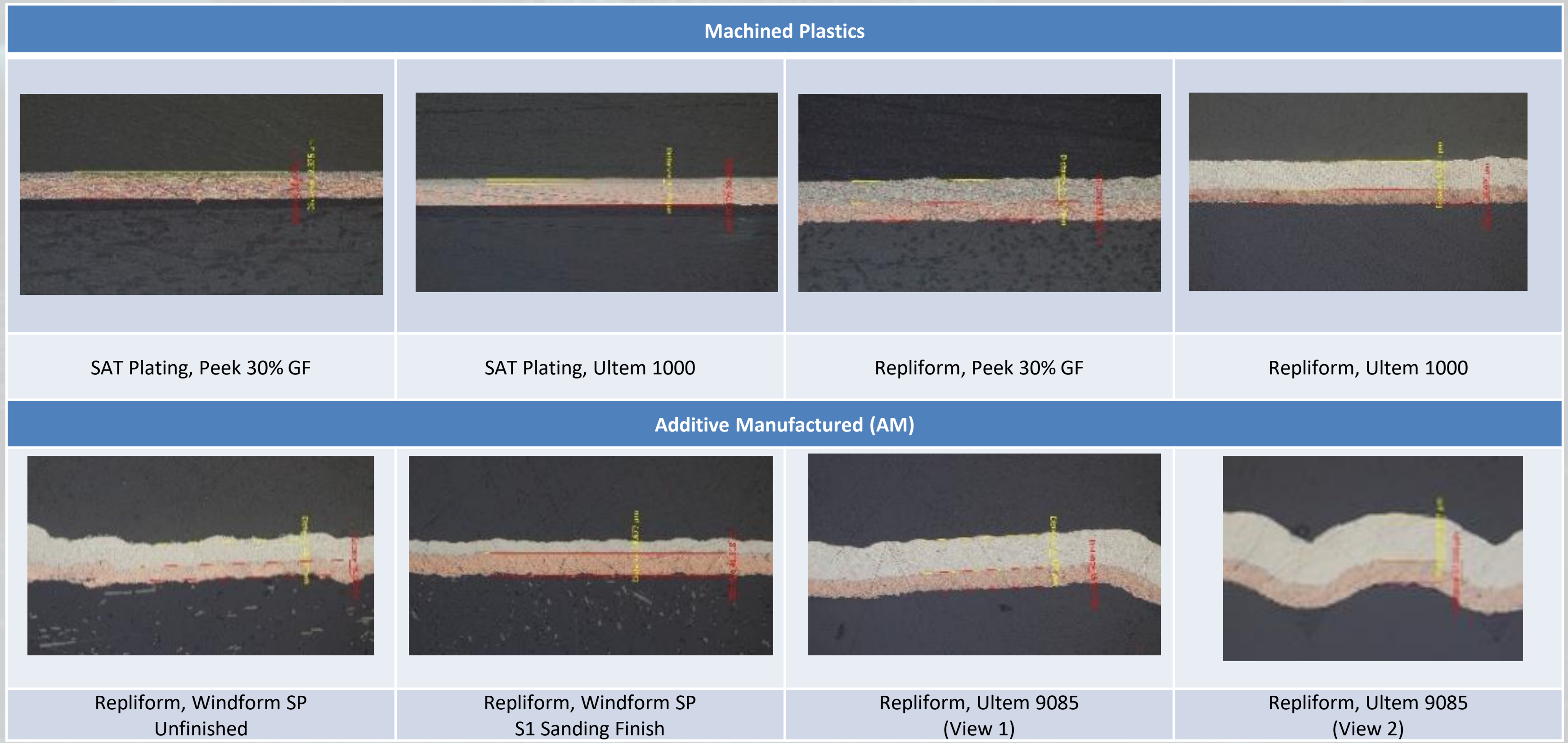
Materials and Standards for Testing

- **Initial Materials Selected for Testing**
  - Carbon Filled Thermoplastics
    - PEEK CF30 (MIL-P-46183)
  - Glass Filled Thermoplastics
    - PEEK GF30 (MIL-P-46183) and Ultem (PEI) 2300 (MIL-P-46184)
  - General Thermoplastics
    - PEEK Natural (per MIL-P-46183) and Ultem (PEI) 1000 (per MIL-P-46184))
  - Additive Manufactured Thermoplastics
    - Windform SP (Nylon 11 +CF) (AM) and Windform XT 2.0 (Nylon 12 +CF) (AM)
- **Recommended supplemental testing for advanced materials in spaceflight**
  - General Thermoplastic Tests
    - ASTM-D4065 – Dynamic Mechanical Analysis (DMA) for temperature performance
    - ASTM-D256 – Izod Impact Test
    - ASTM-D7332 – Pull out test for fasteners
    - ASTM-D3846 – Shear strength of plastic
    - ASTM-D570 – Water Absorption Tests
    - ASTM-E328 – Creep Test
    - ASTM-D2863 - Oxygen Index
    - ASTM-E595 – Outgassing
    - NASA-STD-6001B – Off gassing/toxicity
  - AM Testing
    - ASTM-D638 - Tensile test in multiple print orientations (X-Y/ Z)
  - Plating Testing
    - ASTM-D7127 – Surface Roughness
    - ASTM-C177 – Thermal Conductivity
    - ASTM-D638 – Tensile Properties
    - ASTM-D4935 – EMI Testing

Plating Preliminary Results

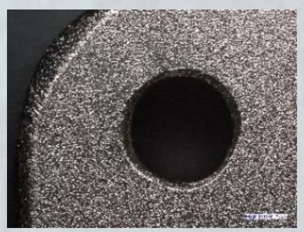
- Multiple vendors were tested for plating thermoplastics
  - Electroless nickel was applied at a 0.003" thickness
  - An underlayer of copper is common for electroless nickel plating
  - Sanding on 3D printing prior to plating substantially improved results
- Samples were mounted to measure plating accuracy
  - Finish closely follows original surface finish
  - Sat plating – AM – incomplete plating
  - SAT plating – Machined – 43-44% diff.
  - Repliform – AM – 14-33% diff.
  - Repliform – Machined – 7-15% diff.
  - Repliform performed most consistently for all materials



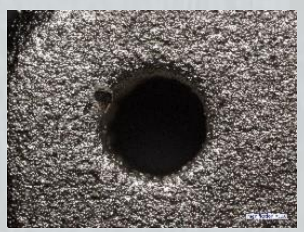


Cut plated samples

Ultem 9085



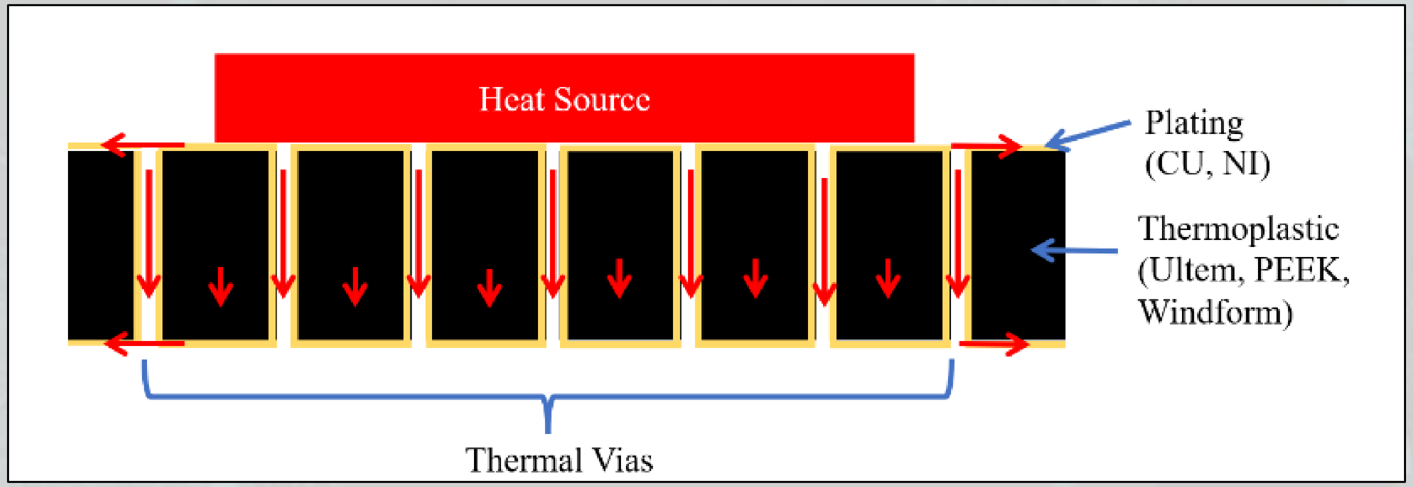
PEEK 30% GF



Windform SP unfinished

Plating Thermal Testing

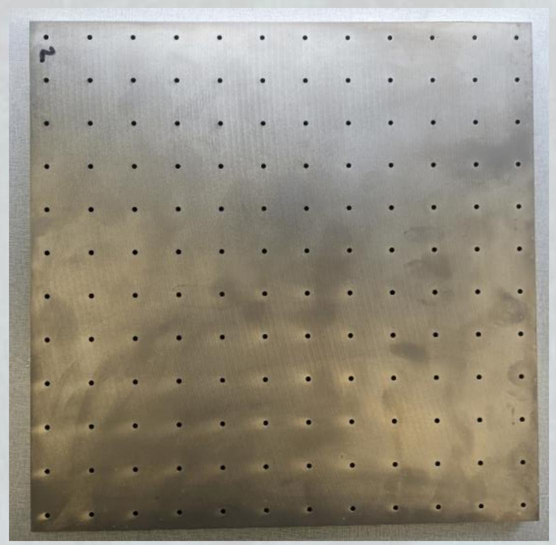
- Plating improves thermal conductivity by implementing "Thermal Vias"
  - Thermal Vias: plated holes through base material to improve thermal conductivity
  - Using thermal resistance equations for a steady 1-D system an approximation of heat transfer can be calculated
- Ultem 1000 material was machined with holes in a 1 ft x 1 ft panel
  - Thermal Conductivity was tested using ASTM C-177
  - Number of holes was varied from 0, 25, and 144
- Results showed lower performance than estimated
  - Plan to verify with a second test



Thermal Vias Diagram

# Holes	Specification	Predicted Thermal Conductivity (W/mK)	Results
-	Ultem Vendor Specification [19]	0.122 (specification)	N/A
0	Plated 0.003"	0.124	0.119
25	Plated 0.003"	0.164	0.122
144	Plated 0.003"	0.361	0.151

$$R_{th} = \frac{\Delta x}{k\,A} \quad (1) \quad | \quad R_{th,total} = R_{th,1} + R_{th,2} + R_{th,3} + \cdots + R_{th,N}$$



Thermal Vias Plate

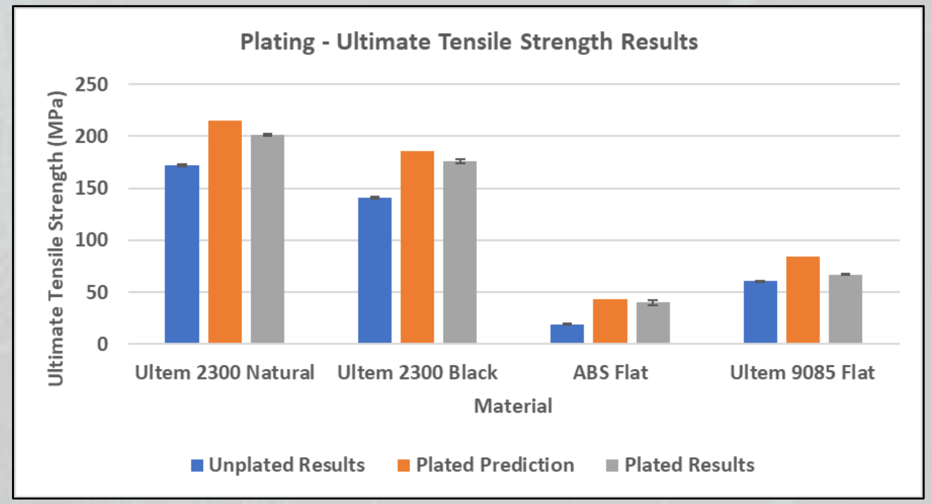
Materials	Tensile Modulus (GPa)	UTS (MPa)	Thermal Conductivity (W/mK)
Structural Copper [16]	90	370	401*
Ductile Nickel [16]	140	860	90.7*
Hard Nickel [16]	146	1558	90.7*
Ultem 2300 [18]	10.4	175	0.31
Ultem 1000 [19]	3.35	115	0.122

Material properties used in plating

Plating Pull Testing

- Plating improves overall tensile properties
  - Provides a thin, but strong outer layer of metal on the plastic
  - Was evaluated for both tensile and bending performance
- Composite material properties could be approximated using the rule of mixtures
  - Combines fractions of the different materials
- Dog bone samples were procured and plated with different thicknesses from two different test series
  - Results matched closely to predicted values – 6%-22% difference overall depending on material
  - Ultimate Tensile Strength (UTS):
    - 17% increase for 2300
    - 22% increase for Ultem 9085
    - 108% increase for ABS
  - Tensile modulus was a little higher than predicted while UTS was a little lower
- Higher plating thicknesses could be used to improve strength more

Plated Dog Bone Sample in Tensile Test

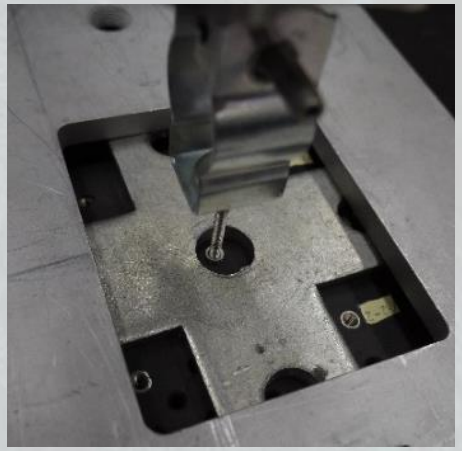


$$E_C = f\,E_1 + (1-f)E_2$$

Cross section of dog bone (not too scale)

Insert Pullout Testing

- Inserts are recommended for usage in thermoplastics to improve pull out strength for bolts
  - Heat inserts and helical inserts were tested
  - Inserts are installed and bolts are pulled using a tensile test machine
- 3 different methods were used depending on the test series
- Insert typically fails in shear against the material
  - This could be used to estimate the pull-out strength; however, shear strength data must be available
- Heat inserts may often bead up against the surface during installation



Many Inserts in Plate

Single Insert in Plate

Single Insert in Cylinder

Heat Insert after Pull Out

Helical Insert after Pull Out

Impression Left in Material from Heat Insert Pull Out

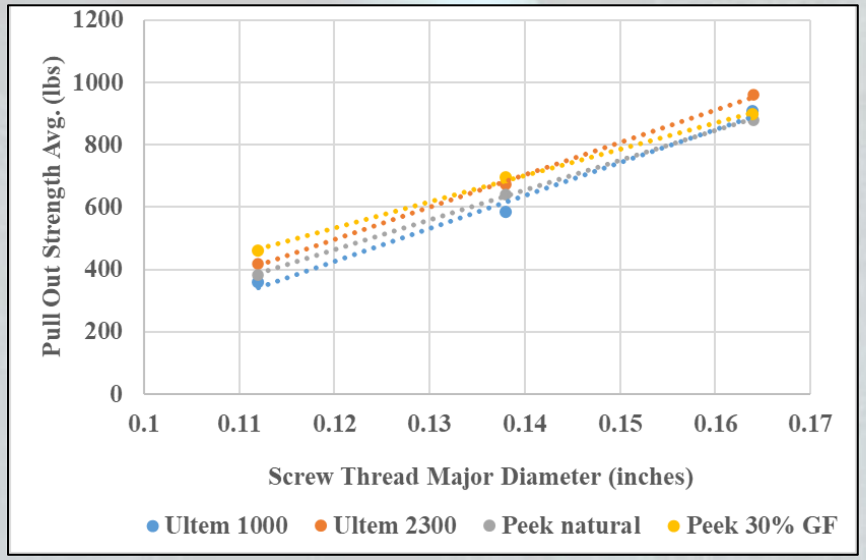
$$\textit{Helical Insert Pull out Strength}\ (lbs) = \left(\frac{\pi * D_m(in)}{TPI} * \%Shear * N\right)_{Area} * \textit{Shear Strength}$$

Insert Pullout Results

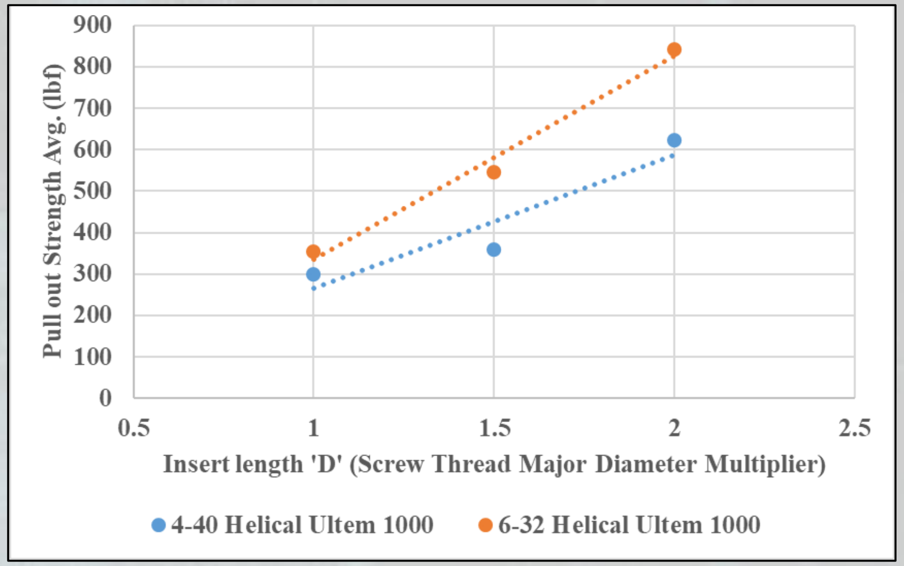
- Heat Insert and Helical Insert data is shown
  - Glass filled material did not allow for installation of some heat inserts even at high temperatures
- Helical inserts vs Heat inserts do not show a large difference relative to similar lengths and diameter
  - Ultem 1000 .219” 4-40 heat insert (634 lbs) vs .224” 4-40 helical insert (622 lbs)
  - Ultem 1000 .250” 6-32 heat insert (807lbs) vs .276” 6-32 helical insert (843lbs)
- Quality of insert installation is critical to achieve consistent results
- Linear relationship with pull out strength and major diameter and insert length
- Helical inserts recommended over implementing heat inserts
  - Removes potential for bead up, improved consistency, can be installed in glass filled plastics, and can be replaced

Hole Size	Type	Length/code	Ultem 1000 Black lbs‡	Ultem 2300 Black lbs‡	Peek natural lbs‡	Peek 30% GF lbs‡	Windform SP lbs‡
4-40	Heat Set	0.135" (IUC-440-1)	-	*	-	*	138 (10)
4-40	Heat Set	0.219" (IUC-440-2)	634 (30)	*	660 (24)	*	232 (25)
6-32	Heat Set	0.150" (IUC-632-1)	-	*	-	*	163 (22)
6-32	Heat Set	0.250" (IUC-632-2)	807 (18)	*	863 (55)	*	362 (38)
8-32	Heat Set	0.185" (IUC-832-1)	567 (52)	*	614 (56)	*	220 (43)
8-32	Heat Set	0.312" (IUC-832-2)	-	*	-	*	347 (20)
4-40	Helical	0.112" (1D)	300 (7)	-	-	-	-
4-40	Helical	0.168" (1.5D)	358 (43)	420 (38)	383 (85)	459 (82)	-
4-40	Helical	0.224" (2D)	622 (37)	-	-	-	-
6-32	Helical	0.138" (1D)	353 (33)	458 (60)	-	-	-
6-32	Helical	0.207" (1.5D)	582 (33)	672 (120)	641 (34)	694 (84)	366 (12)
6-32	Helical	0.276" (2D)	843 (49)	-	-	-	-
8-32	Helical	0.246" (1.5D)	908 (129)	960 (76)	880 (37)	897 (119)	-

*Could not gather data or not recommended for installation
‡Data for table above is shown as: Average - lbs (standard deviation- lbs)



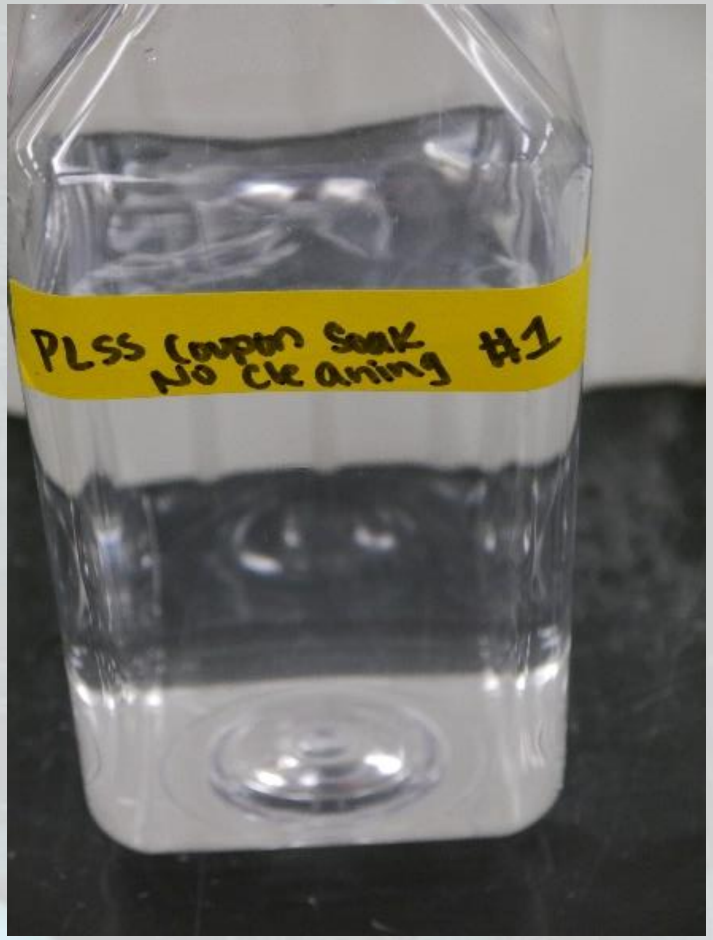
1.5D Helical Insert Pull Out Strength vs Diameter



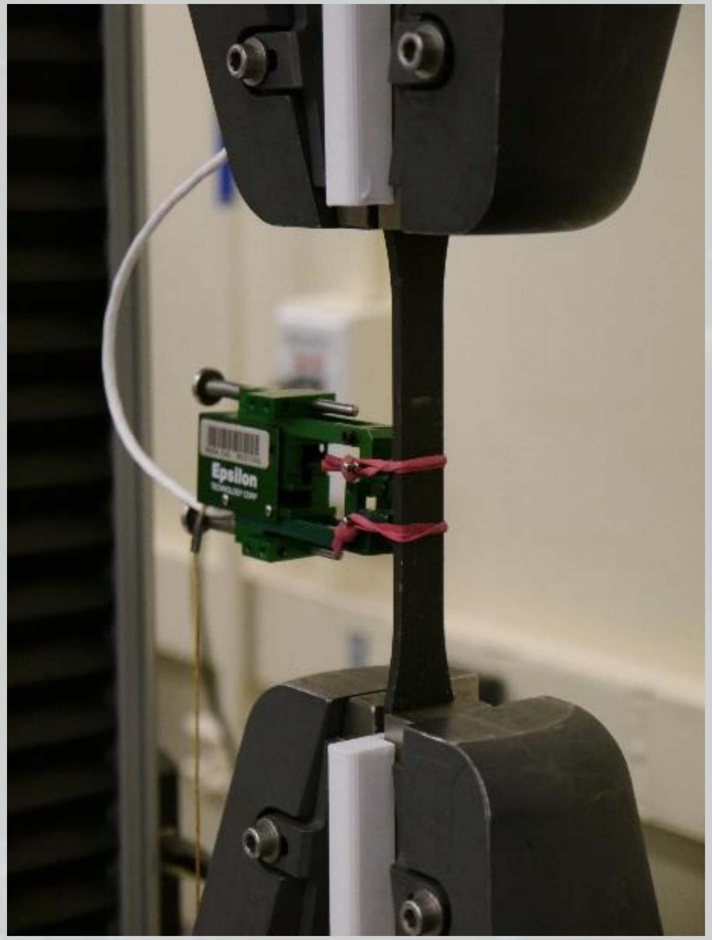
Ultem 1000 Insert Pull Out Strength vs Length

Water Absorption and Pull Tests

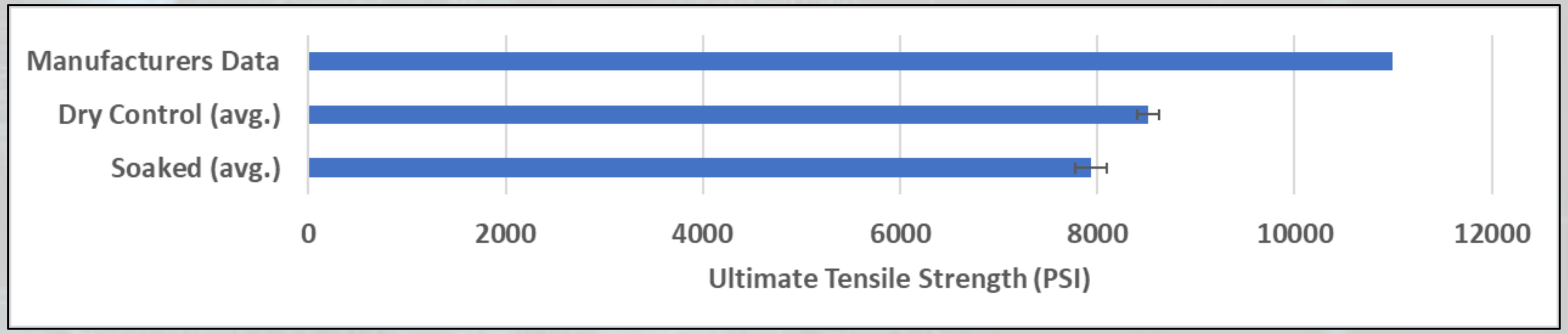
- For water loop components, materials are subjected to a continuous soak of water
  - Evaluated tensile and weight properties for Windform SP
- Procedure:
  - Type I dog bone samples procured for Windform SP
  - Samples were measured prior to soak for weight, and a set of samples was tensile tested to failure
  - Samples were soaked in water
  - Weight was measured after, and tensile test was run again
- Results:
  - 0.1% change in weight
  - 7% decrease in tensile strength



Deionized Water Specimen Container



Tensile Test



Water Absorption and Pull Test Data

Forward Work

- Materials Testing
  - Complete all tests identified to close material gaps for thermoplastics
  - If plating is chosen, the same tests and plating evaluation tests will need to be repeated with plated materials
  - Complete additional AM tests to improve maturity of AM and allow it in criticality 1 locations
  - Material testing should raise TRL level of associated material in spacesuit context to TRL 3/4
- Hardware Infusion
  - Identify PLSS components in which materials could be replaced for thermoplastics
  - Machined thermoplastics should be considered for low complexity parts
  - AM components should be considered for complex parts and novel methods which cannot be made with traditional machining methods or reduce cross drills to lower leakage opportunities
  - Infusion will help raise TRL to 5/6 of the material in a relevant environment

Conclusion

- Advanced materials should be included in future suit designs to lower overall mass of the suit
  - PEEK and PEI (Ultem 1000) should be considered as replacements for metallic parts
  - Glass Fill and Carbon Fill may be added to improve strength, and improve thermal and electrical properties of the material
  - Plating may be added to improve electrical, mechanical, and thermal properties
- Material testing is required to quantify critical spaceflight properties for infusion
  - Cryogenic temperature mechanical properties, pull out of insert, water absorption, creep, oxygen index, and others
  - For infusion and testing, machined thermoplastics should be prioritized first to close the gap of material data
  - AM material testing should be conducted in parallel to improve maturity of AM for integration in criticality 1 locations
- Initial testing was conducted
  - Repliform showed good preliminary results for plating thermoplastics both machined and AM
  - Heat inserts and helical inserts performed similarly performance wise
    - Helical inserts preferred for installation benefits
  - Water absorption tests show only a minor decrease in tensile strength for Windform SP (AM)

Thank you!

Questions?

Please see associated paper for references

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