Process Development and Testing for Lunar Habitats

Presented by Chelsea Pickett, NASA Materials Engineer, for the 2025 Composite Materials and Structures Conference

Overview

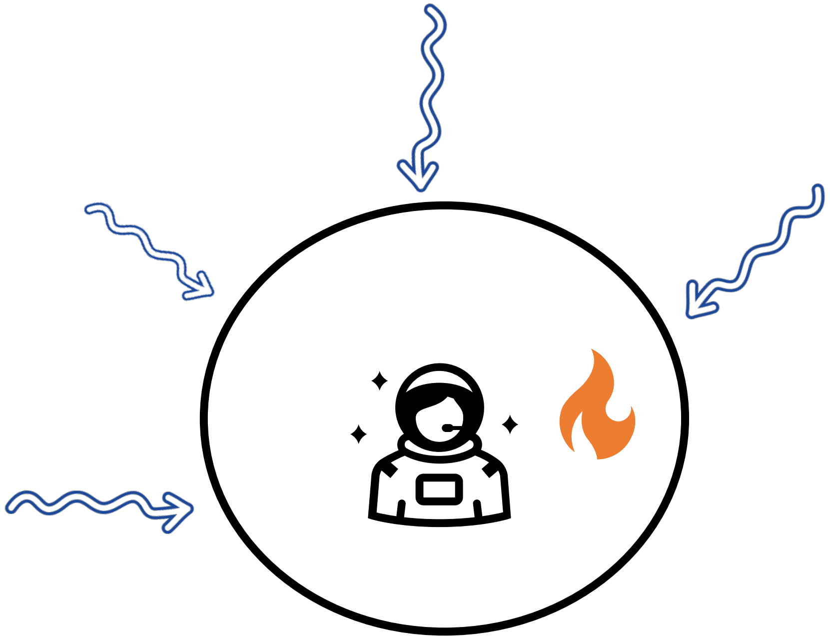
- Background
- Methodology
- Process Development
- Test Results
- Conclusions

Background

Problem Statement

Polymer matrix composite materials may not initially be considered for lunar habitats due to unknown flammability risks and performance in a radiation environment.

This work evaluates several candidate composites.



Lunar Habitat Material Selection

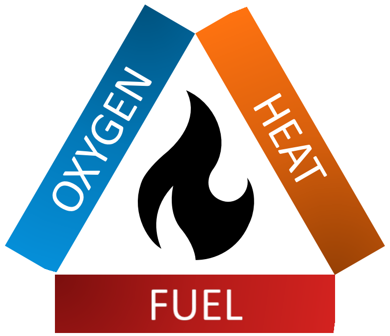
- Many early concepts for lunar habitation feature metallic walls. Metallics have significant heritage use in space structures (ex. ISS modules).
- Polymer matrix composites (PMCs) may be an attractive alternative to the heritage solution due to weight savings and potential radiation shielding capabilities.
- Material selection involves consideration for the target use environment. Two concerns for PMC material choices are:
    1. Internal environments – future space habitats are anticipated to have higher oxygen concentrations
    2. Susceptibility to radiation – material performance may be affected by the unique radiation environment of the lunar surface

Example of a surface habitat concept. Image credit: NASA

Flammability

Consider the three legs of the fire triangle when assessing PMC materials for a space habitat:

- Heat sources in a lunar habitat can be minimized and mitigated, but are necessary (ex. computers, heating).
- Polymeric materials are generally good fuel, although highly engineered PMC matrix materials are more likely to have lower combustion rates.
- The proposed oxygen concentration for Lunar space habitats could be as high as 37%.

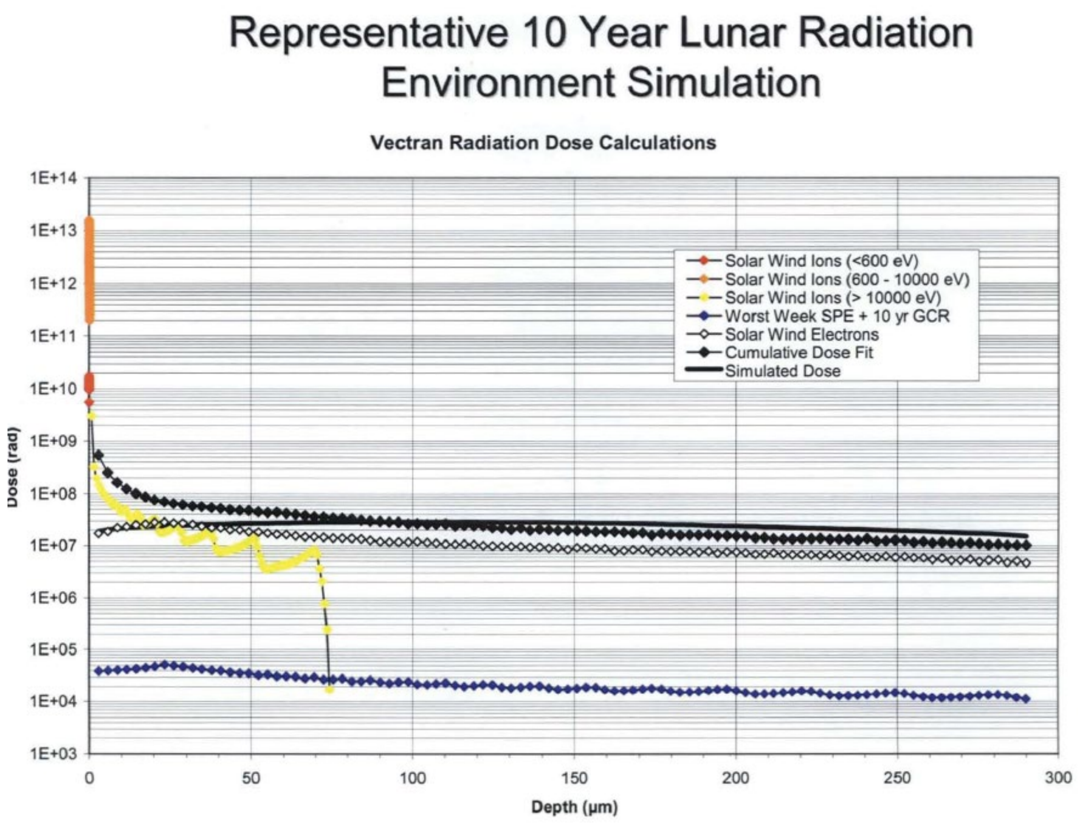


Past NASA Flammability Environments

- Apollo: 100%
  - At least one fatality at this level
- Skylab: 70%
- Shuttle: 30%
- Commercial Crew: 30%
- ISS Airlock: 30%
- ISS = 24.1%

For reference, oxygen concentration on Earth is approximately 21%.

Radiation Environment

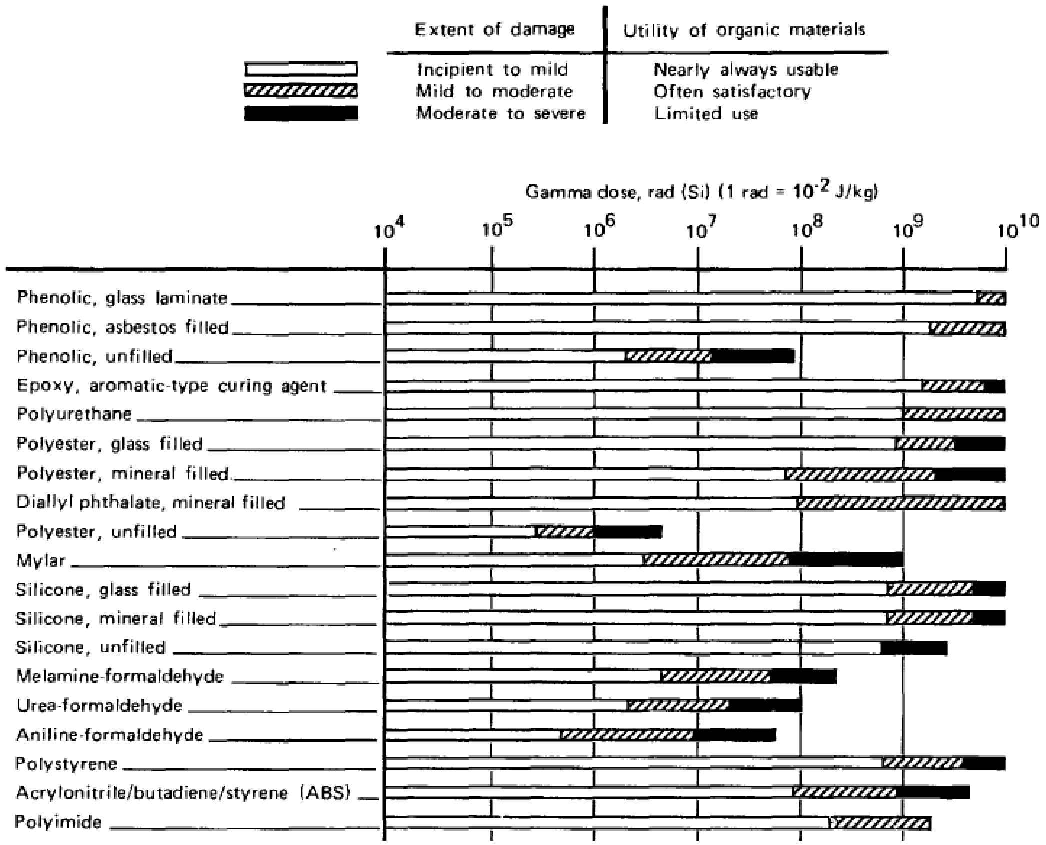


Source: Gwenyth Smithers et. al "A One-piece Lunar Regolith-bag Garage Prototype", 2007

- The lunar surface radiation environment is contributed to by several sources: solar particle events (SPEs), solar wind and galactic cosmic rays.
  - Further characterization of space radiation can be found in SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE).
- The graph at the left summarizes the contributions and cumulative effect of these types of radiation as a function of depth. This dose calculation was created to simulate a 10-year lifetime for fabric building materials.
  - A dose is the amount of radiation that interacts with a material.

Radiation Effects on PMCs

- Radiation interaction with polymeric materials begins with creation of new crosslinks. Once all crosslinking sites have been exhausted, radiation can result in destruction of existing bonds – chain scission. Whereas crosslinking may result in higher material stiffness, chain scission will ultimately yield the opposite effect.
- For ceramics (PMC reinforcement), no radiation interaction is expected at <1E9 rad.



Source: NASA SP-8053 Nuclear and Space Radiation Effects on Materials, 1970

Methodology

Test Objectives

Flammability Testing

Screen candidate materials to inform oxygen compatibility assessment.

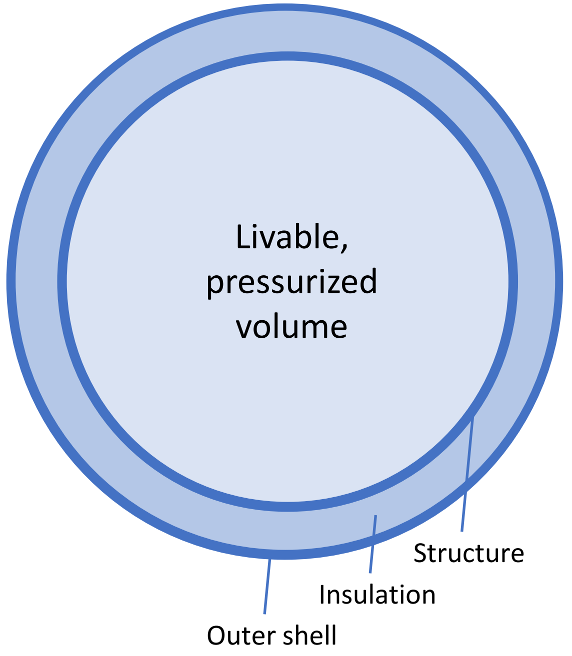
Mechanical Testing of Radiation Effects

Expose candidate materials to a 10-year radiation dose and use mechanical testing (open hole tension) to determine if degradation might be significant.

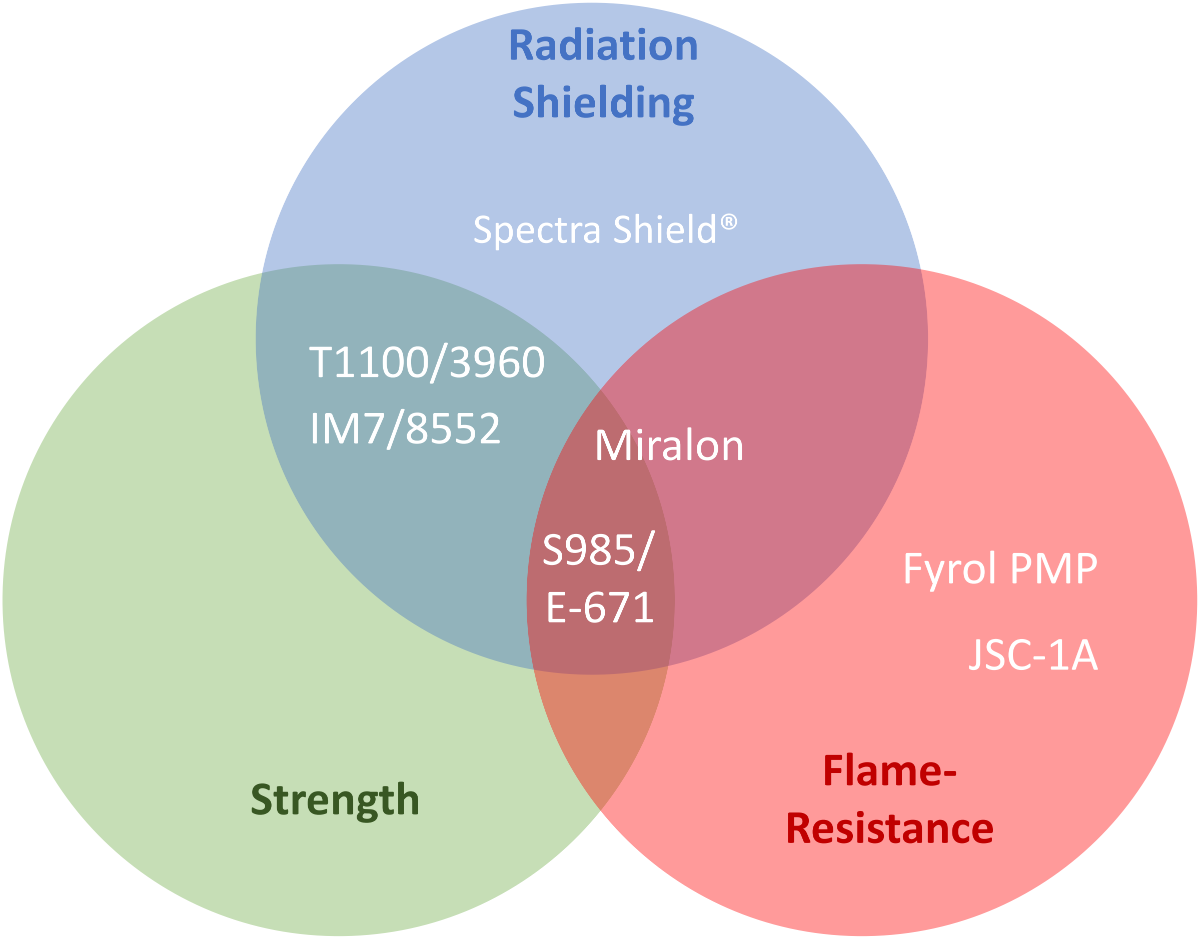
Habitat Layers

- A lunar habitat design may need to incorporate multiple layers to support various functions, such as:
  - Micrometeroids and orbital debris protection
  - Thermal insulation
  - Pressurized, oxygenated environment
- These layers may also have coatings or finishes.
- PMCs may serve a role in some or all habitat layers that exist in a particular design.

Notional layers of a lunar habitat



Material Selection



Selection was also influenced by minimum order quantity and leadtime. Some materials selected had already been purchased for similar applications.

T1100/3960: carbon fiber/epoxy

IM7/8552: carbon fiber/epoxy

S985/E-671: Spectra® fiber/epoxy

Spectra®: UHMWPE fiber

Spectra Shield®: Spectra fiber/PE film

Miralon: carbon nanotube film

Fyrol PMP: flame-resistant additive for epoxy

JSC-1A: regolith simulant

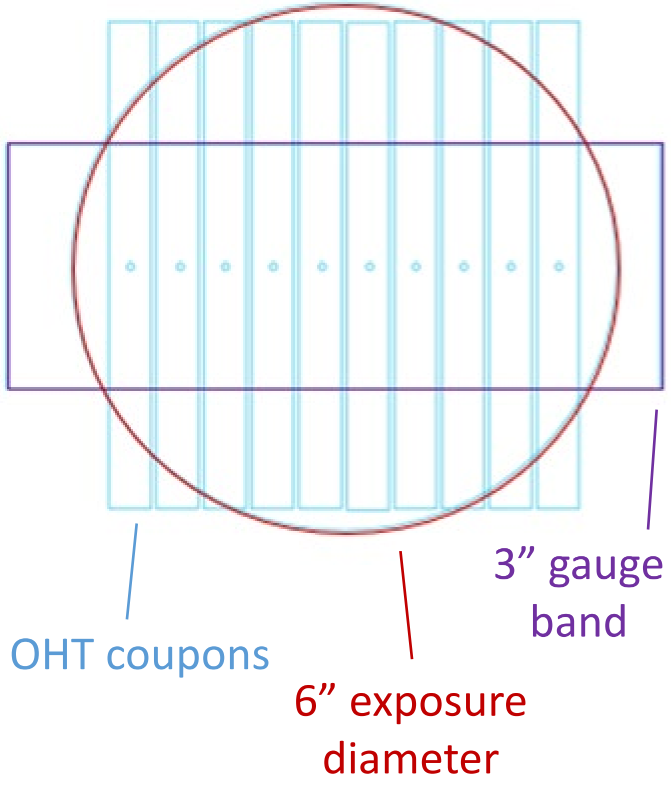
Test Panels

Panel	Material 1	Material 2	Material 3
T-R	T1100/3960		
TM-R	T1100/3960	Miralon	
I-R	IM7/8552		
SM-R	Spectra Shield	Miralon	
E-F	E-671/S985		
I-F	IM7/8552		
T-F	T1100/3960		
~~E-30F~~	~~E-671/S985~~	~~Fyrol PMP~~	
~~E-40F~~	~~E-671/S985~~	~~Fyrol PMP~~	
~~E-50F~~	~~E-671/S985~~	~~Fyrol PMP~~	
S-F	Spectra Shield		
SM-F	Spectra Shield	Miralon	
SJ-F	Spectra Shield		JSC-1A
SMJ-F	Spectra Shield	Miralon	JSC-1A

- Panel nomenclature: R or F suffix for either radiation or flammability testing
- Panel layup: 8-ply, quasi-isotropic $[0_f/45_f]_{2s}$
- Panels were cured per manufacturer's recommendations:
  - 3960 resin system at 50psi and 355°F
  - 8552 resin system at 50psi and 350°F
  - E-671 resin system at 60psi and 255°F
  - Spectra Shield at 50psi and 200°F (Exception: SJ-F)
- Results from panels with Fyrol PMP are not included, as the necessary cure temperature to cross-link with the epoxy was not reached.

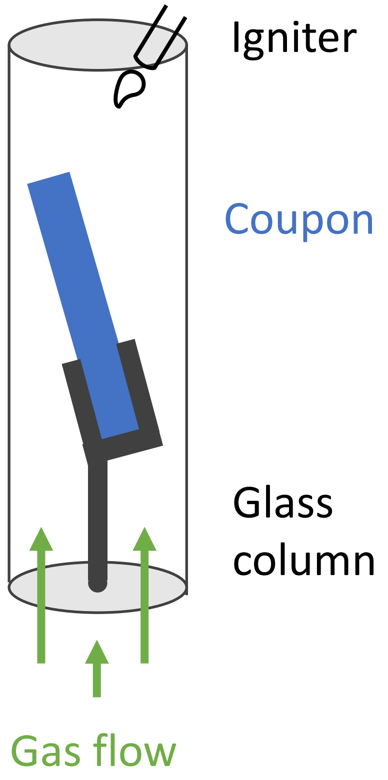
Radiation Exposure

- Radiation exposure occurred in two passes:
  1. Combined near ultraviolet (NUV) and vacuum ultraviolet (VUV) radiation
  2. Electron particle radiation
- UV had the most restricting exposure window of 6-7” diameter. Open hole tension (OHT) coupons were scaled down from standard ASTM D5766 dimensions to fit the gauge area and therefore minimize the number exposure runs.
- All OHT coupons fit within the electron particle exposure window for a single exposure run.



Flammability Testing

- Limiting Oxygen Index (LOI) testing is a useful screening test for determining the minimum oxygen concentration at which combustion occurs. Testing is performed per ASTM D2863 "*Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)".*
  - Combustion: >50mm burn length or >3-minute duration
- Coupons are held in a glass column which is flooded with pre-mixed oxygen, air and nitrogen. An ignitor is inserted from the top of the column, close enough to the coupon to propagate flame (if the conditions are right).
- LOI results cannot be used for "absolute prediction of oxygen compatibility "(NASA-STD-6001) but does provide a starting point for other flammability testing required for oxygen compatibility assessments.



Process Development

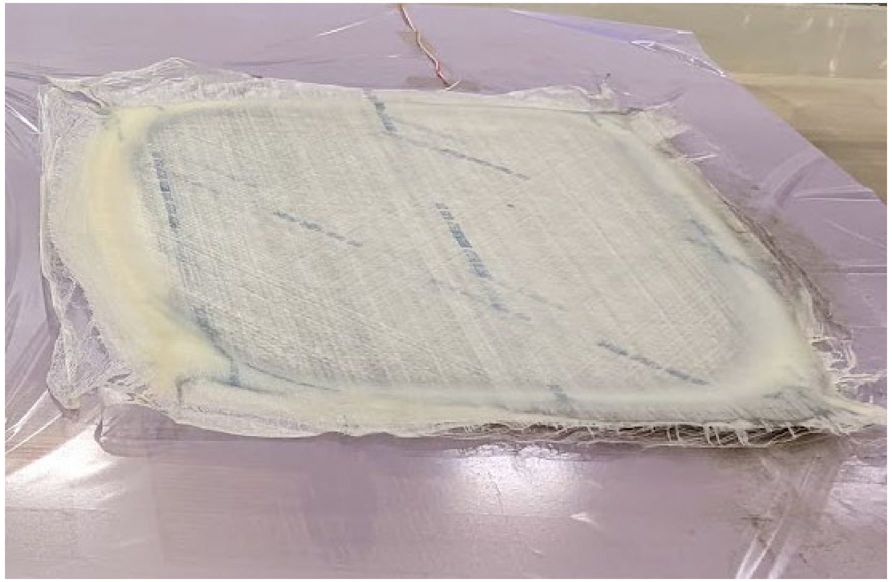
Regolith Adhesion

Water-based coating with sodium silicate binder applied with roller to prepared metallic substrate.

Result: coating flaked off.

Laser cladding using directed energy deposition on various substrates.

Result: coating flaked off.



High temperature (300°F) and pressure (75psi) cycle of Spectra Shield layup with regolith powder underneath.

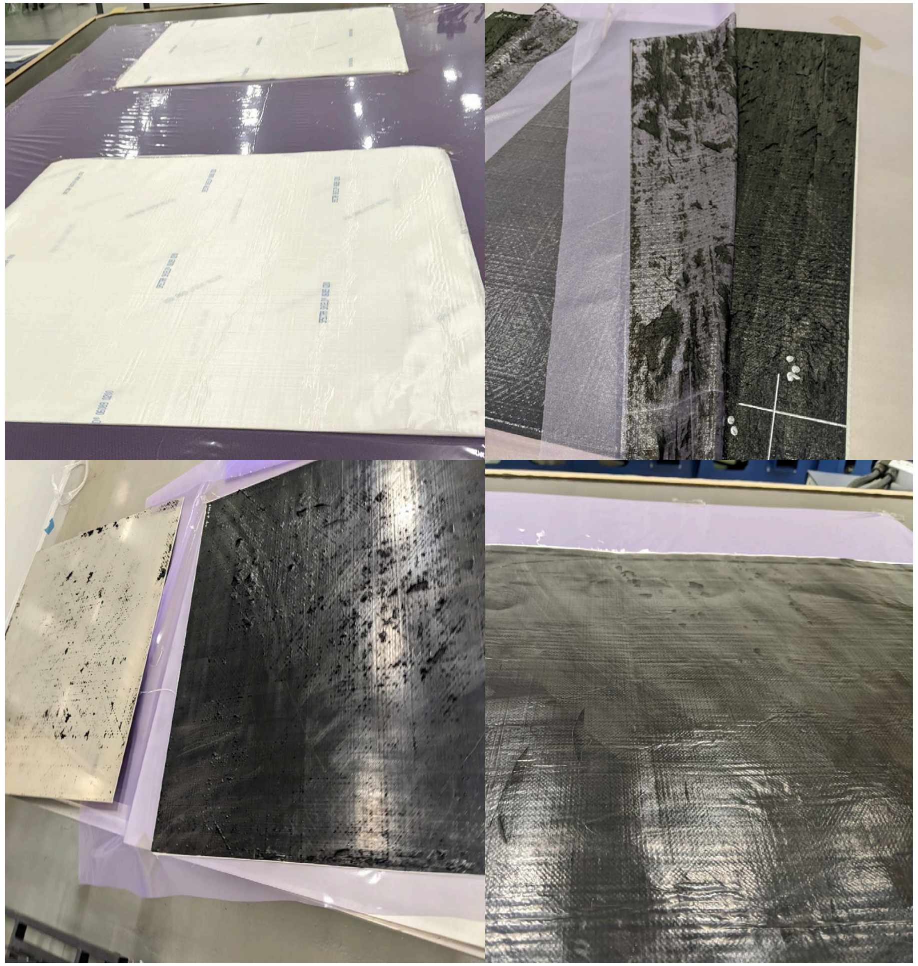
Result: a light level of simulant adhesion was achieved but substrate material was negatively affected.

Fyrol Challenges

- Fyrol PMP requires a 350°F+ cure to properly react with the epoxy. This makes it unsuitable with composites with both a polymeric matrix and reinforcement, such as S985/E-671. S985 is a thermoplastic reinforcement (UHMWPE) with an approximate melt temperature of ~300°F.
- Fyrol was also difficult to incorporate: no instructions were given other than a minimum melt temperature of 160°F. The material was not miscible until the solvent (epoxy) was also raised to an equivalent temperature, however. Additionally, the exact ratio of Fyrol PMP is epoxy-dependent which necessitates more testing to determine the optimal ratio.
- The Fyrol-epoxy mixture required hand-application to substrate panels (best achieved with a squeegee) whereas normally additives are incorporated during composite pre-pregging (highly automated).

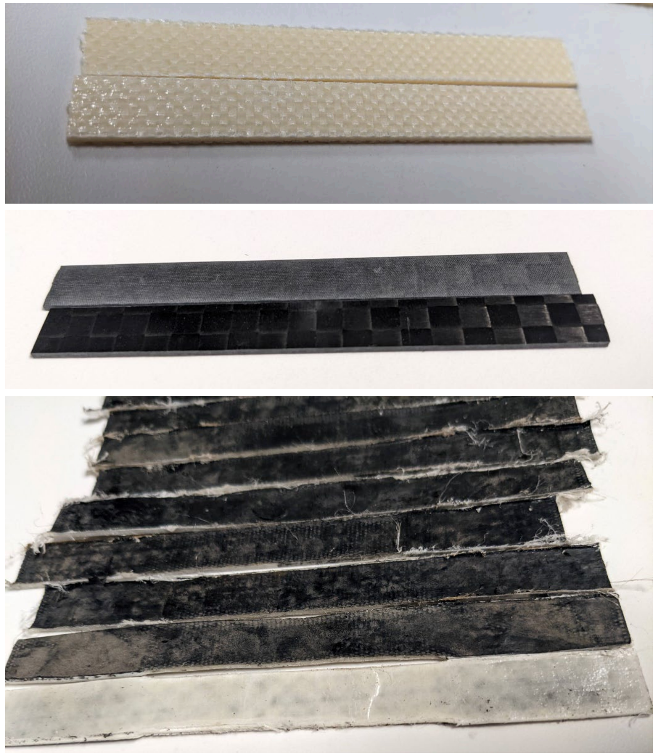
Miralon Adhesion

- The low surface energy of polyethylene typically makes coating/bonding challenging.
- During layup, the Miralon film conformed to the Spectra panels with only hand pressure/warmth. However, after cure, some of the Miralon film stuck to the release film used for bagging. Release film is also typically low surface energy as well, so this was an unexpected result.
- Modifying the bagging sequence with a metallic caul plate improved but did not eliminate the condition. Energetic surface treatment on both Miralon and Spectra mating surfaces produced the best results.



From Panels to Coupons

- Carbon fiber-based panels were cut with a diamond-coated circular saw and edge mill.
- Spectra Shield panels could not be cut with a saw due to high thermal expansion.
  - Uncoated Spectra Shield and Spectra/epoxy panels were cut with a waterjet.
  - Spectra with Miralon and regolith could not be cut with a waterjet due of the fragile state of the material. Coupons were cut using a die press and industrial scissors.



Test Results

Strength Change from Radiation

The epoxy-matrix coupons saw a small reduction in average ultimate tensile strength from open hole testing.

The Miralon film on T1100/3960 appears to have counteracted this effect and further *improved* strength performance.

Spectra Shield also saw a reduction in strength – much more significant than the epoxy composites.

	% Change from Control to Irradiated	In-family?*
IM7/8552	-4%	Yes
T1100/3960	-7%	Yes
T1100/3960/Miralon	+8%	Yes
Spectra/Miralon	-70%	No

*In-family testing was performed using the Anderson-Darling test with α=0.25.

Modulus Change from Radiation

The epoxy-matrix coupons saw a small reduction in average tensile modulus from open hole testing.

The Miralon film on T1100/3960 also appears to have been vulnerable to the modulus decrease from radiation.

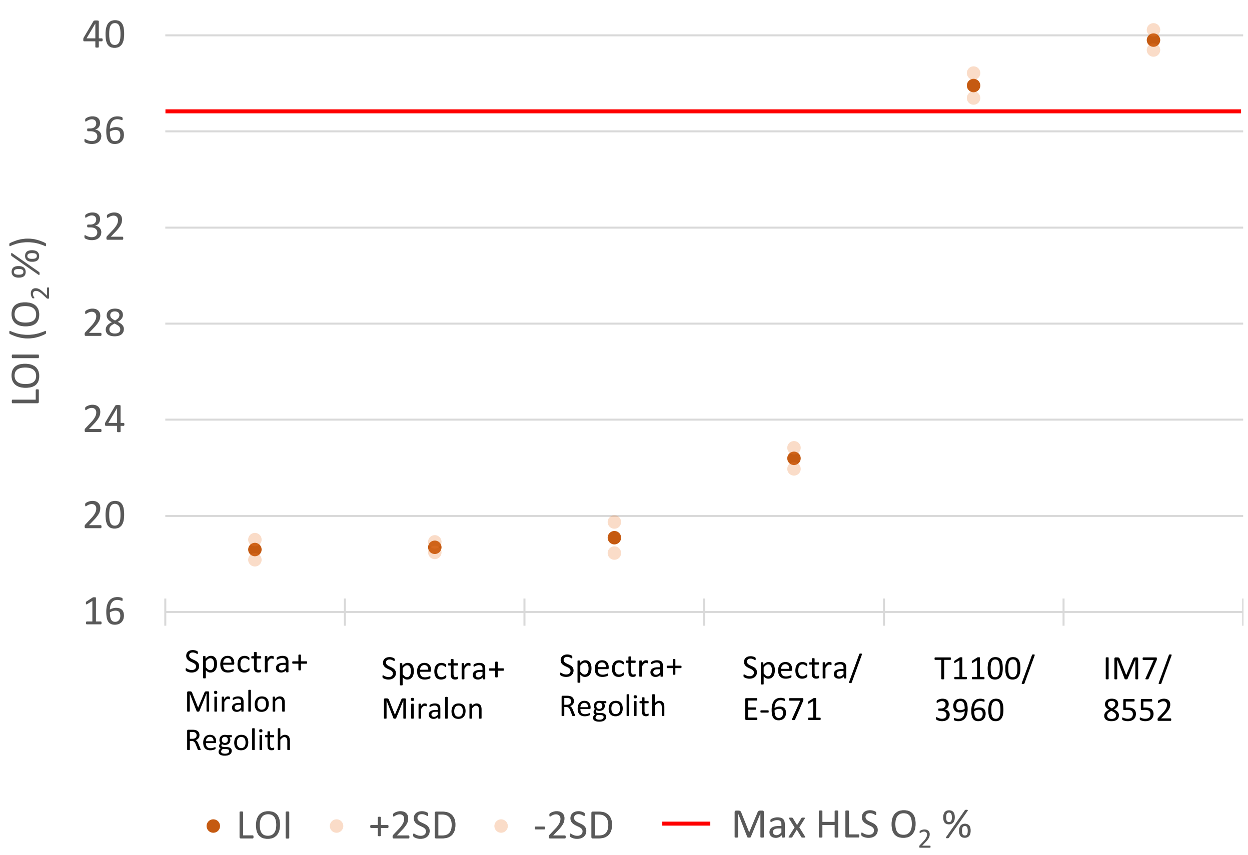
Spectra Shield saw a substantial reduction in modulus.

	% Change from Control to Irradiated	In-family?*
IM7/8552	-1%	Yes
T1100/3960	-6%	Yes
T1100/3960/Miralon	-8%	Yes
Spectra/Miralon	-85%	No

*In-family testing was performed using the Anderson-Darling test with $\alpha=0.25$.

Test Results – Flammability

- Only the carbon PMCs are viable candidates for HLS Exploration Atmosphere.
- With a polyethylene reference Limiting Oxygen Index of 18%, Miralon and JSC-1A coating trials resulted in no noticeable improvement on Spectra Shield material.
- E-671 epoxy is fire-rated for terrestrial applications (21% O2) but would not suffice for space habitats without modification.



Conclusions

Conclusions

- IM7/8552 and T1100/3960 appear to be good candidate materials for a lunar habitat application, both in terms of minimal radiation damage and flammability in an up to 37% oxygen environment.
- Spectra Shield is significantly affected by radiation exposure and therefore should not be used in a load-bearing capacity. Flammability also remains a concern due to unsuccessful coating trials.
- E-671 epoxy is not sufficiently fire-retardant for target space habitat oxygen environments.
- Materials for fire resistance can be challenging to process.

Further Considerations - Radiation

- Additional mechanical testing would be required to certify a composite habitat for use in space habitats.
  - Boeing has evaluated the potential use of composites as a structural material in future space habitats under NASA's NextSTEP Appendix A contract. Reference: "Certification of a Composite Habitat for Deep Space" by Ziegler and Eichinger.
- Combined effects of radiation/strain, radiation/strain/cryogenic temperature may represent worse cases that should be evaluated as well.

Further Considerations - Flammability

- LOI testing does provide certification for space flight hardware. Materials meeting a minimum LOI for an environment should be confirmed through configurational stackup using NASA-STD-6001, Test 1.
- Additional process development with Fyrol PMP, regolith and Miralon may show benefits of these materials.
- Propagation and convection properties (due to gravity) are being incorporated into flammability testing discussions.
  - Both these factors are being studied by NASA for programs such as HLS.

NASA Flammability Testing

Recent flammability testing performed in support of HLS missions has uncovered several shortcomings in NASA-STD-6001. Some takeaways for those working with composite materials, particularly PMCs:

- Materials that pass individually may fail when tested in a layup or in combination with other materials. Similarly, fire barriers need to be tested in their assembled configuration (over the material they are protecting from ignition).
- Current NASA-STD-6001B Test 1 ignition energy may not be sufficient. Higher ignition energies may be necessary in some cases.
- Previously-certified hardware may need to be reevaluated.

Backup

Example LOI Results

Part 1: Determination of the preliminary oxygen concentration from one pair of "X" and "O" response at ≤ 1% O2 concentration interval

Oxygen concentration (%)	39.2	40.3	40.5	38.9					
Burning Period (180 s)	<	>	<	>					
Length Burnt (50 mm)	<	>	>	>					
Response (X or O)	O	X	X	X					

Preliminary oxygen concentration (%) = 39.2

Part 2: Determination of The Oxygen Index Value

	N_T series measurements											
	N_L series measurements											C_F
Oxygen concentration (%)	39.2	39.4	39.8					39.8	39.6	39.8	40.0	39.8
Burning Period (180 s)	<	<	>					>	<	<	>	>
Length Burnt (50 mm)	<	<	>					>	<	<	<	<
Response (X or O)	O	O	X →					X	O	O	X	X
	Column (2, 3, 4 or 5): 3							Row (1 to 16): 4				
	k value from table: -0.14											
	k value, with correct sign: -0.14											

$OI = C_F + k * d =$ 39.8 + -0.14 * 0.2 = 39.8

Material Details

	Material Name	Material format	Vendor	Test Plan	Selection Rationale
Substrates	Spectra Shield®	Dry fabric	Honeywell	Flammability, Radiation	High hydrogen content for increased probability of blocking galactic cosmic ray radiation
	IM7/8552	Pre-preg	Hexcel	Flammability, Radiation	Heritage for many NASA applications, previously selected for other NASA structures
	T1100/3960	Pre-preg	Toray	Flammability, Radiation	Currently being used for multiple other NASA structures
	E-671/S985	Pre-preg	Park Aerospace	Flammability	Low minimum order quantity, unique combination of epoxy and Spectra® fiber
Coatings	Fyrol PMP	Solid	ICL	Flammability	Recommended for use with epoxy PMCs
	Miralon	Film	Huntsman	Flammability, Radiation	Carbon nanotube material for shielding, bonding and flame-resistance
	JSC-1A	Powder	JSC	Flammability, Radiation	Heritage simulant, in-situ resource utilization