

Window Material Database



Brief History of Windows



Heritage (glass & ceramic)
Window Designs

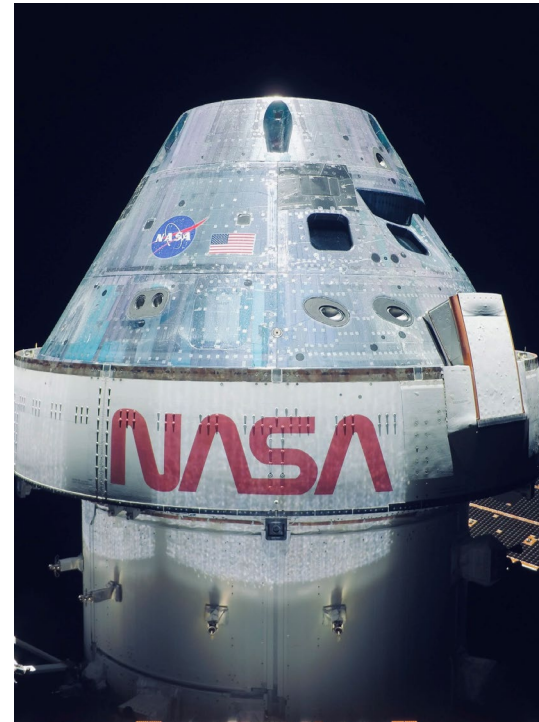
Apollo



ISS &
Shuttle



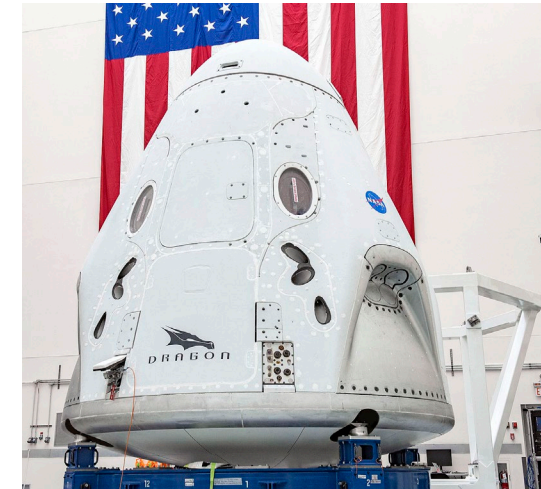
Hybrid



Orion

Gateway

New (polymer) Window Designs

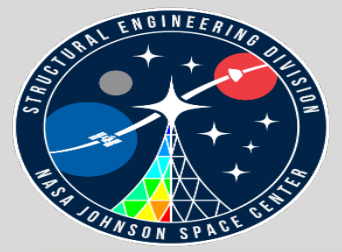


SpaceX –
Crew
Dragon

Future Programs



How did we get here?



- Windows Material Database
 - A database that provides flight relevant data to designers, allowing for quick trade studies between transparent materials.
 - The database contains 4 types of materials: Acrylics, Polycarbonates, Glasses, and Ceramics (various brands), and each is tested using the same method.
 - Acrylic (AC) brands
 - » GKN Cast, GKN Stretched, Plexiglass, Poly II, SAR (coated)
 - Polycarbonate (PC) brands
 - » Lexan 9034, Lexan MR10 (coated), Makrolon (coated, also now Tuffak), & Zelux
 - Glasses and Ceramic Brands
 - » Corning – Fused Silica (FS), Tosoh – Fused Quartz (FQ), & Surmet - ALON
 - Each material is taken through a suite of material and environment testing
 - Environments: **Flammability, Atomic Oxygen, Hypervelocity Impact, Thermal Vacuum, and Radiation & UV**
 - Testing: **Optical, Creep, Strength, and Thermal Property**
 - Materials are tested optically before and after exposure to determine if there was a degradation in optical quality after exposure. Then, the materials were tested for strength after exposure.



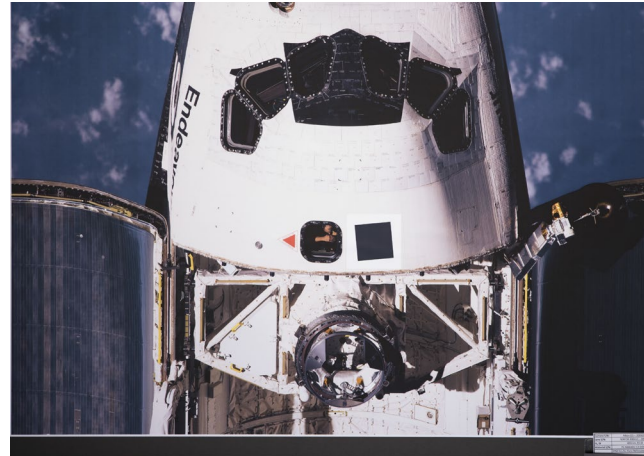
Optical Testing



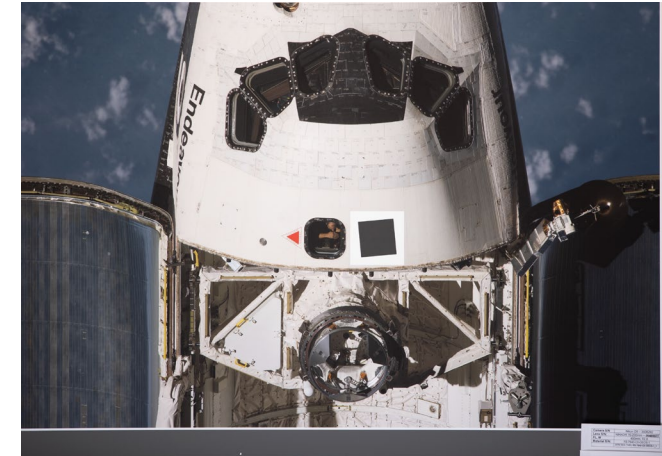
- Test Parameters

- Transmission
 - Visible spectrum
 - Full spectrum (200-3000 nm)
- Reflectance
- Birefringence
- Wavefront
- Striae
- Haze
- Color Balance
- Wedge
- Imagery

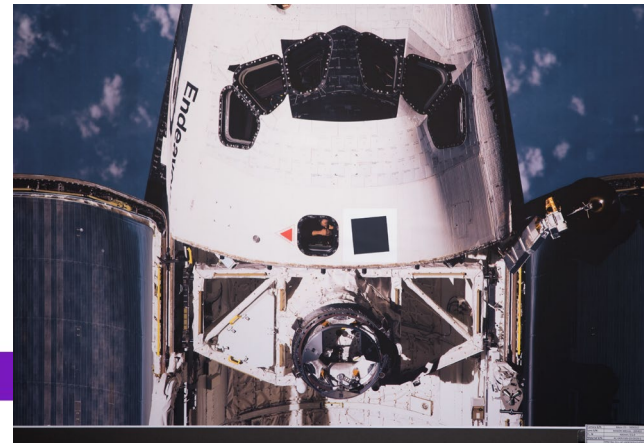
400 mm Lens



No Pane



Fused Silica



GKN Stretched Acrylic



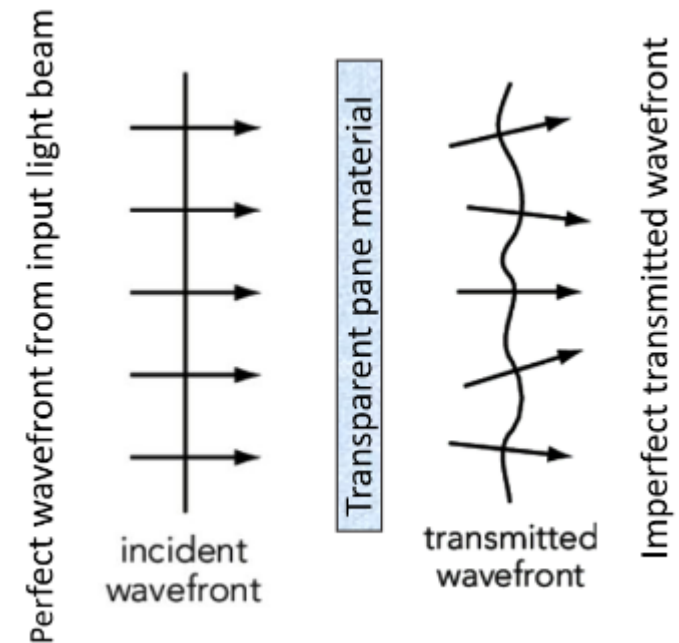
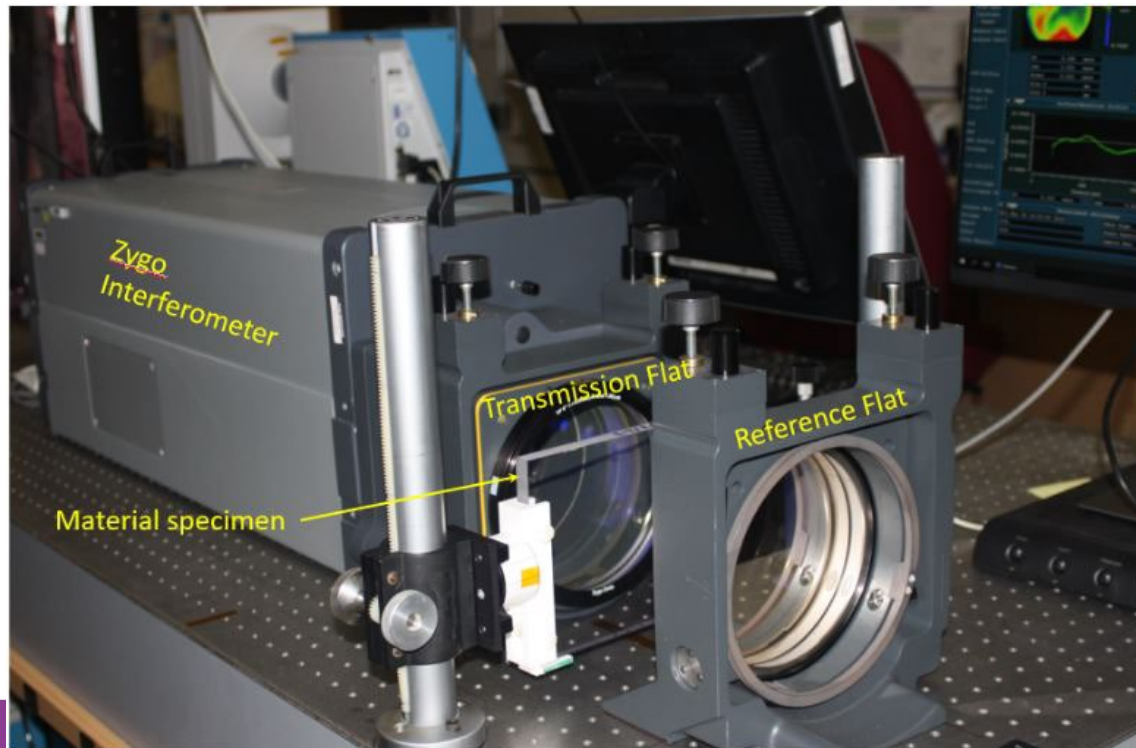
Makrolon Polycarbonate



Wavefront Error

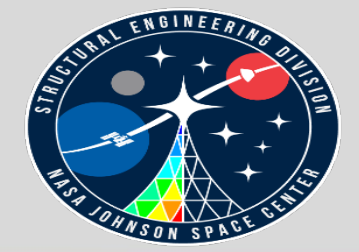


- Test
 - The purpose of the Transmitted Wavefront Error (TWE) Measurement is to determine the change in wavefront of a defined input light beam as it passes through an optically transparent material.
- Test Setup



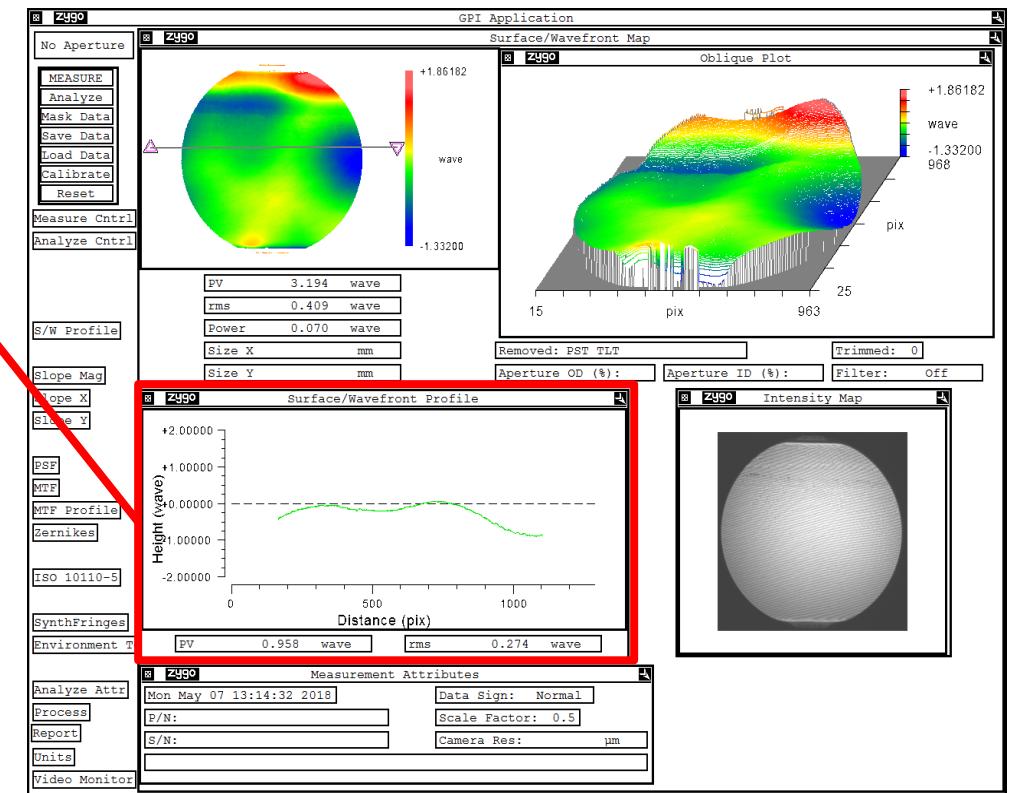
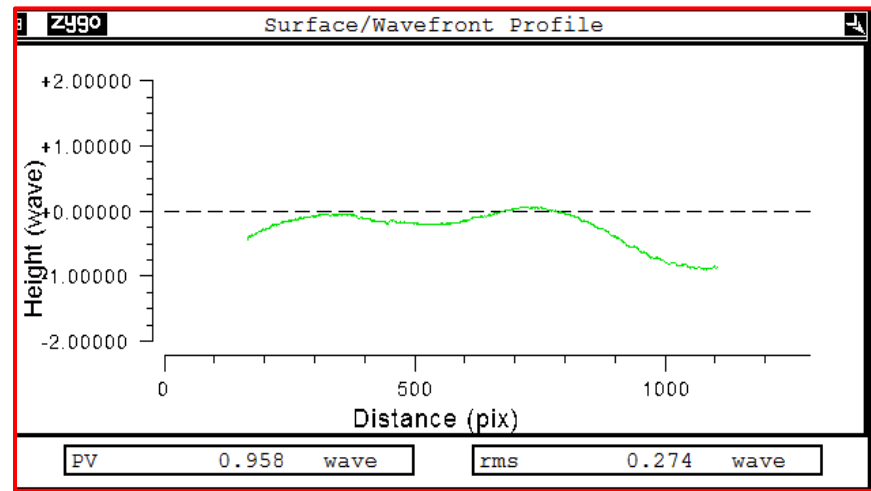


Wavefront Error Data



- The pass/fail criteria of the wavefront error measurement is dependent on the optical quality desired.

- Category E windows do not have a wavefront error requirement



Viewing Angle	P-V Wavefront Error with Piston, Tilt & Defocus Removed (waves)	RMS Wavefront Error with Piston, Tilt & Defocus Removed (waves)
Normal	7	1
30°	10.5	1.5

Allowable Wavefront Error for Category B, C, & D

Interferometer Wavefront Data



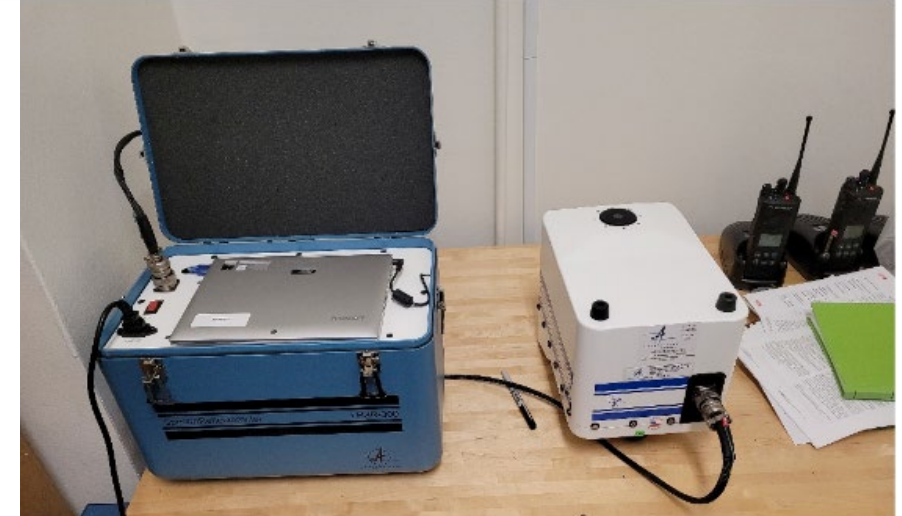
Thermal Property Testing



- Properties Tested
 - Degradation Temperature
 - Q600 SDT Thermogravimetric Analyzer (TGA)
 - Emittance (ASTM E408)
 - Solar Absorptance (LPSR 300 Manual)
 - Some more specific properties for materials currently in use



ET-100 Emissometer



LPSR 300 Spectroreflectometer

Results

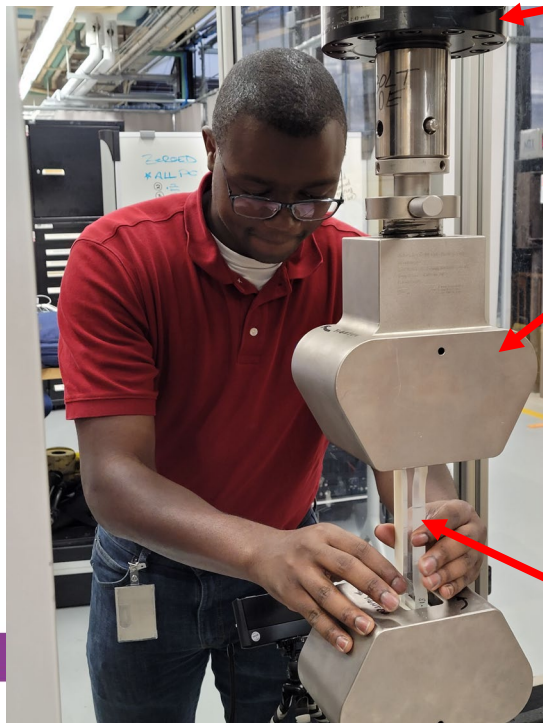
	AC – GKN Cast	AC – GKN Stretched	AC – Plexiglas	AC – SAR	AC – Poly II	PC – 9034	PC – MR10	PC – Makrolon	PC – Zelux	ALON	Fused Silica	Fused Quartz
Degradation Temperature (°C)	370	368	324	326	366	457	463	486	485	N/A	N/A	N/A
Emittance (HTE)	0.93	0.93	0.94	0.96	0.93	0.92	0.83	0.95	0.92	0.85	0.94	0.95
Solar Absorptance	0.33%	0.32%	0.28%	0.29%	0.29%	0.38%	0.31%	0.27%	0.35%	0.30%	0.20%	0.19%



Strength Testing



- Two Tests
 - Tensile testing of dogbone-shaped specimen (polymers – ASTM D638)
 - Biaxial flexure testing of brittle materials (glass and ceramics – ASTM C1499)
- Test Setup



10 kip Load Cell

50 kip grips

Test Specimen & Alignment Tool

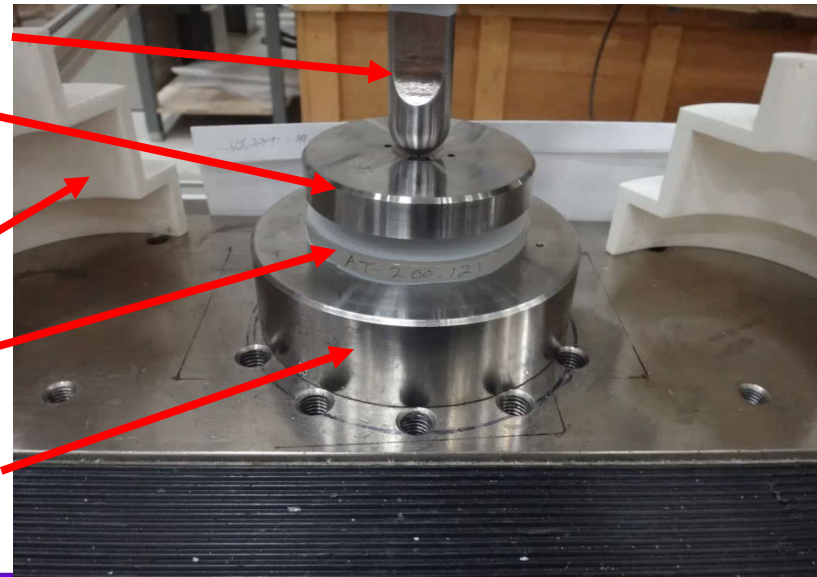
Loading Rod

1.25" Dia Ring

Alignment Tool
(Wedding Cake)

Test Specimen
& Teflon Pucks

2.5" Dia Ring

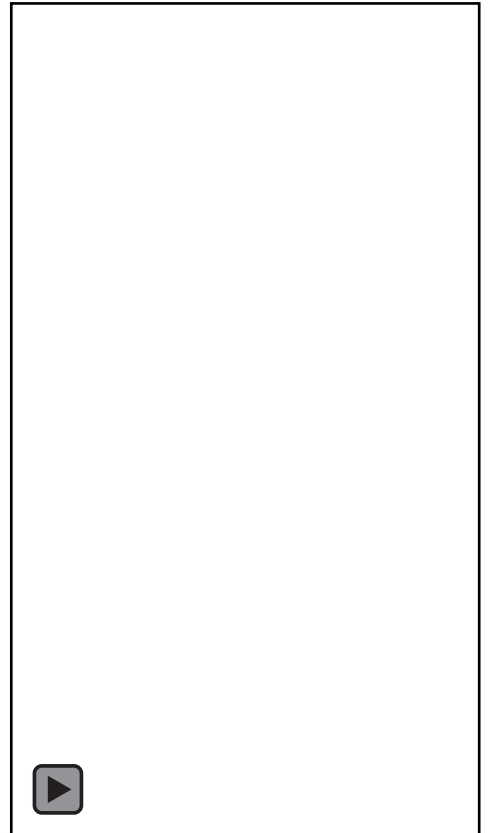
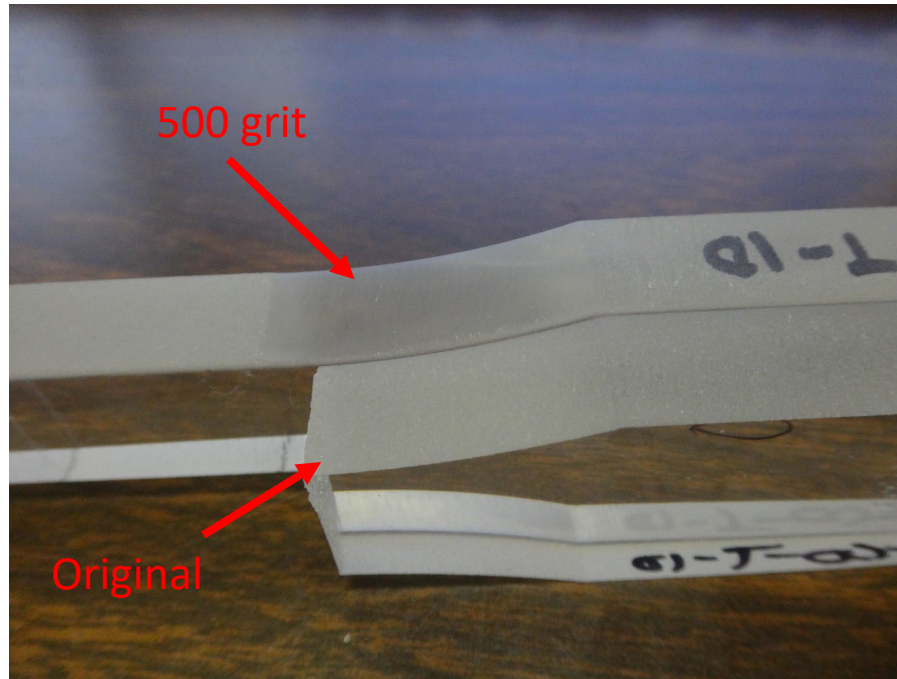
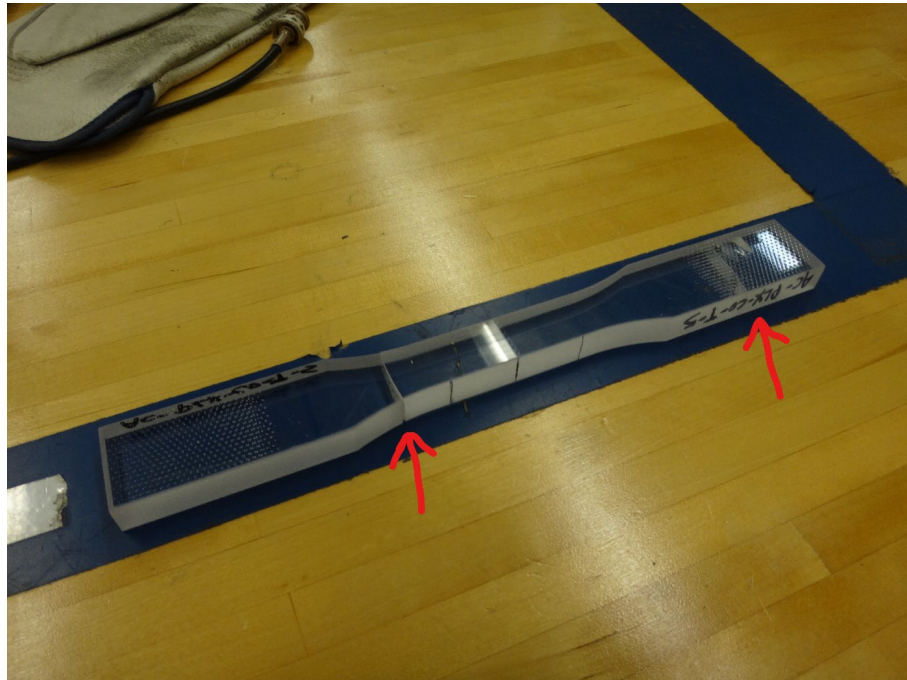




Strength Testing: Prep Lesson Learned



- Issue: Acrylic specimen would break outside of the gage length
 - The issue was resolved by sanding the fillet areas
 - Acrylic also exhibits some notch sensitivity like glass and ceramics

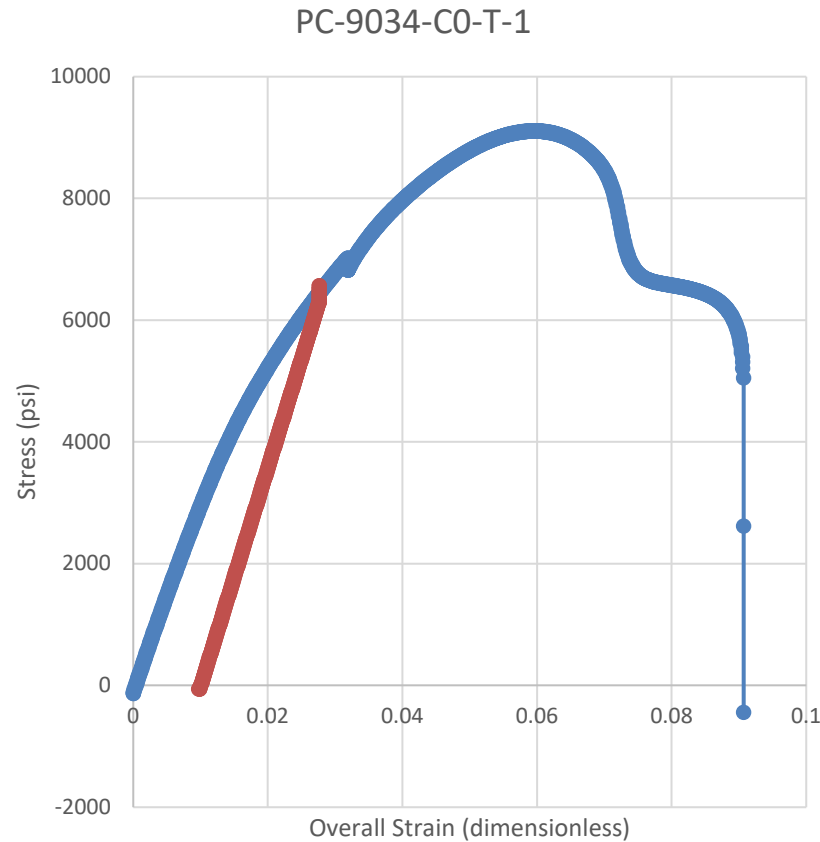




Strength Testing Results



- Calculated Parameters
 - Young's Modulus
 - Yield Strength (1% Offset)
 - Ultimate Strength
 - Residual Strength



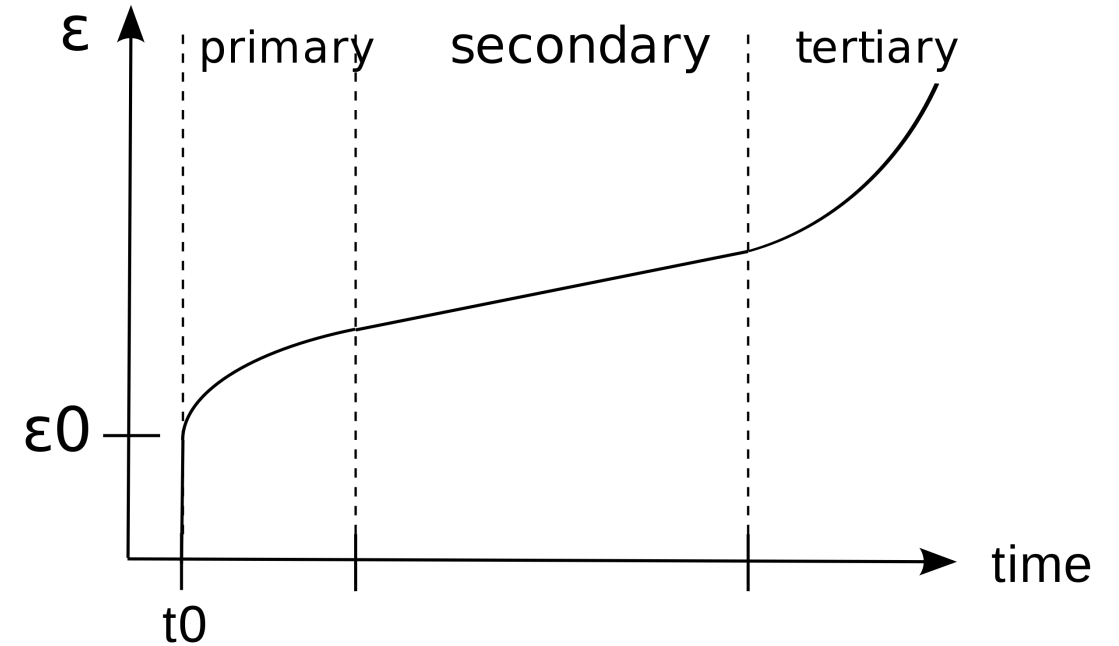
Units: ksi	E	F _y	F _u
AC – GKN Cast	546	N/A	9.0
AC – GKN S	551	N/A	11.9
AC – Plexiglas	512	N/A	8.4
AC – SAR	477	N/A	8.1
AC – Poly II	478	N/A	8.0
PC – 9034	358	7.9	9.0
PC – MR10	366	8.7	9.2
PC – Makrolon	348	9.1	9.6
PC – Zelux	362	8.4	9.1



Creep Testing



- Test Setup – ASTM D790



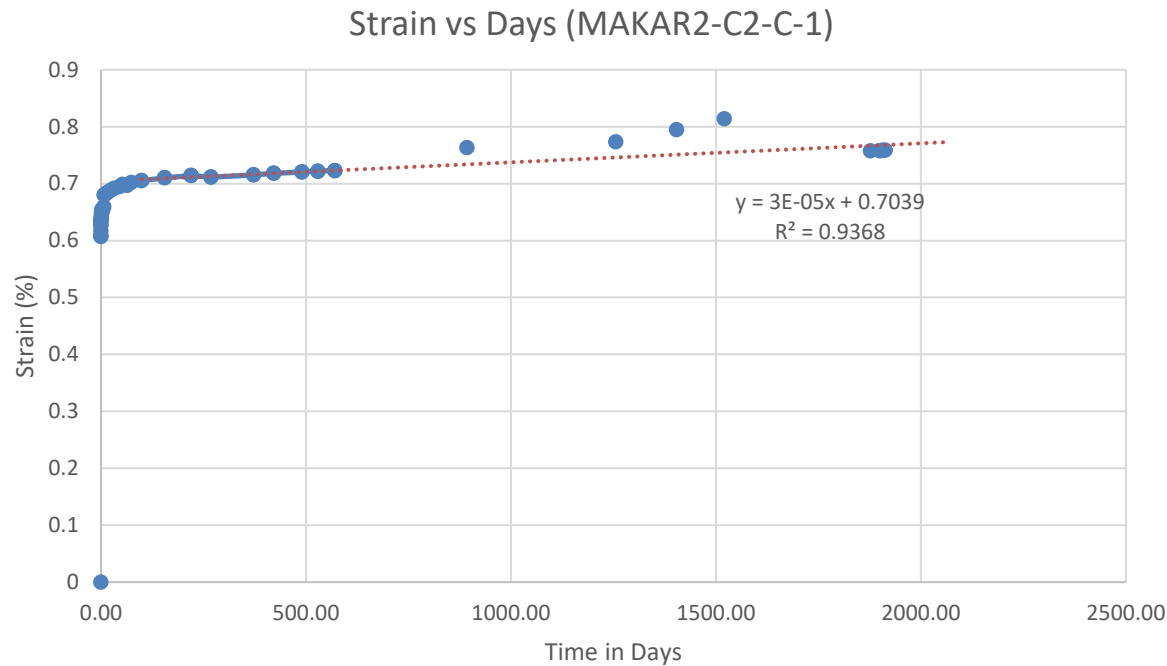
Tested Stressed: 3, 4, 6, 8, & 10 ksi



Creep Data



- Current data shows that the material remains in secondary creep. Some data points lay outside of this range due to test fixture slippage going unnoticed during quarantine.





Flammability Testing



- Test
 - Each material had 3 test specimen
 - **Specimen 1 & 2:** 20.9% oxygen at 14.7 psia
 - **Specimen 3:** 30% oxygen at 10.2 psia (only if first two specimen pass)
 - Pass/Fail Criteria
 - Do not burn more than 6"
 - Does not propagate the flame



Typical Pretest



-10 Post Test

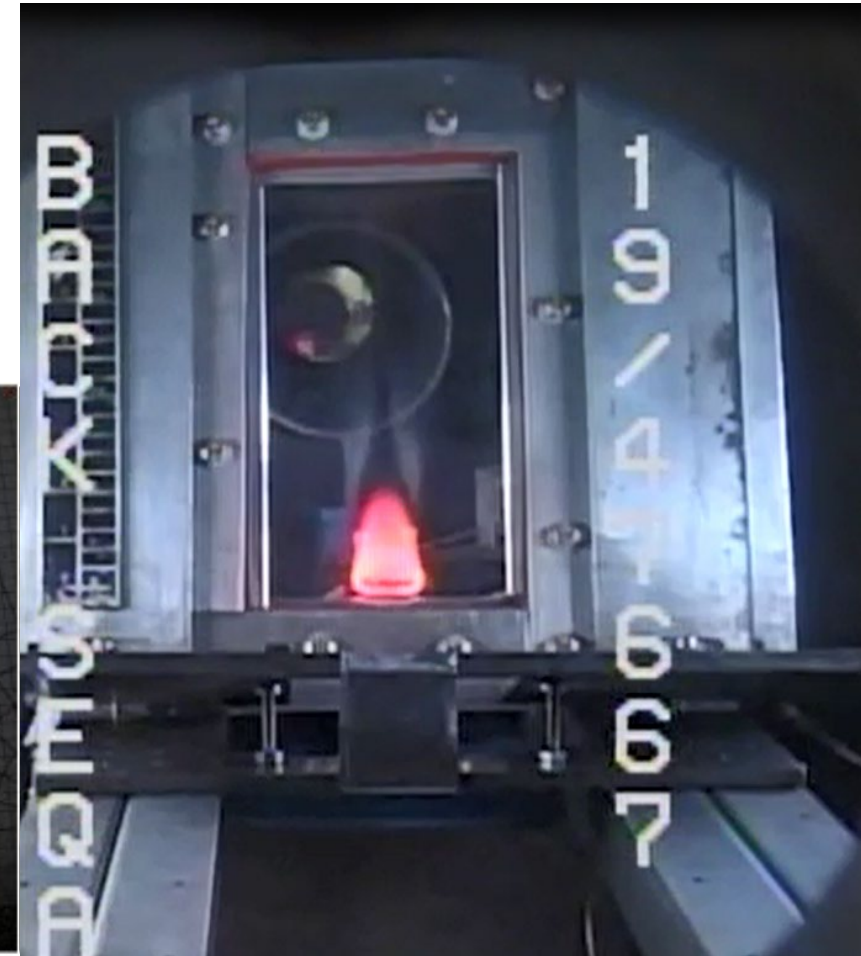
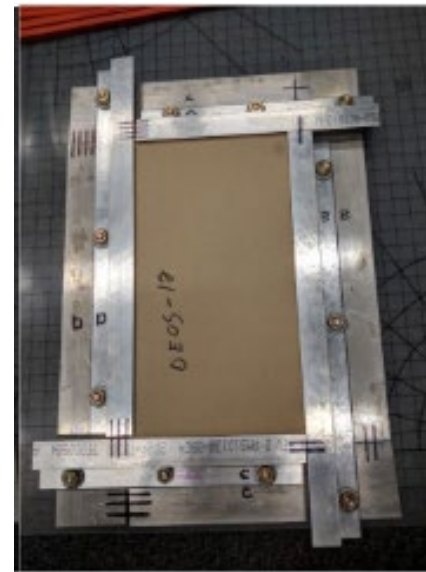


-11 Post Test



-12 Post Test

AC – GKN Cast Results





Flammability Test Results



- Materials passing all 3 tests
 - PC – 9034
 - PC – MR10
 - PC – Makrolon
 - PC – Zelux
 - AC – Poly II
- Materials Passing 1st and/or 2nd tests
 - AC – GKN Cast
 - AC – SAR
 - AC - Plexiglas
- Materials Passing none
 - AC – GKN Stretched



Pretest Typical



-10 Post Test



-11 Post Test



-12 Post Test

PC – Makrolon Results



Pretest Typical



-10 Post Test



-11 Post Test



-12 Post Test

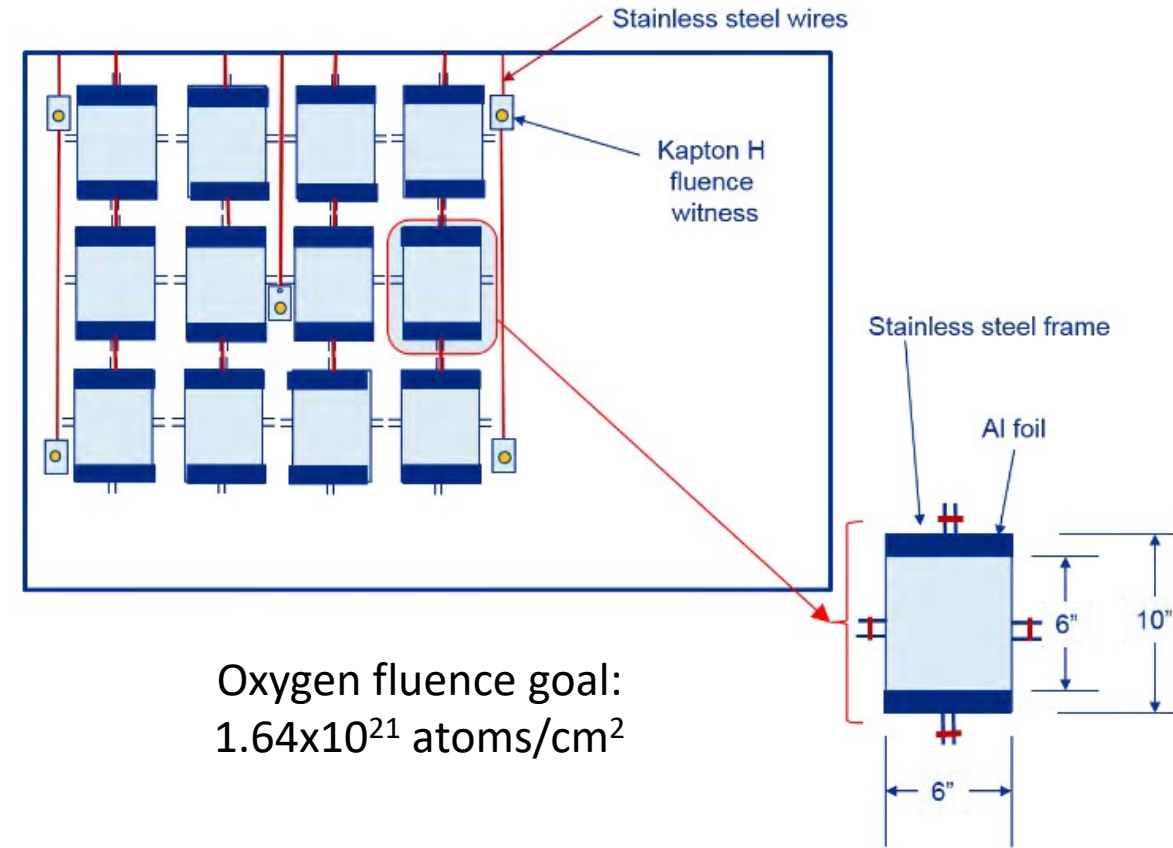
AC – GKN Stretched



Atomic Oxygen Exposure



- Test Setup

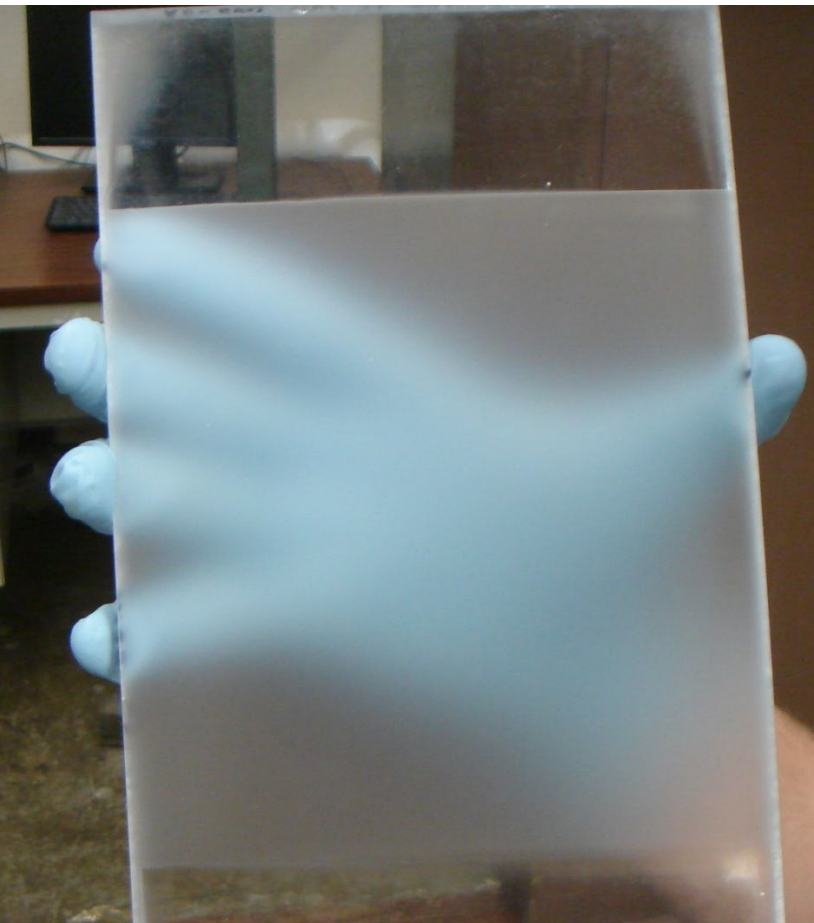




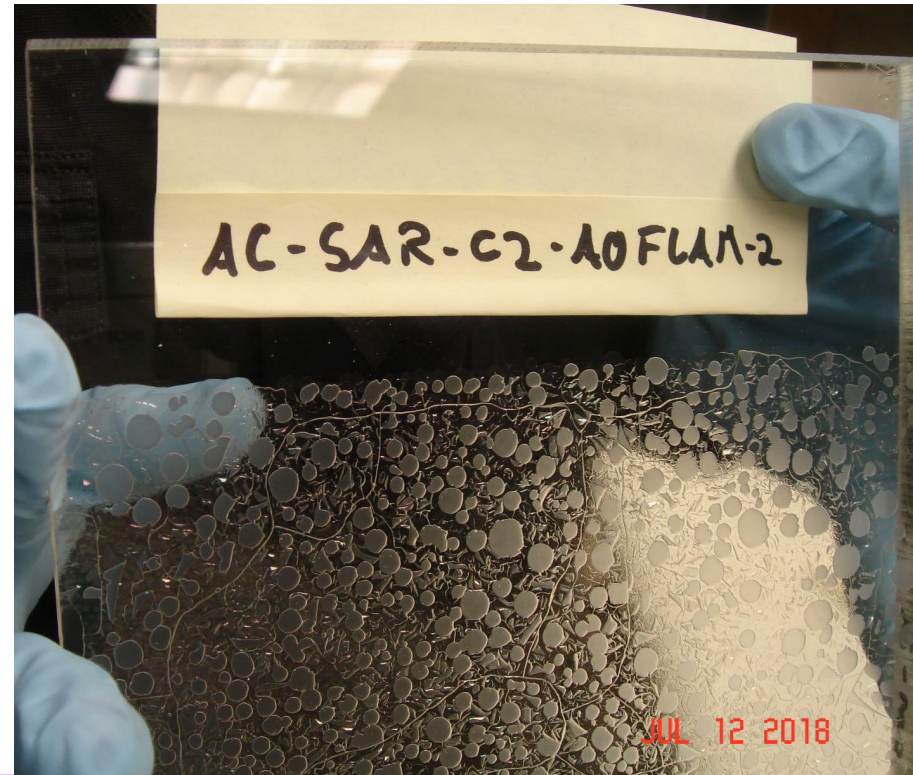
Atomic Oxygen Results



- Optical data was not collected due to loss of optics in the specimen
- Further testing concluded that polysiloxane anti-scratch coatings at flight-like exposure levels protected the polymer materials



Typical Uncoated Specimen



PC – MR10



Hypervelocity Impacting



- Testing

- 3 different projectile materials were used to represent different densities of potential impact material: Soda lime glass (lightest), Stainless steel (heaviest), and Ruby (middle)
- Projectile size and speed varied for a total of 35 shots (shortened to 12 shots for the polymers)

Test #	Projectile Material	Projectile Size (mm)	Requested Velocity (km/s)
1	Soda Lime Glass	0.20	5.00
2	Stainless Steel	0.20	5.20
3	Soda Lime Glass	0.20	6.60
4	Soda Lime Glass	0.20	6.10
5	Soda Lime Glass	0.20	6.80
6	Soda Lime Glass	0.32	4.85
7	Soda Lime Glass	0.20	7.10
8	Soda Lime Glass	0.28	5.05
9	Soda Lime Glass	0.28	5.75
10	Soda Lime Glass	0.28	6.00
11	Ruby	0.15	7.00
12	Ruby	0.20	4.75
13	Ruby	0.20	6.10
14	Ruby	0.25	6.10
15	Stainless Steel	0.20	7.00
16	Stainless Steel	0.15	6.80
17	Stainless Steel	0.15	5.95

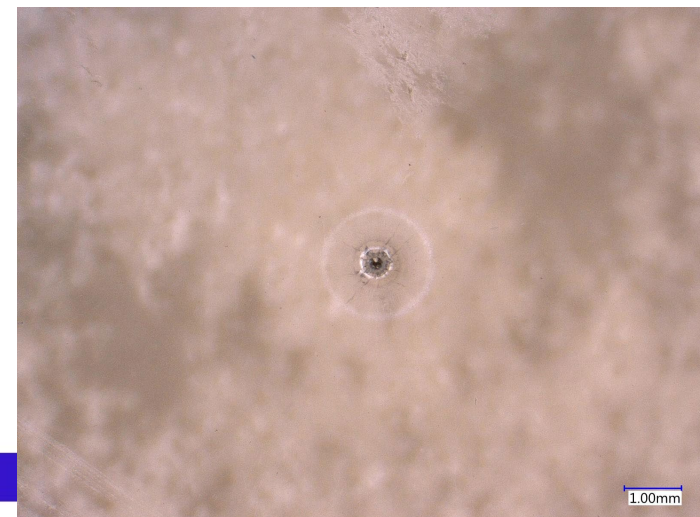
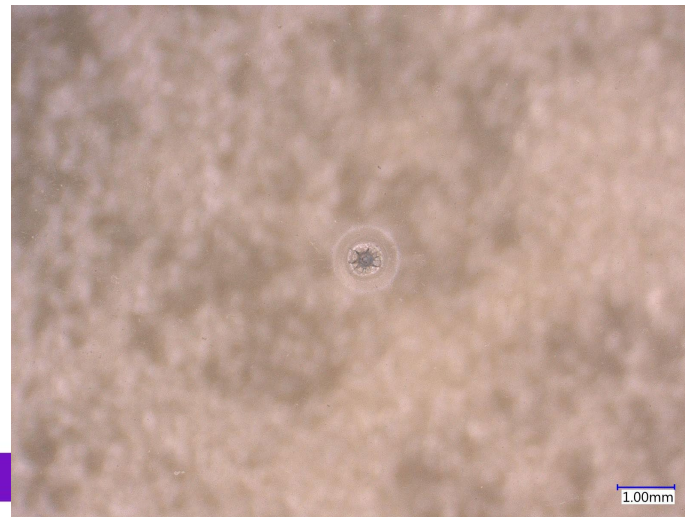
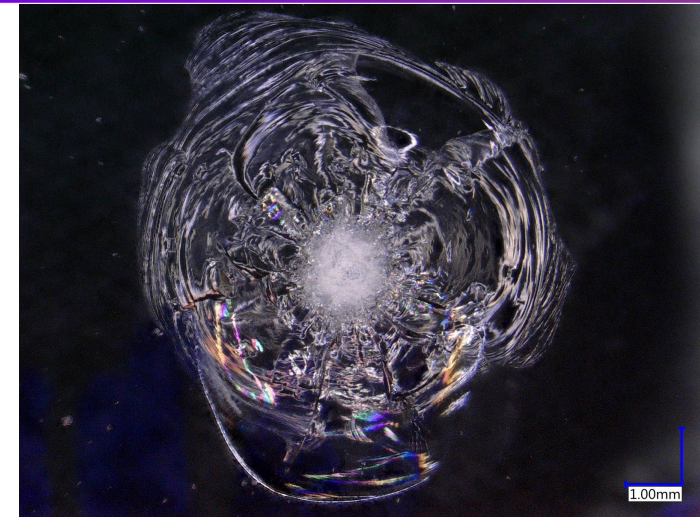
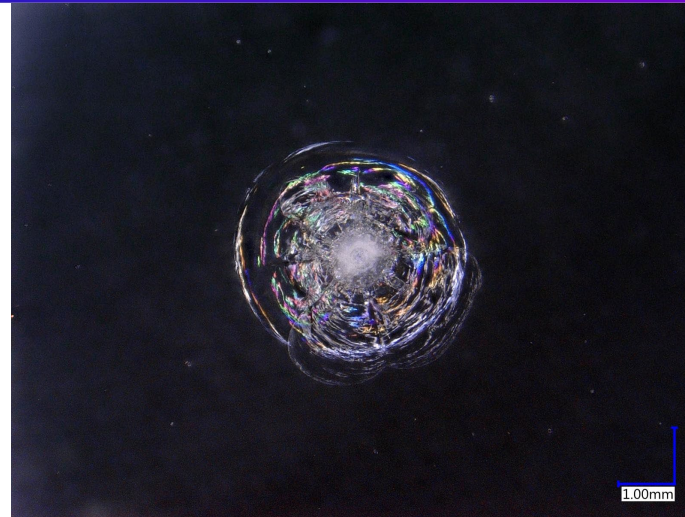
Test #	Projectile Material	Projectile Size (mm)	Requested Velocity (km/s)
18	Stainless Steel	0.20	6.80
19	Stainless Steel	0.25	4.85
20	Stainless Steel	0.10	5.05
21	Stainless Steel	0.10	7.05
22	Stainless Steel	0.20	5.90
23	Stainless Steel	0.25	5.90
24	Ruby	0.25	5.00
25	Ruby	0.25	6.95
26	Ruby	0.30	5.20
27	Ruby	0.30	7.05
28	Ruby	0.20	7.05
29	Ruby	0.20	5.05
30	Ruby	0.25	5.00
31	Ruby	0.20	6.00
32	Ruby	0.20	6.85
33	Soda Lime Glass	0.28	5.05
34	Soda Lime Glass	0.28	6.05
35	Soda Lime Glass	0.19	6.00



Glass & Ceramics vs. Polymers



- The geometry of the defect for glasses and ceramics is unique with each shot.
 - This led to a 35-shot matrix being used to cover any potential difference with material size, density, and speed.
- Polymers do not have a unique response to HVI and are not as notch sensitive as glasses and ceramics
 - A modified 12-shot matrix was used to cover different material sizes, density, and speeds.
 - Shots chosen: # 2, 4, 5, 9, 12, 13, 17, 19, 21, 26, 32, & 33



Shot 1 – Soda Lime @ 5 km/s

Shot 2 – Stainless Steel @ 5 km/s



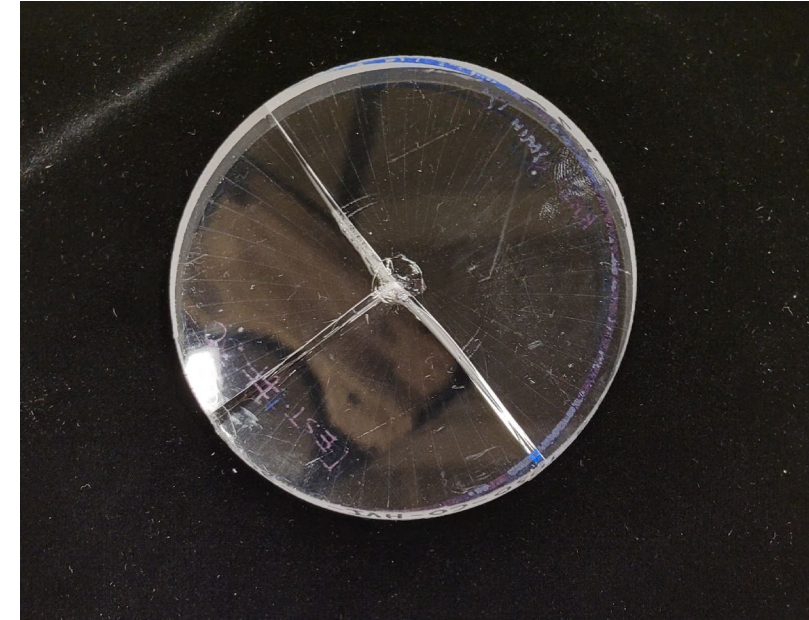
Hypervelocity Impact Residual Strength



- Residual strength averages varied depending on material
 - Polycarbonate: 98% - 99%
 - Stretched Acrylic: 90% - 95%
 - AC-GKN Cast: 57% - 97%
 - AC-Poly II: 84% - 97%
 - AC-SAR: 74% - 91%
 - ALON: 12% - 35%
 - Fused Silica: 9% - 20%



Typical
Polycarbonate
Break



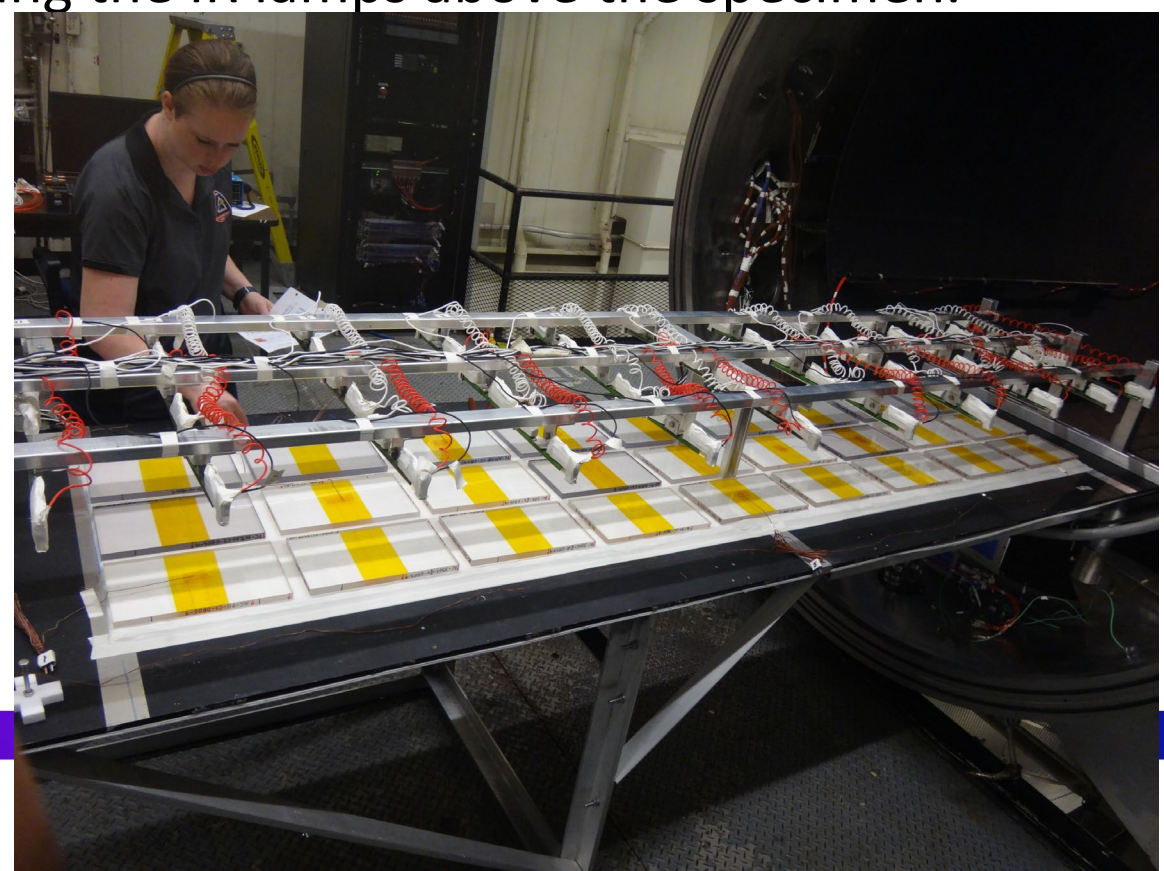
Typical Glass or
Ceramic Break



Thermal Vacuum Exposure



- Test Setup
 - The objective of this test was to expose the polymer material to a vacuum and cycle from -100°F to $+250^{\circ}\text{F}$ for 3 cycles using the IR lamps above the specimen.

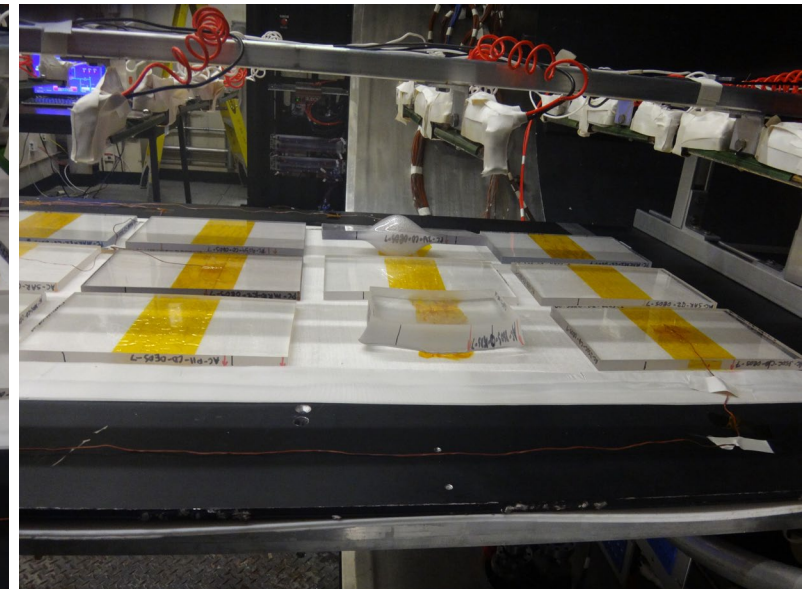
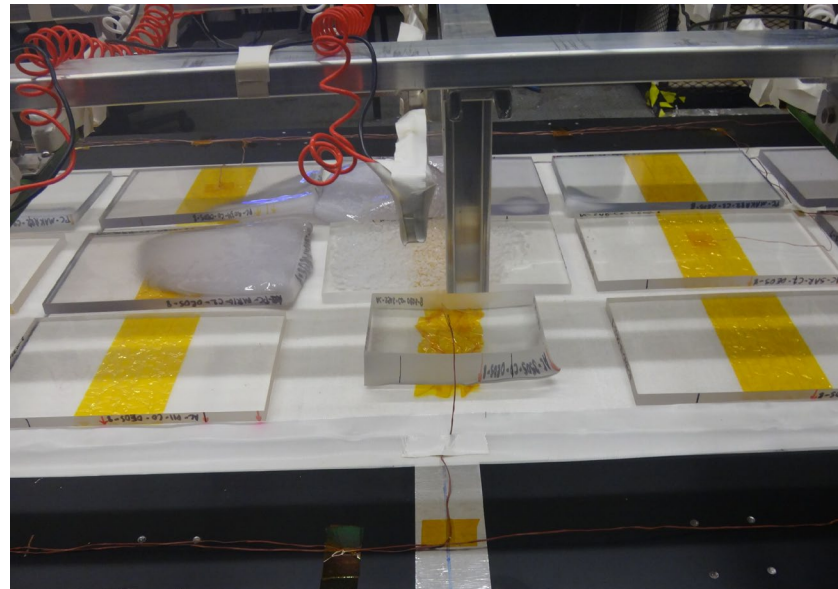
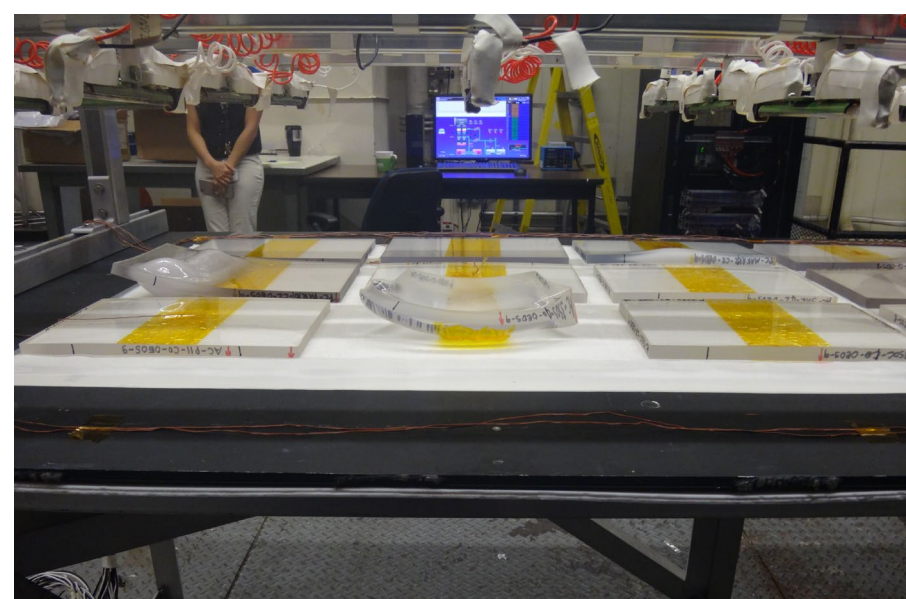




Thermal Vacuum Results



- Due to an anomaly with the thermal vacuum testing, strength testing was indefinitely post-poned.





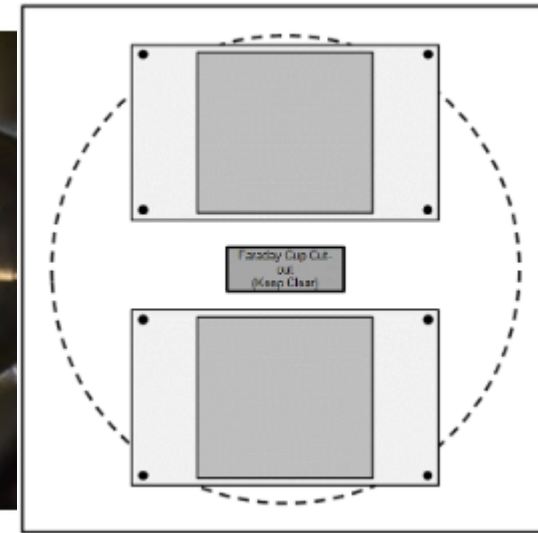
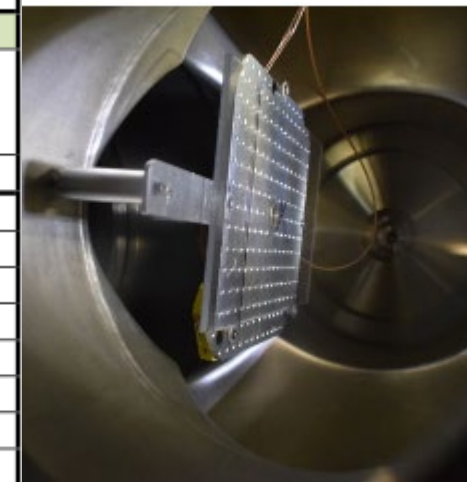
Radiation & UV Exposure



- Test Setup

- Each material was exposed to a UV radiation environment and a proton and electron radiation environment. A single coupon was exposed to both environments to capture compounding effects.
- UV consisted of Near UV (NUV) and Vacuum UV (VUV), which was produced by a 1 kW Mercury-Xenon arc lamp and a Deuterium lamp respectively.

						Combined UV and Radiation			
	Radiation Only			UV Only		Radiation			UV
Specimen Name	Specimen Dash Number	Proton Fluence	Electron Fluence	Specimen Dash Number	Equivalent Sun Hours	Specimen Dash Number	Proton Fluence	Electron Fluence	Equivalent Sun Hours
		(p+/cm ²)	(e-/cm ²)		(ESH)		(p+/cm ²)	(e-/cm ²)	(ESH)
GKN350C	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
GKN350S	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
MAKAR2	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
MR10	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
SAR	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
POLY2	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
PLX	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
ZW	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000
9034	-4	1.0E15	1.9E15	-5	2000	-6	1.0E15	1.9E15	2000

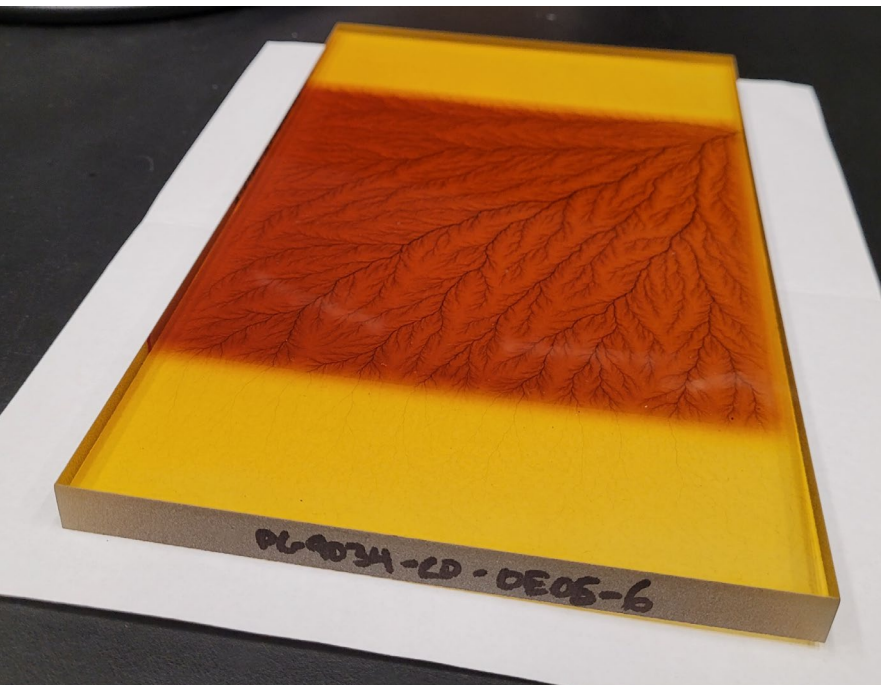




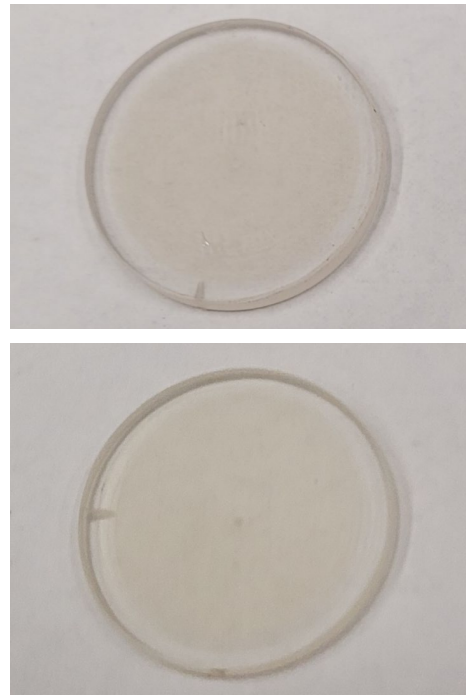
Radiation & UV Results



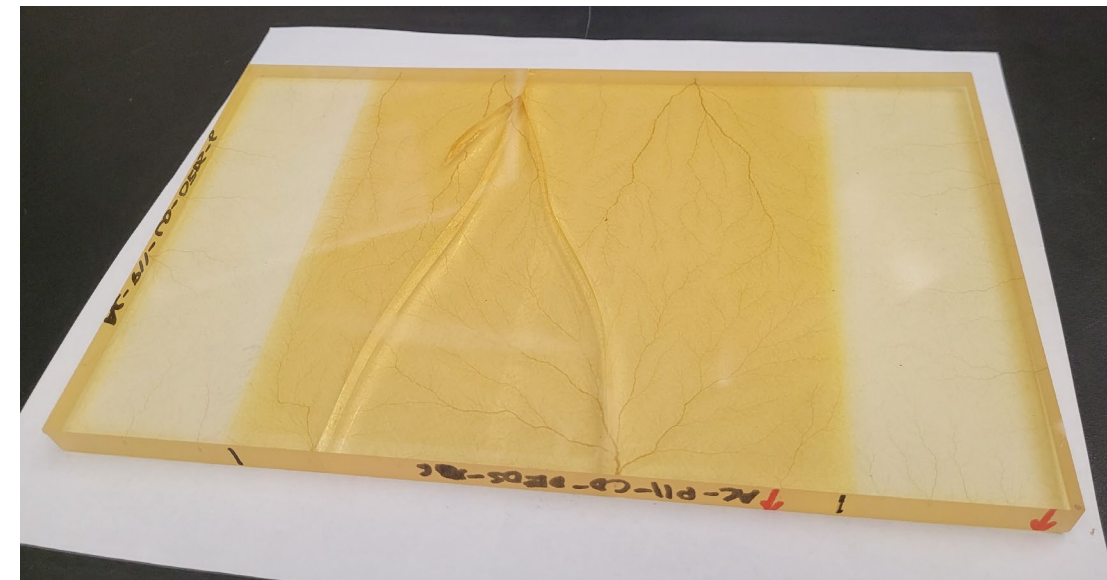
- Severe Lichtenberg lines and yellowing occurred on the specimen.
 - Comparisons to flight data show that this does not occur in flight.
 - Strength testing shows that radiation embrittlement has taken place, but a more testing in a more flight-accurate environment is required.



Polycarbonate (PC – 9034)

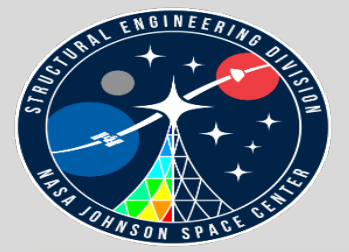


X-37 Samples 2500 ESH



Acrylic (AC – Poly II)

Top: PC – 9034
Bottom: AC – Poly II



Questions?