POLYMER IRRADIATION TESTING FOR NTP SYSTEMS

Jarvis Caffrey[1], Kelsa Benensky[2], Jacob Johnson[3],
Tyler Scogin[1], Jason Reynolds[1]

[1]NASA Marshall Space Flight Center, Huntsville, AL, 35812
[2]Advanced Projects Group, Analytical Mechanics Associates Inc., Denver, CO, 80211
[3]JACOBS (ESSCA Contract at NASA MSFC), Huntsville, AL, 35812

Space Technology Mission Directorate
Technology Demonstration Mission Program
Space Nuclear Propulsion Project

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Irradiation Campaign Overview

The induced radiation environment imposes a new operating environment for heritage materials. To what extent does this need to be accounted for?

- Goal: Understand lifetime limitations and material performance of candidate out-of-reactor NTP engine candidate materials through irradiation testing

- Irradiation conditions chosen to:
  - Reflect doses incurred during operation ***as currently expected***
  - Contribute to a dataset of properties ***valid for future work***

- Both ***gamma*** (Sandia National Laboratory) and ***neutron*** (Oregon State University) irradiation test conditions were investigated

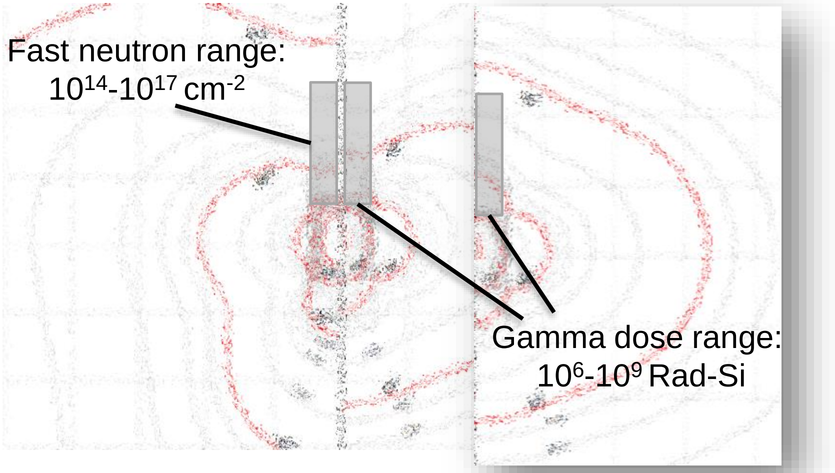
- Gamma irradiations were performed at ***ambient*** and ***cryogenic*** conditions

- Irradiation doses based upon prior work (e.g. NASA-SP-8053 “Nuclear and Space Radiation Effects on Materials”), and MCNP6 Monte Carlo assessments
  - Gamma dose range: **10^6 – 10^8 Rad-Si**
  - Neutron fluence range: **10^{15} – 10^{17} cm^{-2}**

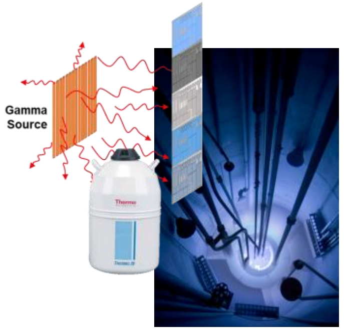
- Simultaneous irradiation: Mechanical ***test coupons***

  \+ Functional ***component samples***

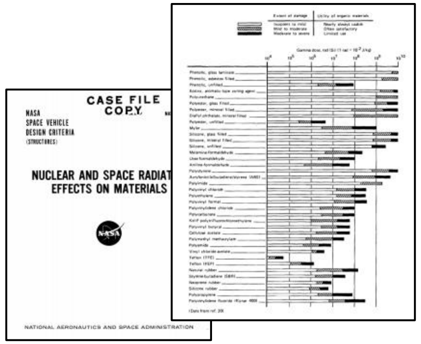
With 200kg shield   No shield



Fast Neutron Flux (cm^{-2}s^{-1})   **Gamma dose (rad/hr)**



Neutron and Gamma Irradiations Performed

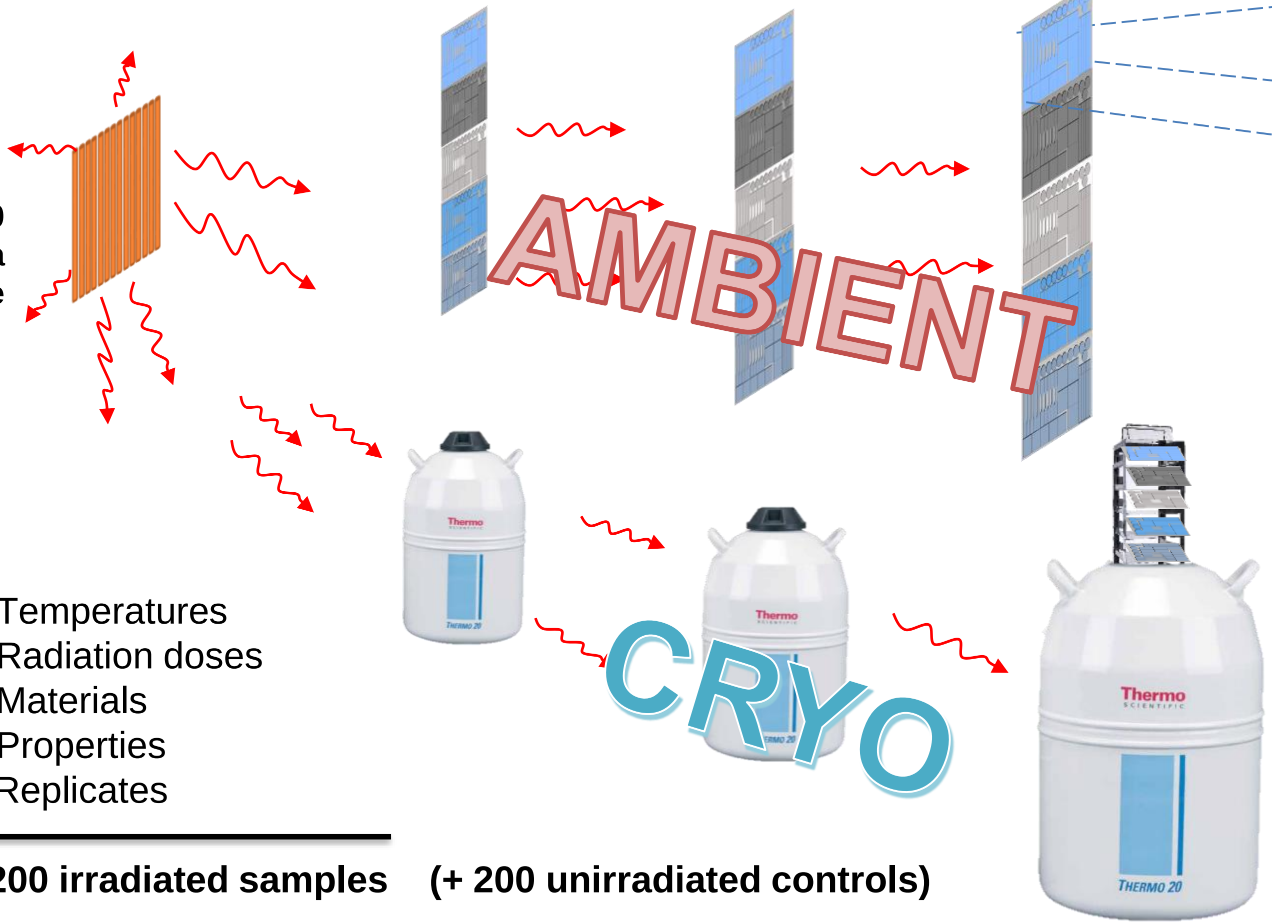


Mechanical property and prototype testing performed to evaluate design limitations

Visual Test Matrix

3 Radiation Doses

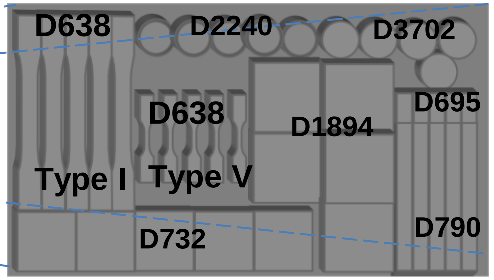
Radiation Dose: **High (10^8 Rad)** **Med (10^7 Rad)** **Low (10^6 Rad)**



2 Temperatures
3 Radiation doses
5 Materials
8 Properties
x 5 Replicates

= 1200 irradiated samples **(+ 200 unirradiated controls)**

Material Specimens



8 ASTM Specimen Types (5 replicates)

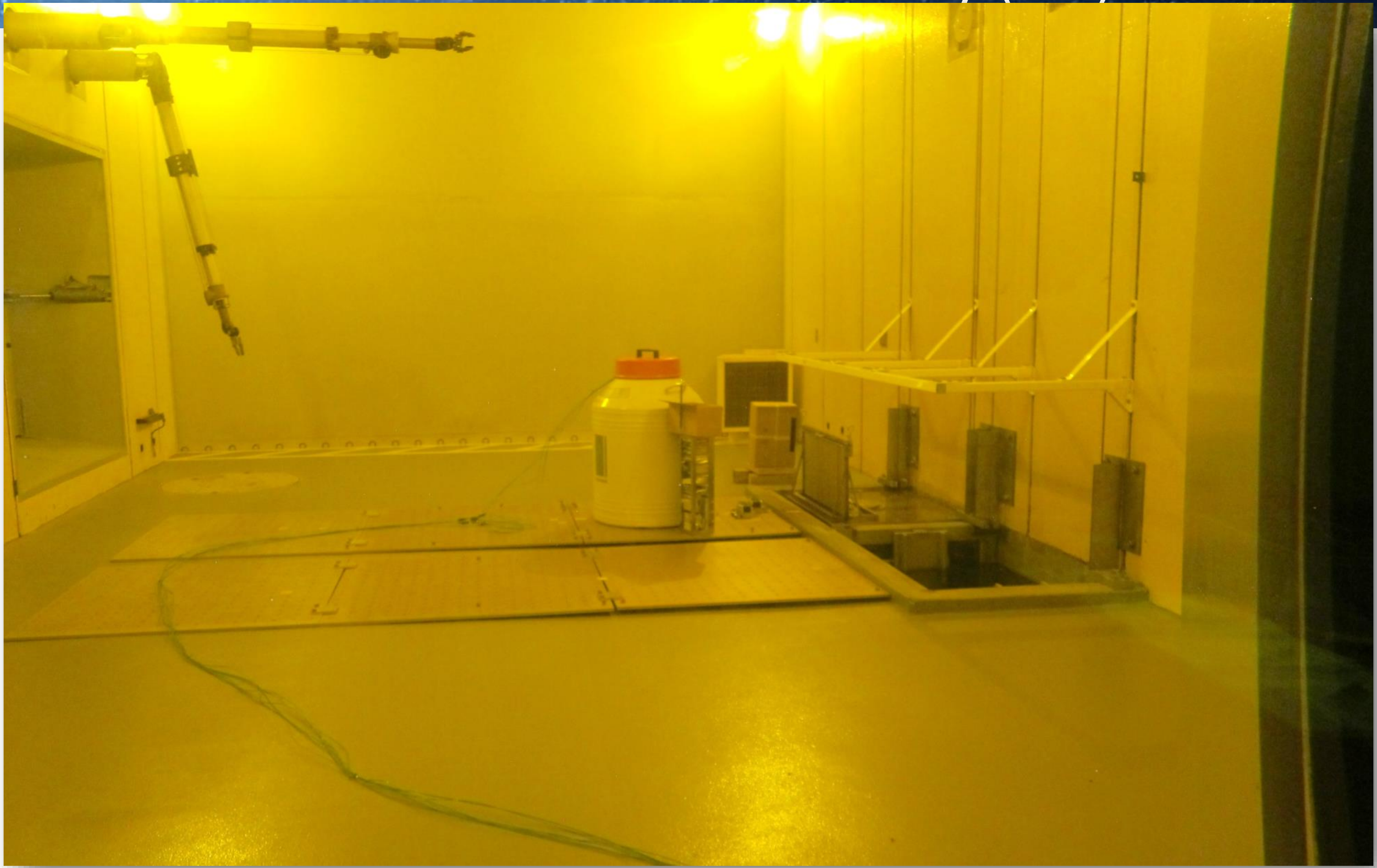
5 Aerospace Polymer Materials:
Polyamide-imide (PAI) / Torlon®
Polychlorotrifluoroethylene (PCTFE) / Kel-F®
Perfluoroalkoxy alkane (PFA) Teflon®
Polytetrafluoroethylene (PTFE) Teflon®
Ethylene propylene diene monomer (EPDM)

+ Various Component Specimens!

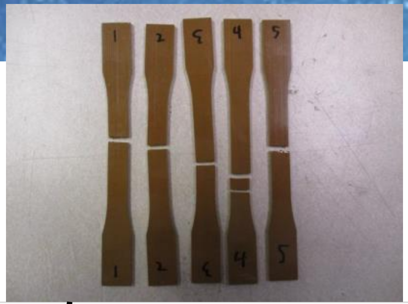
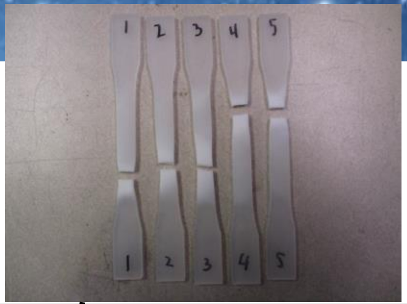
Cryogenic Irradiation – LN2

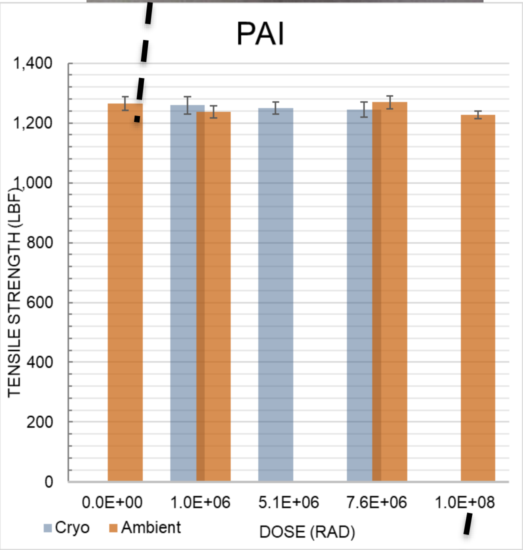
- Submersion in LN2 within large vented cryo-preservation Dewar
- Permits massive quantity of samples to be irradiated at once
- Thermo Fisher ‘Locator 6’ system chosen for size

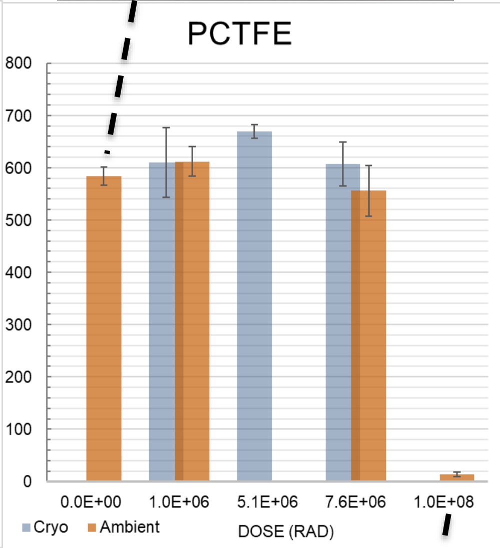
Sandia National Lab:
Gamma Irradiation Facility (GIF)

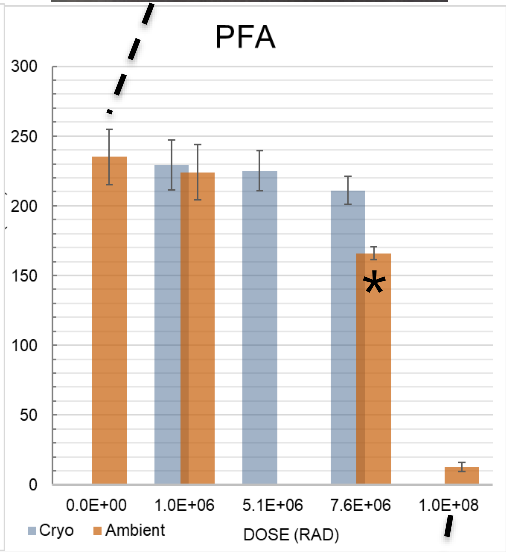


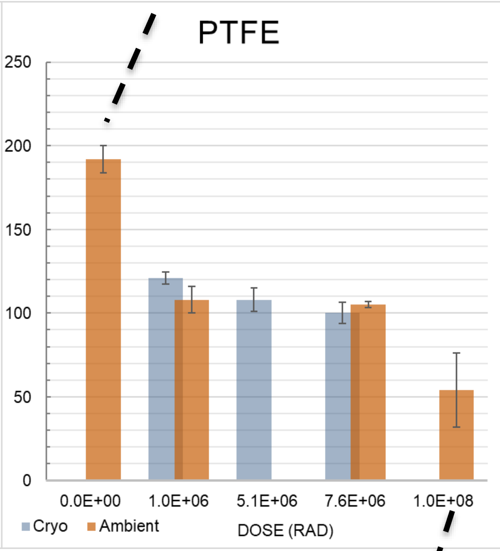
Tensile Strength - D638 Type I

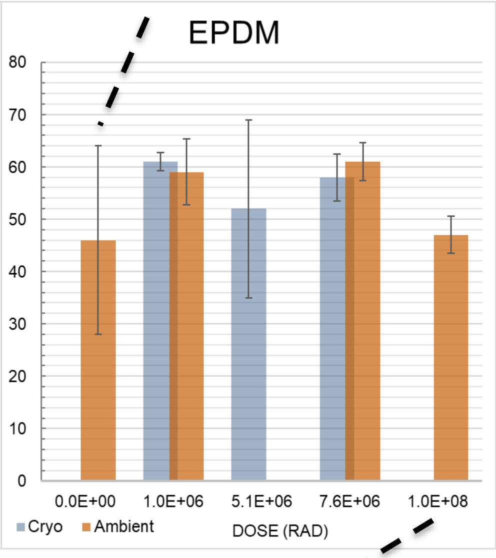



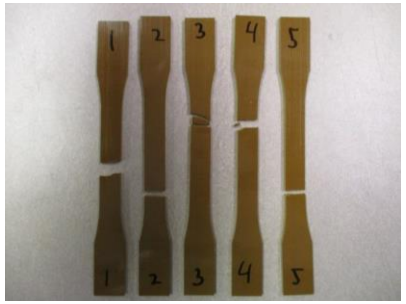
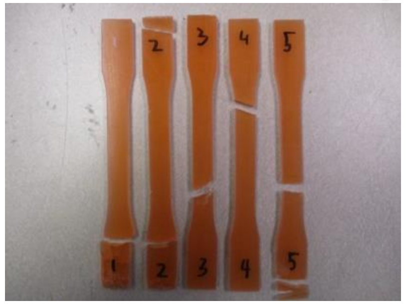
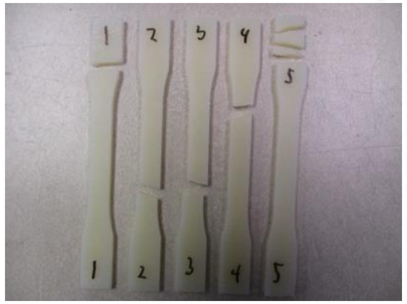
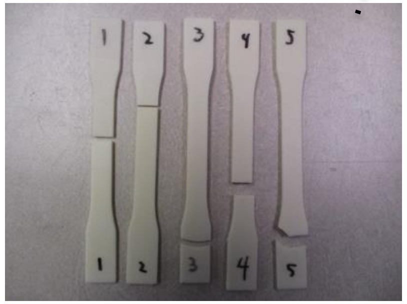
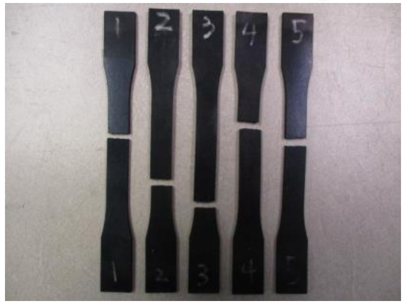









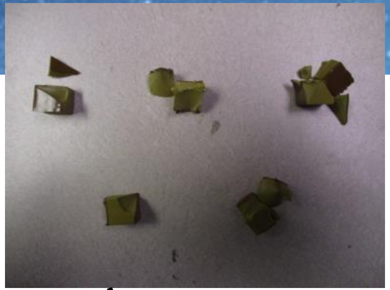


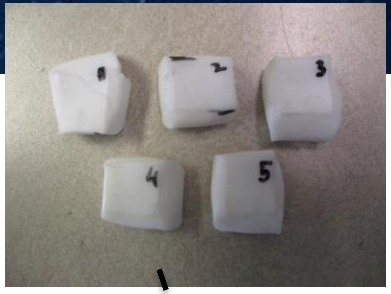






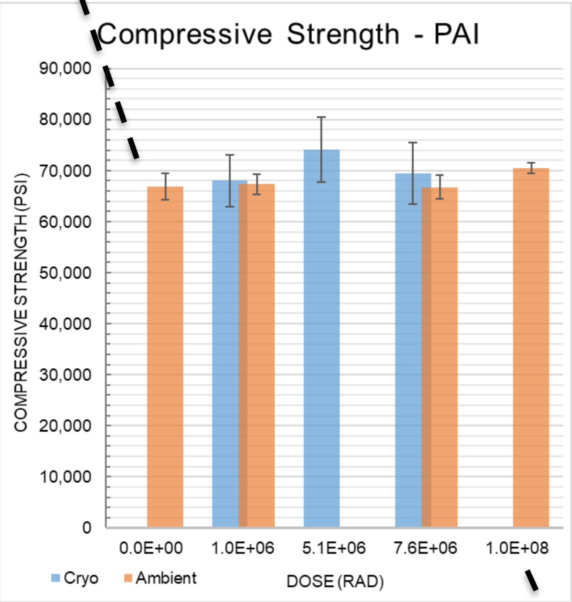
Error bars represent 95% Confidence Interval at mechanical test – ***Dosimetry uncertainty is not shown here***

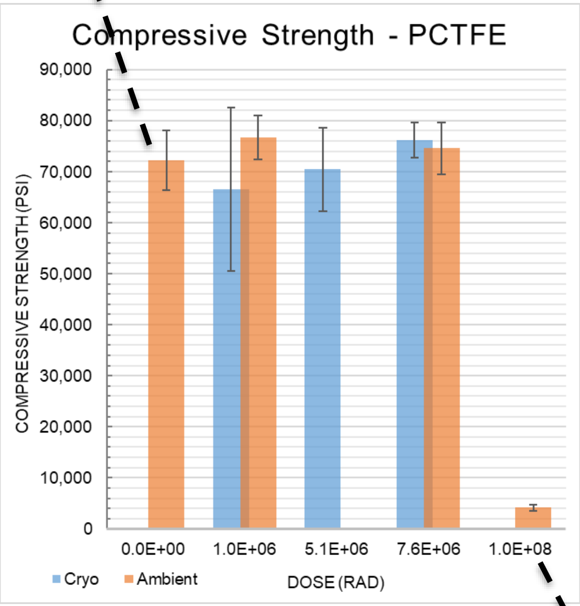
*Pull rate changed at this datapoint

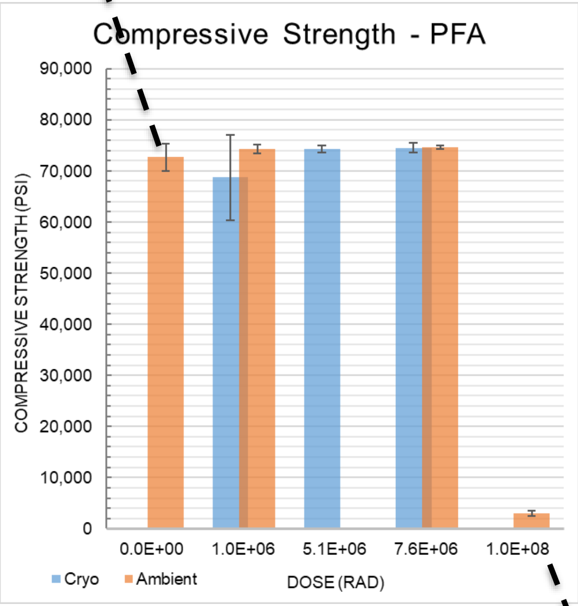
ASTM D695 – Compressive Strength

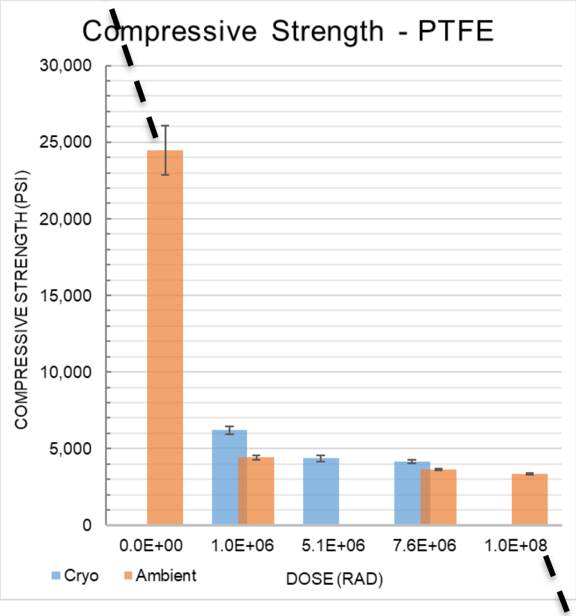


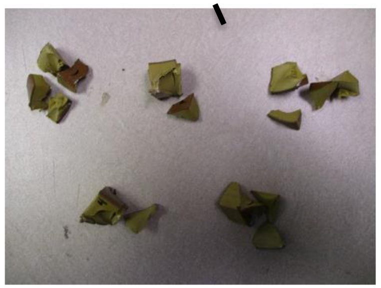



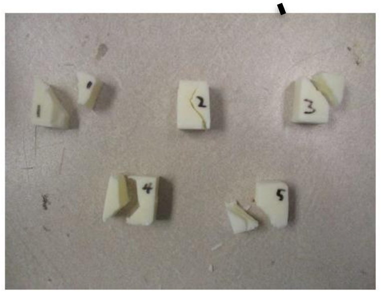










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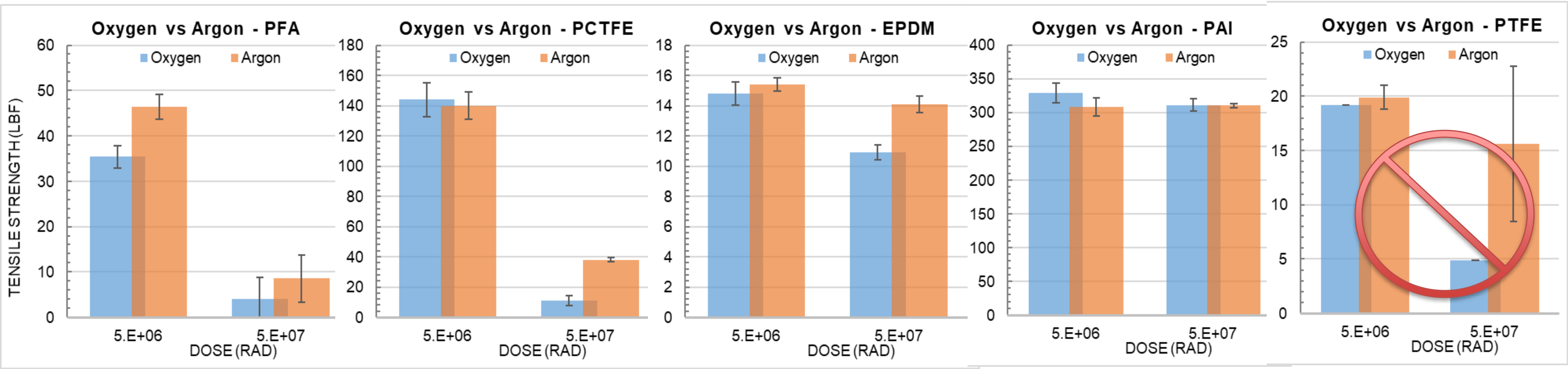
Oxygen Effects – D638-V Subexperiment

- **Presence of oxygen and ozone during irradiation is known to enhance polymer damage**
- **Sub-experiment to evaluate Argon purge effectiveness and/or necessity was included**
- **Sets of 3 microdogbones irradiated to intermediate dose levels, ‘punctured’ vs ‘sealed’**



Oxygen damage enhancement is ***significant*** for:
PFA at 5 Mrad and 50 Mrad,
PCTFE at 50 Mrad
EPDM at 50 Mrad

PAI demonstrated ***no significant*** oxygen damage enhancement at either dose level

PTFE yielded excessive failed parts… **Inconclusive**.

Error bars represent 95% Confidence Interval – ***Dosimetry uncertainty is not shown***

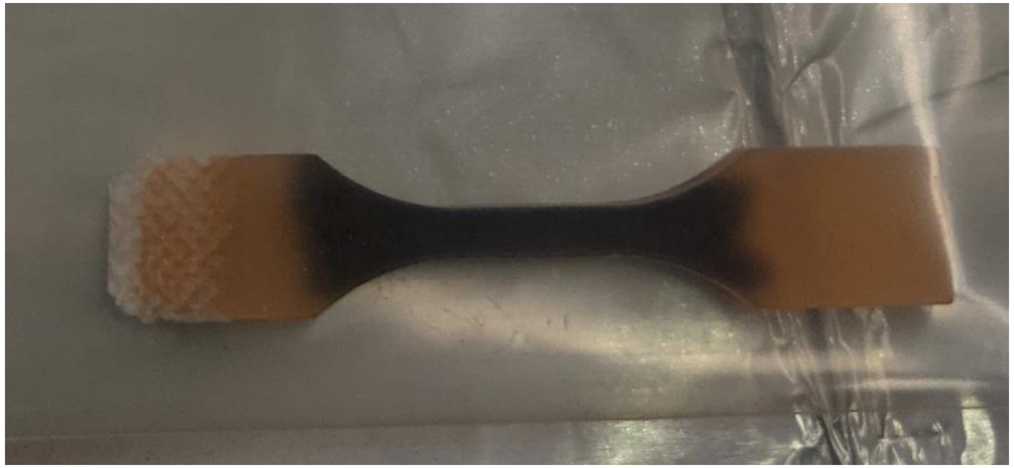
Neutron Irradiated Polymers

Neutrons/cm²	PAI (Torlon)	PTFE (Teflon)	PFA (Teflon)	PCTFE (Kel-F)	EPDM Rubber
$1x10^{17}$					
$3x10^{16}$					
$1x10^{16}$					
$1x10^{15}$					

Hard to get a grip on some!

PCTFE Control

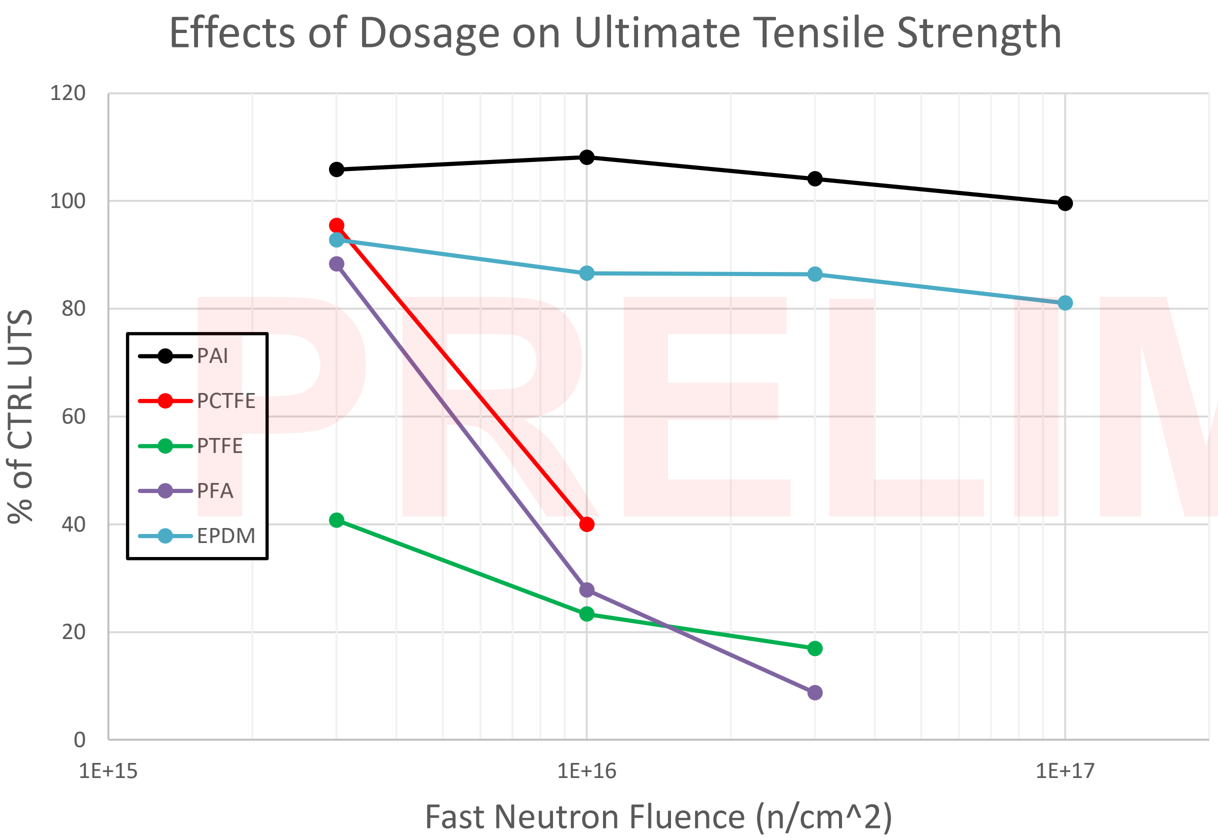
PCTFE at 3E16 n/cm^2

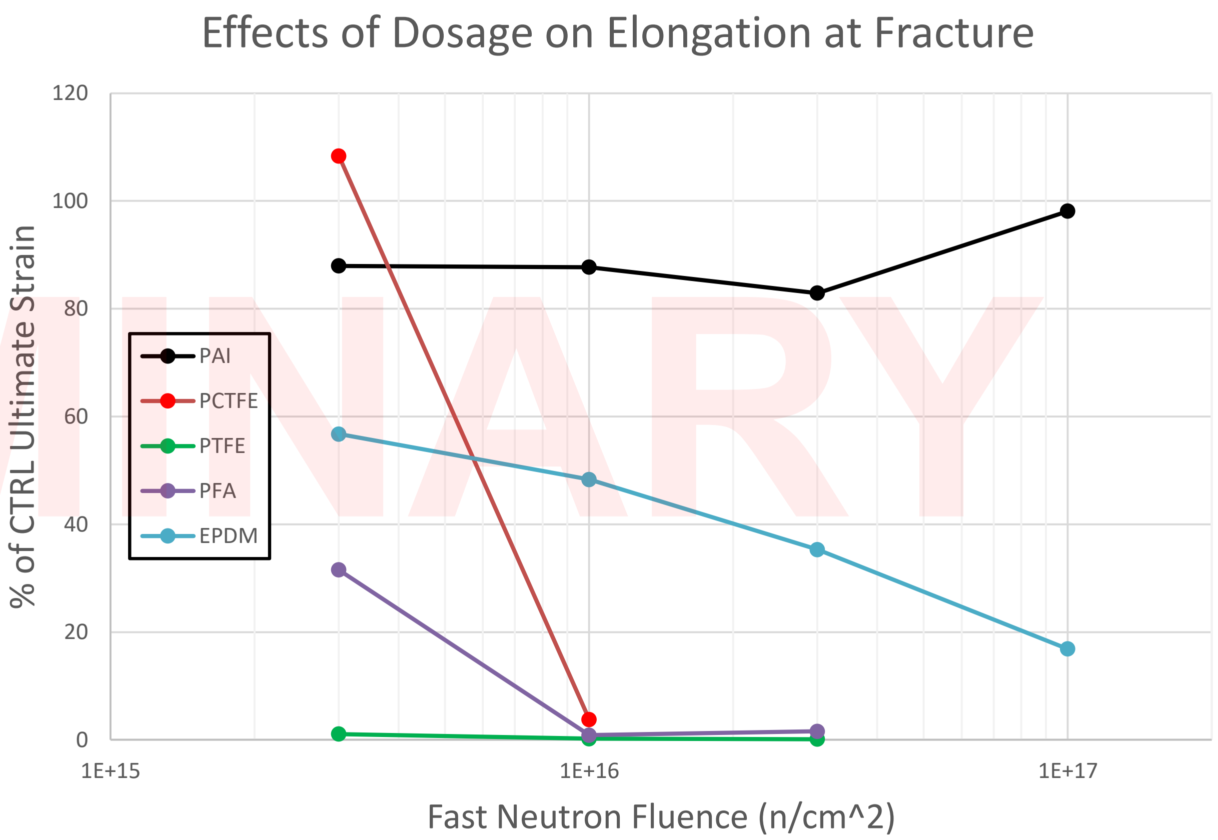


At high dose: PCTFE, PFA, and PTFE become very brittle and could not withstand the necessary grip pressure without complete sample failure

Neutron Irradiated Polymers

Data Preview… Thanks to Cameron Bosley (JACOBS EM22)



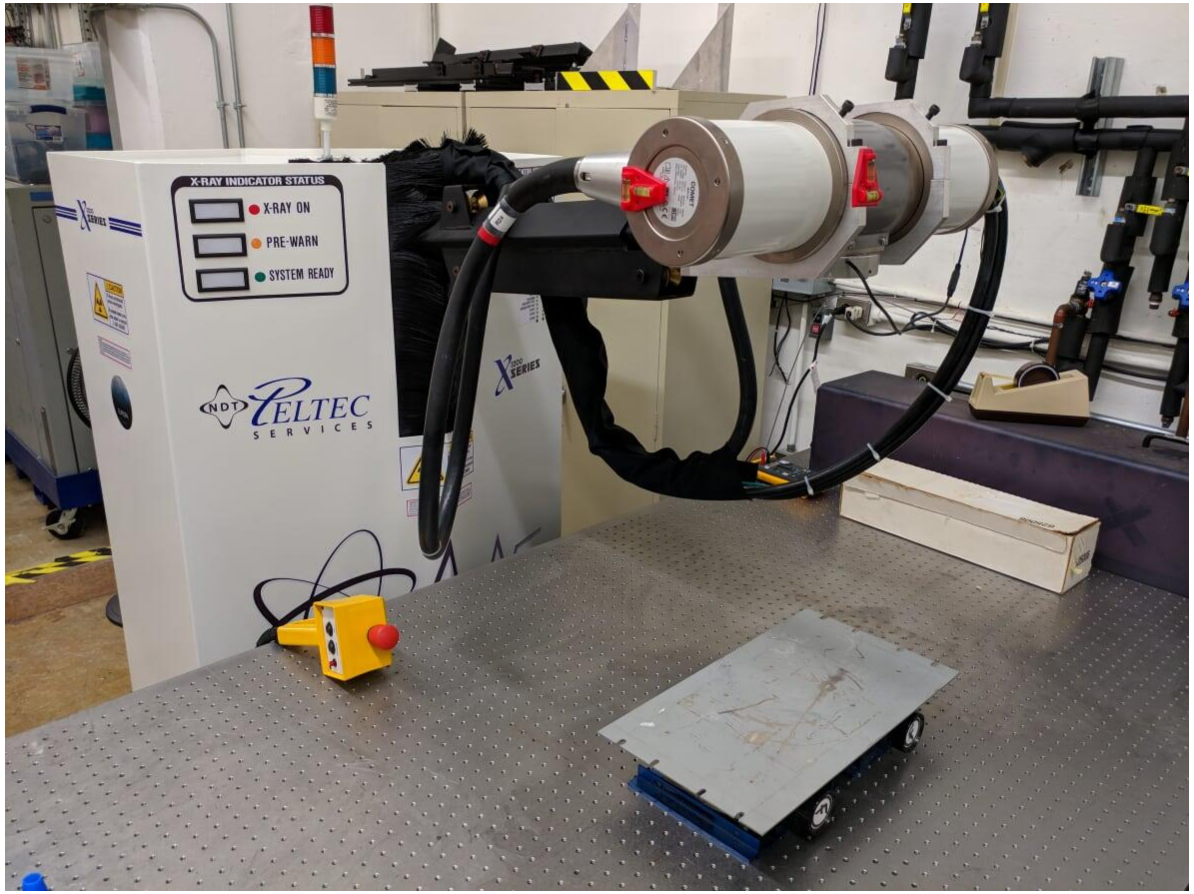


- Dose level in this experiment facility is tracked by Fast Neutron fluence
- Actual test environment includes gamma contribution. Gamma contribution is being characterized (in work)

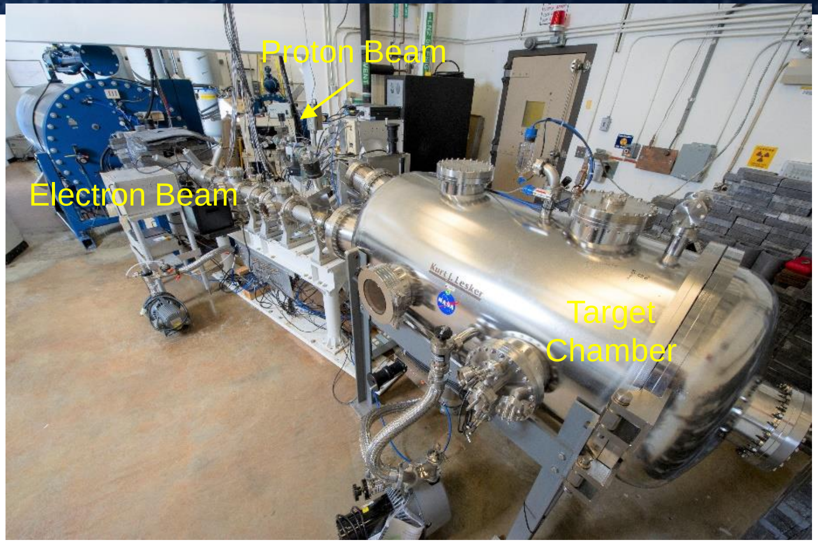
In-house irradiation capability

Electron beam gives high dose rates at cryo/vac condition, but limited thickness

‘Repurposed’ NDE X-ray with MXR-321 beam head…
It works well but with limited through-put



Valve seal tests for completion April 2021



CEEF at MSFC

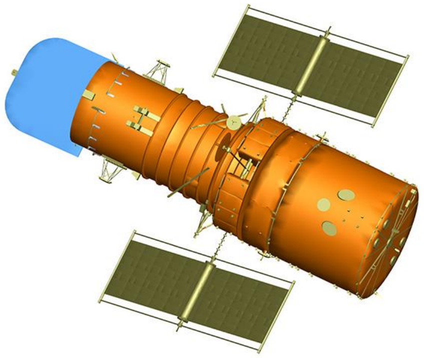
Preparing sample plate with live propellant

Questions Investigated Here

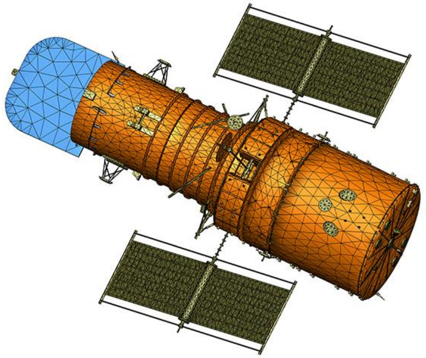
- **Are there obvious material ‘stand-outs’, both good and bad?**
  - PTFE appears to perform very poorly even at the lowest specified dose of 1 Mrad (no surprise here)
  - PAI Performs very well across all conditions
- **Where are the thresholds (or ‘shoulders’) of effects for each material treatment?**
  - Depends on material and parameter – Present dataset helps us narrow down where to be concerned
- **Is cryogenic radiation testing necessary, or is ambient radiation data adequate?**
  - Inconclusive, given much of dataset captures ‘subthreshold’ behavior
- **Is oxygen exposure during irradiation a significant confounder?**
  - Very dependent upon material and dose level
  - May evaluate on a case-by-case basis
- **Do micro-tensile specimens adequately capture radiation effects?**
  - Yes, but with more ‘noise’ and significantly offset results compared to larger tensile specimens
- **Is the LN2 submersion technique an adequate method for cryogenic irradiation?**
  - Dewar failure during irradiation needs further investigation (Shipping damage, thermal shock, radiation-induced?)
  - Great for cheap ‘bulk work’ but probably more difficult to ensure consistent dose across sample sets
  - Post-process labor and uncertainty terms really add up!

In-work: Harnessing Attila4MC Capability

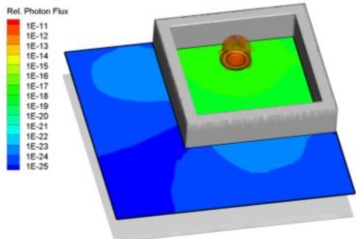
CAD Import and simplification



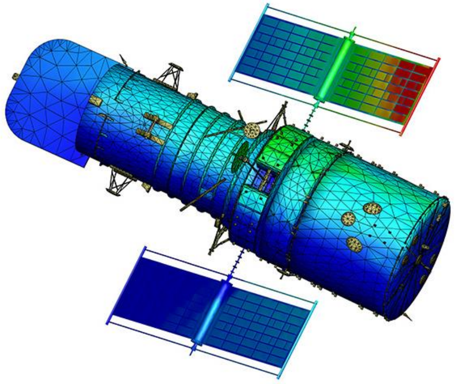
Unstructured Mesh Generation



Deterministic Variance Reduction (Attila)

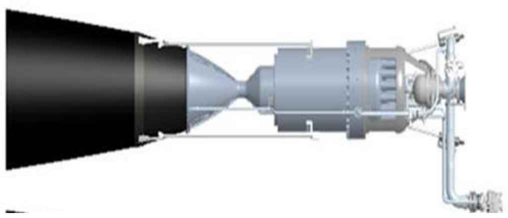


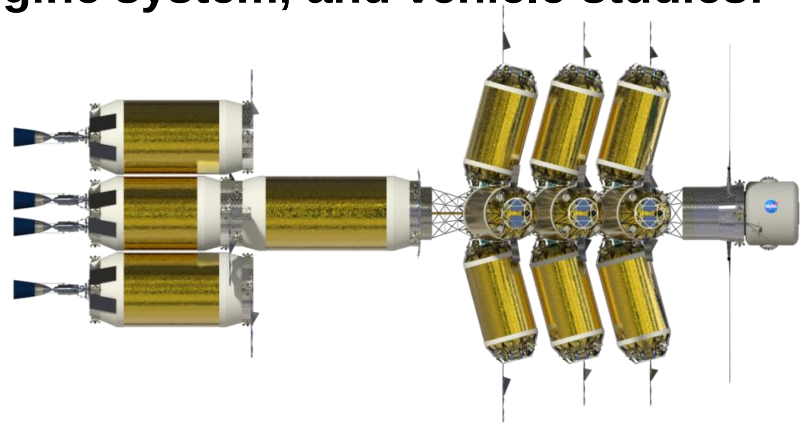
MCNP6 Radiation Transport and TecPlot visualization



- **Efficient integration of CAD**
- **Better physics handling of shields and large structures**

Capabilities apply to reactor, engine system, and vehicle studies:





Backup

Thoughts on radiation survivability workflow

CONCLUDING THOUGHTS

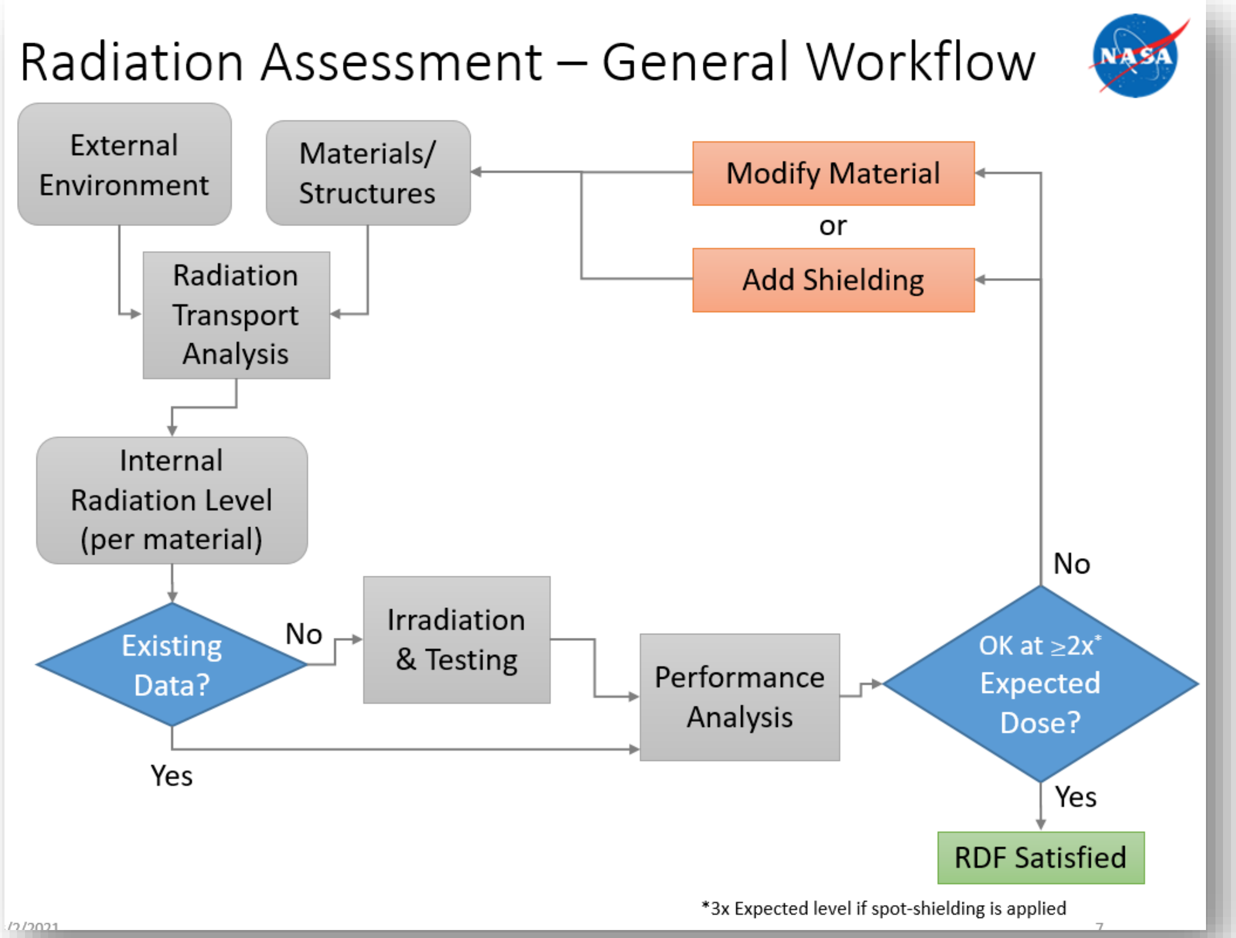
-Look out for polymers (especially Teflon), but don't necessarily rule them out of a design!

-We can choose alternate materials, 'tweak' the existing material, or add localized shielding.

-Radiation challenges reach everywhere… we need integrated solutions.

Here was a concept-flow drafted for other projects dealing with space environment rad-survivability challenges

NOT AN SNP PRODUCT… JUST A VISUAL AID FOR DISCUSSION!

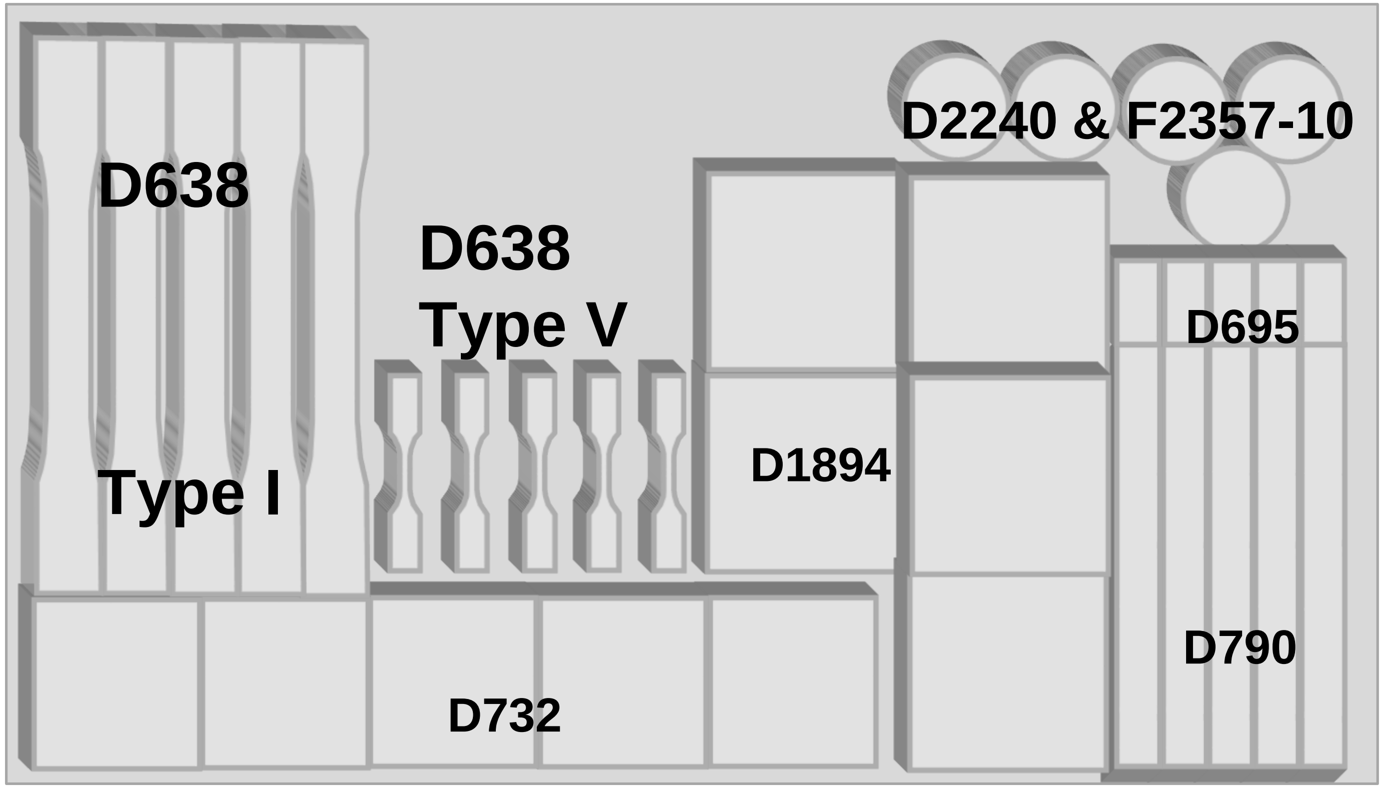


Sample set – 1 treatment

Materials:
Polyamide-imide (PAI) / Torlon®
Polychlorotrifluoroethylene (PCTFE) / Kel-F®
Perfluoroalkoxy alkane (PFA) Teflon®
Polytetrafluoroethylene (PTFE) Teflon®
Ethylene propylene diene monomer (EPDM)

ASTM standard procedures:
Tensile strength and elongation
 (ASTM D638 Type I and Type V)
Compressive strength and modulus
 (ASTM D695)
Hardness (ASTM D2240)
Shear strength (ASTM D732)
Flexural strength (ASTM D790)
Static and kinetic friction (ASTM D1894)
Friction wear (ASTM F2357)

One Sample Treatment



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