The Effect of Dose Rate on Composite Durability When Exposed to a Simulated Long-Term Lunar Radiation Environment

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Human exploration of space beyond low Earth orbit (LEO) requires a safe living and working environment for crew. Composite materials are one type of material being investigated by NASA as a multi-functional structural approach to habitats for long-term use in space or on planetary surfaces with limited magnetic fields and atmosphere. These materials provide high strength with the potential for decreased weight and increased radiation protection of crew and electronics when compared with conventional aluminum structures. However, these materials have not been evaluated in a harsh radiation environment, as would be experienced outside of LEO or on a planetary surface. Thus, NASA has been investigating the durability of select composite materials in a long-term radiation environment.

Previously, NASA exposed composite samples to a simulated, accelerated 30-year radiation treatment and tensile stresses similar to those of a habitat pressure vessel. The results showed evidence of potential surface oxidation and enhanced cross-linking of the matrix[1]. As a follow-on study, we performed the same accelerated exposure alongside an exposure with a decreased dose-rate. The slower dose-rate is comparable to a realistic scenario, although still accelerated. Strain measurements were collected during exposure and showed that with a fast-dose rate, the strain decreased with time, but with a slow-dose rate, the strain increased with time[2]. After the radiation exposures, samples were characterized via tensile tests, flexure tests, Fourier Transform Infrared Spectroscopy (FTIR), and Differential Scanning Calorimetry (DSC). The results of these tests will be discussed.

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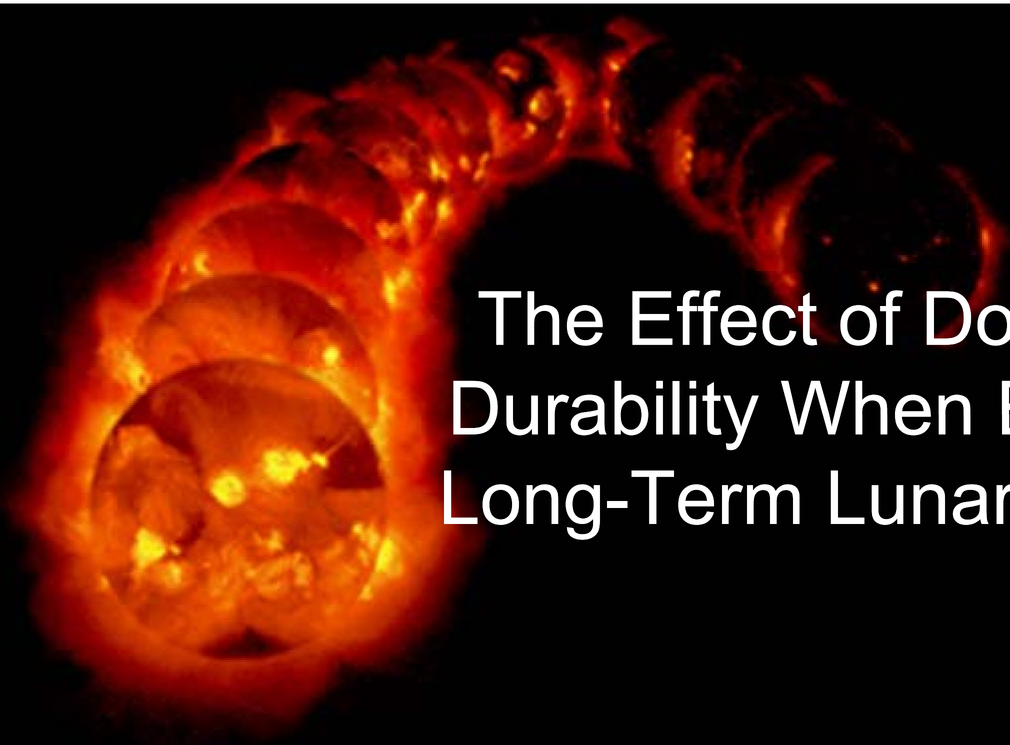
[1] Rojdev, K., et.al. "Long-Term Lunar Radiation Degradation Effects on Materials." Presented at National Space and Missile Materials Symposium, Scottsdale, AZ. June 28-July 1, 2010.
[2] Rojdev, K., et.al. "In-Situ Strain Analysis of Potential Habitat Composites Exposed to a Simulated Long-Term Lunar Radiation Exposure." Presented at Ionizing Radiation and Polymers Conference, College Park, MD. October 25-29, 2010.



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Outline

- Introduction
- Exposures – test setup and in-situ results
- Sample characterization and analysis
- Ongoing Work
- Questions

INTRODUCTION

Motivation/Purpose

- Long-term surface habitation requires large structures that must withstand the environment for the duration of the missions
- Fiber reinforced composites have gained interest
  - Potential weight savings
  - Potential enhanced radiation protection for the crew and electronics
  - Potential for infusing cutting edge research

Problem/Objectives

- Problem: composite materials have not been characterized for the space radiation environment, which is known to cause damage to polymeric materials
- Objective: assess composite durability in a simulated long-term lunar radiation environment

Assumptions

- The habitat is unshielded from radiation on the exterior
  - There is some multi-layer insulation and micrometeorite/surface ejecta shielding, but no galactic cosmic ray shielding (i.e. covering the habitat under regolith)
- The habitat will remain on the surface and be in service for 30 years
- The habitat is pressurized with air at an elevated oxygen concentration
- The habitat is exposed to one large solar particle event during each solar cycle and constant galactic cosmic ray exposure

Previous Work (2009)

- Investigated two materials
  - Carbon fiber + epoxy composite (CF)
  - Boron/Carbon fiber + epoxy composite (BF-CF)
- Exposure groups: control, tension only, radiation only, radiation + tension
- Conclusions: material properties changing, but inconsistent results
  - Need to validate repeatability of data
  - Increase data set for statistical significance
- Work presented at NSMMS 2010:

Rojdev, K., et.al. "Long-Term Lunar Radiation Degradation Effects on Materials." Presented at National Space and Missile Materials Symposium, Scottsdale, AZ. June 28-July 1, 2010

Current work (2010)

- Repeated parts of 2009 study
  - Repeatability
  - Increase statistical significance
- Added exposure group to study the dose-rate effects on the material
  - Fast dose-rate (0.1478 krad/s) vs. Slow dose-rate (0.0139 krad/s)
- Added in a study to look at how proton-radiation, stress, and dose-rate affect the materials' performance during hypervelocity impacts

Test setup and In-situ results

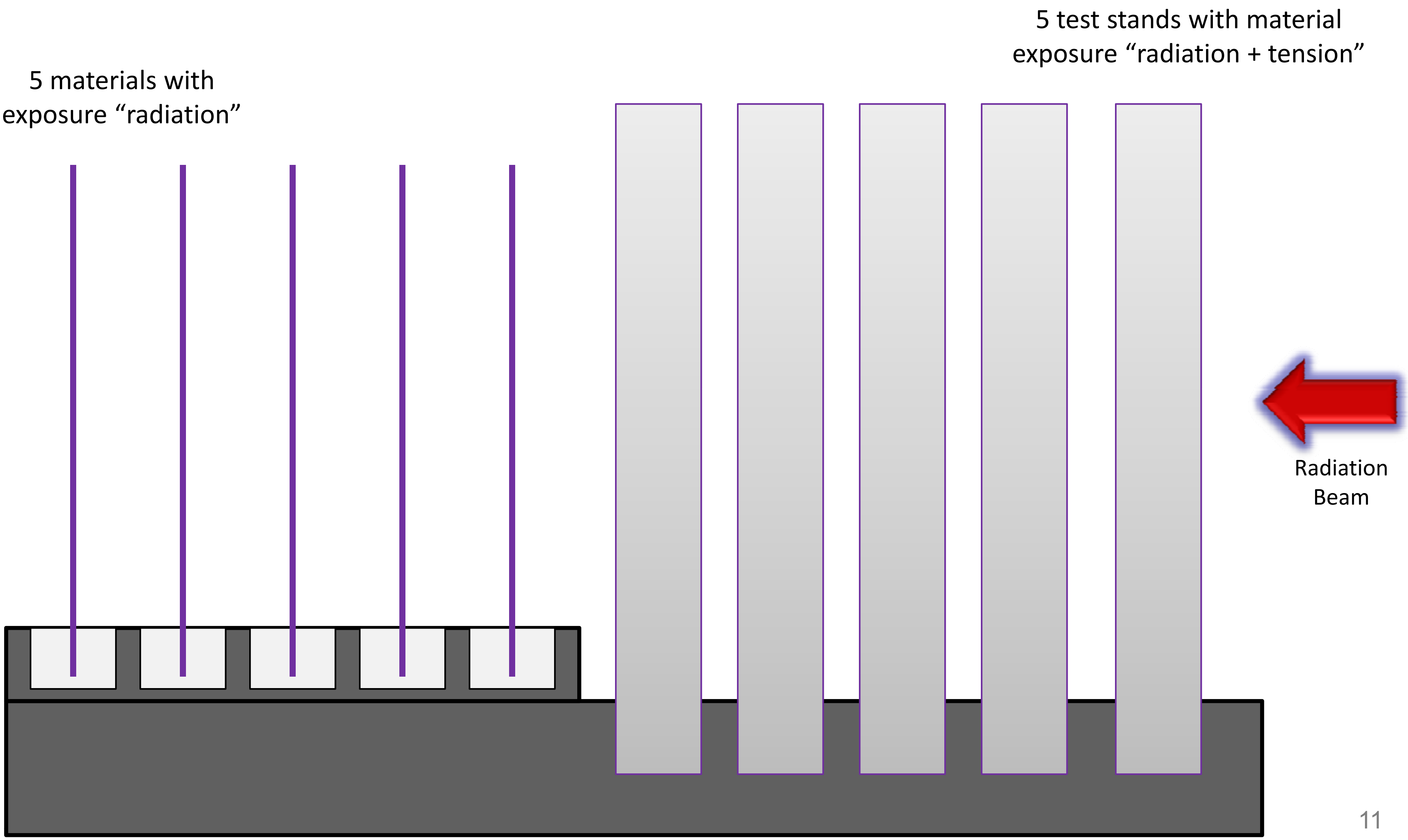
EXPOSURES

Radiation Exposures

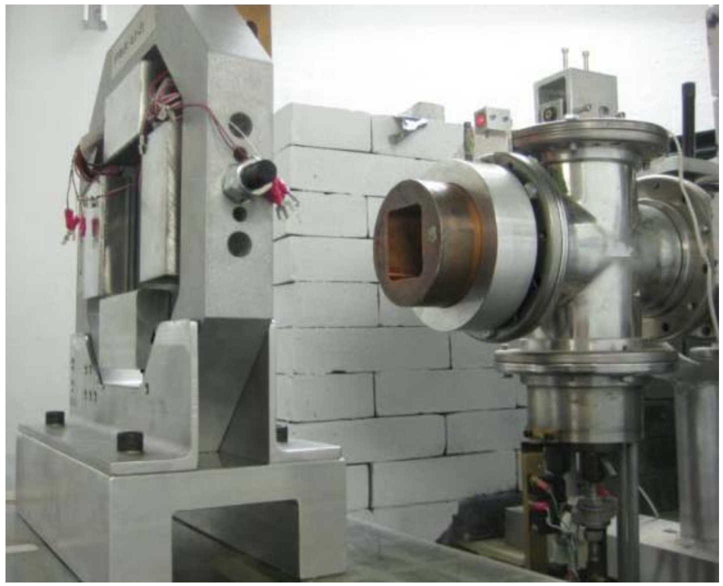
- Indiana University Cyclotron Facility
  - Total dose: 500 krads (200 MeV protons)
  - Fast dose rate: 147.8 rad/s
  - Slow dose rate: 13.9 rad/s

Exposure #	Dose Rate	# of Samples	Material
Exposure 1	Slow	10	BF-CF
Exposure 2	Slow	10	CF
Exposure 3	Fast	2	CF
Exposure 4	Fast	2	CF
Exposure 5	Slow	8	4 – BF-CF, 4 – CF
Exposure 6	Fast	8	4 –BF-CF, 4 – CF

Example Radiation Run



Radiation Test Set up



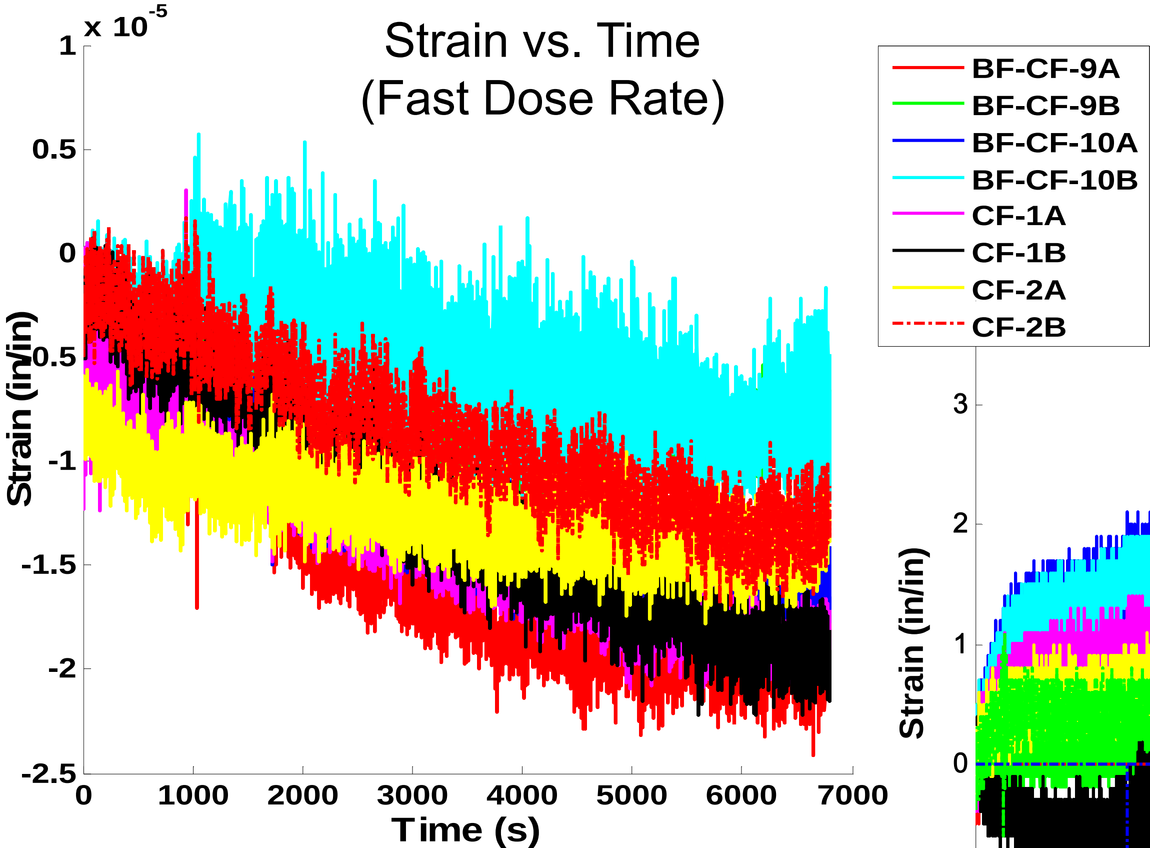
Radiation Beam

Strain gauge in center of sample – gather strain during the radiation exposure (also included thermocouple for sample temperature, not shown)

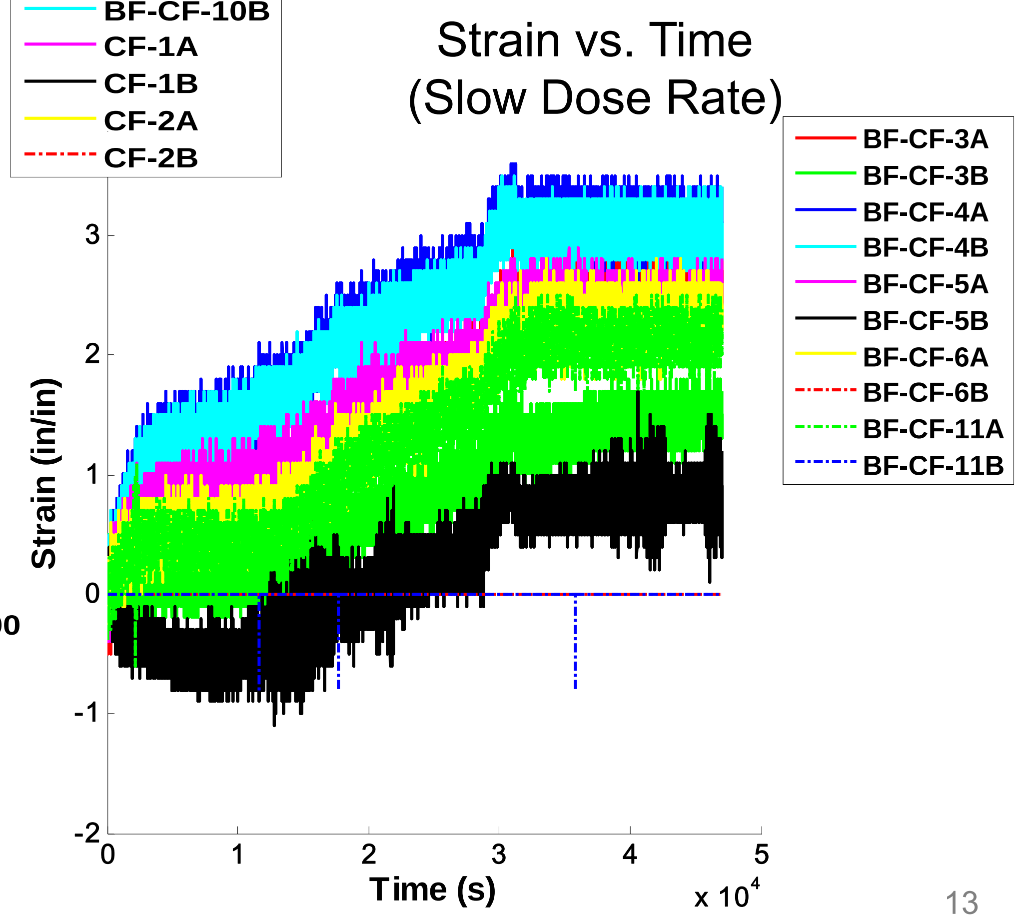
Sample in Test Stand

Beam Exit

In-Situ Strain Measurements



Details presented at Ionizing Radiation and Polymers (IRaP) 2011, College Park, MD.

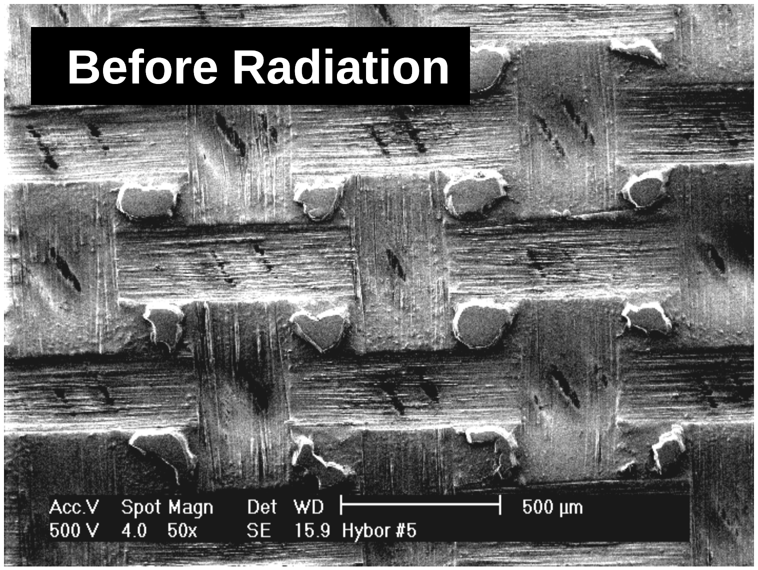


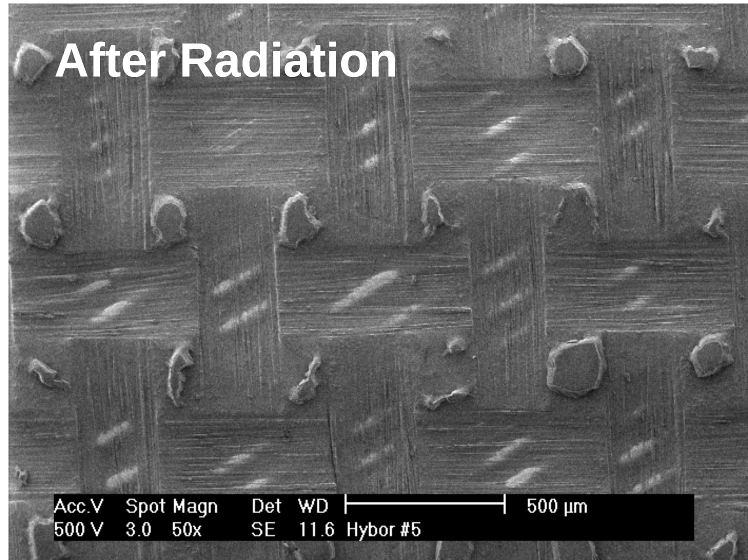
SAMPLE CHARACTERIZATION AND ANALYSIS

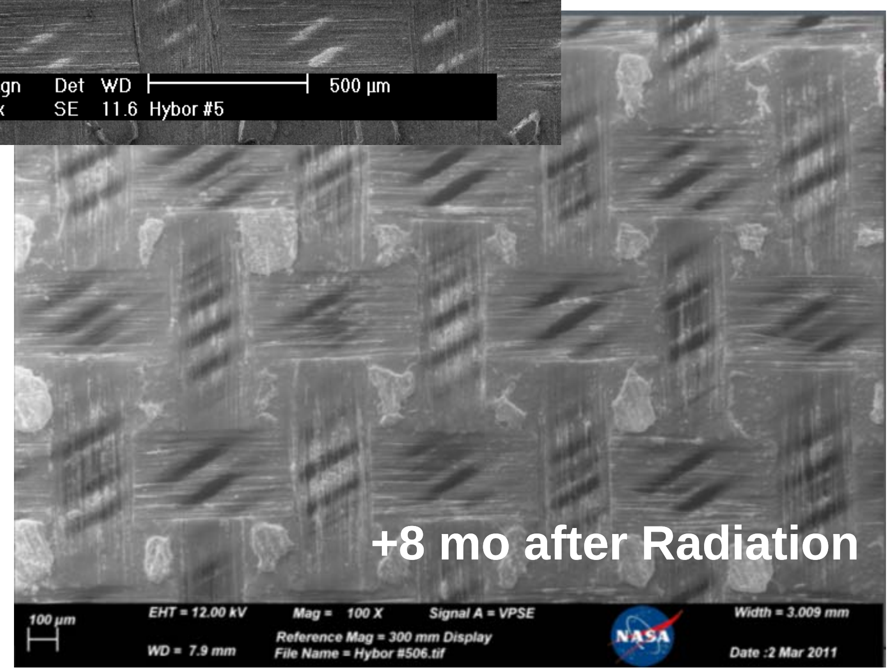
Characterization Completed

- Manufacturing
  - C-scan
- Chemistry
  - Fourier Transform Infrared Spectroscopy (FTIR): bulk chemical composition
- Mechanical Properties
  - Tension: tensile stress, strength, strain, ultimate strain, chord modulus, poisson's ration, stress vs. strain
  - Flexure: Flexural stress, strength, offset yield strength, chord modulus, strain, tangent modulus of elasticity, secant modulus, stress vs. strain
- Thermal Properties
  - Differential Scanning Calorimetry (DSC): heat capacity as a function of temperature, and changes in glass transition temperature
- Surface Properties and Edges
  - Scanning Electron Microscopy (SEM): look at surface for visual changes
  - Post-Fracture Analysis: Scanning Electron Microscopy (SEM): look at fracture edge after tension/flexure tests

Scanning Electron Microscopy (SEM) of Surfaces (Example: BF-CF Sample #5)



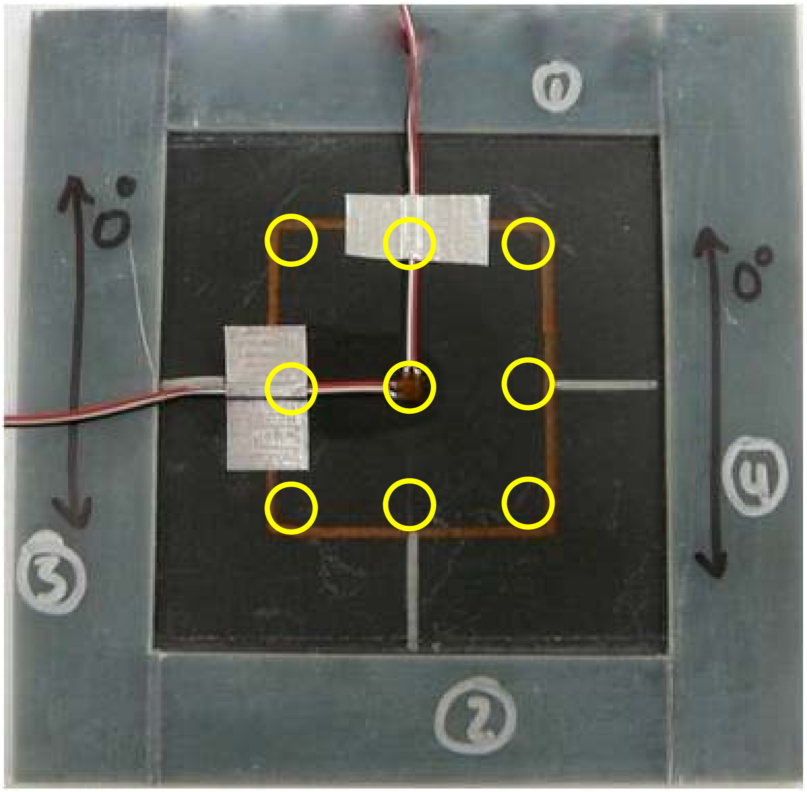




No visible surface morphology changes due to radiation

National Space and Missile Materials Symposium 2011
Madison, WI
June 27-30

Fourier Transform Infrared Spectroscopy (FTIR) Procedure



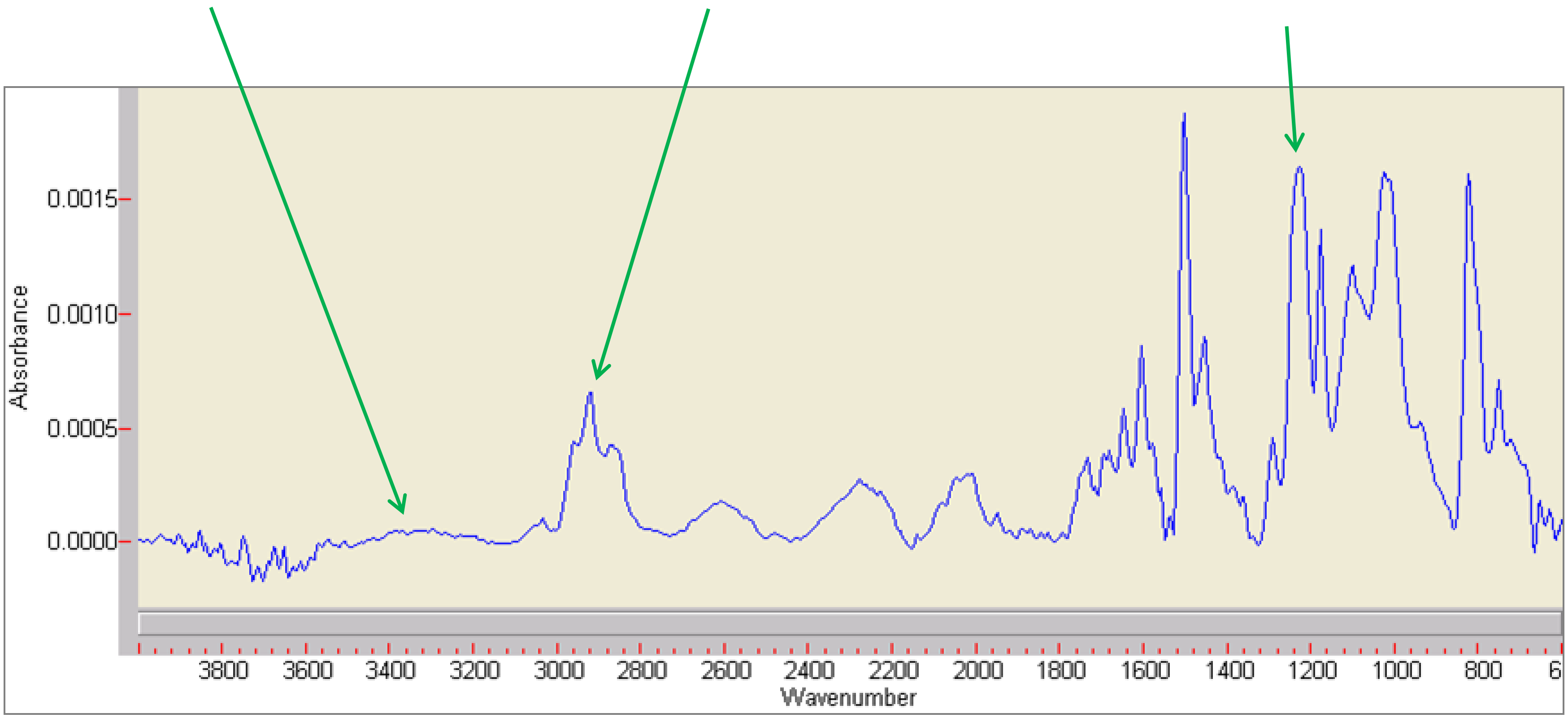
- Before radiation exposure, each sample was characterized by FTIR in 9 locations
- After radiation exposure, each sample was again characterized by FTIR in the same 9 locations
- Analysis focused on center region
- Post-radiation absorbance values were subtracted from pre-radiation absorbance values

FTIR Analysis (example)

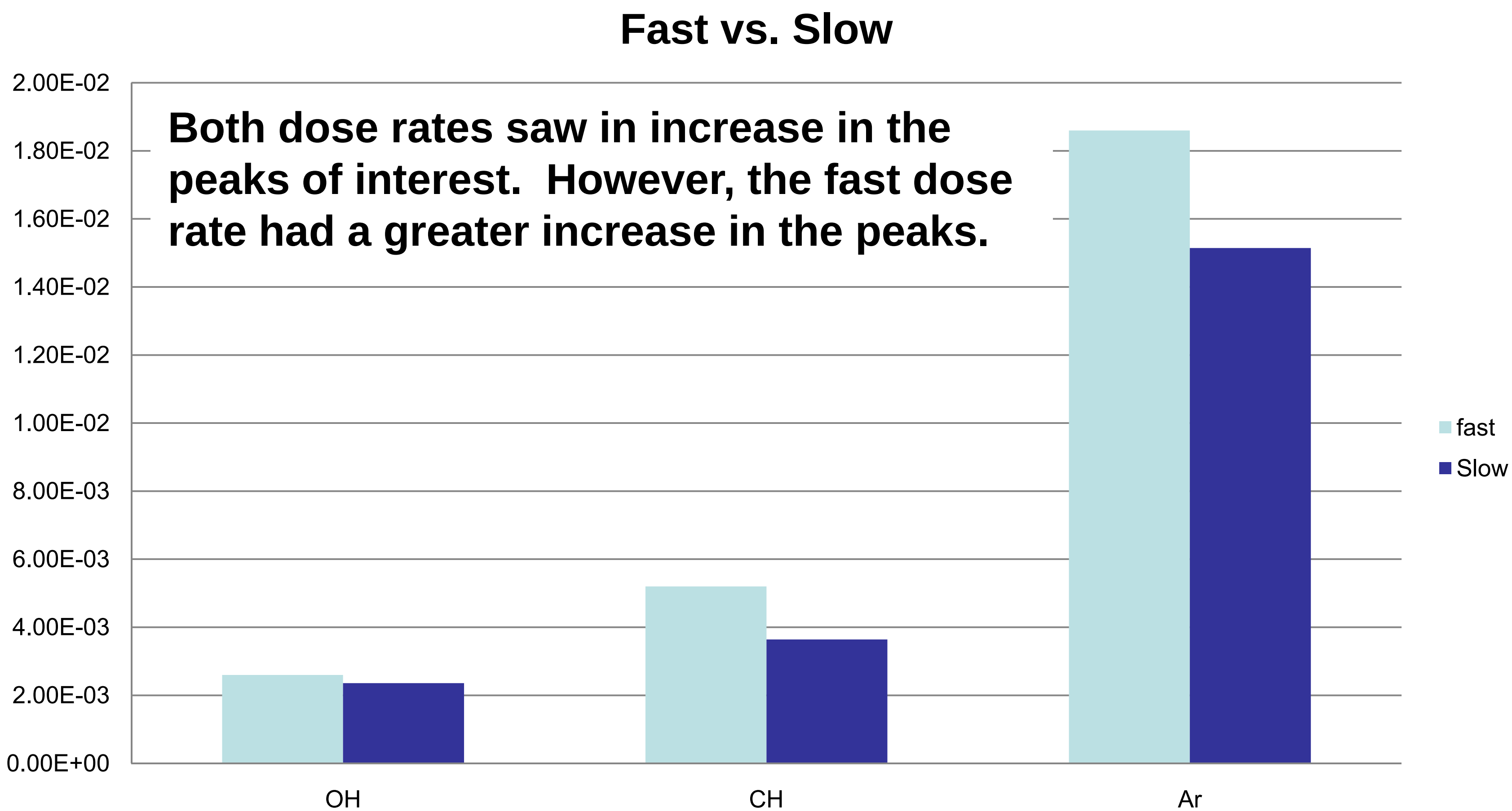
OH peak
Wavenumber 3373

C-H stretch
Wavenumber 2921

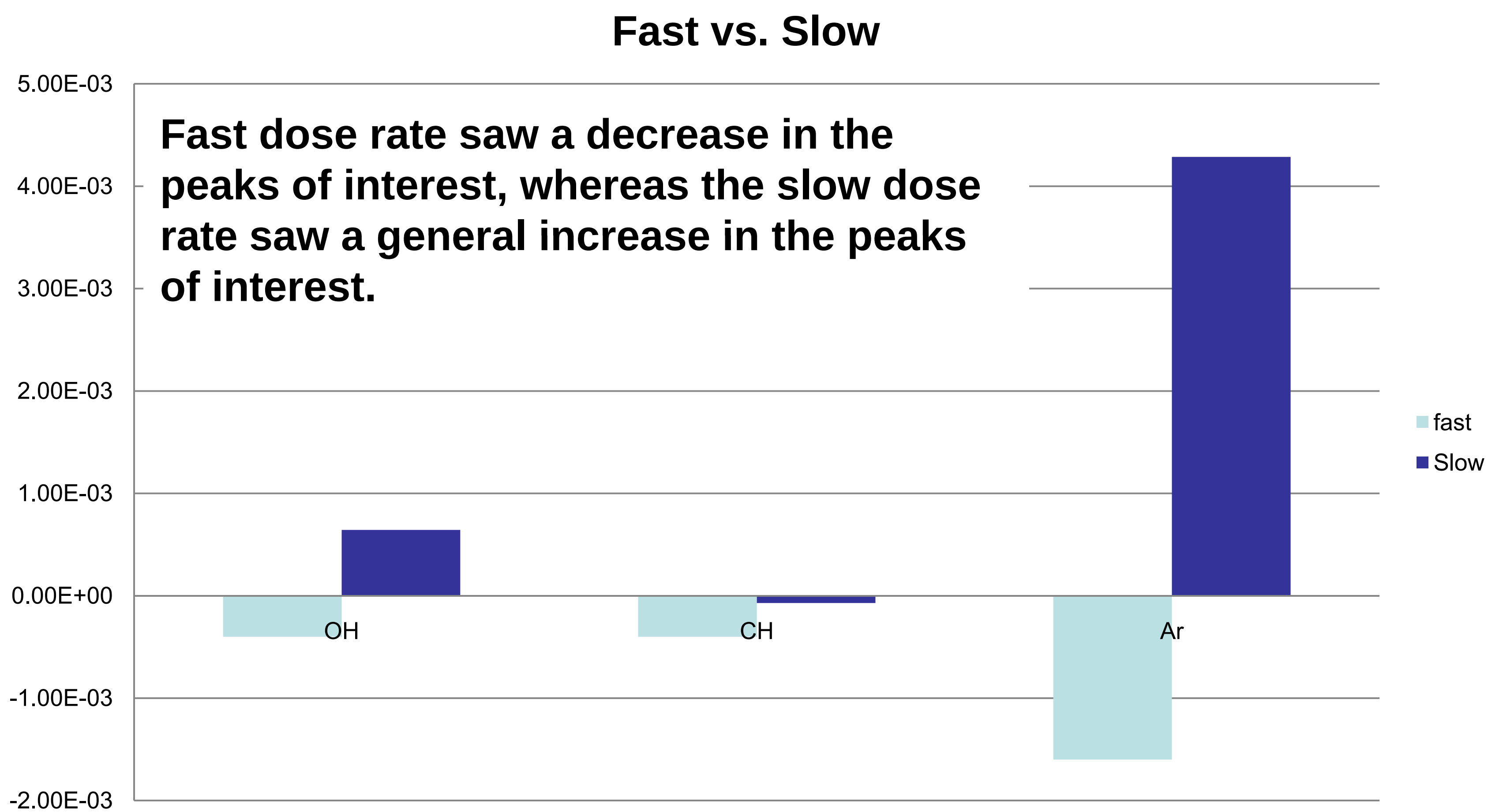
Aromatic peak
Wavenumber 1229



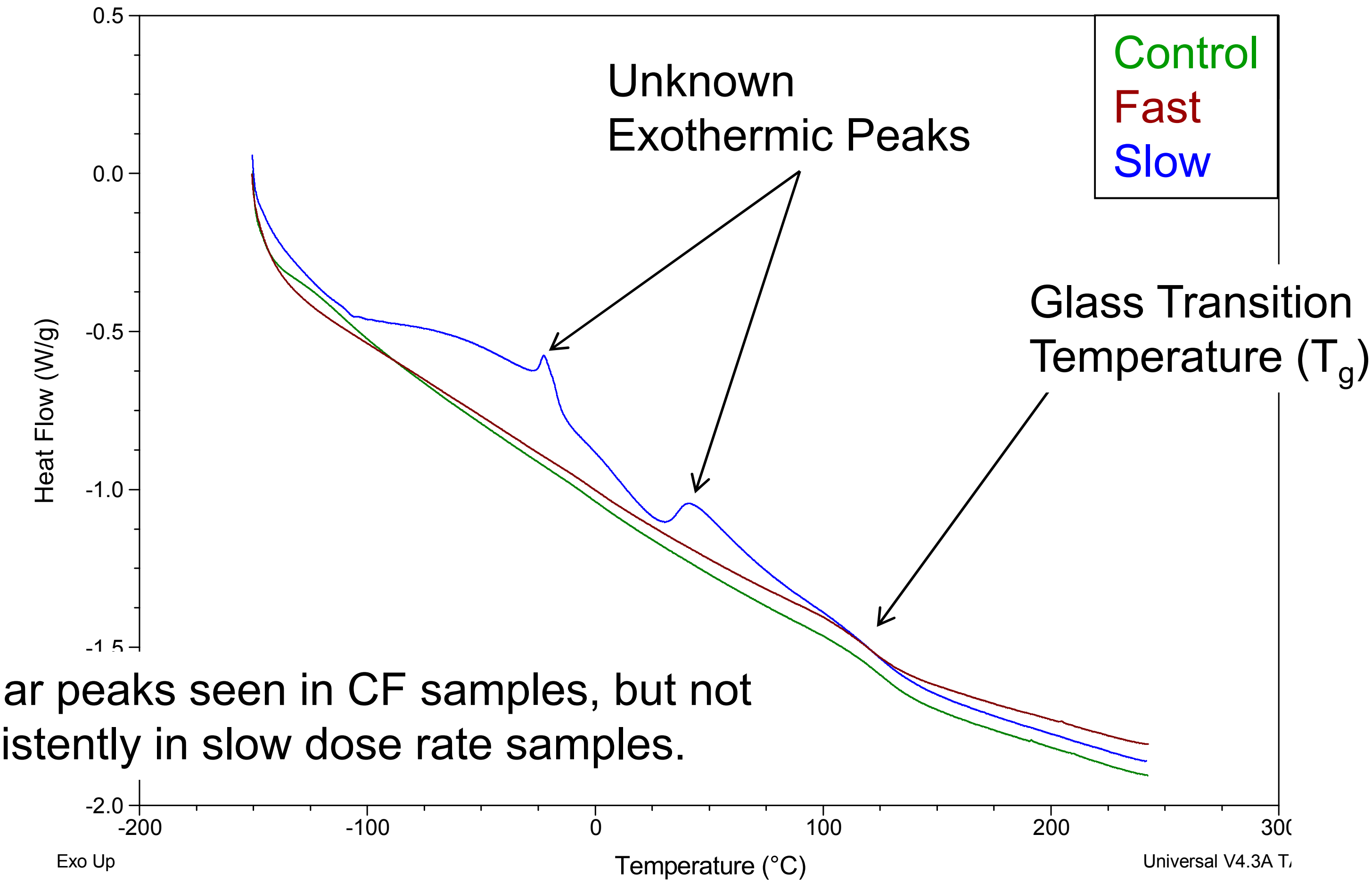
BF-CF Results



CF Results


Fast vs. Slow
Fast dose rate saw a decrease in the peaks of interest, whereas the slow dose rate saw a general increase in the peaks of interest.
5.00E-03
4.00E-03
3.00E-03
2.00E-03
1.00E-03
0.00E+00
-1.00E-03
-2.00E-03
OH
CH
Ar
fast
Slow

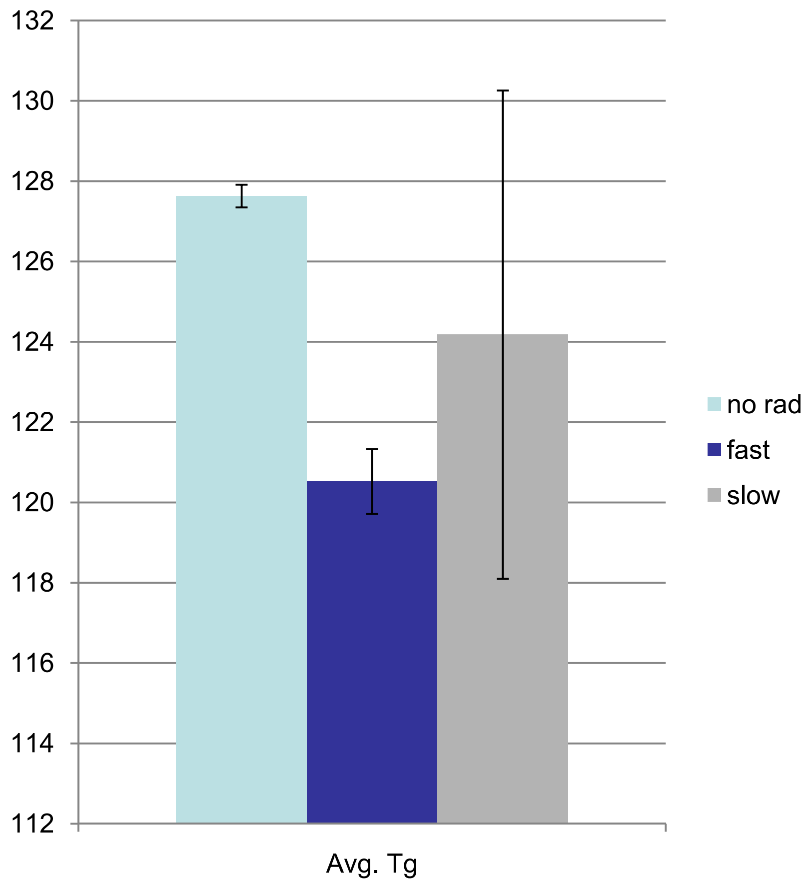
Differential Scanning Calorimetry (DSC): BF-CF sample



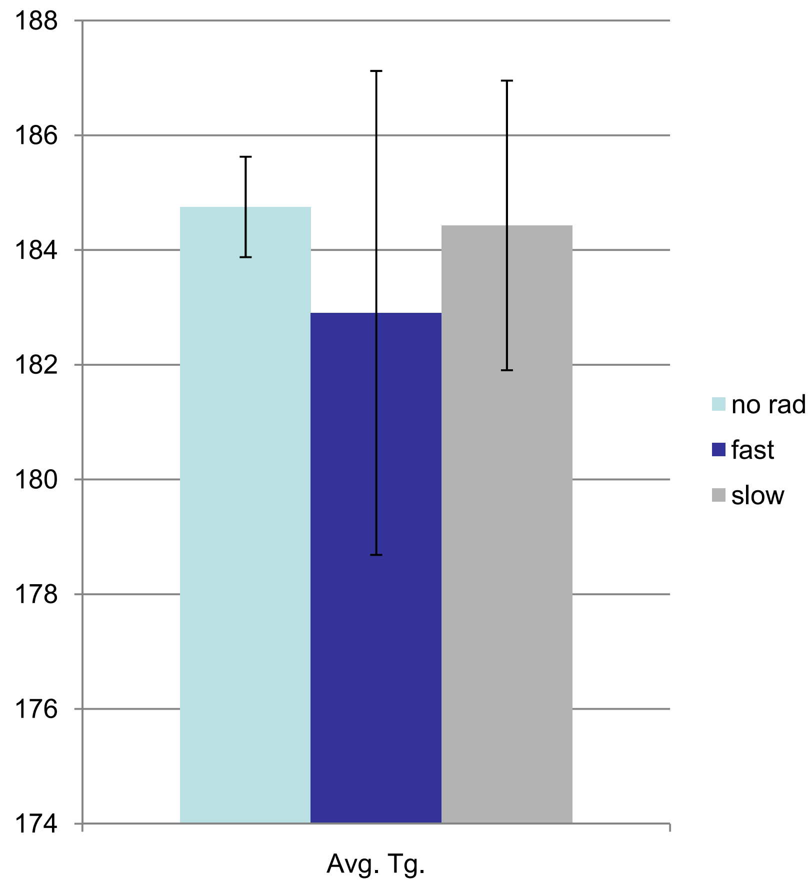
Similar peaks seen in CF samples, but not consistently in slow dose rate samples.

DSC Tg Trends

BF-CF average Tg



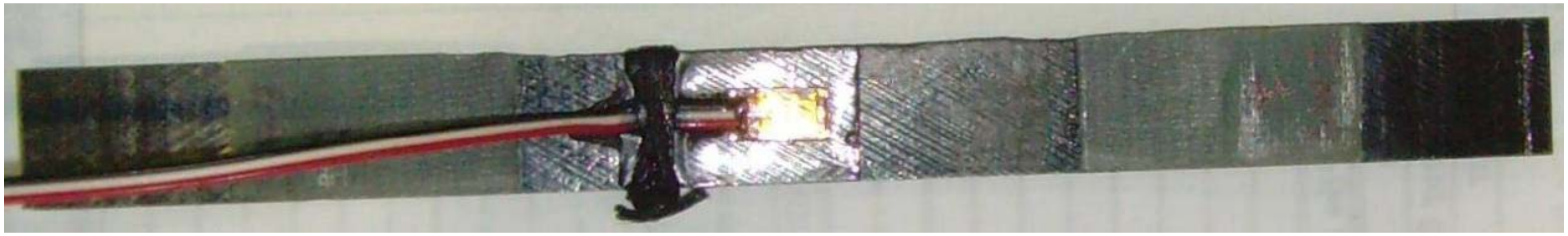
CF average Tg



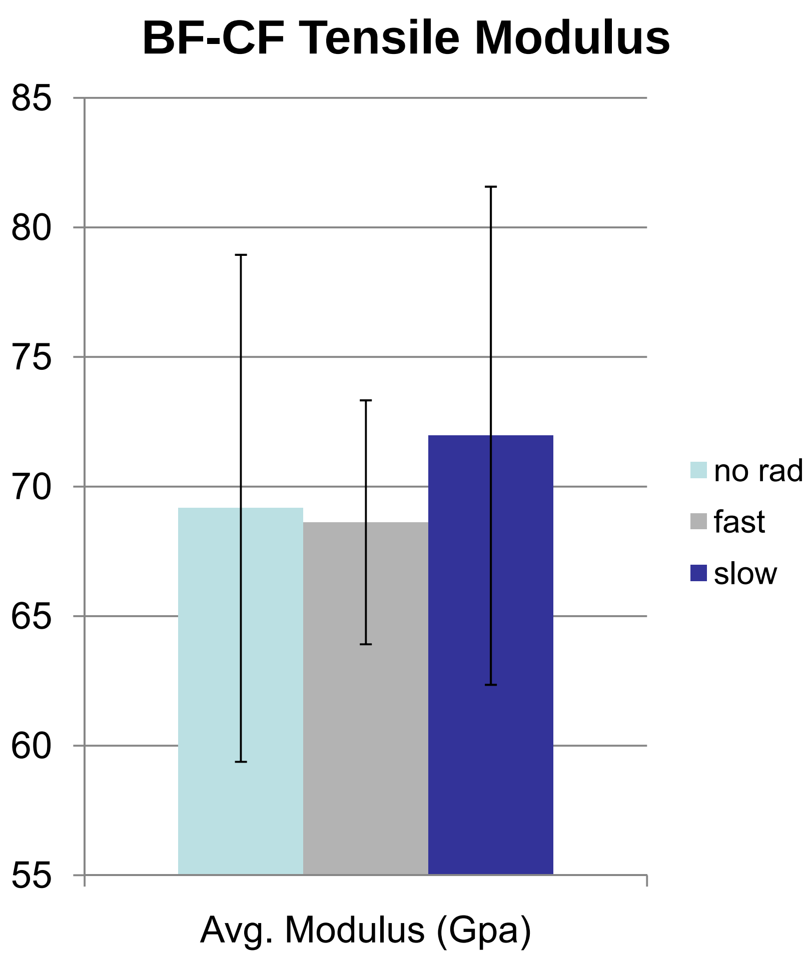
Trends show that radiation decreases the Tg and that the fast dose rate sees the largest decrease in Tg.

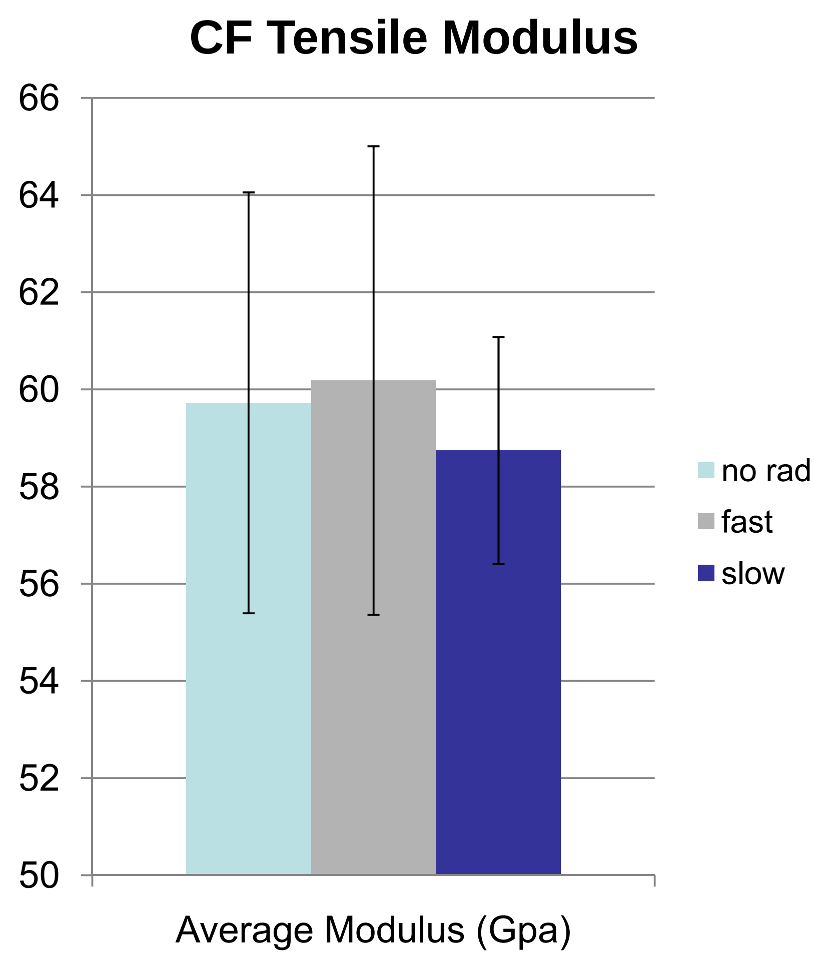
Tensile Test

- 1 coupon was cut per sample
- Coupons were cut perpendicular to 0° plys
  - to highlight any matrix sensitivities in tensile properties
- Each tensile coupon included
  - tabs to protect the material during test
  - single strain gauge in the center to collect tensile data



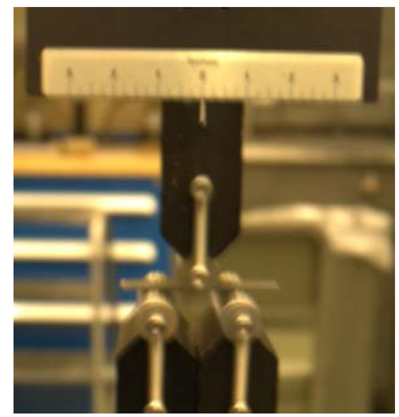
Average Tensile Modulus



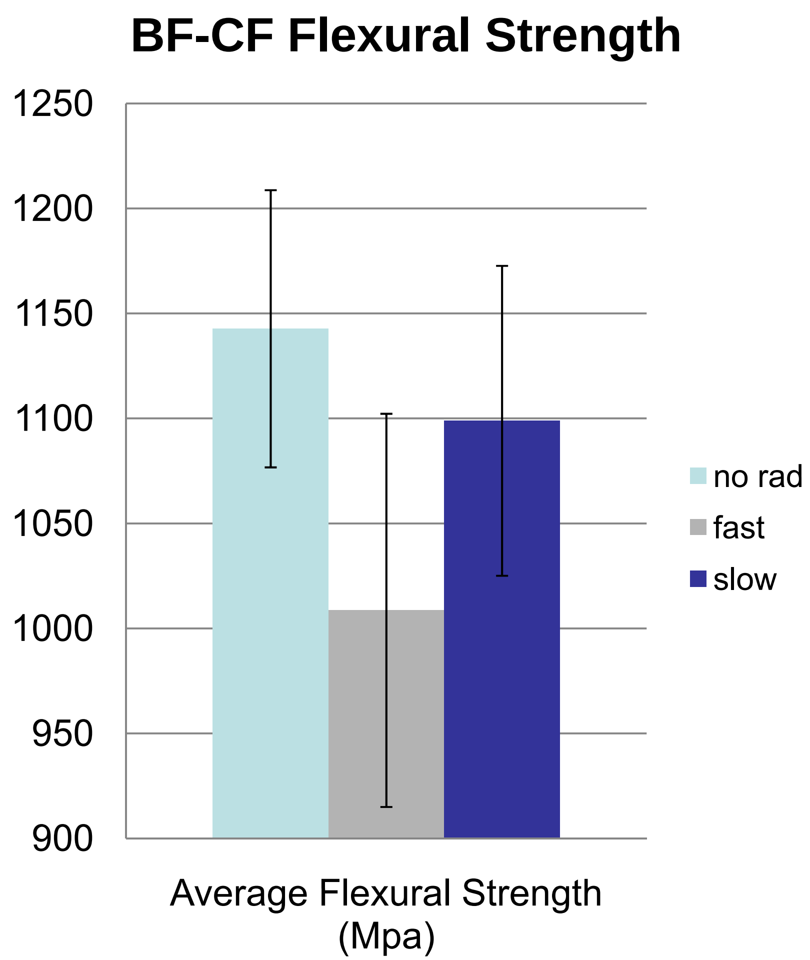


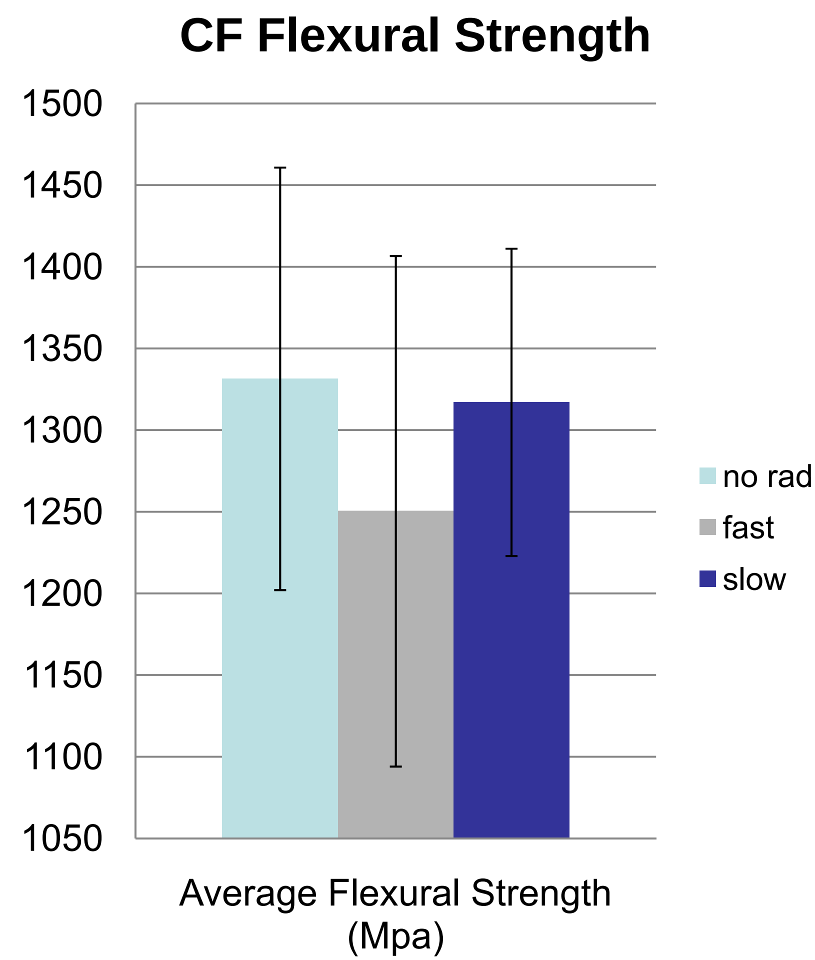
Flexure Test

- 1 coupon was cut per sample
- Coupons were cut perpendicular to 0° plys
  - to highlight any matrix sensitivities in the properties

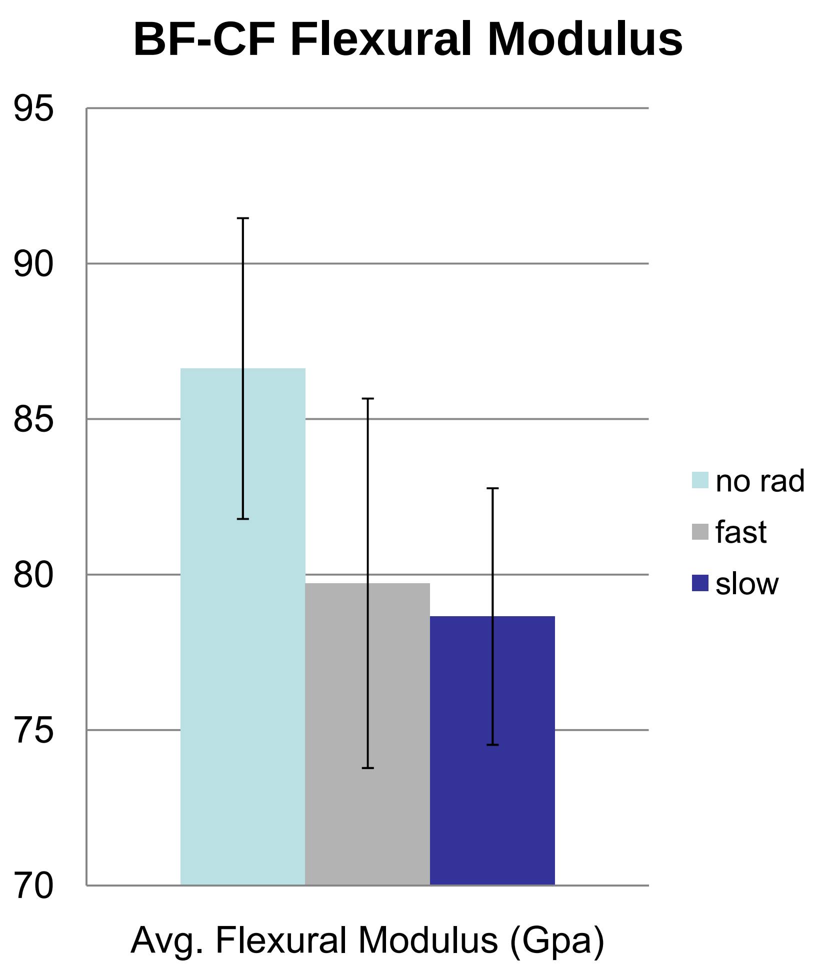


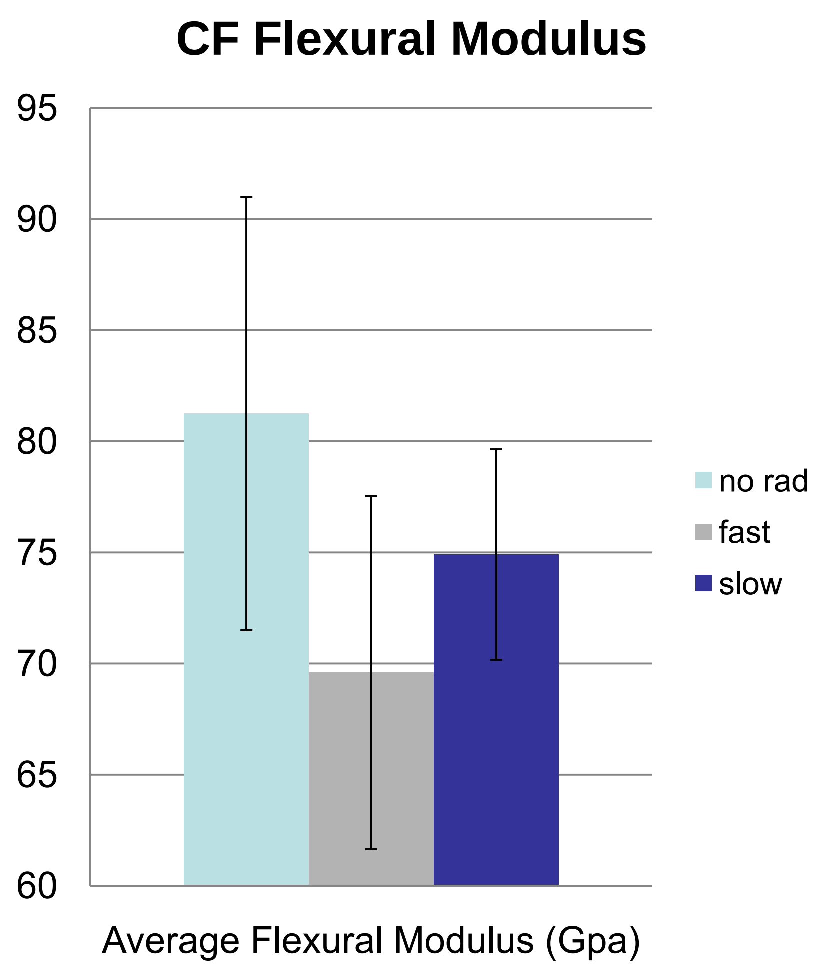
Average Flexural Strength





Average BF-CF Flexural Modulus





Summary of Results

		in-situ strain	SEM of surface	FTIR	DSC Tg	Tensile Modulus	Flexure strength	Flexure modulus
BF-CF	fast	decreasing strain with time	no change	increase in species	decreased Tg, smaller than slow	no change	smallest strength	decreased from control
	slow	increasing strain with time	no change	increase in species	decreased Tg	no change	decreased from control	decreased from control, slightly smaller than fast
CF	fast	decreasing strain with time	no change	decrease in species	decreased Tg, smaller than slow	no change	smallest strength	decreased from control and smaller than slow
	slow	increasing strain with time	no change	increase in species	decreased Tg	no change	decreased from control	decreased from control

Potential Mechanisms

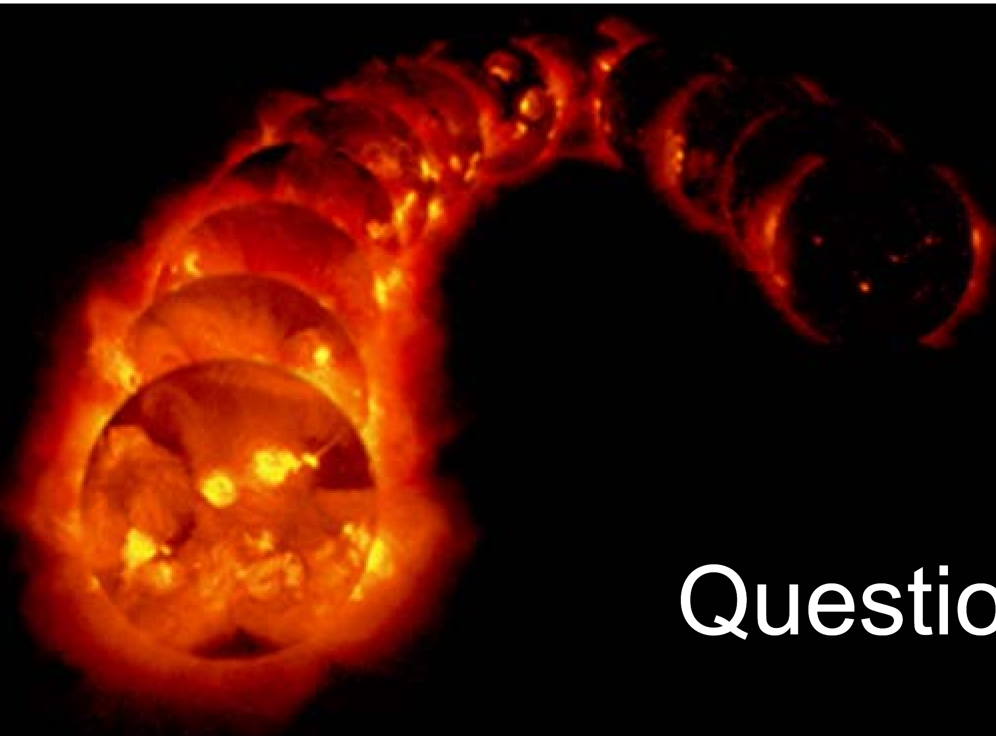
		in-situ strain	SEM of surface	FTIR	DSC Tg	Tensile Modulus	Flexure strength	Flexure modulus
BF-CF	fast	Crosslinking	-	?	Scission	-	Scission	Scission
	slow	Scission	-	?	Scission	-	Scission	Scission
CF	fast	Crosslinking	-	?	Scission	-	Scission	Scission
	slow	Scission	-	?	Scission	-	Scission	Scission

Future Work

- Analyze the fracture mechanisms in the tensile coupons using SEM
- Repeat radiation exposures
  - Gather more data on in-situ strain
    - Investigating potential sources of error
- Repeat tensile tests
  - Changing method of coupon manufacture to attempt to reduce the error bars
- Collect tensile data at + 3 months, +6 months, and +9 months after radiation

Acknowledgements

- Materials and Processes Branch at NASA-JSC
- Lab Staff at NASA-JSC
- Avionics Division at NASA-JSC
- Indiana University Cyclotron Facility
- The Boeing Company
- University of Southern California



Questions

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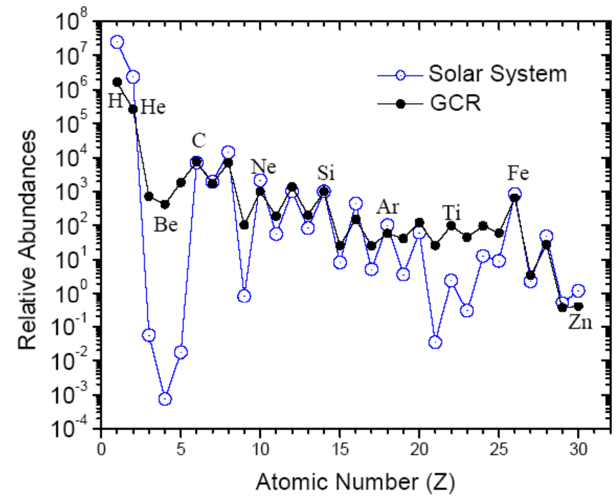
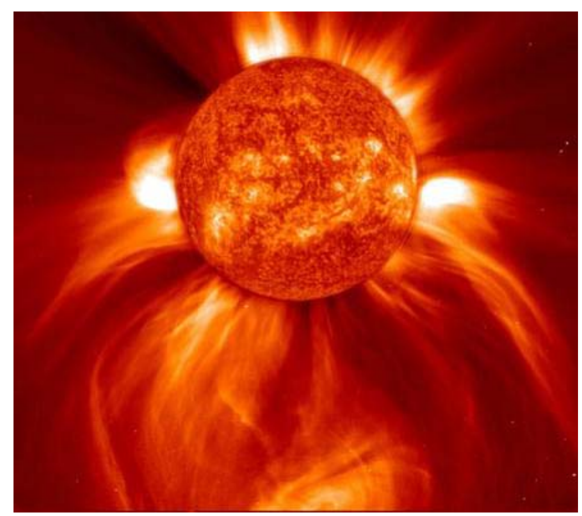
BACKGROUND

Background – Radiation Environment

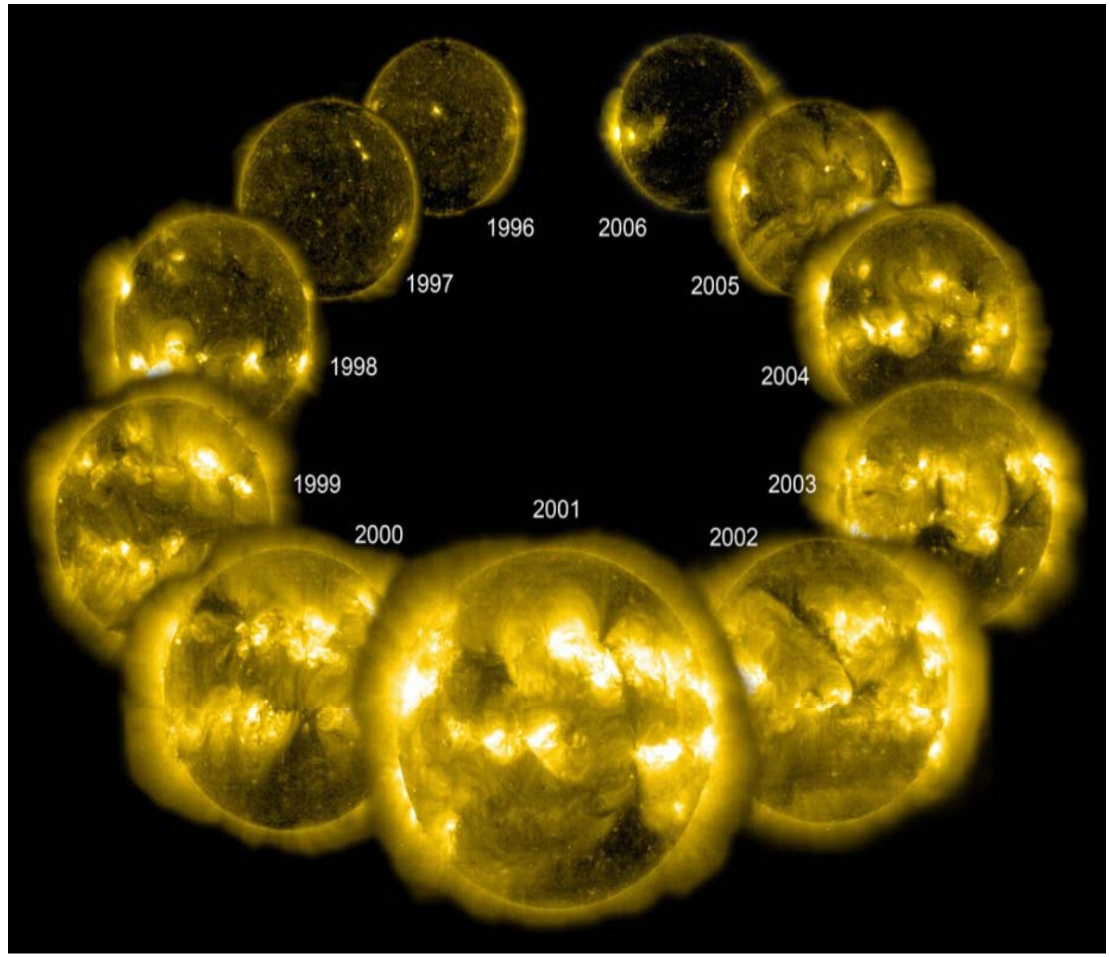
- Primary Radiation Exposure
  - Galactic Cosmic Rays (GCR)
    - Consists of stripped nuclei (hydrogen to uranium)
  - Solar Particle Events (SPE)
    - Consists of mainly high energy protons
- Concerned with high energy particle radiation





Discussion of the Sun

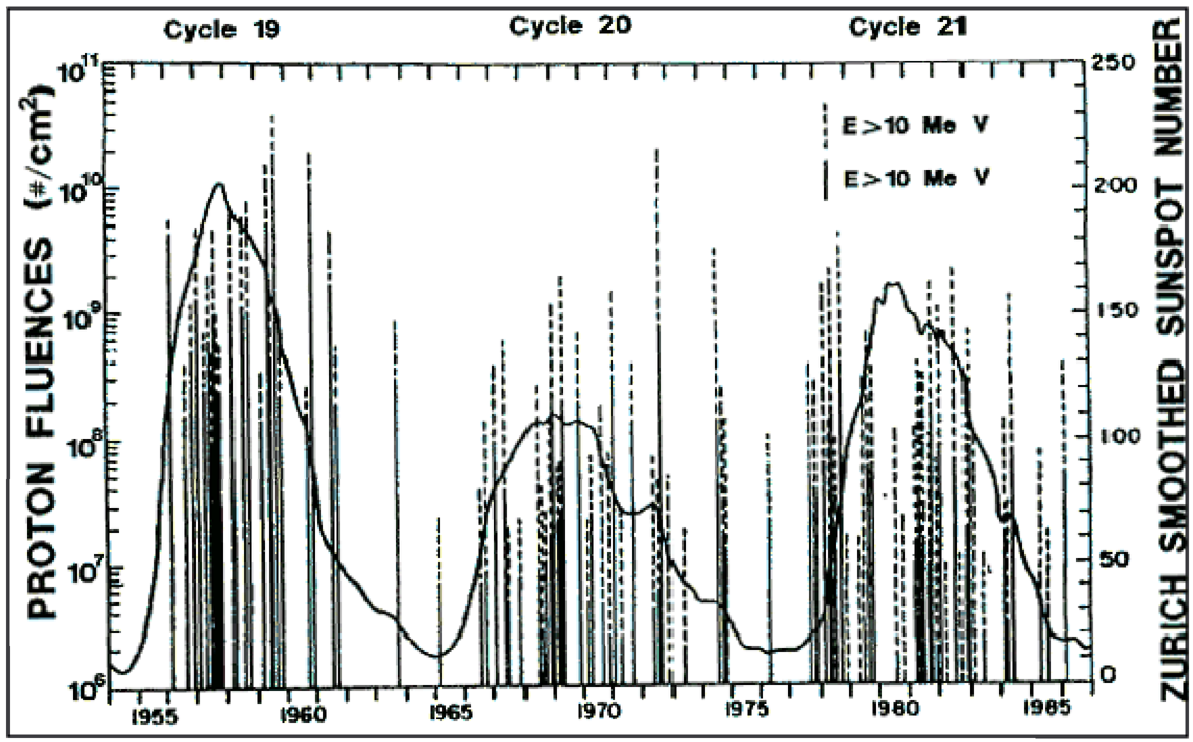
- 11 year cycle
  - Caused by the changing magnetic field of the sun
  - Solar maximum
    - Sunspots
    - Coronal mass ejections
    - Flare phenomenon
  - Solar minimum
    - Minimal activity
- Solar wind always present



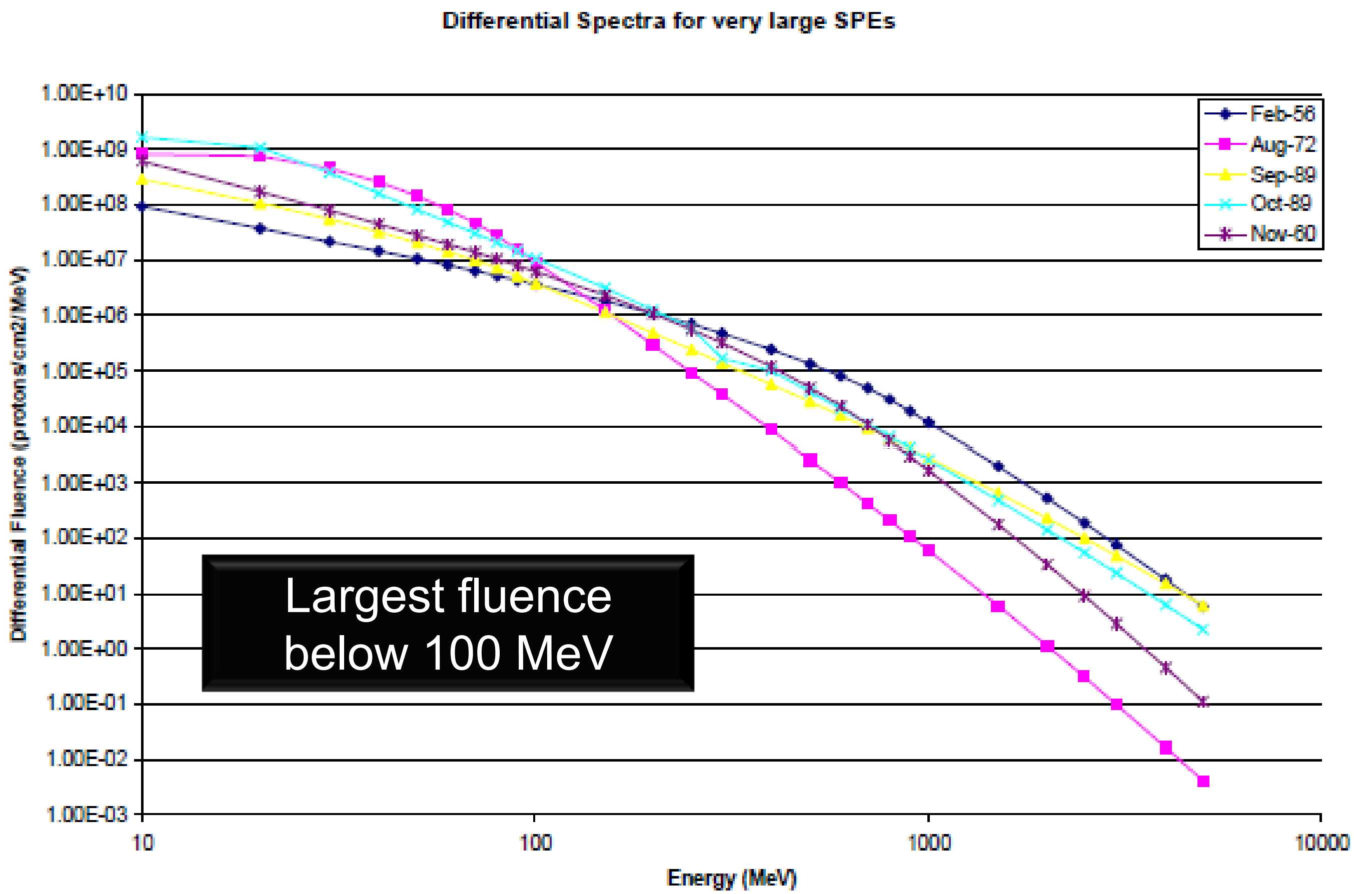
apod.nasa.gov

Solar Particle Events

- Coronal Mass Ejections (CME)
- Fast moving, very high energy particles
  - Bow shock at the front accelerates the particles
  - Mainly protons



Band Fit for Large SPE

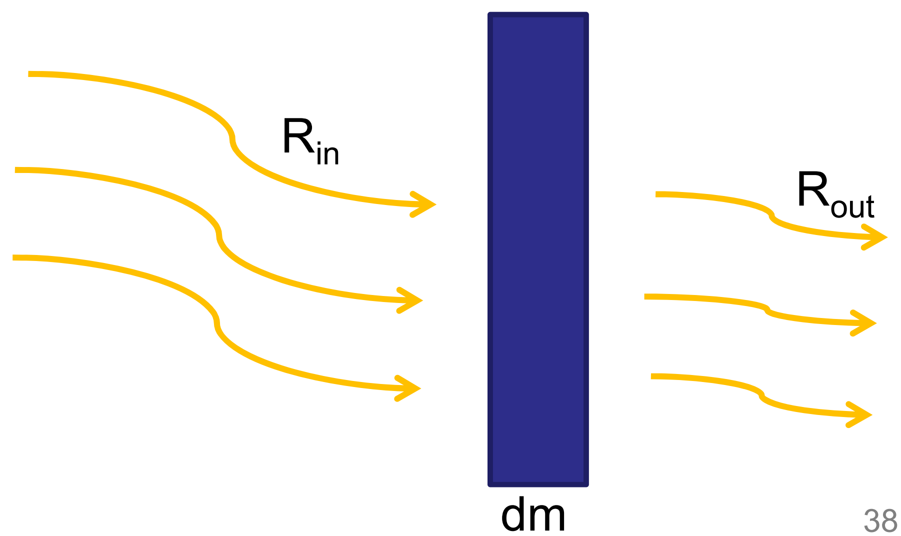


Solar Particle Events and Dose

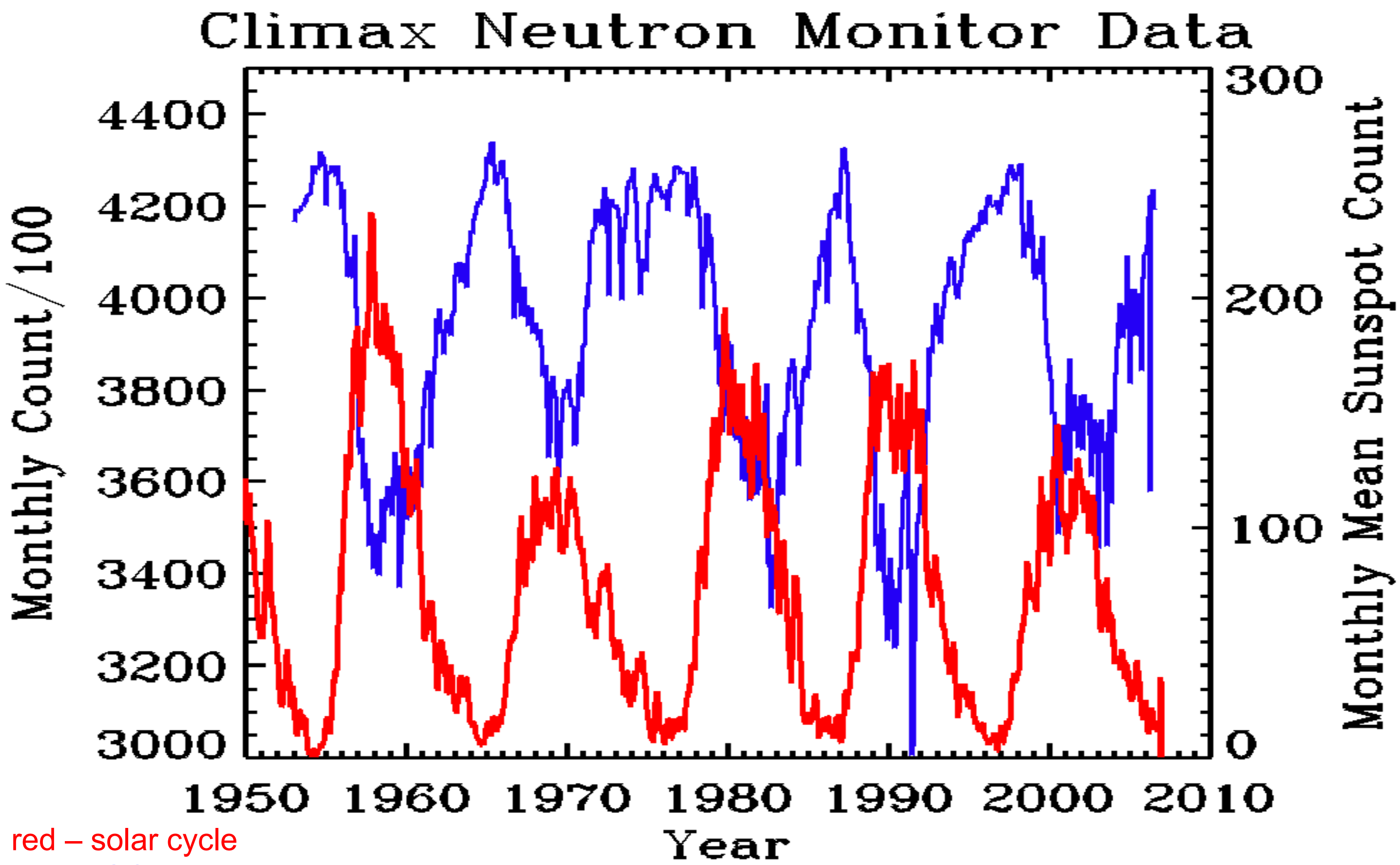
- Absorbed dose (D): change in mean energy imparted to matter over a discrete mass (dm)
- Mean energy (ε): the change in the number of particles emitted, transferred, or received multiplied by the energy of the particles plus the change in rest energy

$$D = \frac{d\bar{\varepsilon}}{dm} = \frac{d\left(R_{in} - R_{out} + \sum Q\right)}{dm}$$

$$R = NE$$

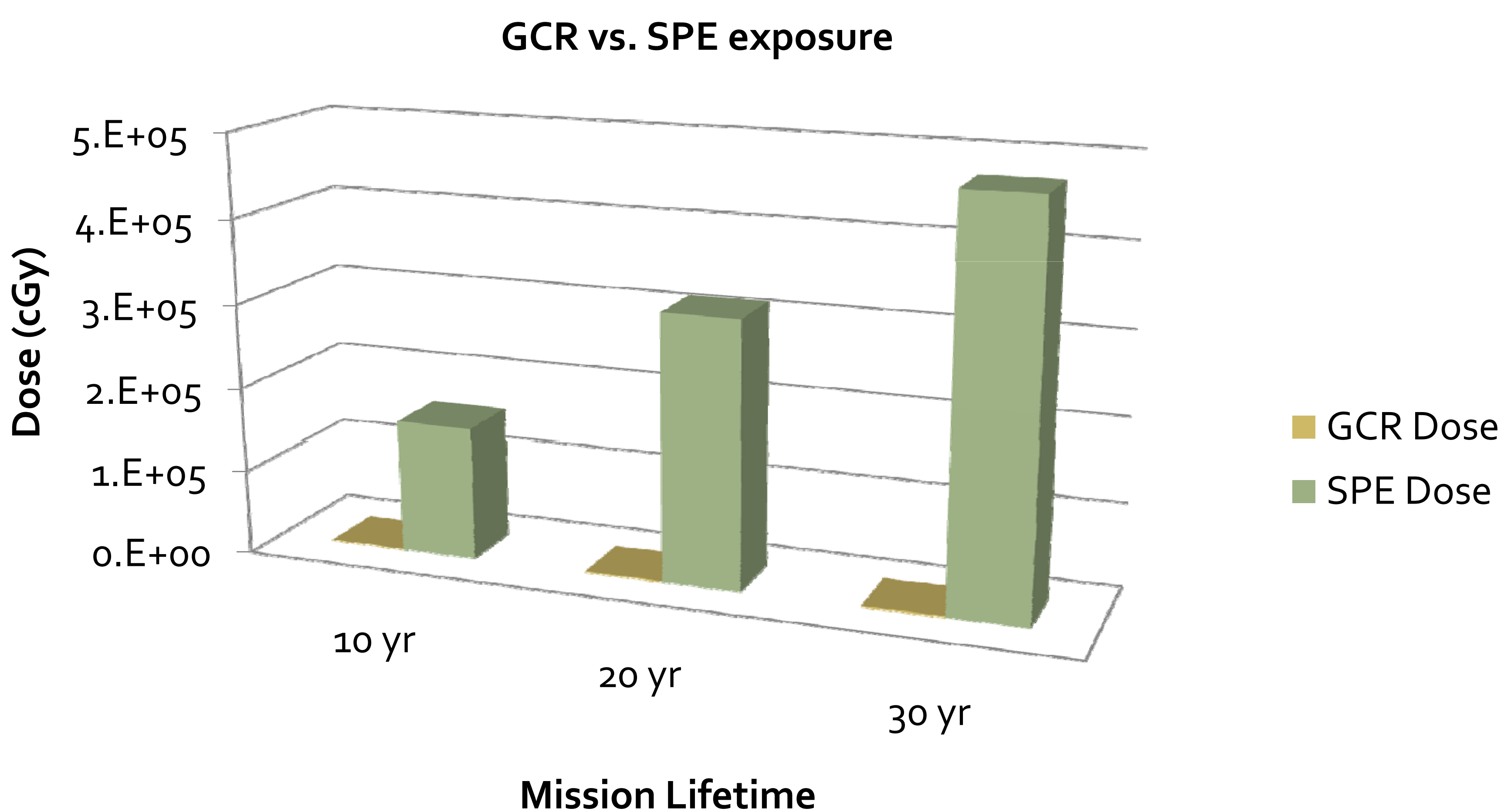


Galactic Cosmic Rays



red – solar cycle
Blue - GCR

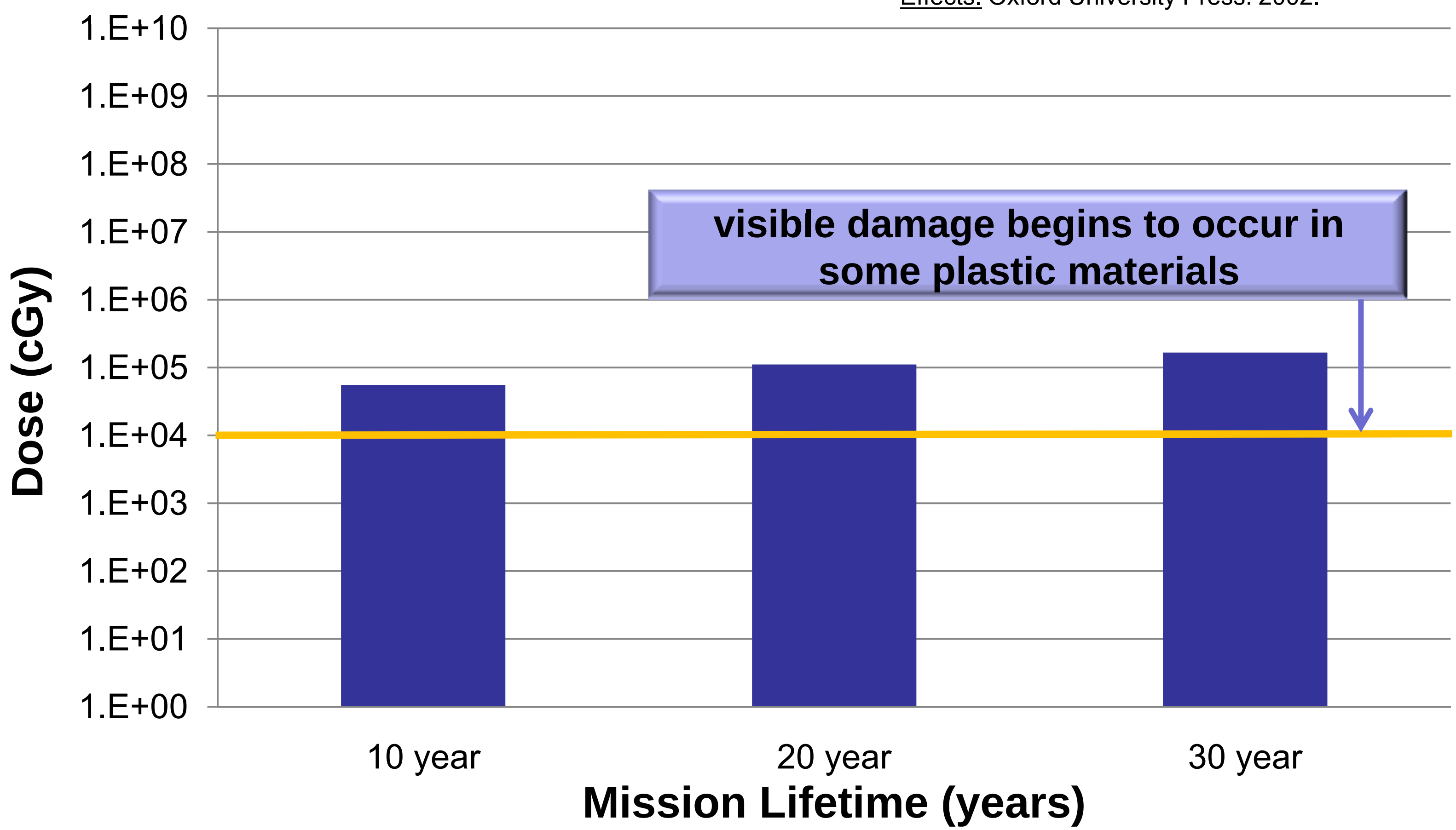
Dominant Radiation on the Lunar Surface



Focus of study is on proton radiation

Doses Material will See Due to this Radiation Exposure

Holmes-Siedel, A., Adams, L., Handbook of Radiation Effects. Oxford University Press: 2002.



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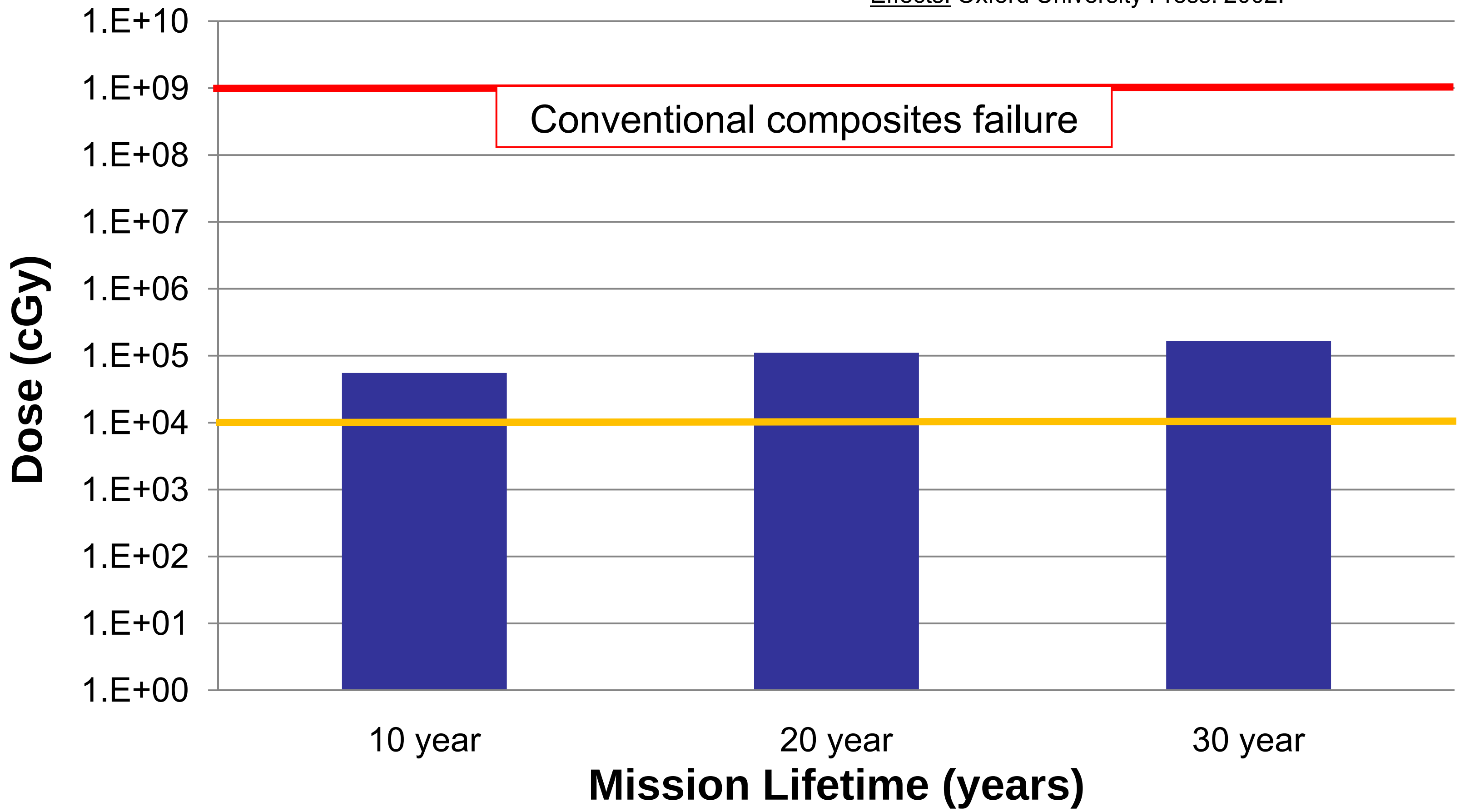
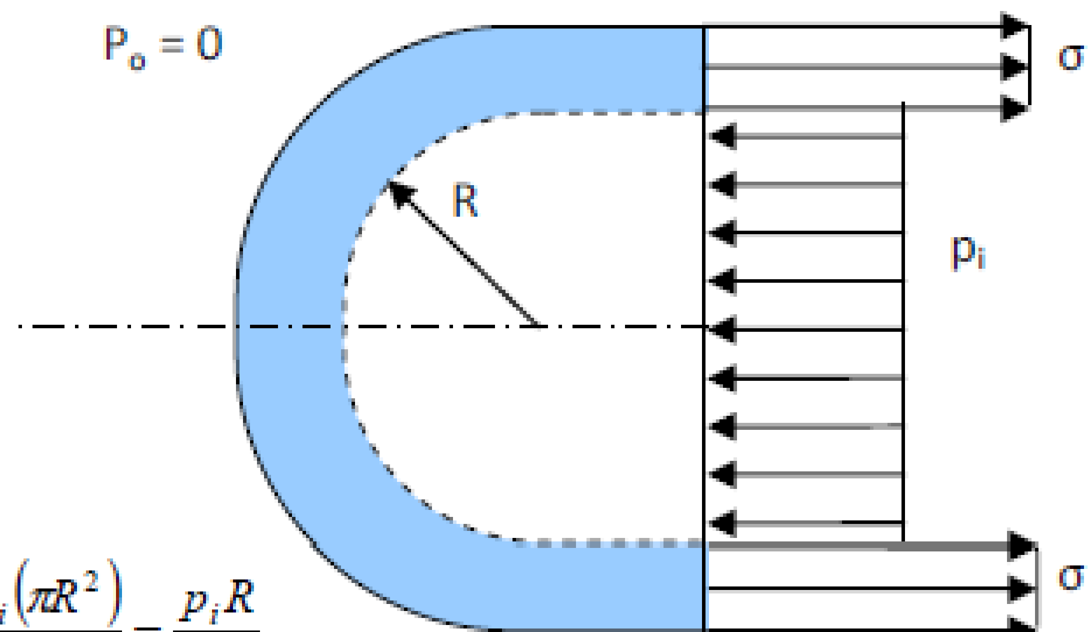


Radiation Effects on Polymeric Materials

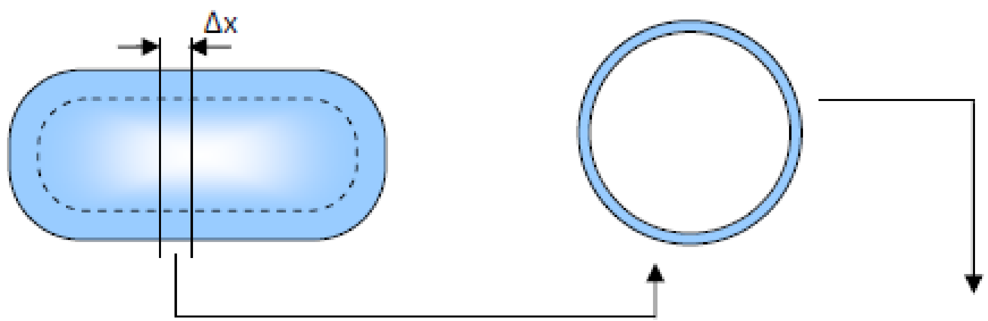
- Previous radiation research on polymers is mainly electron, neutron, or gamma radiation
- Previous research on materials different from today
- Effects discussed in literature
  - Cross-linking – bonds that link one polymer chain to another through chemical reaction
    - Pro: increases stiffness of material, potentially making it stronger
    - Con: if the stiffness is increased too much, the material becomes brittle and easily fractured
  - Chain scission – a chemical reaction that breaks the bonds of the backbone polymer chain
    - Con: weakens the polymer strength

Stresses on a Pressure Vessel – Longitudinal Stress

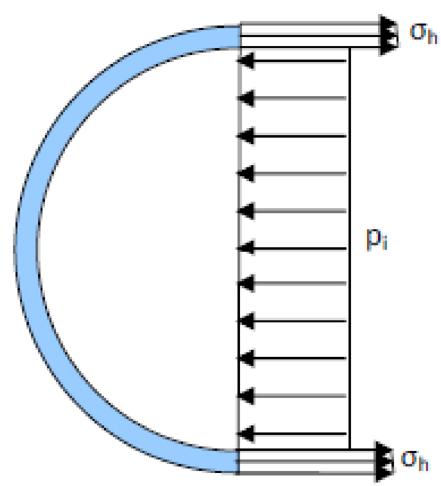


$$\sigma = \frac{p_i(\pi R^2)}{(2\pi R t)} = \frac{p_i R}{2t}$$

Stresses on a Pressure Vessel – Hoop Stress

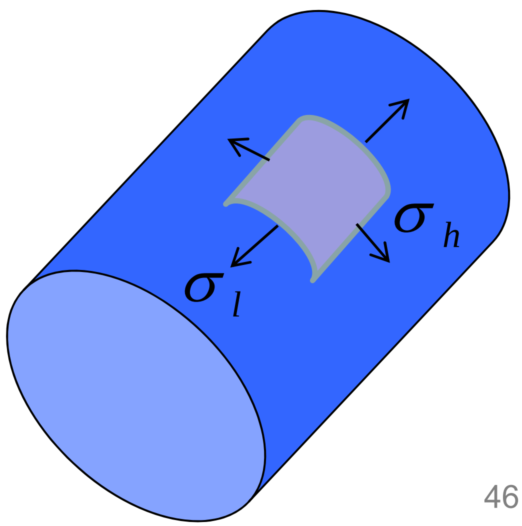


$$\sigma_h = \frac{p_i(2R\Delta x)}{(2t\Delta x)} = \frac{p_i R}{t}$$



Stress on a Pressure Vessel

- Due to the internal pressure of the pressure shell (~ 8psi) and the potential thickness of the material, there will be two tensile stresses imparted on the material
  - Hoop stress (2x longitudinal stress)
  - Longitudinal stress
- Based on the minimum gauge necessary for the habitat, these stresses are the following:
  - Sandwich structure
    - Hoop stress: 5.43 MPa
    - Longitudinal stress: 2.71 MPa
  - Skin-stiffened structure
    - Hoop stress: 40.72 MPa
    - Longitudinal stress: 20.36 MPa



Material Design/Manufacture

- Material #1 (boron/carbon + epoxy)
- Material #2 (carbon + epoxy)

- 6 plies - quasi-isotropic, balanced, and symmetric layup
- [+60°,-60°,0°,0°,-60°,+60°]

- Material #1 (boron/carbon) – press cure
- Material #2 (carbon) – autoclave cure