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Materials for Applications in Space Environments

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Acknowledgements / Collaborators

- ***Radiation shielding composites:*** Joseph Lenhart, John Schroeder
- ***Proton shielding measurements / calculations:*** Paul Dodd, James Schwank, Diana Wrobel
- ***Electron shielding measurements / calculations:*** Ethan Blansett, Gayle Thayer, Paul Dodd, James Schwank, Diana Wrobel

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Presentation Content

- **The space environment presents many materials challenges**
  - Interplay between issues provides further complications
- **Earth orbits present unique radiation challenges**
  - Radiation environment as a function of orbit
- **Radiation shielding approach**
  - Composite materials
  - Effectiveness
  - Processing
- **Additional implications**
  - Other materials for space applications
- **Summary and conclusions**

Materials Challenges for the Space Environment

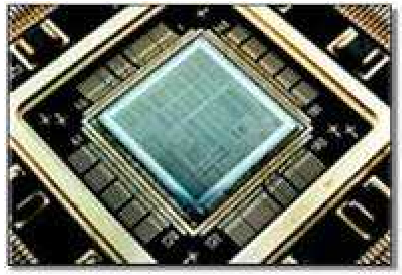
Where can materials have an impact?

- **Size, weight, and power (SWaP)**
  - Weight is of primary importance
  - Impact on launch vehicle
    - How much mass?
    - What orbit?
  - Power impact
    - Solar panel size, etc.
  - Materials issues: structural composites, solar cells & coatings
- **Communications**
  - Information downlink, commanding uplink
  - Trade-off: downlink available vs. onboard processing
  - Trade-off: orbit vs. power consumption
- **Earth coverage**
  - Trade-off: orbit vs. payload sensitivity vs. platform stability
  - Trade-off: payload sensitivity vs. ground stations
  - Materials issues: enhanced payload capabilities

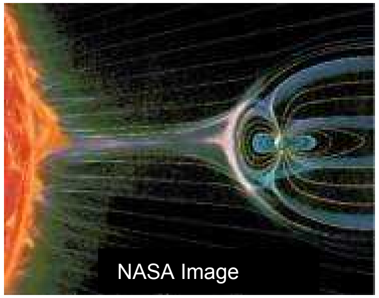
Materials Challenges for Space Environment

Where can materials have an impact?

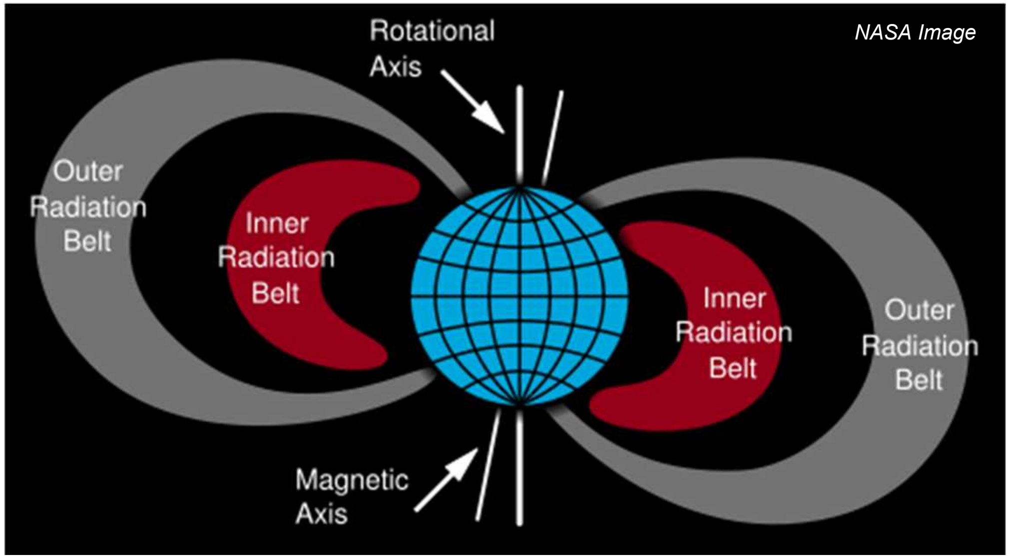
- **Computational power**
  - Primary materials issue: radiation-hard components
  - Low power consumption, large capacity processors
  - Analog / digital conversion
  - Memory
- **Thermal transport / dissipation**
  - Increase in processing power requires improved heat removal
  - Light-weight composite materials typically have poor thermal transport
  - Solutions required for ultra-fine dimensions
  - Thermally conductive, but electrically insulating
- **Radiation environment**
  - Performance degradation or interference in sensors
  - Loss of digital data
  - Single Event Upsets (SEU) in processors
  - Permanent damage to solar cells, microelectronics



Credit: Center for Design of Analog-Digital Integrated Circuits, NSF

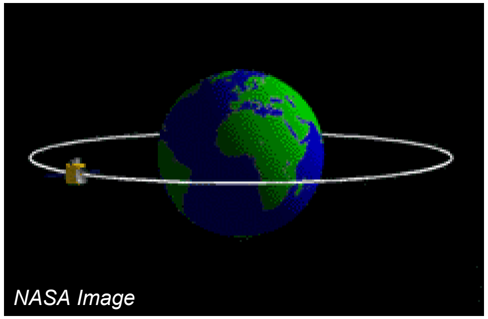


The Space Environment – Radiation

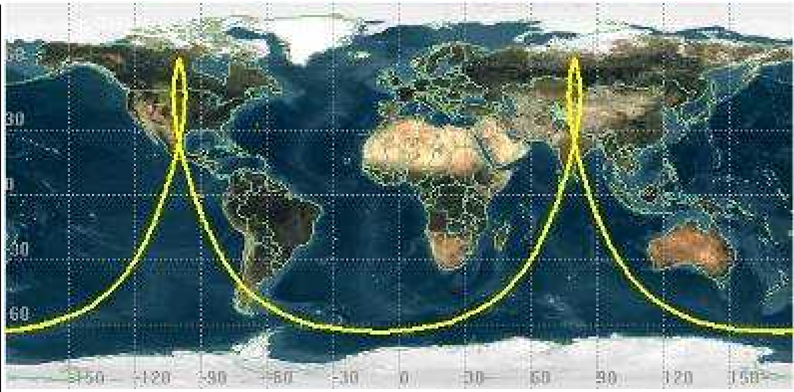


- **Inner Radiation Belt**
  - 700 to 10,000 km
  - Protons with energies above 100 MeV
  - Electrons with energies on the order of 100 keV
- **Outer Belt Radiation**
  - 13,000 to 65,000 km
  - Most intense region is from 14,500 to 19,000 km
  - Primarily electrons with energies in the range 0.1 to 10 MeV
  - Energetic particle fluxes can change dramatically as a result of geomagnetic storms

Some Orbits of Interest



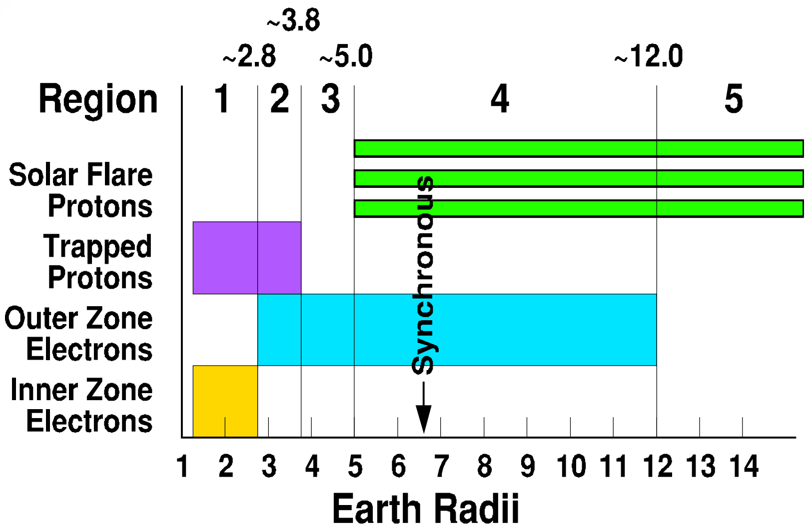
- **Low Earth Orbit (LEO):**
  - 200-2,000 km
  - ~90 min orbital period
  - Pro: most easily reached
  - Con: atmospheric drag
  - International Space Station, commercial imaging satellites, Iridium constellation
- **Medium Earth Orbit (MEO):**
  - 2,000-35,900 km
  - Pro: good global coverage
  - Con: extreme radiation environment
  - GPS constellation at 20,200 km
- **Geosynchronous (GEO):**
  - ~35,800 km
  - ~24 hr orbital period
  - Equitorial: geostationary
  - Pro: broad Earth view
  - Con: distant orbit
  - Some TV and communications satellites



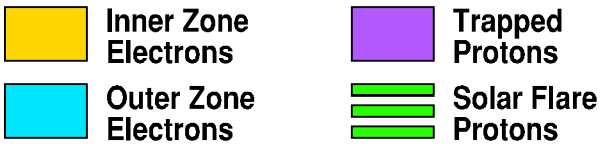
- **Molniya Orbit:**
  - Apogee: 40,000 km
  - Perigee: 500 km
  - ~12 hr orbital period
  - ~8 hr dwell near apogee location
  - Pro: regional coverage from only a few satellites
  - Con: traverse radiation belts

- **Tundra Orbit:**
  - Apogee: ~47,000 km
  - Perigee: ~24,600 km
  - ~24 hr orbital period
  - ~16 hrs/day above northern hemisphere
  - Sirius Satellite Radio

What radiation environment exists at each orbit?



After E. G. Stassinopoulos and J. P. Raymond, Proc. of the IEEE 76, 1423 (1988)



Inner belt

- $1.1\text{-}2.6\ R_e$
- Protons with energies above 100 MeV
- Electrons with energies 100's of keV

Outer belt

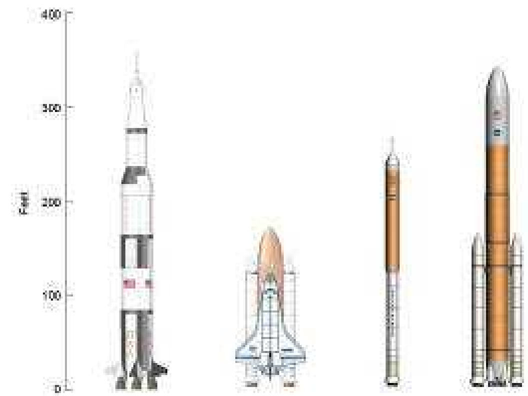
- 3.0-11.2 Re
- Most intense 14,500-19,000 km = $3.3\text{-}4.0\ R_e$
- Mostly electrons with energies 0.1 to 10 MeV

- **LEO**
  - 200-2,000 km
  - 1.0 to 1.3 R_e
  - *Primary concern: high energy protons*
- **GEO**
  - 35,900 km
  - 6.6 R_e
  - *Primary concern: solar activity*
- **MEO / GPS**
  - 20,200 km
  - 4.2 R_e
  - *Primary concern: high energy electrons*
- **Molniya**
  - Perigee 500; Apogee 40,000 km
  - Perigee 1.1; Apogee 7.3 R_e
  - *Primary concerns: high energy protons and high energy electrons*
- **Tundra**
  - Perigee 24,600; Apogee 47,000 km
  - Perigee 4.9; Apogee 8.4 R_e
  - *Primary concerns: high energy electrons*

Radiation exposure introduces multiple challenges

Radiation Shielding
- High-Z elements are most effective shields
- High-Z elements have significant mass

Processing Power
- Radiation environment can damage components or corrupt data
- Radiation-hardened microchips may lag original design by more than a decade (>6 generations)
- Relatively small market, costly redesign
- Many microelectronic components are susceptible



Size, weight, and power
- Weight is a primary cost-driver for launch
- Optimization of radiation shielding vs. weight increase

Radiation Shielding

Radiation shielding with particulate filled composite encapsulants, coatings, and structural materials

Issues

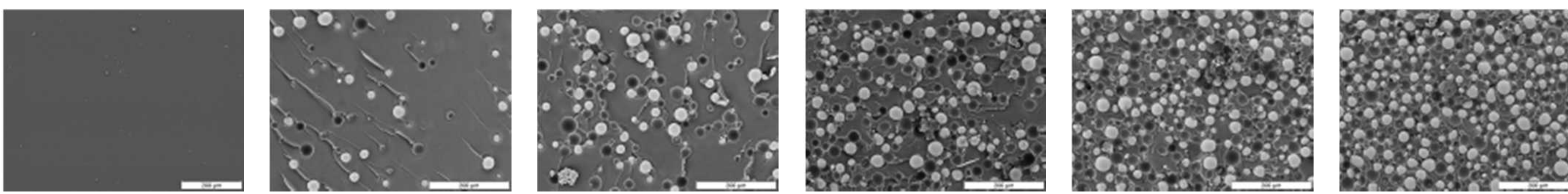
- Need for devices to function in various radiation environments
- Need flexible processing approaches and light weight materials

Objectives

- Develop polymer composites composed of high-Z fillers dispersed in polymer matrix
- Verify radiation shielding performance
- Investigate processing approaches

Advantages

- Reduced mass / volume
- Localized shielding
- Simple and flexible processing for wide range of applications
- Complex geometries



0 % | 10 % | 20 % | 30 % | 40 % | 50 %

Electron Shielding (0 % – 20 %)

X-ray, Gamma, Proton Shielding (30 % – 50 %)

EMI Shielding / Conductivity

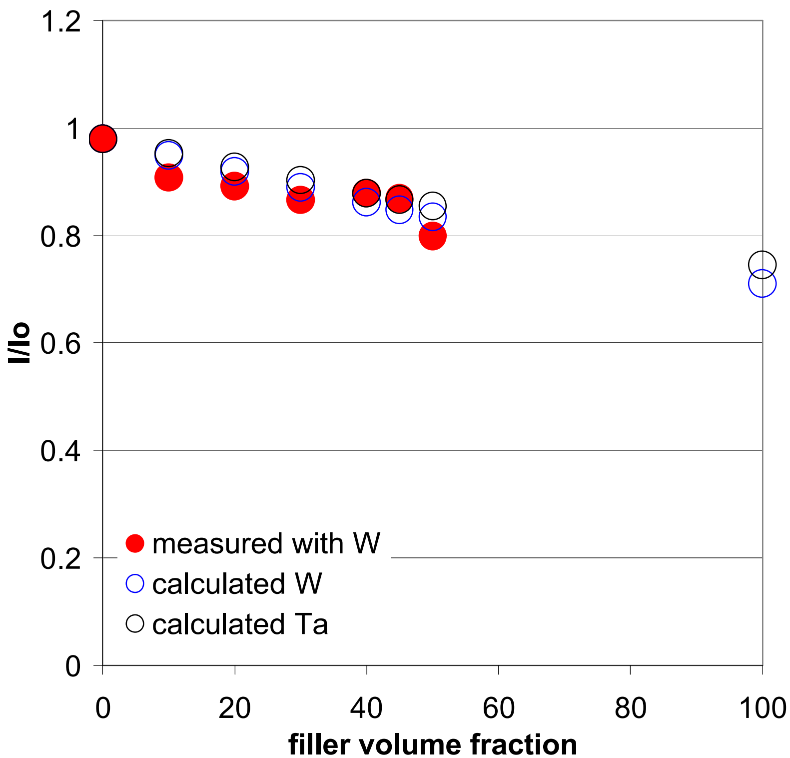
Shielding from a variety of radiation environments

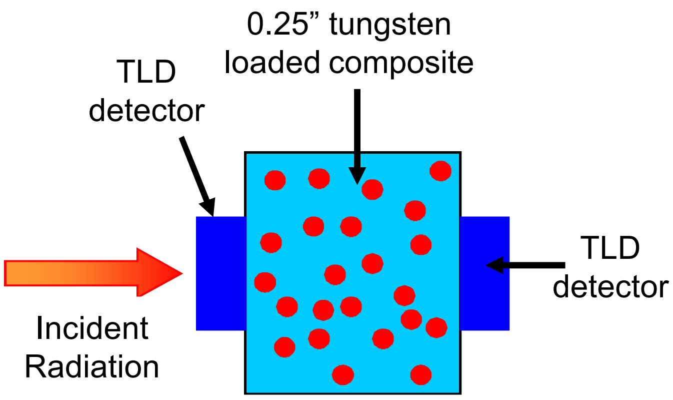
X-ray and Gamma Radiation Attenuation

- 0 to 50 vol% tungsten loading in silicone
- Attenuation measured for ~ 1.3 MeV gamma radiation
- Calculated mass attenuation coefficients from NIST database
- Excellent agreement between measured and predicted attenuation

$$\frac{I}{I_0} = \exp\left[-\left(\mu/\rho\right)_{composite} \rho_{composite} x\right]$$

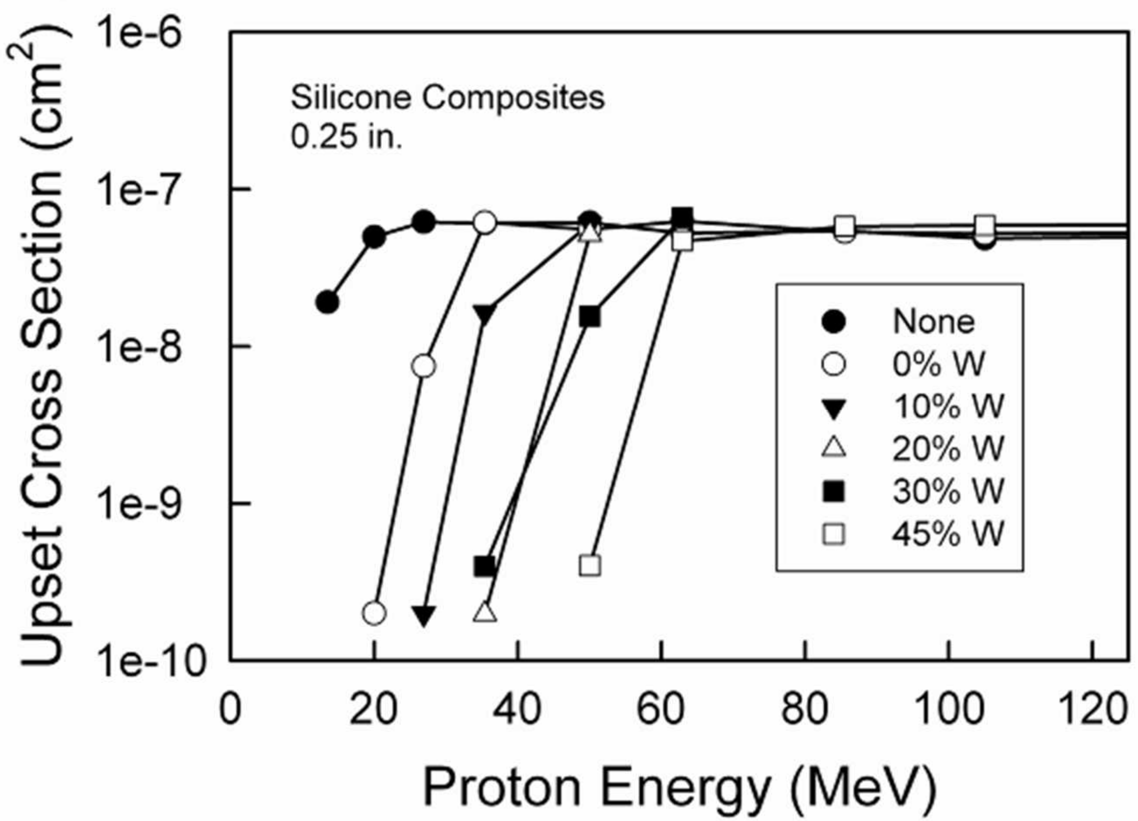
$$\left(\mu/\rho\right)_{composite} = \sum_i w_i \left(\mu/\rho\right)_i$$

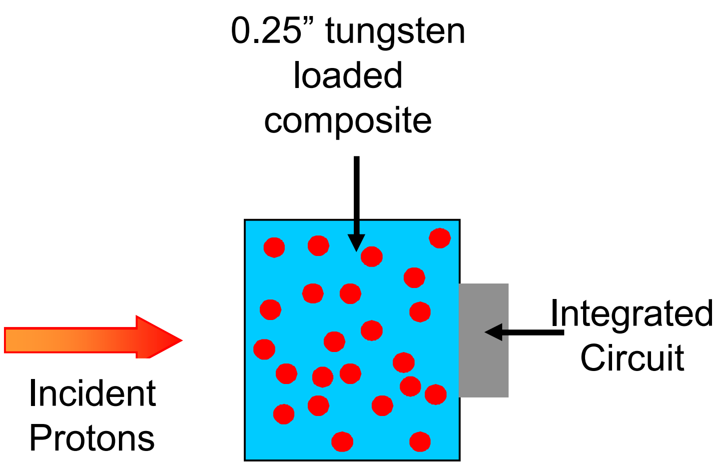




- Modeling in combination with attenuation measurements enable focus on relevant tungsten loadings and coating thicknesses
- Higher loadings are most effective

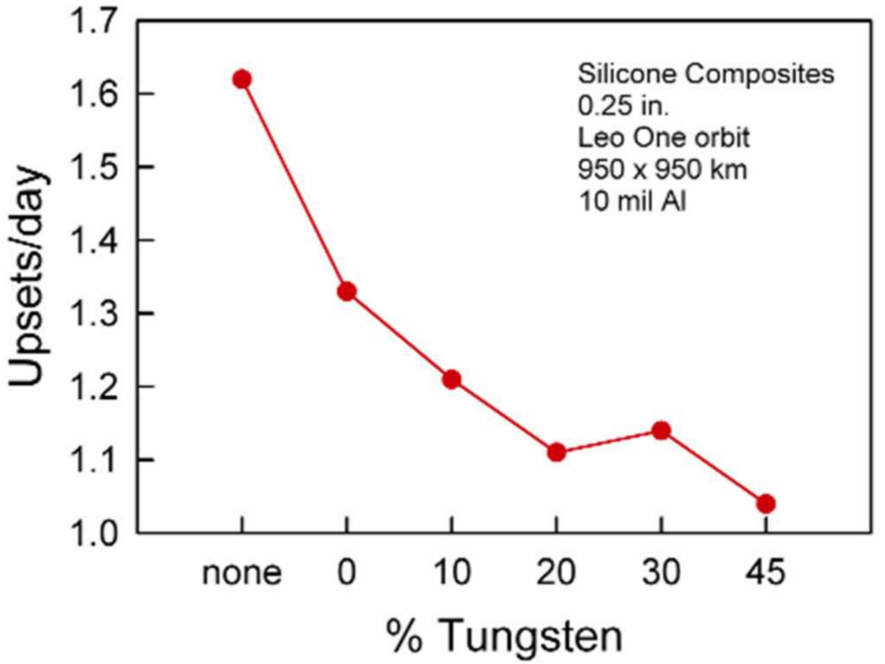
Composite Proton Shielding

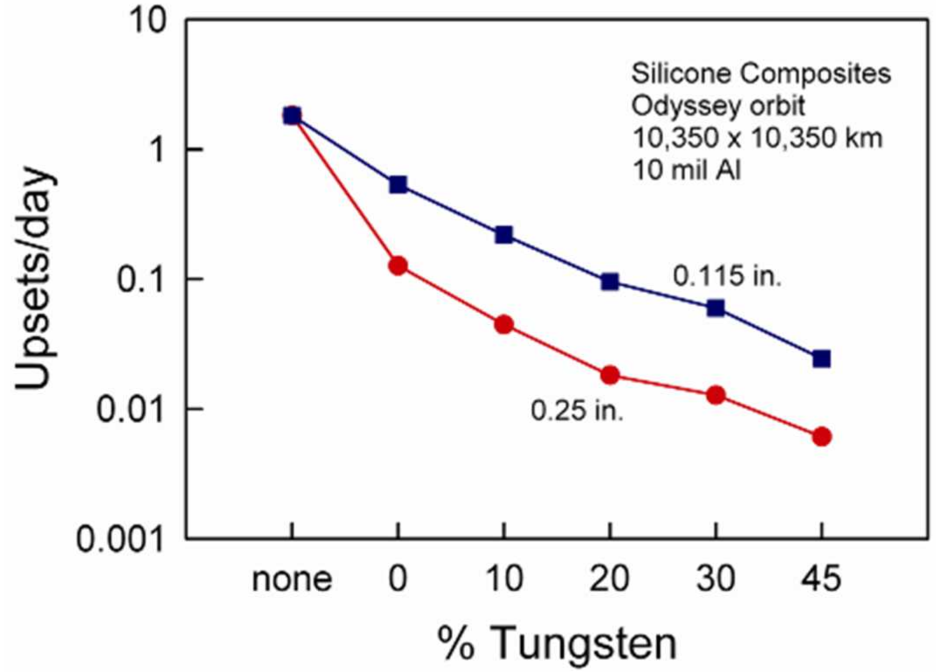




- Measure upsets of integrated circuit behind composite
- Composite can reduce upsets with low energy protons (under 60 MeV)
- High loadings and thick composites are better

Orbital Dependence of Proton Shielding

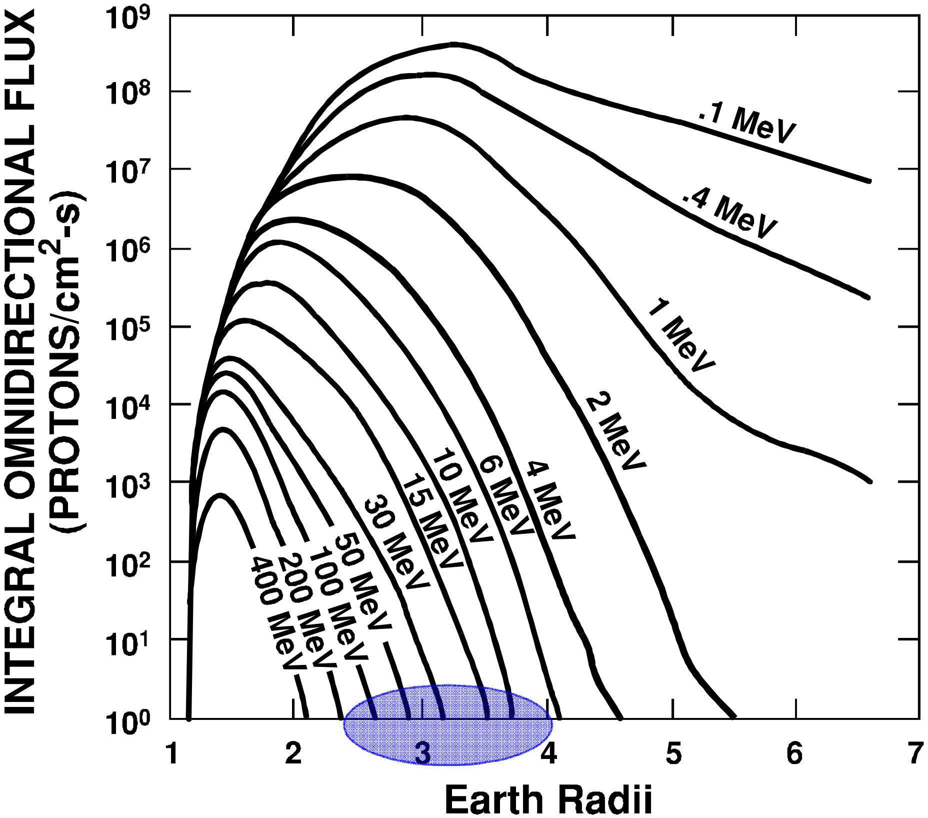




- Composites ineffective in proton shielding with low earth orbits
- High flux of high energy protons is difficult to shield
- Little impact on device upset

- Composites are effective in proton shielding with MEO orbits
- Low / Medium energy protons are effectively shielded
- Upset reduction by more than an order of magnitude with increasing tungsten loading

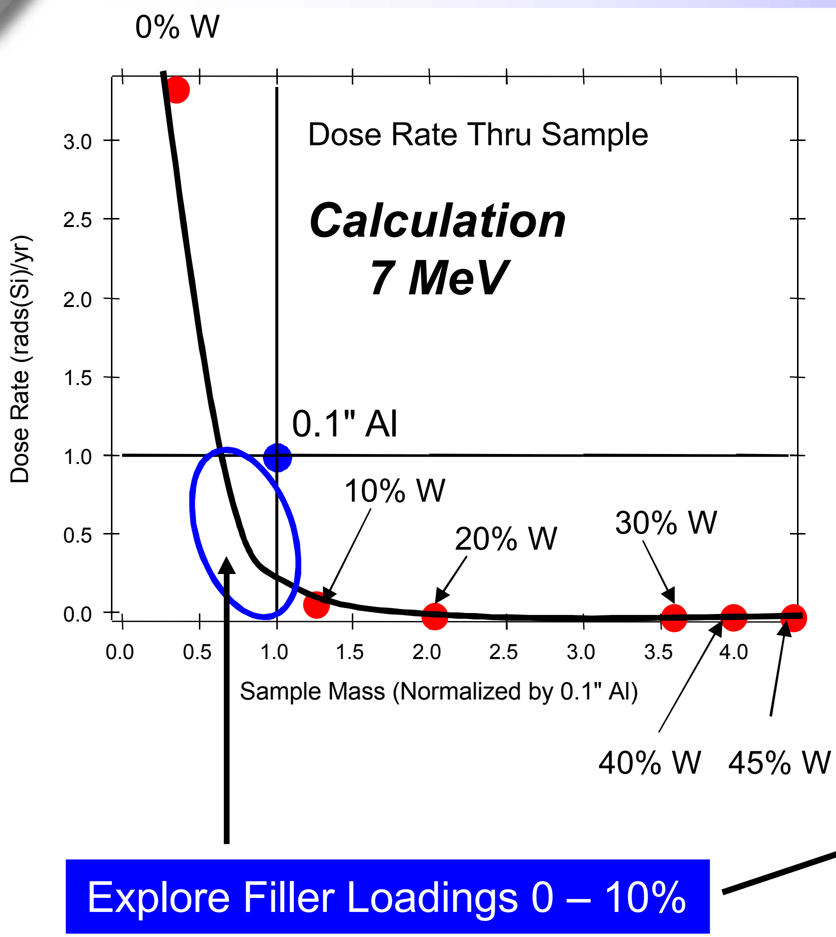
Proton Shielding Summary

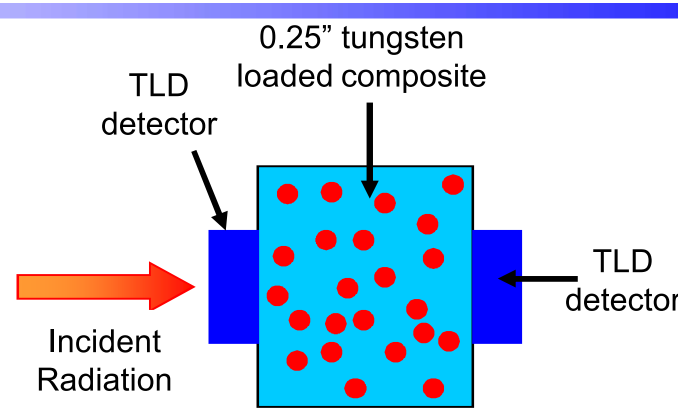


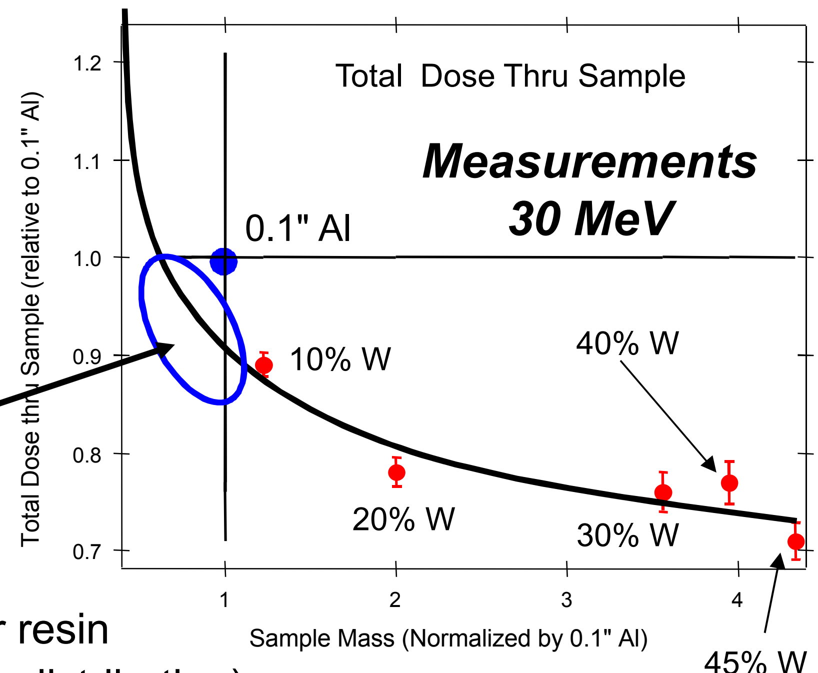
After E. G. Stassinopoulos and J. P. Raymond, Proc. of the IEEE 76, 1423 (1988)

- Typical spacecraft shielding effective for protons less than 10 MeV
- Protons greater than 100 MeV are difficult to shield
- Tungsten-loaded composites can reduce dose / upsets with protons 10 to 60 MeV
- Effective region to reduce dose by several orders of magnitude is orbits 2.5 to 4 times Earth radius
- Higher tungsten loadings are more effective

Initial Electron Shielding

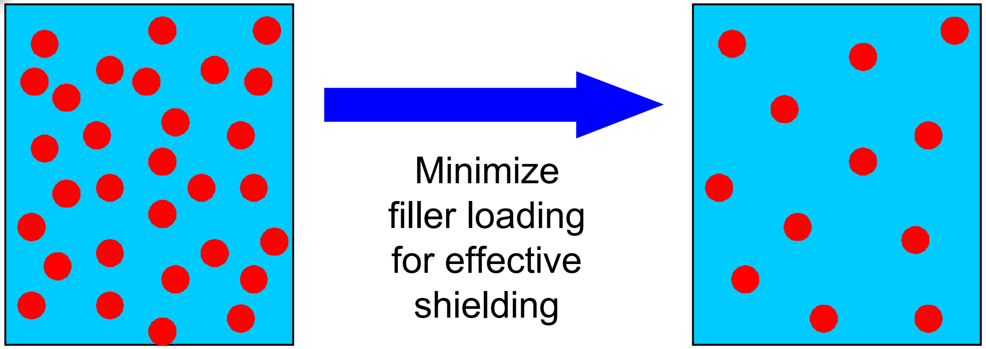






1. 0 to 50 vol% tungsten loading in silicone polymer resin
2. Calculated electron attenuation at (7 MeV narrow distribution)
3. Measured attenuation for higher energy electrons (30 MeV broad distribution)

Reducing Density of Composite Shield

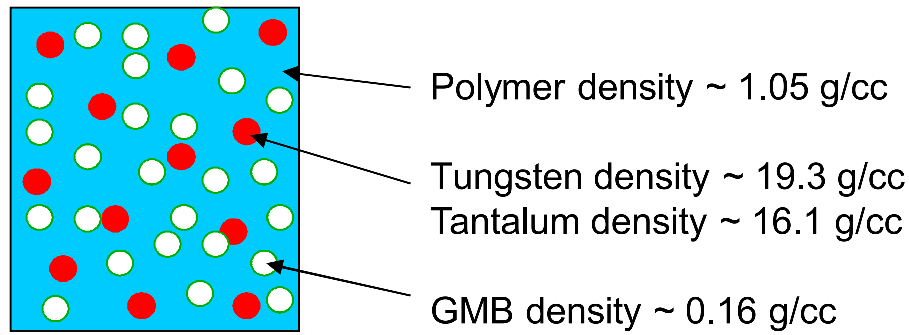


Step 1:

- Investigate tungsten / tantalum loadings of 0 to 10 vol%
- Utilize minimum filler loading to obtain adequate shielding ability

Step 2:

- Incorporate mixed filler strategy to further reduce composite mass
- Small tungsten or tantalum loading
- High loading of glass microballoons (GMB)

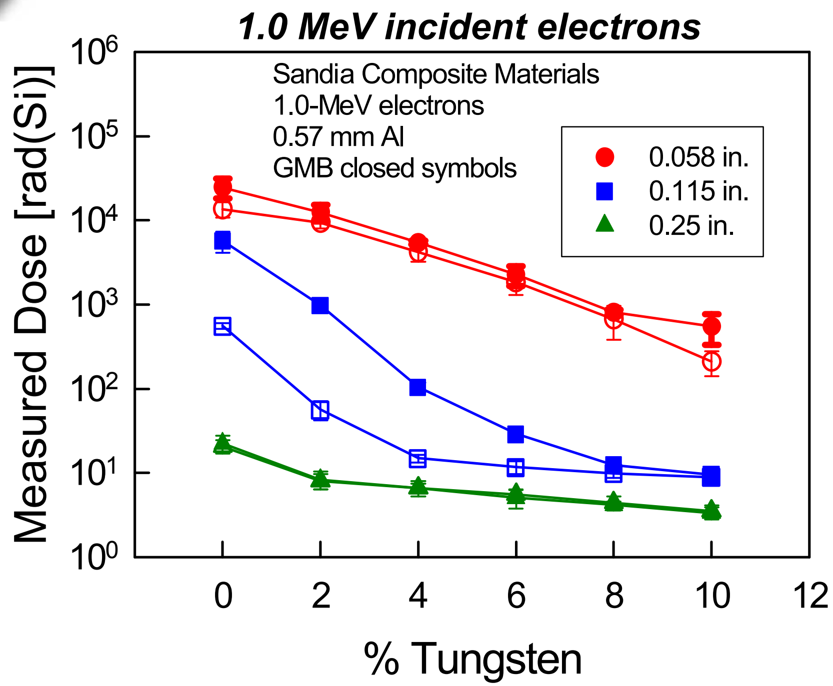


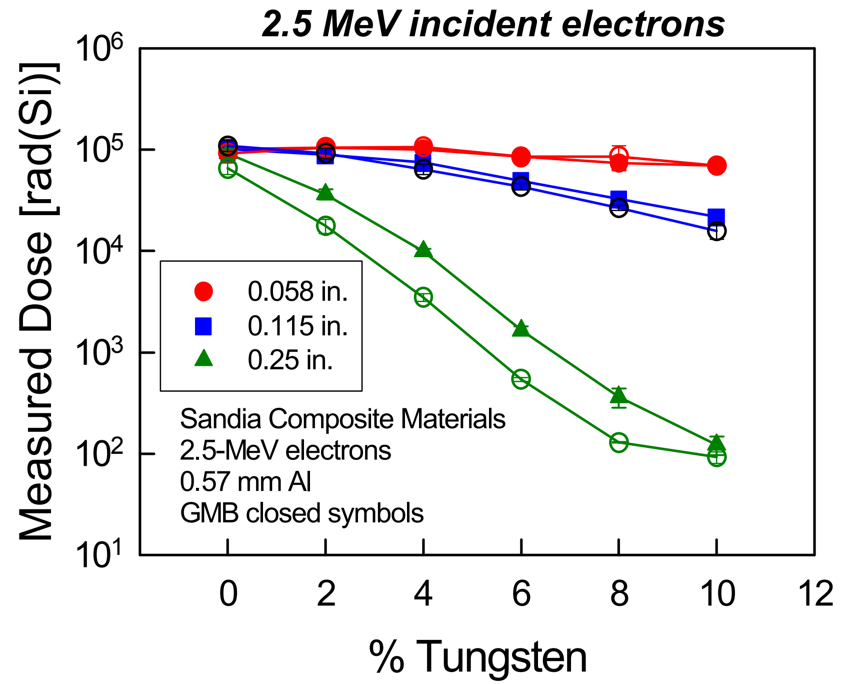
composite volume fractions			composite density (with GMB)	composite density (no GMB)	Percent Change with GMB
GMB	W	silicone			
0.38	0.02	0.6	1.0768	1.415	-24
0.36	0.04	0.6	1.4596	1.78	-18
0.34	0.06	0.6	1.8424	2.145	-14
0.32	0.08	0.6	2.2252	2.51	-11
0.3	0.1	0.6	2.608	2.875	-9

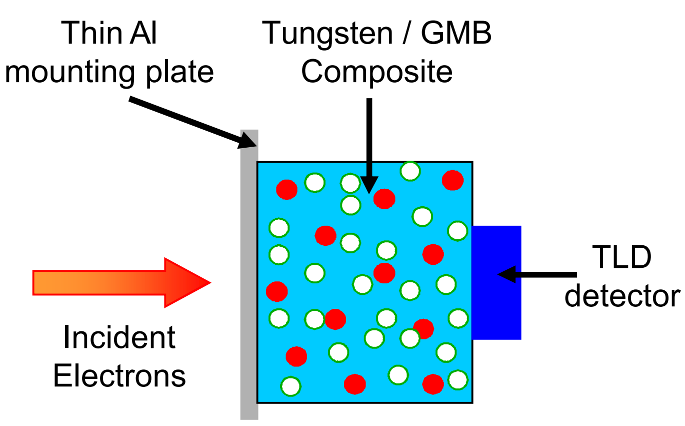
density (g/cc)			
GMB	W	silicone	Al
0.16	19.3	1.05	2.7

- GMB / Tungsten composites less dense than Aluminum and provide superior shielding (verified with 10%)
- How will GMB impact attenuation
- 40 vol% filler loading is still reasonable polymer viscosity for processing

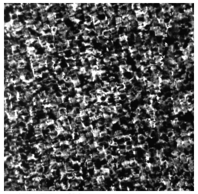
Effective Composite Shielding





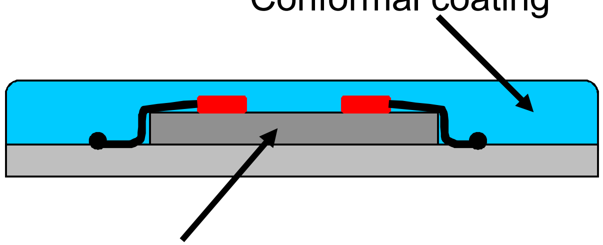


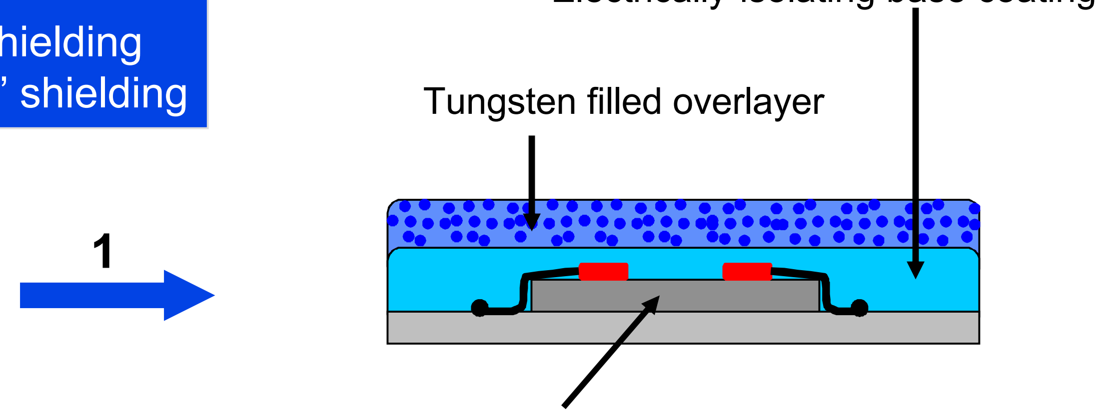
- Thicker composites and higher tungsten loadings increase attenuation
- All thickness and loadings provide some attenuation with 1.0 MeV electrons
- Thicker films and higher tungsten loadings required for attenuation of 2.5 MeV electrons
- Inclusion of GMB decreases attenuation (air verses silicone resin or microstructure?)



Localized "Spot" Shielding

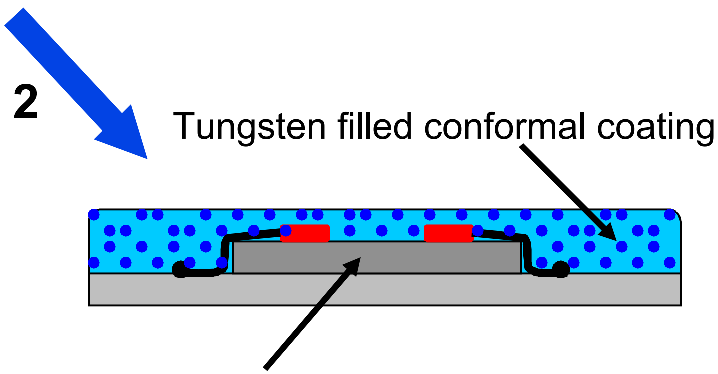
Uses for Polymer Composites:
- Structural composites for global shielding
- Conformal / dip coatings for "spot" shielding





Advantages
- Simple implementation
- Less concerns with particle distribution and layer conductivity

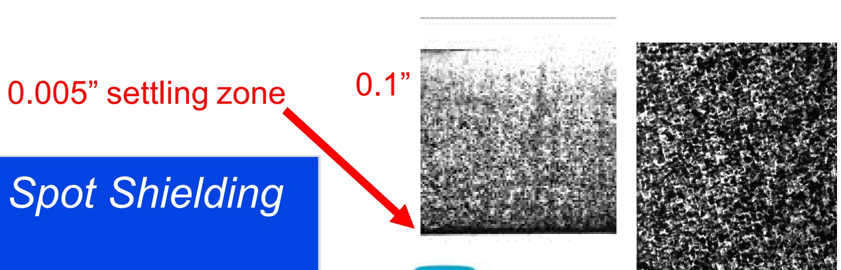
Challenges
- Additional processing step
- Overlayer-base coat compatibility



Advantages
- Single step processing
- Integrate with current conformal coatings

Challenges
- Particulate settling
- Conductivity in conformal coating

Issues for Spot Shielding
- Settling
- Transparency



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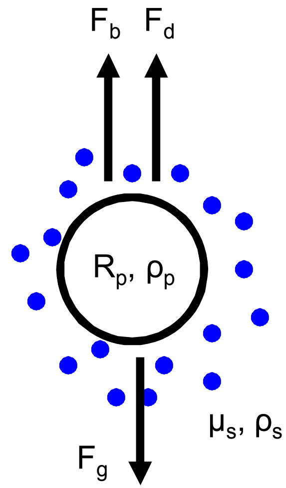
Solutions to Control Processability and Dispersion

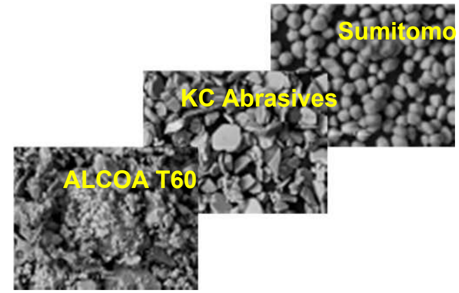
$$V_t = \frac{2gR_p^2(\rho_p - \rho_s)}{9\mu_s}$$

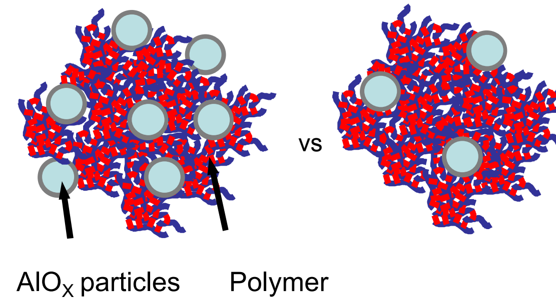
$$\downarrow \rho_p \Rightarrow \downarrow V_t$$

$$\downarrow R_p \Rightarrow \downarrow V_t$$

$$\uparrow \mu_s \Rightarrow \downarrow V_t$$

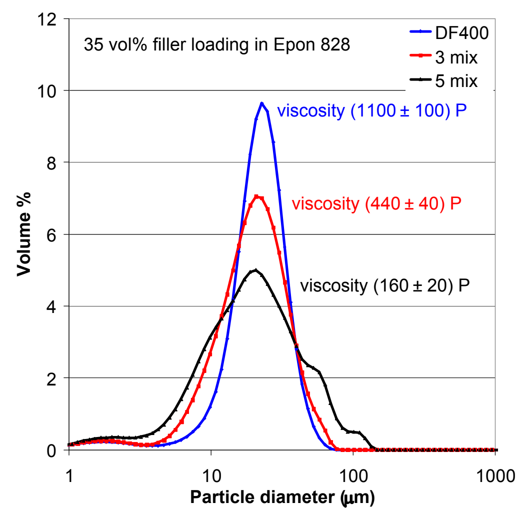


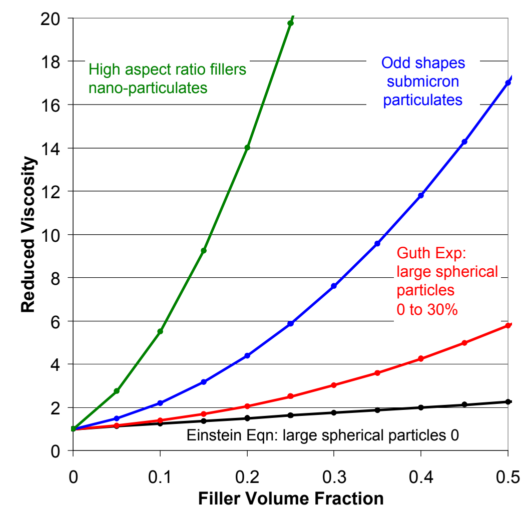




1) Particle shape, size, and size distribution

2) Filler loading





Solutions

- Less dense particles (higher loadings increase viscosity, reduce V_t)
- Sub-micron to nano-particulates (reduced V_t, less transparency)
- Increase viscosity (longer MW monomers, narrow particle size distribution, odd-shaped particles)
- High-Z oxide particulates (avoid electrical conductivity)

- Processablility and microstructure can be controlled through particle type, shape, size, size distribution, loading, polymer Mw, processing additives.

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Radiation Shielding Considerations

1. There are radiation consideration for common orbits

- High-energy protons primary concern nearer Earth (LEO)
- High-energy electrons primary concern in MEO / GPS orbits
- Elliptical orbits can see multiple environments

2. Radiation shielding is not an isolated materials issue

- Shielding cannot increase mass
- Solution must be applicable to payload components

3. Particulate filled high-Z / polymer matrix composites

- Effective at shielding X-rays, gammas, protons, electrons
- X-rays, gammas, protons require higher loadings
- Effective region for proton shielding (10 to 60 MeV)
- Electron shielding with low loadings (<10 volume %)
- Mixed GMB / tungsten composites for lower density

Implications to Other Materials for Space

1. High-Z containing composites require unique processing

- High-Z component settles
  - Can lead to electrical conductivity
  - Difficult to process
- Can reduce settling through viscosity modification
- Surface modification can be used to control dispersion

2. Potential additional applications of technology

- Tough, structural composites
- Electrically conductive composites and films
- Materials for high thermal conductivity
- Controlled, high-porosity materials