Photonics on the Mission to Mars

Michael D. Watson, Ph.D.
Agenda

◆ Mission Overview
  • Mission Trajectory
  • Launch Vehicle
  • Transfer Vehicle

◆ Mission Environments
  • Launch Site
  • Earth Orbit
  • Interplanetary
  • Mars Orbit
  • Total Mission Exposures

◆ Photonic Applications
  • Optical Communications
    - Guided
    - Free Space
  • Optical Gyroscopes
  • LiDAR
  • Optical Sensing
    - Space Environment
    - Reactor Environment
  • Optical Coatings
## Human Rated Space Flight Experience

<table>
<thead>
<tr>
<th>Environment</th>
<th>ITV</th>
<th>Apollo</th>
<th>Shuttle Orbiter</th>
<th>ISS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch Site</td>
<td>6 months</td>
<td>6 months</td>
<td>30 years</td>
<td>6 months</td>
</tr>
<tr>
<td>LEO</td>
<td>18 months</td>
<td>2.5 hours</td>
<td>16 Days (EDO)</td>
<td>12.5 years</td>
</tr>
<tr>
<td>MEO</td>
<td>2 hours/2 hours</td>
<td>2 hours/2 hours</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Interplanetary/Lunar</td>
<td>18 months</td>
<td>12.5 days</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Martian Orbit</td>
<td>12 months</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

**Human Rated Vehicles have more challenging Reliability and Maintenance requirements**

- Must operate for the full duration of the mission without failure
- Should require no scheduled maintenance in flight
  - Limited crew time for maintenance
  - Maintenance requires ease of access for repair or replace
Building on the U.S. Infrastructure

**INITIAL CAPABILITY, 2017–21**

- **Orion Multi-Purpose Crew Vehicle (MPCV)**
  - *Lockheed Martin*

- **Launch Abort System**

- **Interim Cryogenic Propulsion Stage**
  - Early flight certification for Orion
  - Flexible for a range of payloads
  - *Boeing*

- **5-Segment Solid Rocket Boosters**
  - Upgrading Shuttle heritage hardware
  - *ATK*

- **Core/Upper Stage**
  - Common design, materials, & manufacturing
  - *Boeing*

  - **Avionics**
    - Builds on Ares software
    - *Boeing*

- **RS-25 Core Stage Engines**
  - Using Space Shuttle Main Engine inventory assets
  - Building on the U.S. state of the art in liquid oxygen/hydrogen
  - *Initial missions: Aerojet Rocketdyne*
  - *Future missions: Agency is determining acquisition strategy*

**EVOLVED CAPABILITY, Post-2021**

- **Fairings (8.4 m or 10 m)**
  - Right-sized for the payload
  - Received industry input in FY13

- **Upper Stage**
  - Commonality with Core Stage
  - Optimized for Mission Capture

- **Advanced Boosters**
  - Competitive opportunities for affordable upgrades
  - *Risk-reduction contracts awarded in FY13*

**Working with Industry Partners to Develop America’s Heavy-Lift Rocket**
Notional Mars Transfer Mission -- 600 day Mars Piloted Stack

Transfer Vehicle Description:
Transfer Vehicle consists of 3 elements:
1) Core propulsion stage
2) In-line tank
3) Integrated star truss and dual drop tank assembly that connects the propulsion stack to the crewed payload element for Mars mission.

Each 100t element is delivered on an SLS LV to LEO. The core stage uses three engines. It also includes RCS, avionics, power, long-duration CFM hardware and AR&D capability. Interface structure includes fluid transfer, electrical, and communications lines.

Transfer Vehicle Parameters:
- 8.9 m diameter
- Core Stage Length 17 m
- In-line Tank Length 20 m
- Drop Tank Length 14 m
- Truss Length 19 m
- Truss Length 12 m
- Deep Space Habitat Length 12 m
- Vehicle Total Length 80 m

Mission Constraints / Parameters:
- 6 Crew
- Launch site time: 6 months (nom.)
- LEO assembly time: 18 months (nom.)
- Outbound time: 9 months (nom.)
- Stay time: 12 months (nom.)
- Return time: 9 months (nom.)
- Total mission time: 48 months (nom.)

Payload: DSH, CEV, Food, Tunnel, etc.
Vehicle Environments

◆ Oxygen
  • Crew Cabin has a 20% O2/80% N2 environment

◆ Thermal
  • Conditioned Avionics Bay
    - -10 °C to 80 °C operating Range
  • Crew Cabin
    - 10 °C to 40 °C operating Range
Mission Environments

- **Launch Site Environment**
  - Tropical Environment
    - Humidity
      - 8% - 100% RH
    - Temperature
      - 0 °C – 50 °C operating range
    - High Salinity

- **Ascent Flight (US Commercial Launch Vehicle Ranges)**
  - Temperatures can approach 50° C – 95° C due to aero thermal heating
  - 130 -140 dB acoustic environment
  - 3000 – 7000 g shock environment

- **Space Environment**
  - Thermal
  - Ultra-Violet (UV)
  - Oxygen
  - Space Radiation

- **Space Environment varies greatly with proximity to Earth’s atmosphere and the Van Allen Radiation Belt**
  - Low Earth Orbit (LEO)
  - Medium Earth Orbit (MEO)
  - Geosynchronous Earth Orbit (GEO)
  - Interplanetary Space is similar to GEO
Assembly: Low Earth Orbit (LEO)

◆ **Oxygen**
  - Atomic Oxygen is a concern only within 600 km of Earth
  - 1021 atoms/cm²-year at 600 km altitude

◆ **Space Radiation**
  - 600 km circular orbit at 28.5 deg inclination
  - Electrons < 2 MeV dominate fluence
  - South Atlantic Anomaly is the greatest source of radiation fluence
    - Radiation flux closer to Earth due to shift in geomagnetic center from the Earth’s rotation
  - Galactic Cosmic Rays and Solar Protons contribute less to radiation environment than the electron and proton sources from the atmosphere
  - Shielding of 0.76 mm Al reduces dose to 1 krad annually

◆ **Thermal**
  - Varies significantly with spacecraft thermal sources and rotation rates
  - Approximately -50 °C to 150°C operating Range

◆ **Micro Meteorite/Orbital Debris (MMOD)**
  - Large distribution of tiny orbital debris impacting at high energies
Ultra-Violet (UV) Radiation

Solar Irradiance

> 500 mW/m² above 120 nm
Medium Earth Orbit

◆ Space Radiation

- 5000 km circular orbit, 0 deg inclination
- Much greater electron and ion radiation due to the Van Allen radiation belt
- 25.4 mm Al shielding reduces dose to 10 krad
- 0.25 mm to 1.25 mm Al allows a total dose of 10 Mrad annually which leads to severe mechanical damage to electronics
# Interplanetary

## Space Radiation

- Energetic electrons are most significant
- Shielding of 5 - 10 mm reduces dose to ~1 krad (Si)
  - Energetic electrons dominate dose for Al shielding < 7.62 mm
- Solar protons can dominate for Al shielding > 7.62 mm
  - Energies of 10 – 100 MeV
- Solar Flares produce saturation events

![One Way Interplanetary Total Dose vs. Al Shielding]

![Total Radiation Dose from Earth Departure to Earth Return]
Solar Coronal Mass Ejection Event

- In Oct-Nov of 2003, a series of X-class solar events occurred.
  - High particle fluxes were noted.
  - Many spacecraft performed safining maneuvers.
  - Many systems experienced higher than normal (but correctable) data error rates.
  - Several spacecraft had anomalies causing spacecraft safining.
  - Increased noise seen in many instruments.
  - Atmospheric drag and heating issues noted.
  - Power grid systems affected,
  - Communication systems affected.
  - **Multiple Instrument FAILURES occurred.**
  - **Two spacecraft FAILURES occurred.**

Video from Large Angle Spectrometric Coronagraph (LASCO)

Data from SAMPEX
Interplanetary

**Meteorite Distribution**
- Dominated by tiny particles (ng) with relatively low velocity
  - < 200 μJ impact energy
- Impact concerns for particles > 1 μg for external structure
  - > 50 mJ impact energy
**Mars Orbit**

- **Oxygen**
  - Not a concern

- **Space Radiation**
  - Similar to interplanetary space

- **Thermal**
  - Varies significantly with spacecraft thermal sources and rotation rates
  - Approximately -50 °C to 150°C operating range

- **Meteorite Distribution**
  - Dominated by tiny particles (ng) with relatively low velocity
    - < 200 μJ impact energy
  - Impact concerns for particles > 1 μg for external structure
    - > 50 mJ impact energy
Total Mission

◆ Tropical Environment at Launch Site
◆ Atomic Oxygen while in LEO
  • 1021 atoms/cm²-year at 600 km altitude
◆ Meteorite Distribution
  • Dominated by tiny particles (ng) with relatively low velocity
    - < 200 µJ impact energy
  • Impact concerns for particles > 1 µg for external structure
    - > 50 mJ impact energy
◆ Space Radiation
  • 300 krad (Si) total exposure with no shielding
  • 15 krad (Si) total exposure with 0.762 mm Al Shielding
◆ Thermal
  • Varies significantly with spacecraft thermal sources and rotation rates
  • Approximately -50 ºC to 150ºC operating Range
Photonics Applications

- **Optical Communications**
  - Guided
  - Free Space

- **Optical Gyroscopes**

- **LiDAR**

- **Optical Sensing**
  - Space Environment
  - Reactor Environment

- **Optical Coatings**
Photonics Applications

◆ Optical Communications
  - Much spaceflight experience with fiber optic communication networks
    - Fiber Distributed Data Interface (FDDI)
      – On board the International Space Station (ISS) since 2001
    - MIL-STD-1773
      – Small Explorer (SMEX)
      – NRL Microelectronics and Photonics Test Bed (MPTB)
      – Solar Anomalous Magnetospheric Panicle Explorer (SAMPEX)
      – Wilkinson Microwave Anisotropy Probe (WMAP)
      – Rossi X-Ray Timing Explorer (RXTE)
      – Hubble Space Telescope (HST) Solid State Recorder (SSR)
      – Boeing Photonics Space Experiment (PSE)
    - All fiber applications in the space environment depend on very careful control of fiber impurities
    - Need to consider longer cable distances

<table>
<thead>
<tr>
<th>Reference</th>
<th>Device</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation-resistant erbium-doped-nanoparticles optical fiber for space applications</td>
<td>Erbium Doped Fiber Amplifier</td>
<td></td>
<td>Various loss depending on Al 40 (worse) or Si content</td>
<td>gamma ray</td>
</tr>
</tbody>
</table>
Optical Communications

- Free Space Optical Communications has been demonstrated in LEO
  - European Space Agency (ESA) demonstrated optical communications between
    - ARTEMIS and SPOT4
    - ARTEMIS to ground
    - ARTEMIS to an aircraft
  - ESA ARTEMIS and Japanese OICET satellite
  - Near Field Infrared Experiment (NFIRE) and the TerraSAR-X satellites
- Lunar Laser Communication Demonstration (LLCD) flying as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission demonstrating lunar distance communications
**Photonics Applications**

**Optical Communications**
- Interplanetary distances have not yet been demonstrated
  - Laser power levels
  - Tighter beam control
  - Receiver Telescopes

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<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADIATION TESTING OF LIQUID CRYSTAL OPTICAL PHASE SHIFTERS FOR SPACE SURVIVABILITY</td>
<td>Liquid Crystal Optical Phased Array</td>
<td></td>
<td>2200 No EO degradation</td>
<td>gamma ray</td>
</tr>
<tr>
<td>Radiation testing of liquid crystal optical devices for space laser communication</td>
<td>Liquid Crystal Optical Phased Array</td>
<td></td>
<td>2200 No EO degradation</td>
<td>gamma ray</td>
</tr>
<tr>
<td>Space qualification issues in acousto-optic and electro-optic devices</td>
<td>AOTF</td>
<td>0.012545</td>
<td>increased insertion loss and switching time, while reducing Strehl</td>
<td>X-ray</td>
</tr>
<tr>
<td></td>
<td></td>
<td>788.6</td>
<td>-100 C operation, small degradation in AO polarization</td>
<td>proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>small changes in transmission and diffraction efficiency</td>
<td>gamma ray</td>
</tr>
</tbody>
</table>
Photonics Applications

◆ Optical Gyroscopes

• Spaceflight experience in LEO and planetary missions

  - LEO
    – Proton TRS-500
    – Numerous Satellites

  - Planetary
    – Mars Rover LN-200S Fiber Optic Gyroscope (FOG)

Optolink
TRS-500
FOG

L3 Communications
RLGs

Honeywell
FOG

LN-200S on Mars Rovers
Optical Gyroscopes

- Recent research on FOG radiation effects shows good operational performance
  - All components test well
  - Geometrical polarization
- High accuracy, low drift is important
  - Minimize ITV corrections, limiting control system sizing

<table>
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<th>Device</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research on two light sources design in fiber optic gyroscope for space</td>
<td>FOG</td>
<td></td>
<td>PM fiber loss increased due to dopant color centers. Coupler and Detector had loss increases. Integrated Optics Chip not affected</td>
<td>Not specified</td>
</tr>
<tr>
<td>application</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research on the key techniques of fiber optic gyroscopes in the space</td>
<td>FOG</td>
<td></td>
<td>50 PM fiber loss increased</td>
<td>Not specified</td>
</tr>
<tr>
<td>application</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Effects on Opto-Electronic Devices for Fiber-Optic Gyroscopes</td>
<td>FOG</td>
<td></td>
<td>PM fiber loss increased due to dopant color centers in two fibers. A third PM fiber not affected indicating Geometrical birrefringence best. SLD, Coupler, Detector Integrated Optics Chip not affected.</td>
<td>gamma ray</td>
</tr>
</tbody>
</table>
Photonics Applications

**LiDAR**

- Spaceflight experience in LEO and planetary missions
  - LEO
    - LiDAR In-space Technology Experiment (LITE)
    - Ice, Cloud, and land Elevation Satellite (ICESAT)
  - Planetary
    - Mars Global Surveyor (MGS) Mars Orbiter Laser altimeter (MOLA)
    - Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) probe

ICESAT  
MGS MOLA  
MESSENGER
**Photonics Applications**

- **Optical Sensing**
  - Optical Sensor Applications
    - Fiber Bragg Grating (FBG)
      - Temperature
      - Stress/Strain (Pressure)
    - Microbolometers
    - Chemical Sensing of Crew Environment
  - Radiation
  - Imaging
    - Infrared
    - Visible

National Instruments “*Fundamentals of FBG Optical Sensing*”

- **Space Environment**
  - Good thermal environment characteristics based on material selection
  - 300 krad (Si) total exposure with no shielding
  - 15 krad (Si) total exposure with 0.762 mm Al Shielding

<table>
<thead>
<tr>
<th>Reference</th>
<th>Device</th>
<th>Energy MeV</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing of Digital Micromirror Devices for Space-Based Applications</td>
<td>DMD</td>
<td></td>
<td>21</td>
<td>100% failure. Failure onset at 29 krad</td>
<td>proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34.5</td>
<td></td>
<td>100% failure. Failure onset at 31 krad</td>
<td>proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40.9</td>
<td></td>
<td>100% failure. Failure onset at 29 krad</td>
<td>proton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>173 K. No radiation. No errors.</td>
<td></td>
</tr>
</tbody>
</table>
## Photonics Applications

### Advanced end-to-end fiber optic sensing systems for demanding environments

<table>
<thead>
<tr>
<th>Reference</th>
<th>MATERIALS</th>
<th>VIABLE TEMP RANGE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibers</td>
<td>Slica</td>
<td>Close to 0 K to 1190°C when softening occurs - (Pure silica can withstand to 1800°C)</td>
<td>Standard optical fiber material. Can withstand strains on the order of 1% in tension &amp; 5% compression.</td>
</tr>
<tr>
<td></td>
<td>Sapphire</td>
<td>Melting point = 2040°C</td>
<td>Obtaining long lengths &amp; adding claddings is challenging.</td>
</tr>
<tr>
<td></td>
<td>PMMA</td>
<td>Low- 68 K to 400 K (127°C)</td>
<td>Have been reported to measure strains over 15%</td>
</tr>
<tr>
<td>Coatings</td>
<td>Acrylate</td>
<td>-40°C to 85°C</td>
<td>Standard optical fiber coating</td>
</tr>
<tr>
<td></td>
<td>Silicone</td>
<td>-40°C to 180°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>-190°C to 385°C</td>
<td>Most common temperature resistant coating</td>
</tr>
<tr>
<td>Coatings</td>
<td>Nitrides</td>
<td></td>
<td>Developmental</td>
</tr>
<tr>
<td></td>
<td>Carbides</td>
<td></td>
<td>Developmental</td>
</tr>
<tr>
<td></td>
<td>Gold</td>
<td>Melting point = 1040 °C</td>
<td>Most common hi-temp coating generally used up to 800°C. However gold is very soft and has been most successfully used in combination with nickel</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
<td>Melting point = 1455 °C</td>
<td>Commonly used under gold coatings</td>
</tr>
<tr>
<td></td>
<td>Platinum</td>
<td>Melting point = 1772 °C</td>
<td>Extreme hi-temp coating</td>
</tr>
<tr>
<td>Tubing</td>
<td>Inconel</td>
<td>Melting point = 1372°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stainless Steel</td>
<td>Melting point = 1400°C to 1480°C depending on composition</td>
<td></td>
</tr>
<tr>
<td>Attachment</td>
<td>Epoxies</td>
<td>to 370°C</td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>Adhesives</td>
<td>to 1100°C</td>
<td>Can have problems when attaching to metals due to thermal expansion mismatch with metals</td>
</tr>
<tr>
<td>Soldering</td>
<td></td>
<td></td>
<td>Promising method for attaching metal coated optical fibers to metals</td>
</tr>
</tbody>
</table>
Photonics Applications

◆ Optical Sensing
  - Reactor Applications
    - Communications
    - Fiber Bragg Grating (FBG)
      - Temperature
      - Stress/Strain (Pressure)
    - Extensometer (material elongation)
    - Photometer
# Photonics Applications

## Optical Sensing

- **Reactor Environment**
  - 35 Grad (Si) total dose over 4 years, 200 °C

<table>
<thead>
<tr>
<th>Reference</th>
<th>Device</th>
<th>Temperature</th>
<th>Total Dose rad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature monitoring of nuclear reactor cores with multiplexed fiber Bragg grating sensors</td>
<td>FBG</td>
<td>70 C</td>
<td>4.22M</td>
<td>23 day exposure, Small shift in FBG response</td>
<td>gamma rays and neutrons</td>
</tr>
<tr>
<td>Fibre Optic Extensometer for High Radiation and High Temperature Nuclear Applications</td>
<td>Fiber</td>
<td>150 C</td>
<td>1.60T</td>
<td>91 day exposure, optical loss increased. Able to compensate for shifts.</td>
<td>gamma rays and neutrons</td>
</tr>
<tr>
<td></td>
<td>Fiber</td>
<td>150 C</td>
<td>460G</td>
<td>27 day exposure, optical loss increased. Some drift still unexplained.</td>
<td>gamma rays and neutrons</td>
</tr>
<tr>
<td>Radiation Testing of Optical Fibers for a Hot-Cell Photometer</td>
<td>Fiber</td>
<td>22 C</td>
<td>18.0M</td>
<td></td>
<td>gamma rays</td>
</tr>
<tr>
<td>Fiber-optic link components for maintenance tasks in thermonuclear fusion environments</td>
<td>Fiber</td>
<td>200 C</td>
<td>1.34G</td>
<td>Pure SiO2 fiber had low losses</td>
<td>gamma rays and neutrons</td>
</tr>
<tr>
<td>Si Detector</td>
<td>200 C</td>
<td>330M</td>
<td>Degraded quickly. One failed.</td>
<td>gamma rays and neutrons</td>
<td></td>
</tr>
<tr>
<td>InGaAs Detector</td>
<td>200 C</td>
<td>330M</td>
<td>Quick and permanent degradation</td>
<td>gamma rays and neutrons</td>
<td></td>
</tr>
<tr>
<td>EEL</td>
<td>200 C</td>
<td>1.54G</td>
<td>Degraded with exposure time and increasing temperature. One failed.</td>
<td>gamma rays and neutrons</td>
<td></td>
</tr>
<tr>
<td>VCSEL</td>
<td>200 C</td>
<td>1.34G</td>
<td>Lens darkening.</td>
<td>gamma rays and neutrons</td>
<td></td>
</tr>
</tbody>
</table>
Optical Coatings

- Shows promise for protection of optical surfaces from contaminants
- Need to investigate resistance to abrasion from predicted particle impact energies
  - $< 200 \mu\text{J}$ impact energy

<table>
<thead>
<tr>
<th>Reference</th>
<th>Device</th>
<th>Energy MeV</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces</td>
<td>polydimethylsiloxane (PDMS) polymers</td>
<td>63.8</td>
<td>148.6</td>
<td></td>
<td>protons</td>
</tr>
<tr>
<td></td>
<td>polydimethylsiloxane (PDMS) polymers</td>
<td></td>
<td>152</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment</td>
<td>Silicone</td>
<td>64</td>
<td>148.6</td>
<td>no degradation in outgassing</td>
<td>protons</td>
</tr>
<tr>
<td></td>
<td>Silicone</td>
<td>64</td>
<td>148.6 years</td>
<td>No degradation over 8 years</td>
<td>protons</td>
</tr>
<tr>
<td></td>
<td>Silicone</td>
<td></td>
<td>182.8</td>
<td>no degradation in outgassing</td>
<td>gamma rays</td>
</tr>
</tbody>
</table>
Summary of Polymer Photonics Total Dose Testing

◆ Polymers show promise for application in Space Environment
  • Low adhesion shown to particles and moisture
  • Total dose testing generally below 1 Mrad (Si)
    - Some polymers showed degradation or shifts in performance
      – Needs to be compensated for in instrument design
      – Reliability needs to be considered
    - Some polymers showed improvements sustained for large total doses (> 300 krad (Si))
  • Abrasion resistance needs to be assessed for polymers used as optical coatings
### Summary of Polymer Photonics Proton and Electron Total Dose Testing

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Energy MeV</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation of hydrophobic coating materials by gamma-rays and protons: Space applications</td>
<td>dimethylsilicone (DMS) w 30% SMO</td>
<td>63.8</td>
<td>198.2</td>
<td>No statistical change in response</td>
<td>protons</td>
</tr>
<tr>
<td>Overview of photonic materials and components for application in space environments</td>
<td>Ge doped Si FBG</td>
<td>63</td>
<td>10000</td>
<td>Shift in optical power wavelength center and reflection</td>
<td>protons</td>
</tr>
<tr>
<td></td>
<td>Mach Zehnder LD-3 polymer</td>
<td>64</td>
<td>600</td>
<td>EO Polylmer Degradation</td>
<td>protons</td>
</tr>
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<td>DR-1/MA film</td>
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<td>500</td>
<td>EO Polylmer Degradation</td>
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<td>polyimide waveguide</td>
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<td>600</td>
<td>EO Polylmer Degradation</td>
<td>protons</td>
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<tr>
<td>Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces</td>
<td>polydimethylsiloxane (PDMS) polymers</td>
<td>63.8</td>
<td>148.6</td>
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<td>protons</td>
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<tr>
<td>Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment</td>
<td>Silicone</td>
<td>64</td>
<td>148.6</td>
<td>No degradation in outgassing</td>
<td>protons</td>
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<tr>
<td>Effect of Radiation on the Molecular and Contamination Properties of Silicone-Based Coatings</td>
<td>Silicone</td>
<td>64</td>
<td>148.6</td>
<td>No degradation over 8 years</td>
<td>protons</td>
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<tr>
<td>Space application requirements for organic avionics</td>
<td>CLD1/APC optical modulator</td>
<td>0.1</td>
<td>12% increase in Vpi over 2 weeks after exposure</td>
<td>electrons</td>
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<tr>
<td></td>
<td>TP7 optical modulator</td>
<td>0.1</td>
<td>20% increase in Vpi over 2 weeks after exposure</td>
<td>electrons</td>
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<td>An all-optical protocol to determine the molecular origin of radiation damage/enhancement in electro-optic polymeric materials</td>
<td>EO CPW1/APC modulator</td>
<td>25.6</td>
<td>100</td>
<td>Significantly improved Vpi</td>
<td>proton</td>
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</table>
# Summary of Polymer Photonics Gamma Ray Total Dose Testing

<table>
<thead>
<tr>
<th>Reference</th>
<th>Material</th>
<th>Energy MeV</th>
<th>Total Dose krad(Si)</th>
<th>Result</th>
<th>Source</th>
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<tbody>
<tr>
<td>Irradiation of hydrophobic coating materials by gamma-rays and protons: Space applications</td>
<td>dimethylsilicone (DMS) w 30% SMO</td>
<td>1.17&amp;1.33</td>
<td>184.956</td>
<td>No statistical change in response</td>
<td>gamma rays</td>
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<tr>
<td>Overview of photonic materials and components for application in space environments</td>
<td>Mach Zehnder LD-3 polymer</td>
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<td>4000 EO Polymer Degradation</td>
<td>gamma rays</td>
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<td>polyimide waveguide</td>
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<td>580 EO Polymer Degradation</td>
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<td>polyimide siloxane (PDMS) polymers</td>
<td>152</td>
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<td>gamma rays</td>
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<td>Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces</td>
<td>Polydimethylsiloxane (PDMS)</td>
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<td>gamma rays</td>
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<td>Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment</td>
<td>Silicone</td>
<td>182.8</td>
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<td>No degradation in outgassing</td>
<td>gamma rays</td>
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<tr>
<td>Overview of New and Emerging Radiation Resistant Materials for Space Environment Applications</td>
<td>Polymer w/ Fullerene on Siloxane</td>
<td>1.17&amp;1.33</td>
<td>204.7</td>
<td>Improved Optical Transmission</td>
<td>gamma rays</td>
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<td>Polymer w/ DR1 on Siloxane</td>
<td>1.17&amp;1.33</td>
<td>204.7</td>
<td>Improved Optical Transmission</td>
<td>gamma rays</td>
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<td>Polymer w/ NLS-1 on Siloxane</td>
<td>1.17&amp;1.33</td>
<td>204.7</td>
<td>Improved Optical Transmission</td>
<td>gamma rays</td>
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<td>Polymer w/ SWCNT</td>
<td>1.17&amp;1.33</td>
<td>175.4</td>
<td>No change (several day delay in post irradiation measurement)</td>
<td>gamma rays</td>
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<tr>
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<td>Polymer w/ MWCNT</td>
<td>1.17&amp;1.33</td>
<td>175.4</td>
<td>No change (several day delay in post irradiation measurement)</td>
<td>gamma rays</td>
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<tr>
<td>An all-optical protocol to determine the molecular origin of radiation damage/enhancement in electro-optic polymeric materials</td>
<td>CLD1/APC</td>
<td>1.17&amp;1.33</td>
<td>208</td>
<td>No change in EO performance Thermal relaxation biggest effect</td>
<td>gamma rays</td>
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<tr>
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<td>CLD1/APC</td>
<td>1.17&amp;1.33</td>
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<td>No change in EO performance Thermal relaxation biggest effect</td>
<td>gamma rays</td>
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<td>CLD1/APC</td>
<td>1.17&amp;1.33</td>
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<td>No change in EO performance Thermal relaxation biggest effect</td>
<td>gamma rays</td>
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<td>EO CPW1/APC modulator</td>
<td>1.17&amp;1.33</td>
<td>100</td>
<td>No change to improvement in Vpi</td>
<td>gamma rays</td>
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<td>EO CPW1/APC modulator (Dupont)</td>
<td>1.17&amp;1.33</td>
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<td>No change in z, one degraded Vpi</td>
<td>gamma rays</td>
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<td>EO CPLD75/APC modulator</td>
<td>1.17&amp;1.33</td>
<td>55</td>
<td>Some degradation in Vpi</td>
<td>gamma rays</td>
</tr>
</tbody>
</table>
Key Considerations

- Thermal
  - Environments
    - 40°C – 80°C internal
    - 150°C external
    - 200°C internal reactor
  - Conductive Cooling
    - Must be minimized or eliminated to keep spacecraft radiators small
      - < 5 W for components
      - < 20 W for a packaged system
  - Radiative Cooling
    - If exposed to a cooler field of view
- UV Exposure
  - Externally exposed devices must be protected
Key Considerations

- Abrasion Resistance (for exposed components)
  - Need to investigate resistance to abrasion from predicted particle impact energies
    - < 200 μJ impact energy
- Radiation Effects
  - Space Environment
    - 300 krad (Si) total exposure with no shielding
    - 15 krad (Si) total exposure with 0.762 mm Al Shielding
  - Reactor Environment
    - 35 Grad (Si) total dose over 4 years