Atomic Oxygen Effects

Sharon K.R. Miller
NASA Glenn Research Center
Cleveland, Ohio

Spacecraft Anomalies and Failures Workshop – Act II, Chantilly, VA
July 24, 2014

This presentation does not include any material covered by ITAR
Environment Interaction Visible on Space Shuttle Tail Section
Atmospheric Composition

- Earth's Surface:
  - N₂: 78.0%
  - O₂: 21.0%

- 400 km Orbit:
  - N₂: 95.9%
  - O: 4.1%
Atomic Oxygen in Low Earth Orbit

- AO is the predominant species from 180-650 km
- Average ram energy $\approx 4.5$ eV

LDEF Spacecraft CTFE after
8.99 x $10^{21}$ atoms/cm²

Photodissociation of $O_2$

UV Radiation
$E = h\nu > 5.12$ eV (<243 nm)

$O_2$ Diatomic Molecule

Atomic Oxygen

Polychlorotrifluoroethylene (CTFE)
Basic Atomic Oxygen Interaction with Organic Surfaces
Material Testing in an Atomic Oxygen Environment Using Ground-Based Systems
Material Tests in Low Earth Orbit (LEO) for Environment Interactions

Materials International Space Station Experiment (MISSE)

Long Duration Exposure Facility (LDEF)
<table>
<thead>
<tr>
<th>Material</th>
<th>Abbrev.</th>
<th>$E_y$ (cm$^3$/atom)</th>
<th>$E_y$ Uncertainty (%)</th>
<th>Material</th>
<th>Abbrev.</th>
<th>$E_y$ (cm$^3$/atom)</th>
<th>$E_y$ Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile butadiene styrene</td>
<td>ABS</td>
<td>1.09E-24</td>
<td>2.7</td>
<td>Polyamide 6 or nylon 6</td>
<td>PA6</td>
<td>3.51E-24</td>
<td>2.7</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>CA</td>
<td>5.05E-24</td>
<td>2.7</td>
<td>Polyamide 66 or nylon 66</td>
<td>PA66</td>
<td>1.80E-24</td>
<td>12.6</td>
</tr>
<tr>
<td>Poly-(p-phenylene terephthalamide)</td>
<td>PPD-T (Kevlar)</td>
<td>6.28E-25</td>
<td>2.6</td>
<td>Polymide</td>
<td>PI (CP1)</td>
<td>1.91E-24</td>
<td>2.8</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>PE</td>
<td>3.74E-24</td>
<td>2.6</td>
<td>Polymide (PMDA)</td>
<td>PI (Kapton H)</td>
<td>3.00E-24</td>
<td>2.7</td>
</tr>
<tr>
<td>Polynyl fluoride</td>
<td>PVF (Tedlar)</td>
<td>3.19E-24</td>
<td>2.6</td>
<td>Polymide (PMDA)</td>
<td>PI (Kapton HN)</td>
<td>2.81E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Crystalline polyvinylfluoride w/white pigment</td>
<td>PVF (White Tedlar)</td>
<td>1.01E-25</td>
<td>4.1</td>
<td>Polymide (BPDA)</td>
<td>PI (Upilex-S)</td>
<td>9.22E-25</td>
<td>3.0</td>
</tr>
<tr>
<td>Polyoxymethylene; acetal; polyformaldehyde</td>
<td>POM (Delrin)</td>
<td>9.14E-24</td>
<td>3.1</td>
<td>Polymide (PMDA)</td>
<td>PI (Kapton H)</td>
<td>3.00E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Polyacrylonitrile</td>
<td>PAN</td>
<td>1.41E-24</td>
<td>3.3</td>
<td>High temperature polyimide resin</td>
<td>PI (PMR-15)</td>
<td>3.02E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Ally digycol carbonate</td>
<td>ADC (CR-39)</td>
<td>6.60E-24</td>
<td>2.6</td>
<td>Polybenzimidazole</td>
<td>PBI</td>
<td>2.21E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>PS</td>
<td>3.74E-24</td>
<td>2.7</td>
<td>Polycarbonate</td>
<td>PC</td>
<td>4.29E-24</td>
<td>2.7</td>
</tr>
<tr>
<td>Polymethyl methacrylate</td>
<td>PMMA</td>
<td>5.60E-24</td>
<td>2.6</td>
<td>Polyetheretherketone</td>
<td>PEEK</td>
<td>2.99E-24</td>
<td>4.5</td>
</tr>
<tr>
<td>Polyethylene oxide</td>
<td>PEO</td>
<td>1.93E-24</td>
<td>2.6</td>
<td>Polyethylene terephthalate</td>
<td>PET (Mjar)</td>
<td>3.01E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Poly(p-phenylene-2 6-benzobisoxazole)</td>
<td>PBO (Zylon)</td>
<td>1.36E-24</td>
<td>6.0</td>
<td>Chlorotrifluoroethylene</td>
<td>CTFE (Kel-f)</td>
<td>8.31E-25</td>
<td>2.6</td>
</tr>
<tr>
<td>Epoxide or epoxy</td>
<td>EP</td>
<td>4.21E-24</td>
<td>2.7</td>
<td>Halar ethylene-chlorotrifluoroethylene</td>
<td>ECTFE (Halar)</td>
<td>1.79E-24</td>
<td>2.6</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>PP</td>
<td>2.68E-24</td>
<td>2.6</td>
<td>Tetrafluorethylene-ethylene-ethylene copolymer</td>
<td>ETFE (Tefzel)</td>
<td>9.61E-25</td>
<td>2.6</td>
</tr>
<tr>
<td>Polybutylene terephthalate</td>
<td>PBT</td>
<td>9.11E-25</td>
<td>2.6</td>
<td>Fluorinated ethylene propylene</td>
<td>FEP</td>
<td>2.00E-25</td>
<td>2.7</td>
</tr>
<tr>
<td>Polysulphone</td>
<td>PSU</td>
<td>2.94E-24</td>
<td>3.2</td>
<td>Polytetrafluoroethylene</td>
<td>PTFE</td>
<td>1.42E-25</td>
<td>2.6</td>
</tr>
<tr>
<td>Polyeurethane</td>
<td>PU</td>
<td>1.56E-24</td>
<td>2.9</td>
<td>Perfluoroalkoxy copolymer resin</td>
<td>PFA</td>
<td>1.73E-25</td>
<td>2.7</td>
</tr>
<tr>
<td>Polyphenylene isophthalate</td>
<td>PPPA (Nomex)</td>
<td>1.41E-24</td>
<td>2.9</td>
<td>Amorphous Fluoropolymer</td>
<td>AF</td>
<td>1.98E-25</td>
<td>2.6</td>
</tr>
<tr>
<td>Graphite</td>
<td>PG</td>
<td>4.15E-25</td>
<td>10.7</td>
<td>Polyvinylidene fluoride</td>
<td>PVDF (Kynar)</td>
<td>1.29E-24</td>
<td>2.7</td>
</tr>
<tr>
<td>Polyetherimide</td>
<td>PEI</td>
<td>3.31E-24</td>
<td>2.6</td>
<td>*$E_y$ &gt; this value because sample stack was partially or fully eroded through</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Atomic Oxygen Erosion Yields of Polymers Flown on MISSE-2 (PEACE)
Issues With Protective Coatings

Imperfections in Thin Film Coatings

Dust Particle

Protective Coating

Scratch or Rill

Polymer

Unprotected Polymer

Protected Polymer

Aluminized Kapton Flown on LDEF
Blanket Box Cover Failure of Aluminized Kapton Observed on ISS
Monte Carlo Computational Model Predictions

- 2-D Computational modeling of atomic oxygen erosion of polymers based on observed in-space results
- Takes into account:
  - Energy dependence of reaction probability
  - Angle of impact dependence on reaction probability
  - Thermalization of scattered oxygen atoms
  - Partial recombination at surfaces
  - Atomic oxygen scattering distribution functions
- Modeling parameters tuned to replicate in-space erosion

Aluminized on both sides

Aluminized on exposed side only
Atomic Oxygen Scattering

12 inch diameter polycarbonate window

L/X $\approx$ 165

Thermal Energy Plasma

Metal screen
Glass
Polycarbonate
Change in Sensitivity of Cosmic Origins Spectrograph on Hubble Space Telescope

Experienced a far UV sensitivity decline ranging from 3-15%/year
(based on data from June 2009 through mid-February 2010)
Scattering and Thermal Accommodation of Low Earth Orbital Atomic Oxygen

Possible Events Upon Impact:

- Reaction
- Recombination
- Scattering
- Partial thermal accommodation
- Ejection out the entrance

LEO ≈ 4.5eV

-0.04 eV
Test of Mock Aperture with Various Types of Liners

Ratio of Effective Flux Inside-to-Outside

Metals and Oxides
- Aluminum
- Copper
- Gold coated...
- SiO2 Kapton H
- Stainless Steel

Polymers and Graphite
- Kapton H
- Grafoil
- Teflon FEP
- POM
- Polyethylene
- CTFE
Total Transmittance as a Function of Wavelength for Coverglass Prior to and After Exposure to Atomic Oxygen

AR Coated

- As Received
- After AO Exposure to an Effective Fluence of 1.06e22 atoms/cm^2

Conductive AR Coated

- As Received
- After AO Exposure to an Effective Fluence of 1.06e22 atoms/cm^2
Mirrored Silver Back of Solar Cell Prior to and After Exposure to Atomic Oxygen

As Received

After Exposure to an AO Effective Fluence of $2 \times 10^{21}$ atoms/cm$^2$
Oxidative Cracking of Silicone

DC 93-500 Silicone
Exposed to LEO Atomic Oxygen on STS-46

Fluence = $2.3 \times 10^{20}$ atoms/cm$^2$

Pre-flight

Post-flight
Stress Dependent Atomic Oxygen Erosion of Black Kapton XC

Polymers Exposed Under Stress on MISSE 6

Stressed UV-S-2

Exposed

Unstressed UV-U-2

Stressed (left) and Unstressed (right)
Black Kapton XC

Stress level: Force/Area = ~4000psi (2.76e7 N/m²)
Strain = Stress/Modulus = 4000 psi/480000 psi (3.3e9 N/m²) = ~0.008
For Kapton XC this represents ~3% of the maximum strain and ~24% of the tensile strength

Kapton XC experienced a factor of 4 higher erosion rate under tension
Summary

- Atomic oxygen is the most predominant specie in LEO
- Atomic oxygen is reactive and energetic enough to break chemical bonds in materials
- Reaction products with polymers and carbon containing materials are volatile (typically CO and CO₂)
- Metals and inorganics experience surface oxidation in some cases leading to shrinkage and cracking or spalling
- Atomic oxygen can thermalize on contact and scatter from surfaces leading to further reaction, which is dependent on the materials it contacts and geometry
- The effect that atomic oxygen has on a particular material on a spacecraft is dependent upon how much atomic oxygen arrives at the surface, atom energy, and can be affected by mechanical loading, temperature, and other components in the environment (UV radiation, charged particles…)
- Each situation is unique and for accurate prediction of degradation of a material or component, it should be tested or modeled in a configuration representative of how it will be used
Atomic Oxygen Team at NASA GRC in Environmental Effects and Coatings Branch, Materials and Structures Division:

Sharon Miller, NASA
Kim de Groh, NASA
Deborah Waters, NASA
Bruce Banks, SAIC at NASA

Publications:
http://ntrs.nasa.gov

Website:
http://www.grc.nasa.gov/www/epbranch/ephome.htm

For Further Information Contact:
Sharon Miller
NASA Glenn Research Center
21000 Brookpark Road
Cleveland, Ohio, 44135
(216) 433-2219
sharon.k.miller@nasa.gov