Atomic Oxygen Effects

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

Earth's Surface

- O₂: 21.0%
- N₂: 78.0%

400 km Orbit

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

- AO is the predominant species from 180-650 km
- Average ram energy ≈ 4.5 eV

Photodissociation of O₂

UV Radiation
E = hν > 5.12 eV (<243 nm)

O₂ Diatomic Molecule

Atomic Oxygen

LDEF Spacecraft CTFE after
8.99 x 10²¹ atoms/cm²

Polychlorotrifluoroethylene (CTFE)
Basic Atomic Oxygen Interaction with Organic Surfaces

UV Radiation

O₂

OH

O

O

CO or CO₂
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)
## Atomic Oxygen Erosion Yields of Polymers Flown on MISSE-2 (PEACE)

<table>
<thead>
<tr>
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<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>
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<tr>
<td>Cellulose acetate</td>
<td>CA</td>
<td>5.05E-24</td>
<td>2.7</td>
<td>Polyamide 66 or nylon 6</td>
<td>PA66</td>
<td>1.80E-24</td>
<td>12.6</td>
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<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>
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<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>
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<tr>
<td>Polyvinyl 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>
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<tr>
<td>Crystalline polyvinyl fluoride 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>
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<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>
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<td>Polycrystalline</td>
<td>PAN</td>
<td>1.41E-24</td>
<td>3.3</td>
<td>High temperature polymide resin</td>
<td>PI (PMR-15)</td>
<td>3.02E-24</td>
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<td>Allyl diglycol carbonate</td>
<td>ADC (CR-39)</td>
<td>6.80E-24</td>
<td>2.6</td>
<td>Polybenzimidazole</td>
<td>PBI</td>
<td>2.21E-24</td>
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<td>Polystyrene</td>
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<td>3.74E-24</td>
<td>2.7</td>
<td>Polycarbonate</td>
<td>PC</td>
<td>4.29E-24</td>
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<td>Polymethyl methacrylate</td>
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<td>5.60E-24</td>
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<td>Polyetheretherketone</td>
<td>PEEK</td>
<td>2.99E-24</td>
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<td>Polyyethylene oxide</td>
<td>PEO</td>
<td>1.93E-24</td>
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<td>Polyethylene terephthalate</td>
<td>PET (Mjar)</td>
<td>3.01E-24</td>
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<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>
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<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>
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<tr>
<td>Polypropylene</td>
<td>PP</td>
<td>2.68E-24</td>
<td>2.6</td>
<td>Tetrafluoroethylene-ethylene copolymer</td>
<td>ETFE (Tefzel)</td>
<td>9.61E-25</td>
<td>2.6</td>
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<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>
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<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>
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<td>Polyurethane</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>
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<tr>
<td>Polypyrrole (Nomex)</td>
<td>PPPA</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>
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<tr>
<td>Graphite</td>
<td>PG</td>
<td>4.15E-25</td>
<td>10.7</td>
<td>Polynvinylidene fluoride</td>
<td>PVDF (Kynar)</td>
<td>1.29E-24</td>
<td>2.7</td>
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<tr>
<td>Polyetherimide</td>
<td>PEI</td>
<td>3.31E-24</td>
<td>2.6</td>
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</tbody>
</table>

*Ey > this value because sample stack was partially or fully eroded through*
Issues With Protective Coatings

Imperfections in Thin Film Coatings

Aluminized Kapton Flown on LDEF

Unprotected Polymer

Protected Polymer
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

\[ L/X \approx 165 \]
Relative sensitivity at 174.3 nm

Atomic oxygen fluence, atoms/cm²

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
~ 4.5 eV

0.04 eV
Test of Mock Aperture with Various Types of Liners

Ratio of Effective Flux Inside-to-Outside

- Aluminum
- Copper
- Gold coated...
- SiO2 Kapton H
- Stainless Steel
- Kapton H
- Grafoil
- Teflon FEP
- POM
- Polyethylene
- CTFE

Metals and Oxides
Polymers and Graphite
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 $1.06 \times 10^{22}$ atoms/cm$^2$

Conductive AR Coated

- As Received
- After AO Exposure to an Effective Fluence of $1.06 \times 10^{22}$ 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

Stress level: Force/Area $= \sim 4000\text{psi (2.76e7 N/m}^2\text{)}$

Strain $= \text{Stress/Modulus} = 4000\text{ psi/480000 psi (3.3e9 N/m}^2\text{)} = \sim 0.008$

For Kapton XC this represents $\sim 3\%$ of the maximum strain and $\sim 24\%$ of the tensile strength

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

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 CO$_2$)
• 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
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