Atomic Oxygen Environments, Effects and Mitigation

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Atomic Oxygen in Low Earth Orbit

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

LDEF Spacecraft CTFE after 8.99 x 10^{21} atoms/cm^2

Photodissociation of O_2

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

O_2 Diatomic Molecule

Atomic Oxygen

Polychlorotrifluoroethylene (CTFE)
Atomic Oxygen Effects

• Extent of damage dependent on:
  • Quantity arriving
  • Atom energy
  • Material reactivity (can vary with temperature, radiation, contamination, mechanical loading)

• Reaction can cause changes in:
  • Mechanical properties
  • Electrical properties
  • Optical properties
  • Thermal properties
  • Surface (cracking and shrinkage as oxides form)

• Where atomic oxygen reacts:
  • Primarily on the surface
  • Can scatter into pinwindow defects in coatings and into crevices
Atmospheric Composition Comparison Between Earth and Mars

Graphs Courtesy of NASA JPL
MAVEN

- Mars Atmospheric and Volatile Evolution Mission
- Launched in November, 2013 to understand the role the loss of volatiles from the atmosphere to space has played in the history of Mars atmosphere and climate
- Insertion into Mars orbit September, 2014
Issues on the Mars Atmosphere and Volatile Evolution (MAVEN) Spacecraft

• Payload was designed to tolerate exposure to atomic oxygen
• Changes in the Langmuir probe were observed when full science operation commenced
• Current-voltage curves showed continual changes for the first 6 months of the mission before probe measurements became semi-stable
• Three months after orbit insertion, the electrical properties of the electrostatic analyzer (ESA) RAM sectors were changed so the surface potential over a portion of the curved plates were slightly different from others which de-tuned the ESA
• Changes attributed to the low Mars orbital environment
MAVEN Environment

- Highly elliptical orbit
- Apoapsis: 6000 km, Periapsis: 160 to 180 km, 60 degree inclination
- At periapsis, the atmosphere is predominantly O, CO, CO$_2$, N$_2$, and O$_2$
- Maximum ram velocity of ~4 km/sec

Velocity of the MAVEN spacecraft as a function of time from closest approach for periapsis number 2441.

Atmospheric density of the MAVEN spacecraft as a function of time from closest approach for periapsis number 2441.

MAVEN Atmosphere Ram Energy

![Graph showing the variation of Ram Energy (eV) with Altitude Above Mars Surface (km) for O and CO2.](image-url)
Understanding the Differences Between LEO and LMO

• Determine if there is a reactivity difference due to chemistry by operating ground based atomic oxygen system on pure oxygen gas which is used to simulate LEO and on a mixture of 75.4% CO₂, 11.9% N₂, 10% O₂, and 2.7% CO to simulate 175 km LMO
• Expose materials that have been characterized in LEO to both the simulated LEO and LMO environments
• Measure the erosion yield (cm³ of material lost for each oxygen atom that arrives), solar absorptance and thermal emittance for each material before and after exposure
• Compare results
Atomic Oxygen Directed Beam System

• 2.45 GHz microwave discharge, 800 W forward power
• Base pressure: 2.7E-4 Pa, Operating pressure: 7.4E-2 Pa
• Maximum sample temperature on water cooled plate 40 °C
Atomic Oxygen Directed Beam System

Operating on Pure Oxygen

Operating on Mars Gas Mixture
Materials Tested

- Polyimide, Kapton H
- Polyimide, Upilex-S/Al
- FEP Teflon/Al
- Pyrolytic Graphite
- Polymethyl methacrylate
- Polyethylene terephthalate
- Polyoxymethylene
- Polycarbonate
Calculation of Erosion Yield

\[ F_E = \frac{4 \times (\Delta m_K)}{\rho_K \pi D^2 E_{yK}} \]

Where:
- \( F_E \) = effective atomic oxygen fluence (atoms/cm²)
- \( \Delta m_K \) = change in mass of Kapton H (g)
- \( \rho_K \) = density of Kapton H (1.4273 g/cm³)\(^1\)
- \( D \) = diameter of area exposed (2.228 cm)
- \( E_{yK} \) = erosion yield of Kapton H (3x10\(^{-24}\) cm³/atom)\(^2\)

\( F_E \) for SLEO = 5.79E20 atoms/cm²,
\( F_E \) for SLMO = 3.17E20 atoms/cm²

\[ E_y = \frac{4 \times \Delta m}{\rho \pi D^2 F_E} \]

Where:
- \( F_E \) = effective atomic oxygen fluence (atoms/cm²)
- \( \Delta m \) = change in mass of the material (g)
- \( \rho \) = density of the material (g/cm³)
- \( D \) = diameter of area exposed (2.228 cm)
- \( E_y \) = erosion yield of the material (cm³/atom)


# Erosion Yield Comparison Between Simulated LEO, Simulated LMO and ISS LEO

<table>
<thead>
<tr>
<th>Material</th>
<th>Density(^1) (g/cm(^3))</th>
<th>(E_y) Simulated LEO (SLEO) (cm(^3)/atom)</th>
<th>(E_y) Simulated LMO (SLMO) (cm(^3)/atom)</th>
<th>(E_y) ISS LEO (LEO)(^{1}) (cm(^3)/atom)</th>
<th>(E_y) SLEO/(E_y) LEO</th>
<th>(E_y) SLMO/(E_y) LEO</th>
<th>(E_y) SLEO/(E_y) SLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide Kapton H</td>
<td>1.427</td>
<td>3.03E-24</td>
<td>3.11E-24</td>
<td>3.00E-24</td>
<td>1.01</td>
<td>1.04</td>
<td>1.03</td>
</tr>
<tr>
<td>Polyimide Upilex-S/Aluminum</td>
<td>1.387</td>
<td>2.37E-24</td>
<td>2.55E-24</td>
<td>9.22E-25</td>
<td>2.57</td>
<td>2.76</td>
<td>1.07</td>
</tr>
<tr>
<td>FEP Teflon/Aluminum</td>
<td>2.144</td>
<td>4.85E-24</td>
<td>4.63E-24</td>
<td>2.00E-25</td>
<td>24.27</td>
<td>23.13</td>
<td>0.95</td>
</tr>
<tr>
<td>Polymethyl methacrylate</td>
<td>1.163</td>
<td>5.99E-24</td>
<td>1.14E-23</td>
<td>&gt;5.6E-24</td>
<td>&lt;1.07</td>
<td>&lt;2.03</td>
<td>1.90</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>1.393</td>
<td>3.78E-24</td>
<td>3.82E-24</td>
<td>3.01E-24</td>
<td>1.25</td>
<td>1.27</td>
<td>1.01</td>
</tr>
<tr>
<td>Polyoxyethylene</td>
<td>1.398</td>
<td>3.73E-23</td>
<td>3.43E-23</td>
<td>9.14E-24</td>
<td>4.08</td>
<td>3.75</td>
<td>0.92</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1.123</td>
<td>5.35E-23</td>
<td>3.59E-24</td>
<td>4.29E-24</td>
<td>12.48</td>
<td>0.84</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Polymethylmethacrylate – PMMA

As Received

SLEO
$F_E = 5.79 \times 10^{20}$ atoms/cm$^2$
$E_y = 5.99 \times 10^{-24}$ cm$^3$/atom

SLMO
$F_E = 3.17 \times 10^{20}$ atoms/cm$^2$
$E_y = 1.14 \times 10^{-23}$ cm$^3$/atom

Polycarbonate - PC

As Received

SLEO
$F_E = 5.79 \times 10^{20}$ atoms/cm$^2$
$E_y = 5.35 \times 10^{-23}$ cm$^3$/atom

SLMO
$F_E = 3.17 \times 10^{20}$ atoms/cm$^2$
$E_y = 3.59 \times 10^{-24}$ cm$^3$/atom
## Comparison of Solar Absorptance for Simulated LEO and LMO

<table>
<thead>
<tr>
<th>Material</th>
<th>(a_s) As Received</th>
<th>(a_s) After SLEO Exposure</th>
<th>% Change (from Received to After SLEO)</th>
<th>(a_s) After SLMO Exposure</th>
<th>% Change (from Received to After SLMO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide Kapton H</td>
<td>0.336</td>
<td>0.341</td>
<td>1.49</td>
<td>0.339</td>
<td>0.89</td>
</tr>
<tr>
<td>Polyimide Upilex-S/Aluminum</td>
<td>0.409</td>
<td>0.509</td>
<td>24.45</td>
<td>0.492</td>
<td>20.29</td>
</tr>
<tr>
<td>FEP Teflon/Aluminum</td>
<td>0.141</td>
<td>0.154</td>
<td>9.22</td>
<td>0.147</td>
<td>4.26</td>
</tr>
<tr>
<td>Pyrolytic Graphite</td>
<td>0.741</td>
<td>0.937</td>
<td>26.45</td>
<td>0.890</td>
<td>20.11</td>
</tr>
<tr>
<td>Polymethyl methacrylate</td>
<td>0.013</td>
<td>0.011</td>
<td>-15.38</td>
<td>0.006</td>
<td>-55.38</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>0.061</td>
<td>0.065</td>
<td>6.56</td>
<td>0.060</td>
<td>-1.64</td>
</tr>
<tr>
<td>Polyoxyethylene</td>
<td>0.082</td>
<td>0.044</td>
<td>-46.34</td>
<td>0.094</td>
<td>14.63</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.108</td>
<td>0.097</td>
<td>-10.19</td>
<td>0.107</td>
<td>-0.93</td>
</tr>
</tbody>
</table>
Polyethylene terephthalate – PET

As Received

SLEO
\[ F_E = 5.79 \times 10^{20} \text{ atoms/cm}^2 \]
\[ E_y = 3.78 \times 10^{-24} \text{ cm}^3/\text{atom} \]

SLMO
\[ F_E = 3.17 \times 10^{20} \text{ atoms/cm}^2 \]
\[ E_y = 3.82 \times 10^{-24} \text{ cm}^3/\text{atom} \]

Polyoxymethylene - POM

As Received

SLEO
\[ F_E = 5.79 \times 10^{20} \text{ atoms/cm}^2 \]
\[ E_y = 3.73 \times 10^{-23} \text{ cm}^3/\text{atom} \]

SLMO
\[ F_E = 3.17 \times 10^{20} \text{ atoms/cm}^2 \]
\[ E_y = 3.43 \times 10^{-23} \text{ cm}^3/\text{atom} \]
### Comparison of Thermal Emittance for Simulated LEO and LMO

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon_{T300}$ As Received</th>
<th>$\varepsilon_{T300}$ After SLEO Exposure</th>
<th>% Change (from Received to After SLEO)</th>
<th>$\varepsilon_{T300}$ After SLMO Exposure</th>
<th>% Change (from Received to After SLMO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide Kapton H</td>
<td>0.828</td>
<td>0.832</td>
<td>0.48</td>
<td>0.825</td>
<td>-0.36</td>
</tr>
<tr>
<td>Polyimide Upilex-S/Aluminum</td>
<td>0.835</td>
<td>0.848</td>
<td>1.56</td>
<td>0.834</td>
<td>-0.12</td>
</tr>
<tr>
<td>FEP Teflon/Aluminum</td>
<td>0.792</td>
<td>0.754</td>
<td>-4.80</td>
<td>0.775</td>
<td>-2.15</td>
</tr>
<tr>
<td>Pyrolytic Graphite</td>
<td>0.522</td>
<td>0.642</td>
<td>22.99</td>
<td>0.507</td>
<td>-2.87</td>
</tr>
<tr>
<td>Polymethyl methacrylate</td>
<td>0.589</td>
<td>0.338</td>
<td>-42.61</td>
<td>0.508</td>
<td>-13.75</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>0.803</td>
<td>0.814</td>
<td>1.37</td>
<td>0.798</td>
<td>-0.62</td>
</tr>
<tr>
<td>Polyoxymethylene</td>
<td>0.874</td>
<td>0.698</td>
<td>-20.25</td>
<td>0.849</td>
<td>-2.86</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.870</td>
<td>0.860</td>
<td>-1.15</td>
<td>0.860</td>
<td>-1.15</td>
</tr>
</tbody>
</table>
Pyrolytic Graphite

**SLEO**

\[ F_E = 5.79 \times 10^{20} \text{ atoms/cm}^2 \]

\[ E_y = 6.42 \times 10^{-25} \text{ cm}^3/\text{atom} \]

**SLMO**

\[ F_E = 3.17 \times 10^{20} \text{ atoms/cm}^2 \]

\[ E_y = 6.69 \times 10^{-25} \text{ cm}^3/\text{atom} \]
Summary of Results

- Kapton H, Upilex-S/Al, FEP Teflon/Al, pyrolytic graphite, PET and POM: good agreement between simulated LEO (SLEO) and simulated LMO (SLMO) erosion yields
- PMMA erosion yield nearly double in SLMO compared to SLEO
- Polycarbonate erosion yield SLMO 0.07 times SLEO
- SLEO erosion yield is in general higher than LEO, most are fairly close, but FEP Teflon/Al, POM, and polycarbonate are significantly higher (sensitivity to electrons or ions?)
- SLMO erosion yield is lower than LEO for polycarbonate
- In general, the solar absorptance change increases with erosion
- Thermal emittance was comparable between SLEO and SLMO for Kapton H, Upilex-S, PET and polycarbonate, but pyrolytic graphite had a much higher emittance for SLEO even though erosion yields were comparable
- FEP Teflon/Al and POM had greater reduction in emittance with erosion, but the effect was opposite for PMMA
- Likely material dependent changes in surface morphology and chemistry due to differences in atmospheric composition
Mitigation

- Complicated by degradation being dependent on material and specific environment
- May not be able to use LEO data to predict behavior in LMO
- Typical methods of mitigation for LEO
  - Barrier coatings
  - Implantation of atoms to form protective oxide
  - Material modification or use of alternate material
- Similar techniques may work for LMO but need more understanding of material reactivity for LMO to select effective barrier materials, implantation species and alternate materials
- Undercutting and scattering in LMO may be different as well (difference reaction and recombination probabilities and activation energies)
Conclusions

• Atomic oxygen has detrimental effect on spacecraft and is present in upper atmosphere of Earth and other planetary bodies such as Mars
• Changes in sensor surfaces not seen in LEO occurred in LMO
• Testing of selected materials indicated differences in erosion yield, optical and thermal properties based on composition of the atmosphere for many materials
• More testing is needed to understand mechanisms for erosion in LMO and to better quantify changes for durability assessment for LMO spacecraft