TFAWS 2015
Thermal Coatings Seminar Series Training
Part 2: Environmental Effects

NASA GSFC Contamination and Coatings Branch – Code 546
Hosted by: Jack Triolo - SGT, Inc.
Agenda

• Orbital Environments versus Orbital Altitude
• Tests for Environmental Effects on Coatings
• Orbital In-flight Test Descriptions
• Orbital In-flight Test Results versus Orbital Altitude
• In-flight Results versus Laboratory Test Results
• Atomic Oxygen In-flight Tests and Results
• Returned Flight Hardware
• Coating Issues
Earth Radius=6,300 km (4,000 mi)
Induced Environments

• All Orbits
  • Direct view of contamination source to sensitive surface combined with UV, CP, AO.

• LEO
  • Ambient return flux in ram (velocity) direction. Outgassing molecules colliding with ambient atmosphere and returning to spacecraft surface.

• MEO/GEO
  • Electrostatic Return (ESR). Molecule ionized by UV and attracted back to charged s/c surface

• Space Debris
  • Anything from paint flacks to nuts, bolts, and tools.
Orbital Altitudes

- LEO -- <1000km ---- UV, AO, Low Flux Charged Particles (CP)

- GEO -- 35,786km ---- UV, High Flux CP

- MEO -- >1000km to 25,000km ---- UB, Very High Flux CP

- L1, L2, Lunar ---- UV, Solar Wind (Low Energy Protons + Electrons)

- Elliptical ---- All of the above but lower fluxes
How do we Test for Environmental Effects?

• Laboratory Testing (measured in-situ or ex-situ)

  • Vacuum UV (1216 Å to 1800 Å)
  • UV (1800 Å to 4000 Å)

  • Charged Particles – electrons and protons tested to adsorbed energy – Rads (material specific) with mono energetic electrons and protons, which can be combined or separate and with or without UV

  • Atomic Oxygen – with or without UV

  • All of the above + intentionally introduced molecular contaminates
NASA-GSFC Coatings Space Environmental Test Facilities

- Calorimetric Emittance Facility
- Multisedes “UV” Degradation Chamber
- Solar Wind Facility
- Electrostatic Charge Facility
- Thermal Cycling Chambers
- Various Vacuum Chambers
ALZAK UV DATA

Damage varies with wavelength and material
On-Orbit In-Flight Testing

- LEO
  - OSO-8
- GEO
  - ATS-1, ATS-2, ATS-3, SCATHA (P87-2)
- MEO
  - NTS-2
- 35 Earth Radii
  - IMP-8
- CMP
  - LDEF, STS-8 (GAS-CMP), STS-11 (GAS-CMP), EOIM-3
COATINGS CALORIMETER

Calorimeter design with inner cup and sample disk having the same area
AST-2

ATS-2 Coatings Experiment GEO orbit
OSO-8 Coatings
Experiment intergraded into the S/C
OSO-8 Coatings Experiment
LEO orbit
## Comparison of Flight Data for Various Orbits

<table>
<thead>
<tr>
<th>COATING</th>
<th>LEO (OSO-8) 348X203 miles</th>
<th>MEO (NTS-2) 10,000 miles</th>
<th>GEO (ATS-1 &amp; SCATHA)</th>
<th>EX-GEO (IMP-8) 136,000 miles</th>
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<tbody>
<tr>
<td></td>
<td>Delta a /3yrs</td>
<td>Delta a /month</td>
<td>Delta a /3yrs</td>
<td>Delta a /3yrs</td>
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<tr>
<td>AL/SiOx</td>
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<td>0.10</td>
<td>0.05</td>
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<tr>
<td>CC/AL</td>
<td>0.0</td>
<td>0.02 /month</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>MS-74</td>
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<td>0.02 /month</td>
<td>0.34</td>
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<tr>
<td>Ag FEP</td>
<td>0.01</td>
<td>0.012 /month</td>
<td>0.08</td>
<td>0.06</td>
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<tr>
<td>Al FEP</td>
<td>0.02</td>
<td></td>
<td></td>
<td>0.04</td>
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<tr>
<td>NS43C/G</td>
<td></td>
<td>0.023 /month</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>OSR</td>
<td>0.01 /month</td>
<td></td>
<td>0.02 (0.04/10yrs)</td>
<td></td>
</tr>
<tr>
<td>Kapton</td>
<td></td>
<td></td>
<td>0.10</td>
<td>0.14</td>
</tr>
</tbody>
</table>

MEO has the highest degradation rate

LEO has the lowest degradation rate
Black paint shows effect of bleaching with UV exposure
Metalized Teflon degradation (in geosynchronous orbit unless otherwise indicated)

Solar absorptance changes orbit and s/c cleanliness dependence
Same orbital and s/c cleanliness dependence
Comparisons Between In-Flight and Laboratory Testing
$\Delta q$ as a Function of Solar and Electron Irradiation and Comparison With ATS-1 Data for $\text{Al}_2\text{O}_3/\text{K}_2\text{SiO}_3$
\[ \Delta \alpha \text{ of 2 mil Kapton/Al as a function of Orbital exposure—from IMP-H, compared with Boeing laboratory test data.} \]
ATS-1 / LABORATORY COMPARISON

$\Delta \alpha$ as a Function of Solar and Electron Irradiation and Comparison With ATS-1 Data for Dow Corning Q90-090
IMP-8 / LABORATORY COMPARISON

\[ \Delta \alpha \] of MS-74 white paint as a function of orbital exposure—from IMP-H, compared with Boeing laboratory test data.

IMP-H 5 MIL FEP TEFLON/AL

\[ n_L = 0.15 \quad n_r = 0.13 \]

\[ \Delta \alpha \] of FEP Teflon, coated on the back surface with evaporated Al or Ag, as a function of orbital exposure—from IMP-H.
ALZAK
1 X SPECTOLAB X 25 SOLAR SIMULATOR IFILTERED X NASA HEAL TIME
2 ◦ MICROWAVE RESONANCE LAMP (185 – 200nm)
3 ○ X-25 SAME AS 11 BUT TIME SCALING WITH ATS III SHIELDED DATA
4 ESTIMATED FROM 12 & 13
5 ◼ OSOH THERMAL CONTROL COATINGS MONITOR

Δα of Alzak "Control" – Comparison of Laboratory and In-flight Test Data
Atomic Oxygen Effects

• What affects AO flux?
  • Altitude
  • Solar Cycle
  • Ram Direction

• In-Flight Results

• Reaction Rates for Various Materials
LOW EARTH ORBITAL ENVIRONMENT

ATOMIC OXYGEN

TEXT
Large range of flux between solar max and min
ATOMIC OXYGEN

LOW EARTH ORBITAL
ATOMIC OXYGEN ENERGY DISTRIBUTION

- 400 km orbit
- 28.5° inclination
- 996 K

Number of Oxygen Atoms of Energy E

Energy E, eV
Slight spread effects past 90 degrees
On-Orbit In-Flight Testing

- LEO - OSO-8
- GEO - ATS-1, ATS-2, ATS-3, SCATHA (P87-2)
- MEO - NTS-2
- 35 Earth Radii - IMP-8
- EMP
  - LDEF (Long Duration Exposure Facility), STS-8 (GAS-CMP), STS-11 (GAS-CMP), STS-13-EOIM 3
Samples located around the surface provided every angle of attack including the wake
Delayed recovery made for more interesting results
STS-3 Cargo Bay
GSFC Contamination Monitor Package (CMP)
First time AO material erosion test vs time
Package design to STS-8 delivery was 56 days!
Pre-flight inspection
Post flight shows both eroded and non-eroded Kapton surfaces
Can you guess STS-8 was bay-to-ram?
What is inside the GAS can?
STS-8

Notches in data are artifices of QCM solar effects
QCM not in ram
CONTAMINATION MONITORING PACKAGE

Quartz Crystal Microbalances

- 15 megahertz TQCM’s manufactured by Faraday
- TQCM’s were maintained at 30° throughout mission to prevent contaminant build-up on crystals.
- TQCM Coatings:
  1. Carbon
  2. Kapton
  3. Teflon
  4. Polyurethane
  5. Uncoated (control sample)
QCM measures increased mass in ram
EOIM3/EMP Kapton coated QCM
EMP PRELIMINARY RESULTS

On-Orbit Results

- Results during mission showed a significant accumulation of contaminants on all the TQCM crystals instead of expected material erosion due to atomic oxygen.
- Greatest rate of accumulation observed with shuttle bay into the ram.
- Contaminant believed to be SiO$_x$ originating from an unknown silicone source.
- Contaminant thickness of 4205 Angstroms accreted on the uncoated TQCM through out the mission.
IN-FLIGHT AO TESTING / EIOM-3
Uncoated QCM used to detect contamination
EMP provided real time data during flight
EIOM 3 location in cargo bay
# AO Erosion Yields for various materials

## ATOMIC OXYGEN

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>EROSION YIELD, $10^{\text{EXP}-24}$ CM$^3$/ATOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAPTON H</td>
<td>3.0</td>
</tr>
<tr>
<td>CHEMGLAZE Z306</td>
<td>0.35</td>
</tr>
<tr>
<td>FEP TEFLON</td>
<td>0.037-0.50</td>
</tr>
<tr>
<td>CARBON</td>
<td>0.9-1.7</td>
</tr>
<tr>
<td>DIAMOND</td>
<td>0.021</td>
</tr>
<tr>
<td>OSMIUM</td>
<td>0.314</td>
</tr>
<tr>
<td>SILVER</td>
<td>10.5</td>
</tr>
<tr>
<td>TEDLAR (CLEAR)</td>
<td>3.2</td>
</tr>
<tr>
<td>TEDLAR (WHITE)</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>EPOXY</td>
<td>1.7</td>
</tr>
<tr>
<td>AL/SiO2</td>
<td>0.0</td>
</tr>
<tr>
<td>GOLD</td>
<td>0.0</td>
</tr>
<tr>
<td>AL</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Loss of Thickness Calculation

- Example: 400 km altitude, AO flux for solar max and min, Kapton surface in ram for 3 yrs

- Thickness loss/solar max
  \[ \text{Thickness loss/solar max} = (5 \times 10^{14} \text{ atoms cm}^{-2}\text{sec}^{-1}) \times (3 \times 365 \times 24 \times 3600 \text{ sec}) \times (3.0 \times 10^{-24} \text{ cm}^3/\text{atom}) \]
  \[ = 0.14 \text{ cm (55 mils)} \]

- Thickness loss/solar min
  \[ \text{Thickness loss/solar min} = (2 \times 10^{13} \text{ atoms cm}^{-2}\text{sec}^{-1}) \times (3 \times 365 \times 24 \times 3600 \text{ sec}) \times (3.0 \times 10^{-24} \text{ cm}^3/\text{atom}) \]
  \[ = 0.0057 \text{ cm (2.3 mils)} \]
First returned hardware from on orbit S/C. Although looked contaminated, it tested very clean by surface analyses.
The GSFC engineering team has an extensive hands-on experience in materials, coatings, contamination, and space environmental effects.

- HST
- LDEF
- Solar Max

- Slow crack growth in polymers was experienced at levels below accepted normal damage thresholds.

- Lesson learned from HST was that even when the environment is well defined, synergistic effects can still result in unforeseen degradation of materials.
Teflon tape came separated from substrate
Hubble’s FEP Degradation Due to Space Environmental Effects

(Material provided by Jackie Townsend.)

- **HST at SM2 (6.8 years in LEO)**
  - 5-mil FEP Teflon with more than 100 cracks

- **Slow Crack Growth:** Synergistic effects of radiation (electron, proton, UV, VUV) and load (internal, blanket build and assembly, thermal cycling). Evaluated temperatures accelerates degradation.
Contamination Effects

• How Does Contamination affect Coating Solar Absorptance?

• Before on-orbit exposure? – Minor effects since hydrocarbons have low absorptance in the solar spectral region.

• During on-orbit? – Hydrocarbons are fractured by UV and CP leaving only carbon films which adsorb heavily in the solar spectral region.

• Only carbon residues are seen on returned hardware. Silicones contaminates will also leave forms of SiO especially when AO is contained in the environment.
CARBON DEPOSITED ON CCAg MIRROR

Measured Reflectance of Carbon on GSFC Silver Composite on Optically Smooth Glass

- 150 Å C: $\alpha(s) = 0.34, \epsilon(n) = 0.69$
- 50 Å C: $\alpha(s) = 0.16, \epsilon(n) = 0.68$
- 20 Å C: $\alpha(s) = 0.12, \epsilon(n) = 0.68$
- Prior to Carbon Deposition: $\alpha(s) = 0.06, \epsilon(n) = 0.68$

August 6, 2015
MODELED CARBON CONTAMINATION

Modeled CCaG Coating with Carbon Layers of Various Thickness

Reflectance Percent

Wavelength (nm)

Reflectance with Amorphous Carbon Layer 150 Å - α = 0.46
Reflectance with Amorphous Carbon Layer 50 Å - α = 0.27
Reflectance with Amorphous Carbon Layer 20 Å - α = 0.18
Reflectance with Amorphous Carbon Layer 0 Å - α = 0.09

August 6, 2015
CARBON DEPOSITED ON ALUMINUM MIRROR

Measured Reflectance of Carbon on Vapor Deposited Aluminum

- Prior to Carbon Deposition - $\alpha(s) = 0.08$, $\varepsilon(n) = 0.68$
- 20Å C - $\alpha(s) = 0.09$, $\varepsilon(n) = 0.68$
CARBON DEPOSITED ON CCAg ROUGHENED SURFACE

Measured Reflectance of Carbon on GSFC Silver Composite on Roughened Aluminum

- Reflectance Percent
- Wavelength (nm)

- Prior to Carbon Deposition - $\alpha(s) = 0.16$, $\varepsilon(n) = 0.73$
- 20Å C - $\alpha(s) = 0.22$, $\varepsilon(n) = 0.72$
- 50Å C - $\alpha(s) = 0.29$, $\varepsilon(n) = 0.72$
- 150Å C - $\alpha(s) = 0.47$, $\varepsilon(n) = 0.73$

August 6, 2015
Delta absorptance same as contaminated CCAg
Normal emittance ($\epsilon_n$) shows no change with deposit of the 1st quarterwave of SiOx. Hemispherical emittance ($\epsilon$) shows a steady increase with SiOx deposition.
Compare delta absorptance with OSRs
Paint Thickness Issues

• White Paint Solar Absorptance versus Coating Thickness (versus adhesion)

• Black Paint Low Temperature Emittance versus Thickness
Emittance at 300K is 0.84.
Emittance at 100K is 0.58.
Z306 (1.5 mils) HEMISPHERICAL EMITTANCE

AeroGlas Z306 (1.5 mils)

Hemispherical Emittance

Temperature (°K)
Teflon Adhesive Bleeding

- Silver cracking during application
- Adhesive UV Degrading
- Cures
Adhesive bleeding and UV darkening

Note contamination darkening at vent covers
Adhesive bleeding at the corner of the louver frame