Degradation of β-Cloth Covering for a Battery Orbital Replacement Unit in Low Earth Orbit

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Motivation

• NASA plans future long duration missions
  • Missions in cis-lunar space
  • Missions supporting a return to the moon
  • Asteroid redirect mission
  • Missions to Martian orbit and surface
• Will expose EVA systems to much longer durations
  • Lunar surface missions may last 6 months
  • Martian surface missions may last > 1 year
• How well will EVA materials hold up?
  • No current spacesuits have > few days exposure to space
  • Hubble materials degraded faster than expected
• Space station components exposed for many years
  • Orbital Replacement Units (ORU’s) housing batteries use $\beta$-cloth cover
  • Similar to space suit pressure garment fabrics
  • The degradation of long-exposed ORU’s can give insight into spacesuit degradation
Battery Orbital Replacement Unit

- ISS uses β-cloth covered ORUs to house replaceable components
  - Used for pumps, storage tanks, controller boxes, antennas, batteries
  - Enables easy on-orbit replacement by EVA or Dextre robotic arm
  - Stored on External Stowage Platforms or ExPRESS Logistics Carrier
- Batteries an array of Ni-H cells
  - Store energy from PV arrays to provide power during eclipse
  - Eclipse 35 min/90 min orbit
  - Design life of 6.5 yr - replaced several times
ORU S/N 15 Position on ISS

- **Launched November 2000**
  - One of 6 battery ORUs installed on P6 truss segment
  - P6 supported first set of PV arrays and batteries
  - P6 moved to starboard side of Z1 segment
  - ORU oriented orthogonal to ram and zenith for 6.9 yr
- **Moved to end of P5 truss October 2007**
  - P6 segment removed from Z1 by ISS robotic arm
  - Moved to end of P5 truss by Shuttle Discovery robotic arm
  - Faced zenith when $\beta$-gimbal = 0°
  - Gimbal rotates to follow sun
  - ORU cycled zenith, ram, nadir, and wake for 1.7 yr
- **Returned to Earth July 2009**
  - Total exposure 3156 days (8.6 yr)
Long Duration Exposure Facility

- LDEF in space for 69 months (5.7 yr)
  - Launched on Challenger April 1984
  - Retrieved by Columbia January 1990
- Carried β-cloth sample oriented 22° to ram
  - Well characterized orbital environment
  - AO darkened the β-cloth
  - Erosion of PTFE did not release glass fibers
  - Back side showed no appreciable change

<table>
<thead>
<tr>
<th>LEO Environment</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Radiation</td>
<td>8,680 Estimated Sun hr</td>
</tr>
<tr>
<td>Proton fluence (0.05 – 200 MeV)</td>
<td>10⁹/cm²</td>
</tr>
<tr>
<td>Electron fluence (50 keV/3.0 MeV)</td>
<td>10¹²/cm²</td>
</tr>
<tr>
<td>Atomic oxygen</td>
<td>8.14×10²¹/cm²</td>
</tr>
<tr>
<td>Thermal cycles</td>
<td>~32,000</td>
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</tbody>
</table>

Sampling the ORU

- **ORU sampled before being put in storage**
  - Sections about 0.5 m cut from each of 5 exposed sides
  - Samples about 4 cm cut out for analysis
  - After spectroscopy, 1.7 cm sectioned mounted for imaging, SEM
- **No ISS orientation information was provided**
  - "A" face obvious because of shape
  - "B" and "E" faces had more discoloration
  - "C" and "D" faces must have been more shadowed
  - Orientation in figure best guess at orientation
Analysis

UV-Vis-NIR (250 - 2500 nm)

IR Spectroscopy (2.5 - 25 µm)

Optical Microscopy

FESEM & EDS
Optical Microscopy

- ORU became darker and “redder”
  - Back assumed to be unexposed
  - Samples A1, A2, B2, and E most affected
  - Sides B1, C, and D less so
  - ORU segments not uniform in color (B1 vs B2)
- ORU samples not uniform in color
  - B1 much “cleaner” than B2
  - Black trim lightened where white darkened
- At high magnification, no fiber damage visible

LDEF results indicated a darkening of $\beta$-cloth
Attributed to AO texturing of PTFE
Glass fibers were not released
Optical Microscopy of Exposed Fibers

• Sections of β-cloth were sewn together
  • Stitching pulled some fibers out of PTFE

• Exposed fibers darkened dramatically
  • Fused silica fibers do not darken
  • Fiberglass containing metals does

• Experimentally verified in ground tests
  • Sample of C1 exposed to AO in hyperthermal asher
  • PTFE oxidized away
  • UV in asher did not darkened fibers
  • Fiber darkening probably due to high energy particle radiation

Thanks to B.A. Banks (SAIC) for asher test.
Optical Microscopy of Black Trim

- Microscopy shows upper black layer eroded
  - Black layer contains carbon black
  - "Grey" areas missing top layer
  - Lighter color due to exposed fibers
  - Black pigment remains between fibers
- Darkened area adjacent to grey
  - Darkened areas eroded also
FE Scanning Electron Microscopy

- ORU texture flatter than MISSE-7
  - MISSE-7 FEP exposure
    - ~17 months wake
    - ~1 month ram
    - FEP fibers damaged
  - ORU exposure
    - ~83 months starboard
    - ~20 months rotating
    - Glass fibers not eroded
    - B2 highly eroded
    - A2 little erosion
    - Unable to quantify erosion

- Black ORU trim
  - Black areas show little erosion
  - Grey areas show much erosion

LDEF results indicated erosion of PTFE
Glass fibers were not released
Energy Dispersive Spectra of ORU

- No evidence of contamination from external sources
- Areas of minimal erosion
  - 277 eV (C)
  - 677 eV (F)
  - Expected in the PTFE coating ($C_2F_4)_n$
- Areas where fibers were exposed
  - 525 eV (O)
  - 1740 eV (Si)
  - Small peaks at 1040 (Na), 1486 (Al), and 3690 eV (Ca)
  - Expected from fiber glass
- Black trim stripe and eroded grey areas similar EDS spectra
  - Ratio of carbon to fluorine higher in the black
  - 0.78 vs 0.60 in adjacent grey regions
  - Erosion of carbon black added to the PTFE coating
UV-Vis-NIR Spectroscopy

- Most solar radiation (98+%) emitted 250–2500 nm
  - Want materials to be highly reflective to reduce heat load
  - Exposure lowered reflectivity in 250–650 nm region
- Difference spectrum centered 360–375 nm
  - Higher in UV/blue part of spectrum (so looks redder)
  - Solar spectrum intense in this region
Absorptance of ORU Material

- Total solar absorptance ($\alpha$) calculated from spectral reflectivity ($\rho(\lambda)$)
  - $\alpha(\lambda) = (1 - \rho(\lambda))$
  - $\alpha = \sum_{\lambda=250 \text{ nm}}^{2500 \text{ nm}} \alpha(\lambda)$

- Back side $\alpha$ was 0.248 ± 0.005, with a range of 0.015
  - Front side $\alpha$ was 0.267 ± 0.020 with a range of 0.018
  - Front/Back $\rightarrow$ average $\alpha$ increased 7.7 < 1%
  - If Front/Back under trim $\rightarrow$ average 44%
    - As high as 61%

- The $\alpha$ of black trim decreased
  - Black pigment lost
  - Leaves more reflective fibers exposed

- Ionizing radiation increases $\alpha$ $\rightarrow$ over time spacesuits will need more cooling

<table>
<thead>
<tr>
<th></th>
<th>$\alpha_{\text{back}}$</th>
<th>$\alpha_{\text{front}}$</th>
<th>$\alpha_{\text{front/back}}$</th>
<th>$\alpha_{\text{front/under back}}$</th>
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<tbody>
<tr>
<td>D1</td>
<td>0.247</td>
<td>0.246</td>
<td>1.00</td>
<td>1.33</td>
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<tr>
<td>B1</td>
<td>0.240</td>
<td>0.242</td>
<td>1.01</td>
<td>1.30</td>
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<tr>
<td>C1</td>
<td>0.246</td>
<td>0.253</td>
<td>1.03</td>
<td>1.36</td>
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<tr>
<td>E1</td>
<td>0.255</td>
<td>0.277</td>
<td>1.09</td>
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<td>B2</td>
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<td>0.275</td>
<td>1.10</td>
<td>1.48</td>
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<tr>
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<td>0.246</td>
<td>0.274</td>
<td>1.11</td>
<td>1.48</td>
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<tr>
<td>A2</td>
<td>0.253</td>
<td>0.299</td>
<td>1.18</td>
<td>1.61</td>
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<td>Black</td>
<td>0.963</td>
<td>0.939</td>
<td>0.98</td>
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<tr>
<td>Grey</td>
<td>0.963</td>
<td>0.711</td>
<td>0.74</td>
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<tr>
<td>Under B</td>
<td>0.186</td>
<td>0.199</td>
<td>1.07</td>
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<tr>
<td>Under G</td>
<td>0.185</td>
<td>0.221</td>
<td>1.19</td>
<td></td>
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</tbody>
</table>

LDEF found $\alpha = 0.22 \pm 0.02$
IR Spectra of ORU

- Infrared spectra of the backside of the samples were identical
  - Surfaces not altered by the space environment
  - Or altered by a process not dependent on orientation
  - Or not locally varying environment
    - atomic oxygen exposure
- Only weak spectral features on exposure side
  - Peaks centered near 8.1, 8.25, and 8.7 µm
    - 1235, 1210, and 1150 cm\(^{-1}\)
  - Region of C-F bond motions
    - No specific structural features could be assigned
  - Silicone contamination unlikely
    - No Si-CH\(_3\) stretch at 7.94 µm (1260 cm\(^{-1}\))
Emittance of ORU Material

- Total thermal emittance ($\varepsilon$) calculated from spectral reflectivity ($\rho(\lambda)$)
  - $\varepsilon(\lambda) = \alpha(\lambda) = (1-\rho(\lambda))$
  - $\varepsilon = \sum_{\lambda=2.5 \mu m}^{25 \mu m} \varepsilon(\lambda)B(\lambda, T)$

- The $\varepsilon$ of the backside of the samples decreased monotonically
  - $0.922 \pm 0.001$ at 300 K to $0.655 \pm 0.006$ at 700 K
  - Space exposure $\rightarrow$ no change the $\varepsilon$ ($\Delta < 1\%$)

- The $\varepsilon$ of black trim increased slightly
  - $0.901$ at 300 K to $0.932$ at 700 K
  - Space exposure $\rightarrow$ big change in $\varepsilon$: $0.937$ (300 K) $\rightarrow$ $0.817$ (700 K)

- On space exposure the $\varepsilon$ of the ORU was essentially unchanged

LDEF found $\varepsilon = 0.89 \pm 0.02$
CONCLUSIONS

• Degradation of long-exposed ORU’s can give insight into long term spacesuit degradation

• Radiation exposure increases \( \alpha \rightarrow \) over time spacesuits will need more cooling
  • No evidence was found of significant contamination
  • PTFE darkened by UV/particle radiation-caused bond unsaturation
  • Fiberglass darkening caused by particle radiation

• On space exposure the \( \varepsilon \) of the ORU was essentially unchanged
  • Confirmed LDEF observation

• Change in thermal properties (\( \alpha/\varepsilon \)) over time must be factored into the new spacesuit requirements

• Atomic oxygen erosion not as significant as in the MISSE-7 spacesuit fabric experiment
  • In some regions the PTFE layer was completely eroded, revealing the glass fibers underneath
  • Difficult to judge the actual depth of erosion

• Black trim eroded substantially, loosing the carbon pigment

• No gross mechanical weakening or failures were noted