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

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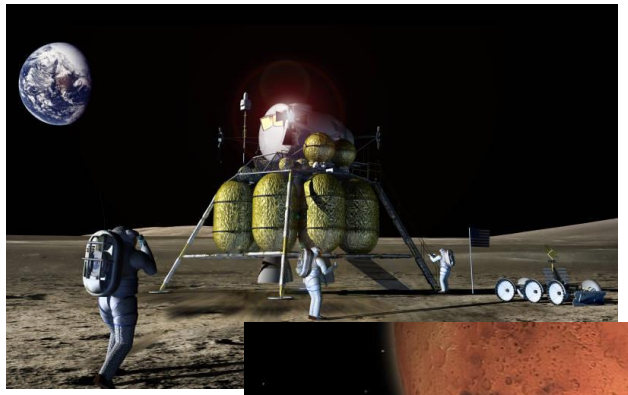
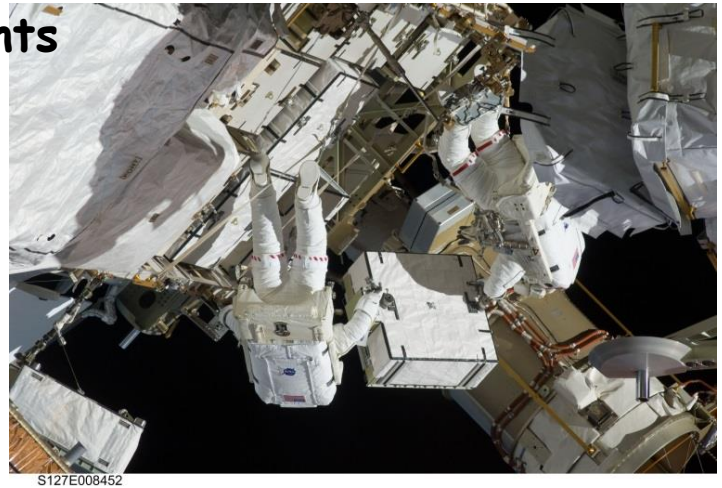
Motivation

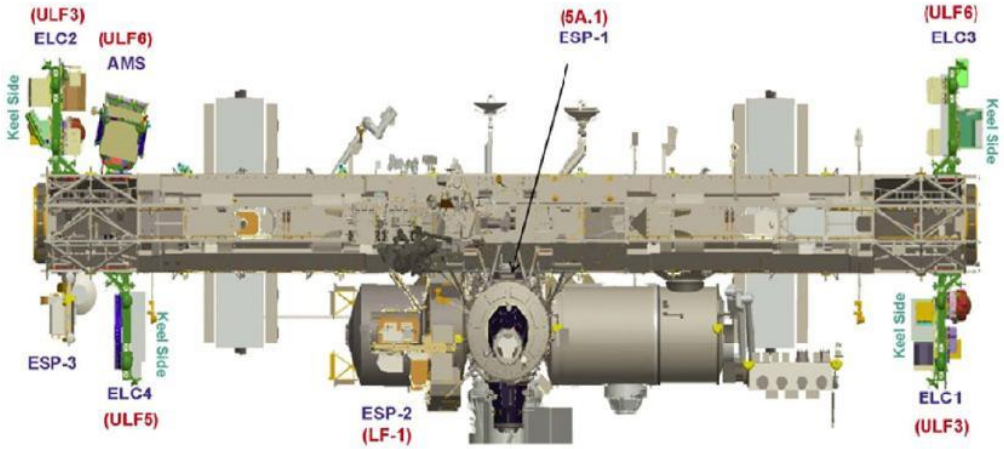
- **NASA plans future long duration missions**
  - Missions in cis-lunar space
  - Missions supporting a return to the moon
  - Asteroid redirect mission
  - Missions to Martian orbit and surface
- **Will expose EVA systems to much longer durations**
  - Lunar surface missions may last 6 months
  - Martian 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 β-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

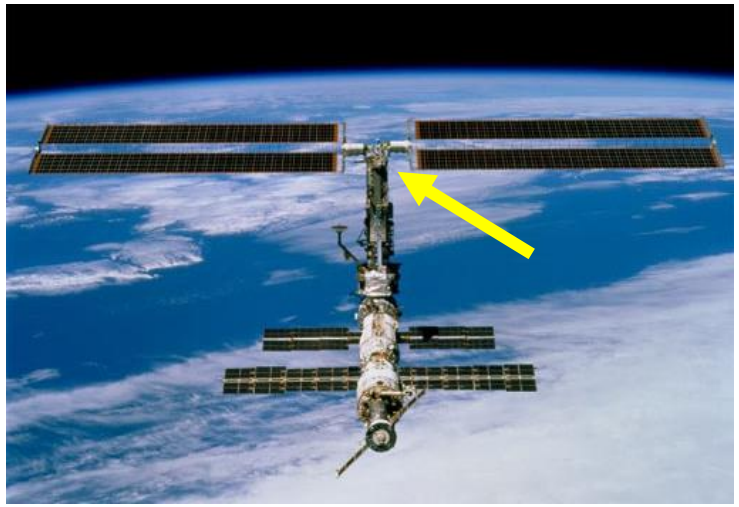
- **ISS uses β-cloth covered ORUs to house replaceable components**
  - Used for pumps, storage tanks, controller boxes, antennas, **batteries**
  - Enables easy on-orbit replacement by EVA or Dextre robotic arm
  - Stored on External Stowage Platforms or ExPRESS Logistics Carrier
- **Batteries an array 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

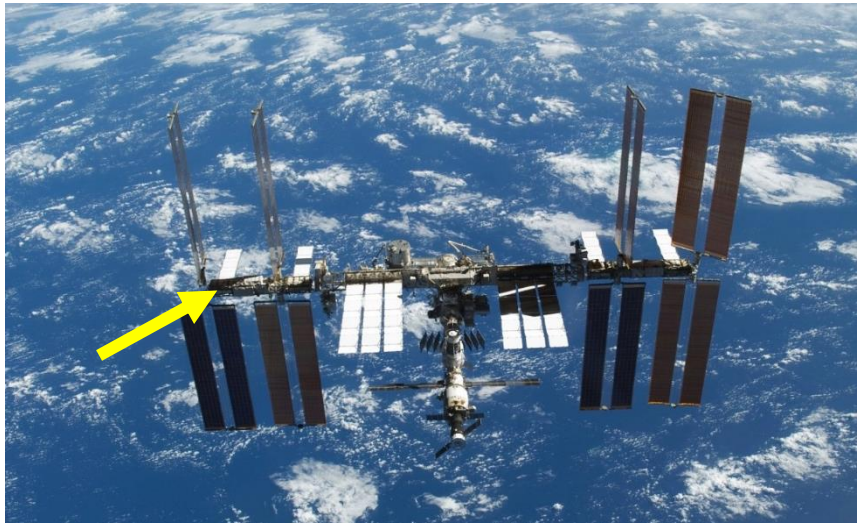


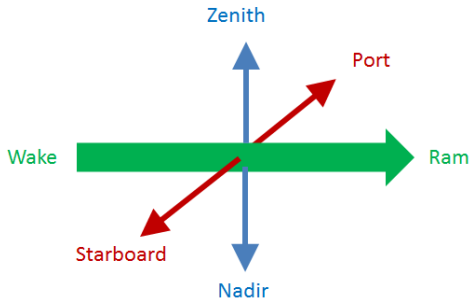


ORU S/N 15 Position on ISS

- **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 β-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)**



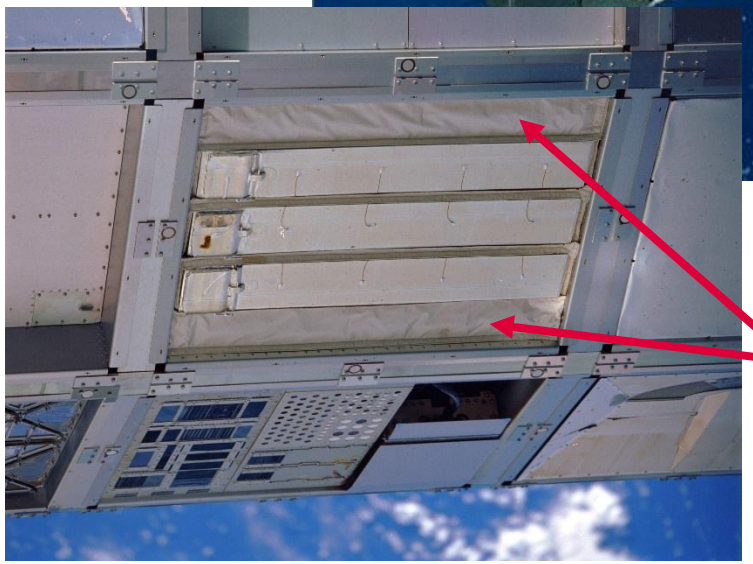




Long Duration Exposure Facility

- **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

LEO Environment	Exposure
UV Radiation	8,680 Estimated Sun hr
Proton fluence (0.05 – 200 MeV)	$10^9/cm^2$
Electron fluence (50 keV/3.0 MeV)	$10^{12}/cm^2$ $10^8/cm^2$
Atomic oxygen	$8.14\times10^{21}/cm^2$
Thermal cycles	~32,000

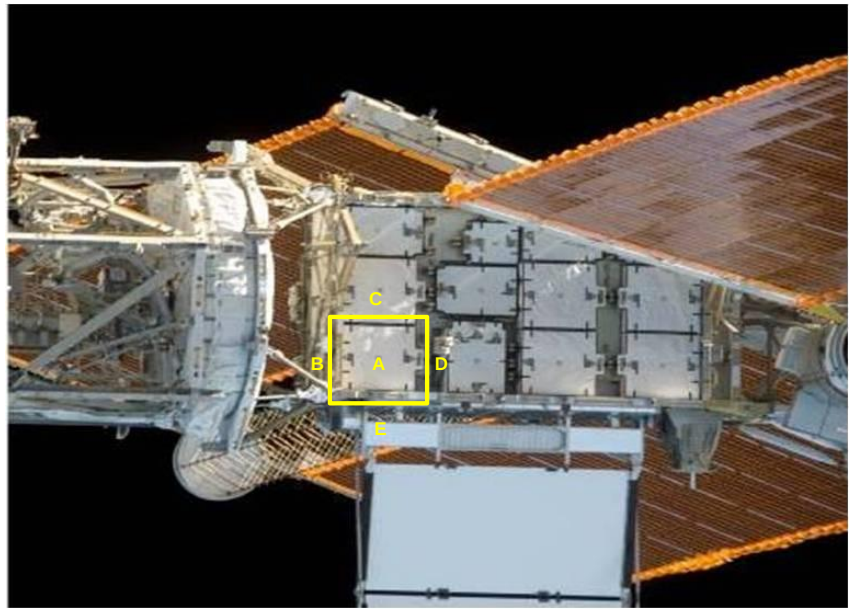


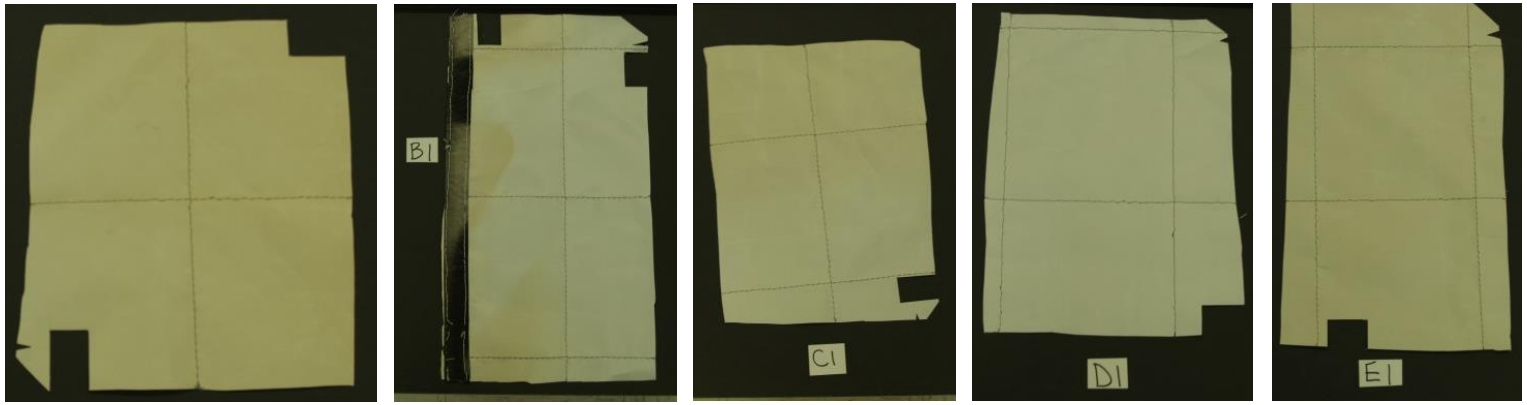
β-Cloth on S1005 Experiment Tray B10

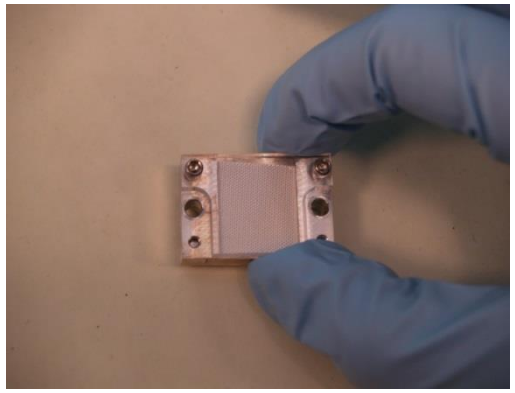
R.C. Linton, A.F. Whitaker, and M.M. Finckenor, "Space Environment Durability of Beta Cloth in LDEF Thermal Blankets", *LDEF Materials Results for Spacecraft Applications*, NASA CP-3257 (1994), 31-45.

Sampling the ORU

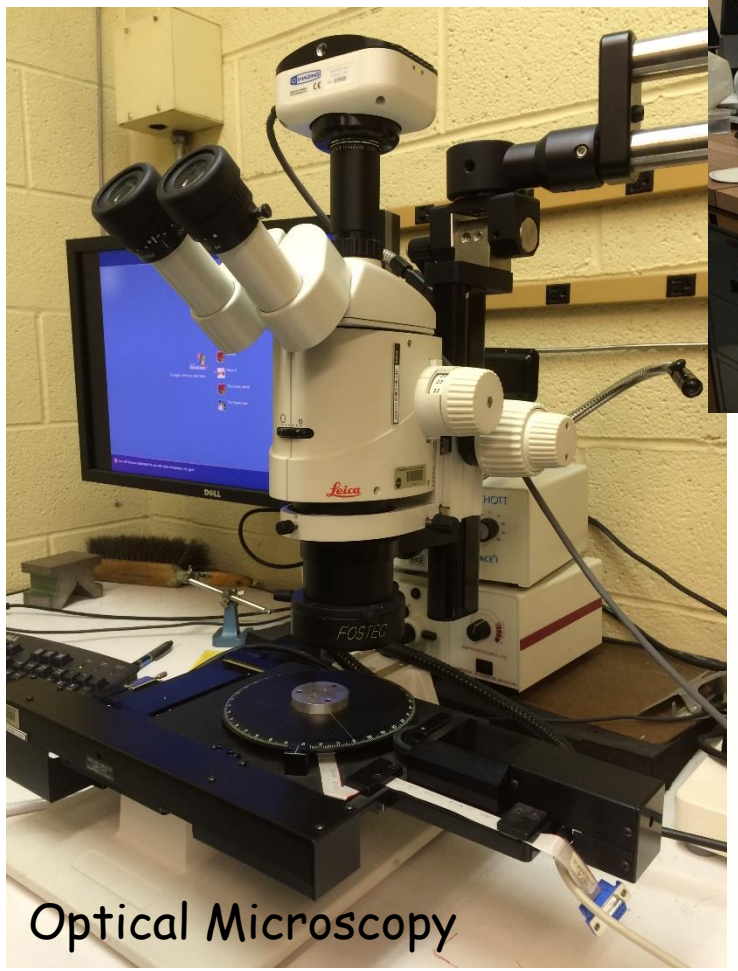
- **ORU sampled before being put in storage**
  - Sections about 0.5 m cut from each of 5 exposed sides
  - Samples about 4 cm cut out for analysis
  - After spectroscopy, 1.7 cm sectioned mounted for imaging, SEM
- **No ISS orientation information was provided**
  - "A" face obvious because of shape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

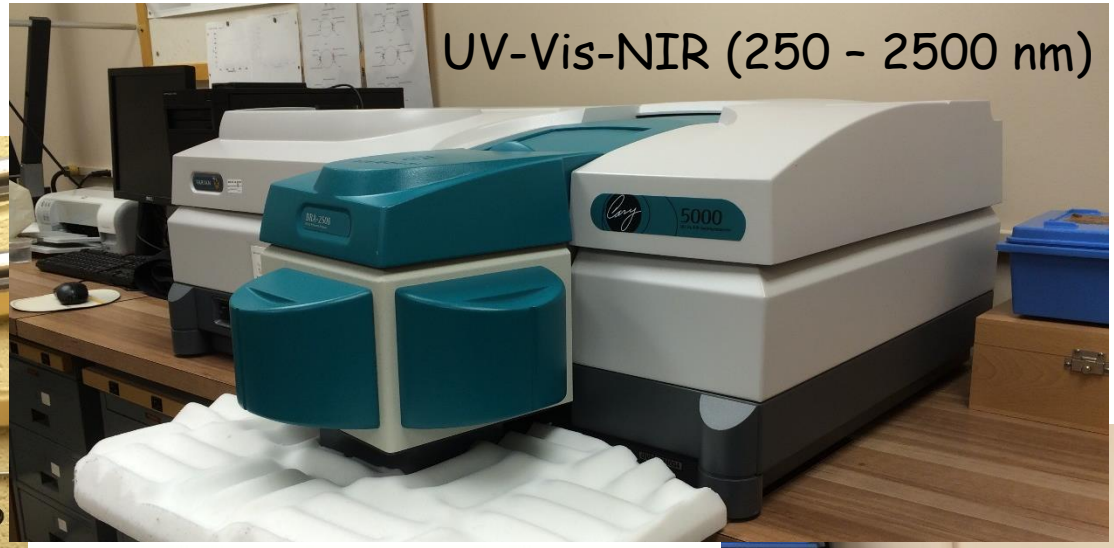




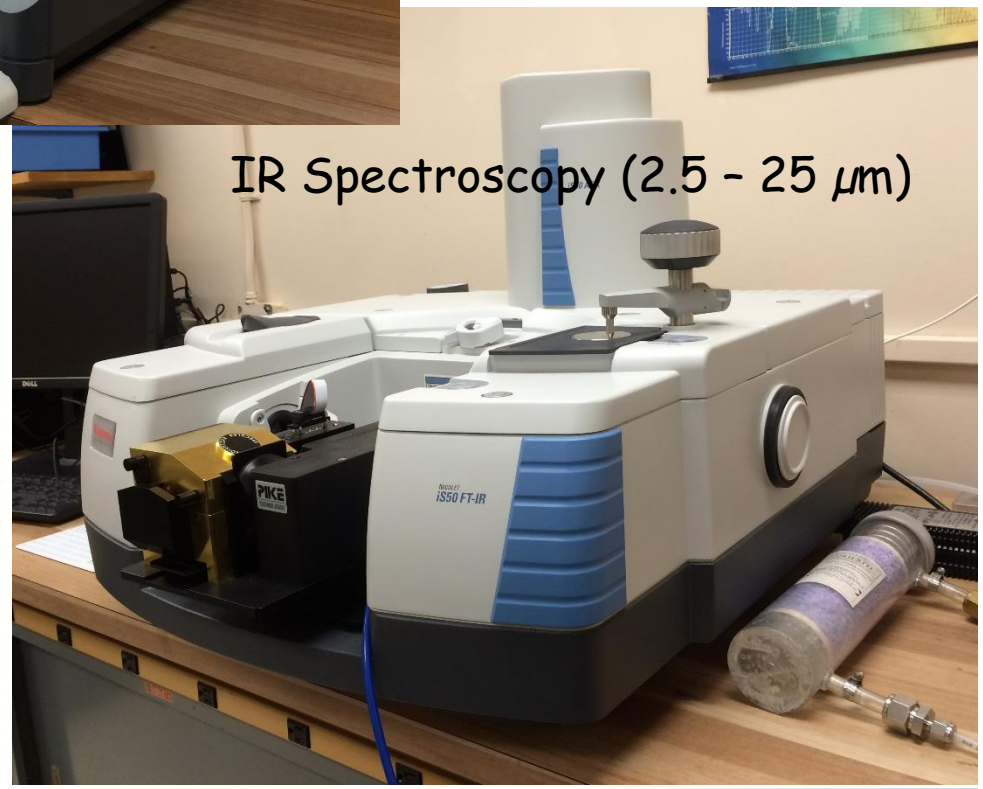


Analysis


Optical Microscopy

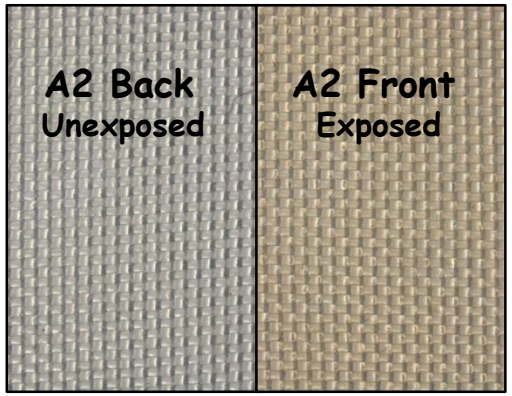

UV-Vis-NIR (250 – 2500 nm)

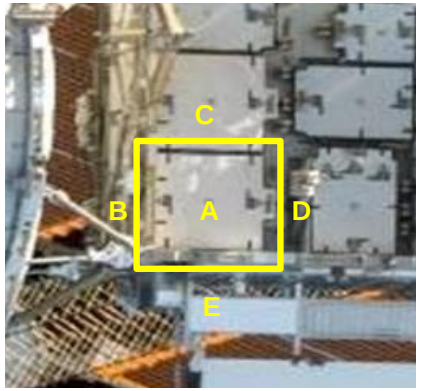
FESEM & EDS


IR Spectroscopy (2.5 – 25 μm)

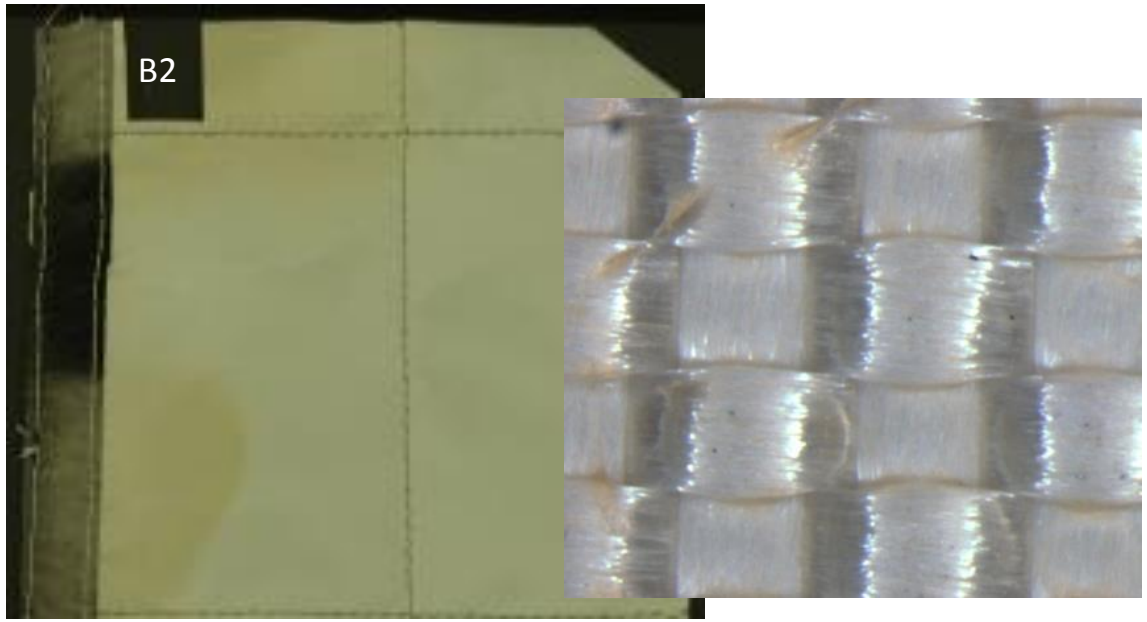
Optical Microscopy

- **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**



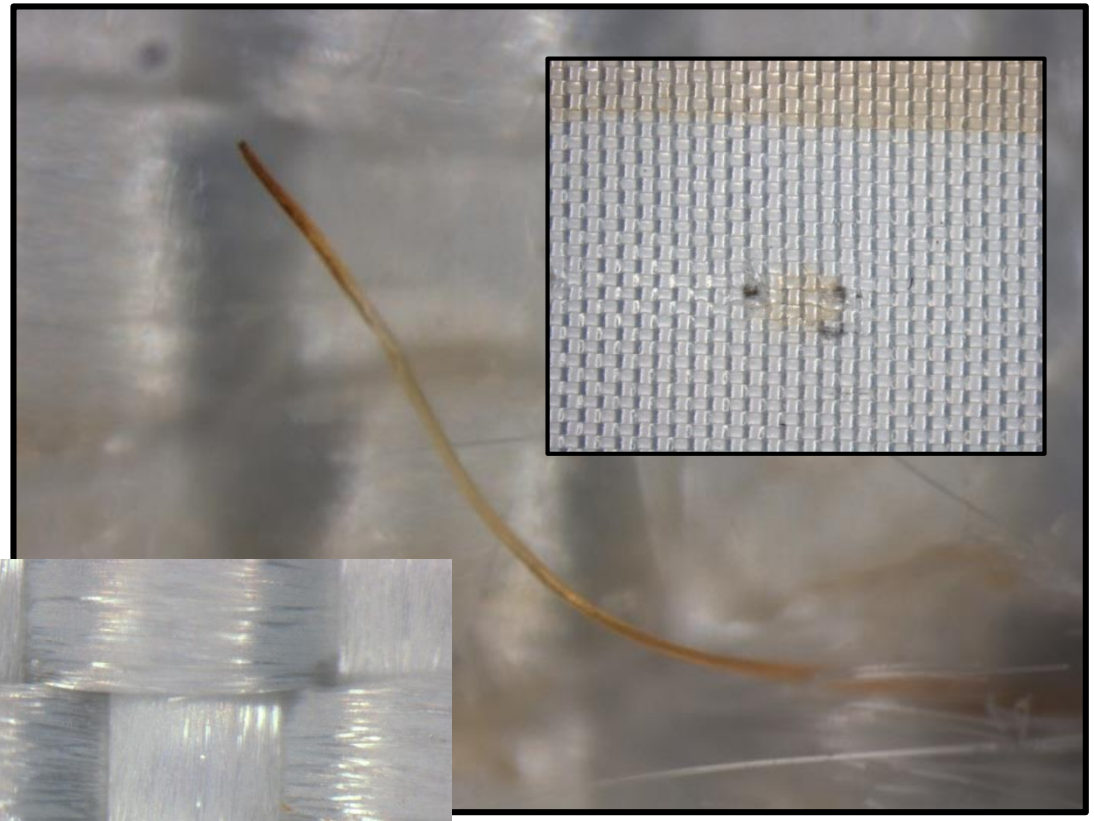


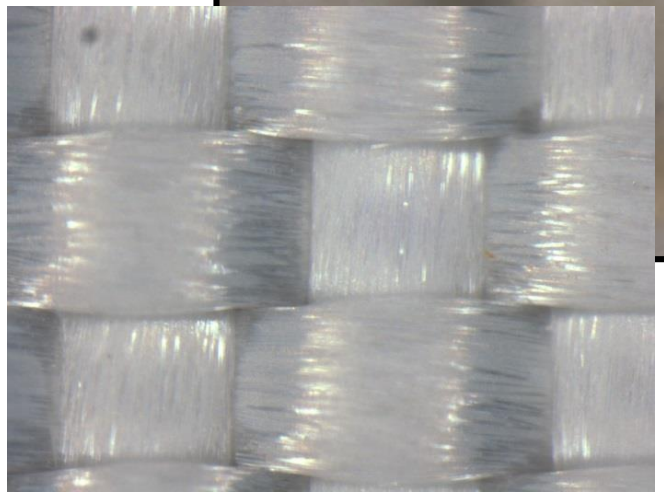
LDEF results indicated a darkening of β-cloth
Attributed to AO texturing of PTFE
Glass fibers were not released



Optical Microscopy of Exposed Fibers

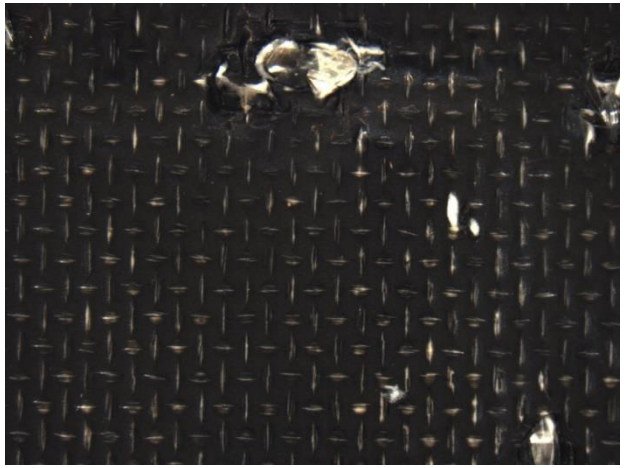
- **Sections of β-cloth were sewn together**
  - Stitching pulled some fibers out of PTFE
- **Exposed fibers darkened dramatically**
  - Fused silica fibers do not darken
  - Fiberglass containing metals does
- **Experimentally verified in ground tests**
  - Sample of C1 exposed to AO in hyperthermal asher
  - PTFE oxidized away
  - UV in asher did not darkened fibers
  - Fiber darkening probably due to high energy particle radiation

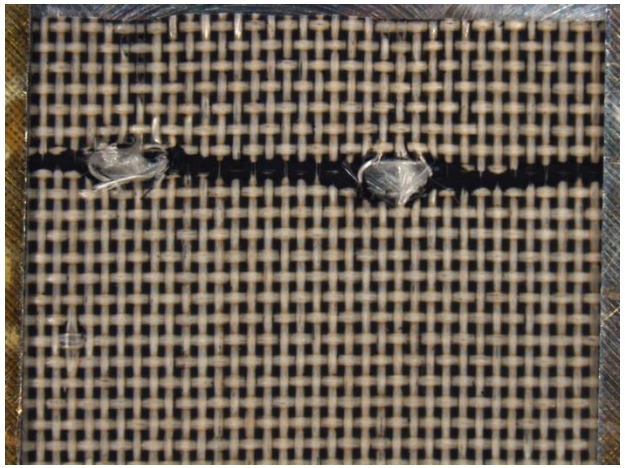




Thanks to B.A. Banks (SAIC) for asher test.

Optical Microscopy of Black Trim





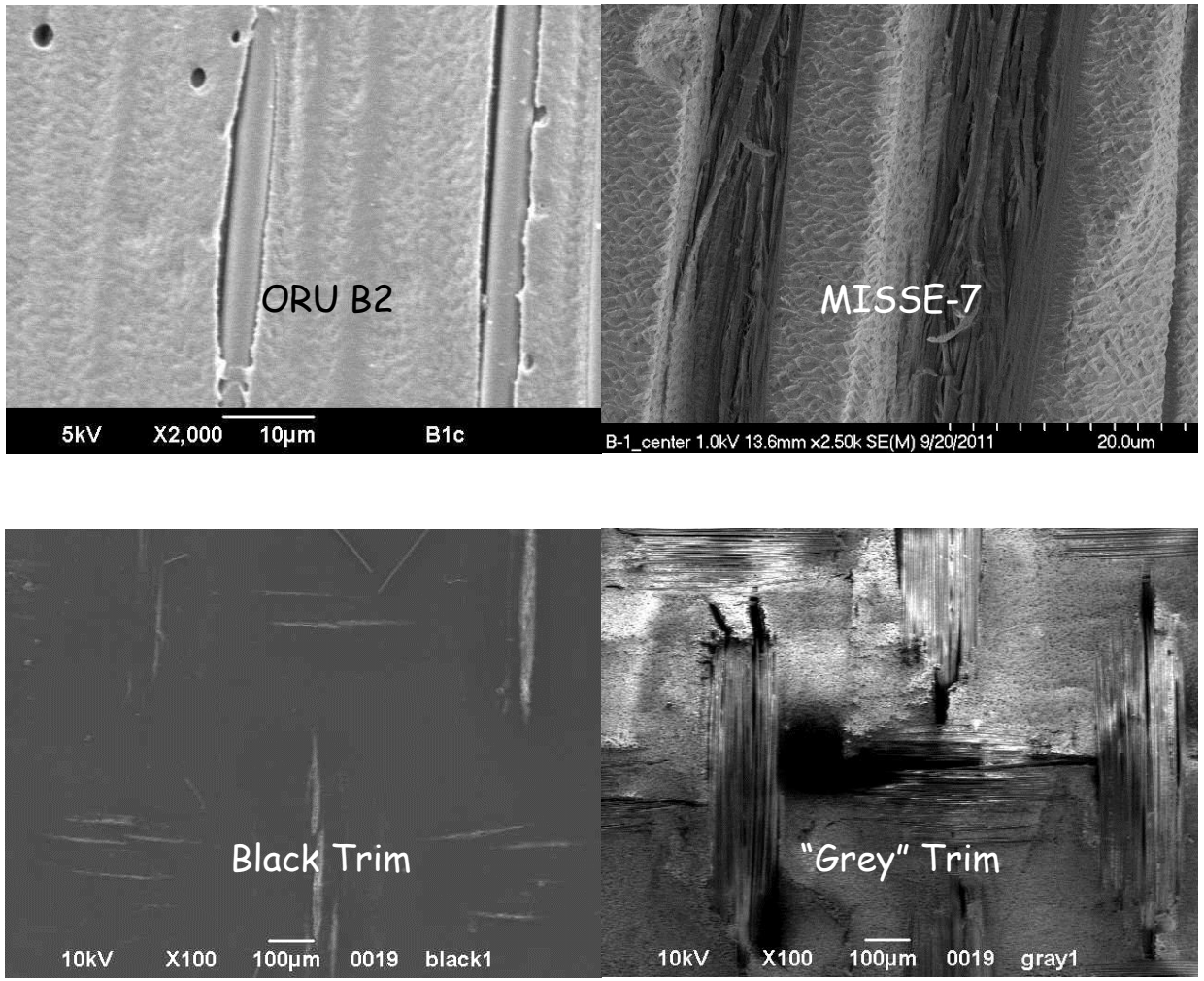
- **Microscopy shows upper black layer eroded**
  - Black layer contains carbon black
  - "Grey" areas missing top layer
  - Lighter color due to exposed fibers
  - Black pigment remains between fibers
- **Darkened area adjacent to grey**
  - Darkened areas eroded also

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

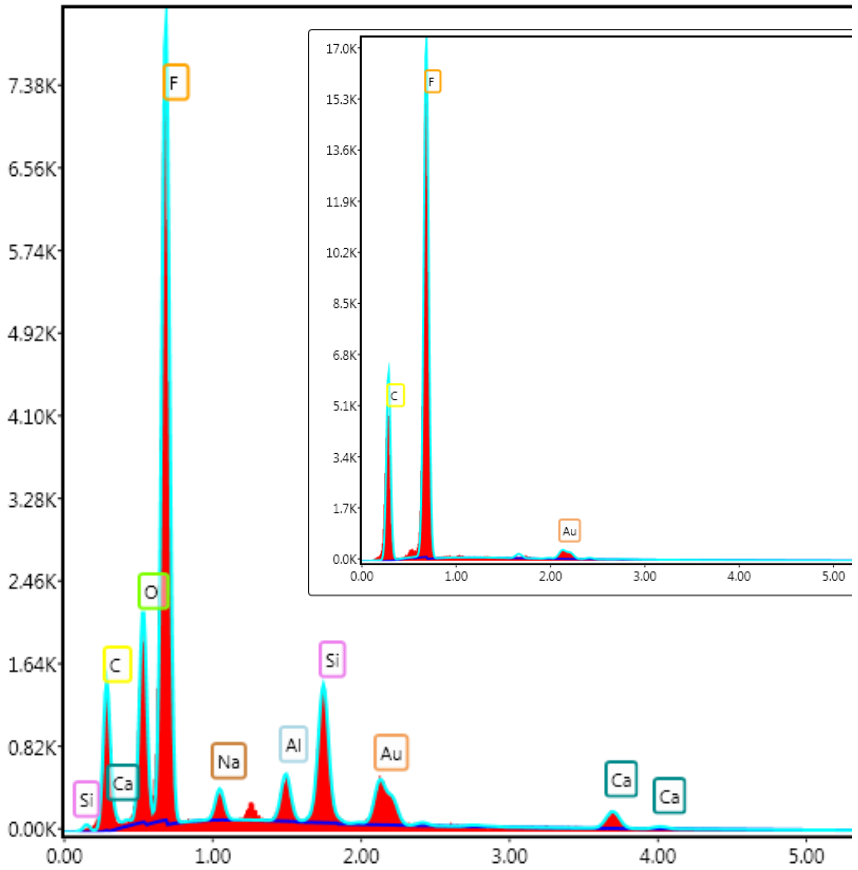
- **Black ORU trim**
  - Black areas show little erosion
  - Grey areas show much erosion

LDEF results indicated erosion of PTFE
Glass fibers were not released



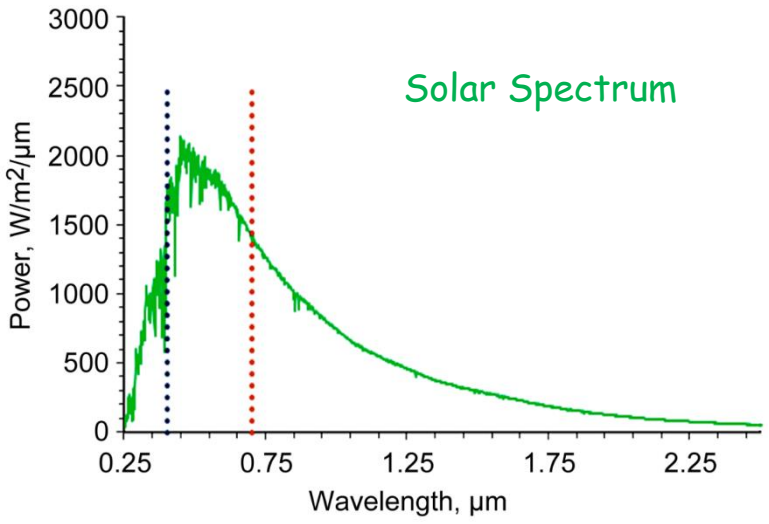
Energy Dispersive Spectra of ORU

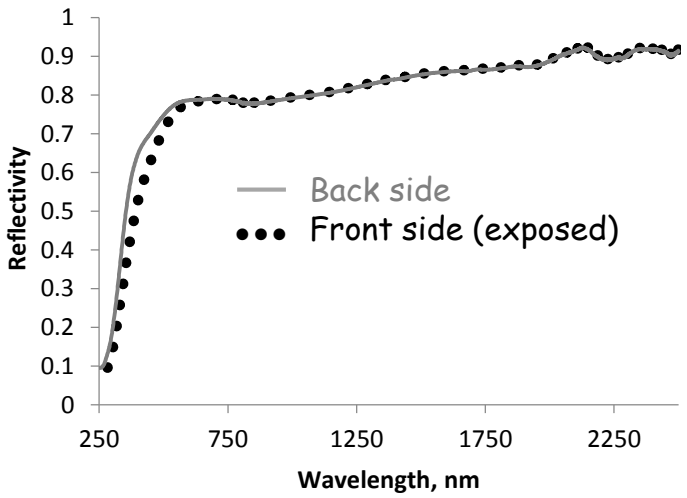
- **No evidence of contamination from external sources**
- **Areas of minimal erosion**
  - 277 eV (C)
  - 677 eV (F)
  - Expected in the PTFE coating $(C_2F_4)_n$
- **Areas where fibers were exposed**
  - 525 eV (O)
  - 1740 eV (Si)
  - Small peaks at 1040 (Na), 1486 (Al), and 3690 eV (Ca)
  - Expected 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

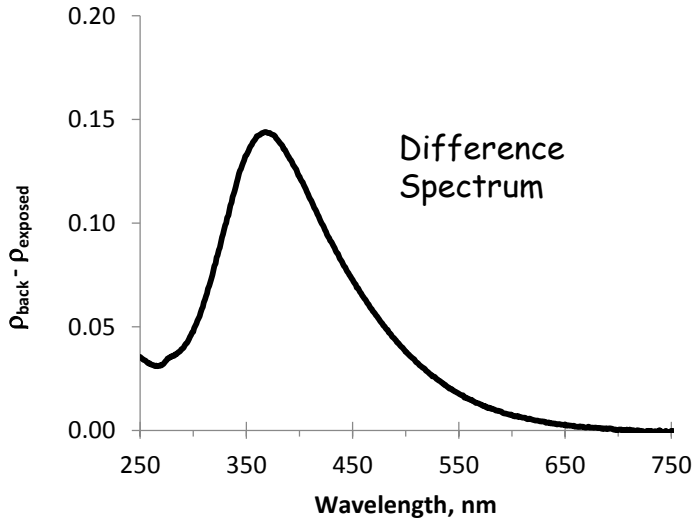


UV-Vis-NIR Spectroscopy

- **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

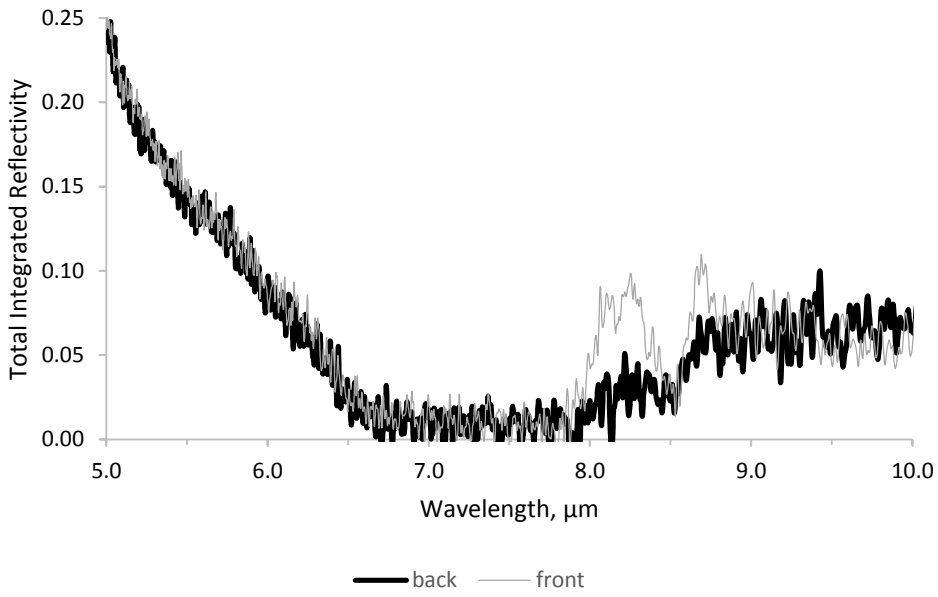
- **Total solar absorptance (α) calculated from spectral reflectivity (ρ(λ))**
  - $\alpha(\lambda) = (1-\rho(\lambda))$
  - $\alpha = \sum_{\lambda=250\,nm}^{2500\,nm} \alpha(\lambda)$
- **Back side α was 0.248 ± 0.005, with a range of 0.015**
  - Front side α was 0.267 ± 0.020 with a range of 0.018
  - Front/Back → average α increased 7.7 < 1%
  - If Front/Back under trim → average 44%
    - As high as 61%
- **The α of black trim decreased**
  - Black pigment lost
  - Leaves more reflective fibers exposed
- **Ionizing radiation increases α → over time spacesuits will need more cooling**

	α_{back}	α_{front}	$\alpha_{front/back}$	$\alpha_{front/under\ back}$
D1	0.247	0.246	1.00	1.33
B1	0.240	0.242	1.01	1.30
C1	0.246	0.253	1.03	1.36
E1	0.255	0.277	1.09	1.49
B2	0.251	0.275	1.10	1.48
A1	0.246	0.274	1.11	1.48
A2	0.253	0.299	1.18	1.61
Black	0.963	0.939	0.98	
Grey	0.963	0.711	0.74	
Under B	0.186	0.199	1.07	
Under G	0.185	0.221	1.19	

LDEF found α = 0.22 ± 0.02

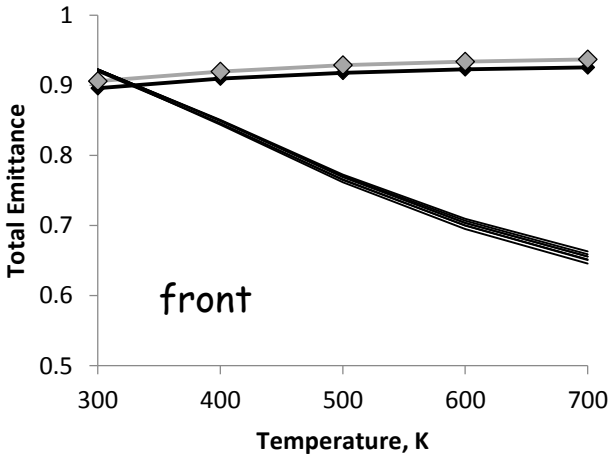
IR Spectra of ORU

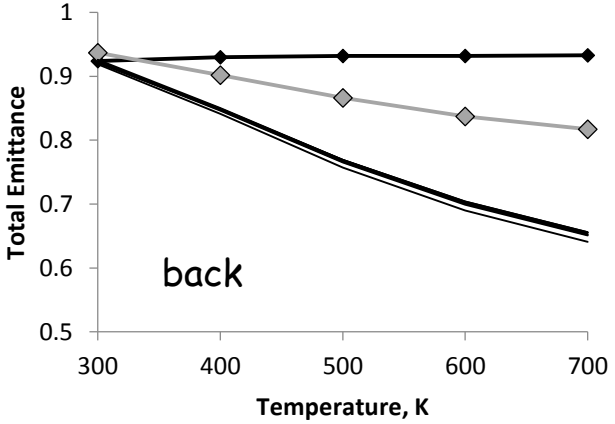
- **Infrared spectra of the backside of the samples were identical**
  - Surfaces not altered by the space environment
  - Or altered by a process not dependent on orientation
  - Or not locally varying environment
    - atomic oxygen exposure
- **Only weak spectral features on exposure side**
  - Peaks 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 (ε) calculated from spectral reflectivity (ρ(λ))**
  - ε(λ) = α(λ) = (1-ρ(λ))
  - $\varepsilon = \sum_{\lambda=2.5\ \mu m}^{25\ \mu m} \varepsilon(\lambda) B(\lambda, T)$
- **The ε of the backside of the samples decreased monotonically**
  - 0.922 ± 0.001 at 300 K to 0.655 ± 0.006 at 700 K
  - Space exposure → no change the ε (Δ < 1%)
- **The ε of black trim increased slightly**
  - 0.901 at 300 K to 0.932 at 700 K
  - Space exposure → big change in ε: 0.937 (300 K) → 0.817 (700 K)
- **On space exposure the ε of the ORU was essentially unchanged**





LDEF found ε = 0.89 ± 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 ε of the ORU was essentially unchanged
  - Confirmed LDEF observation
- Change in thermal properties (α/ε) 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