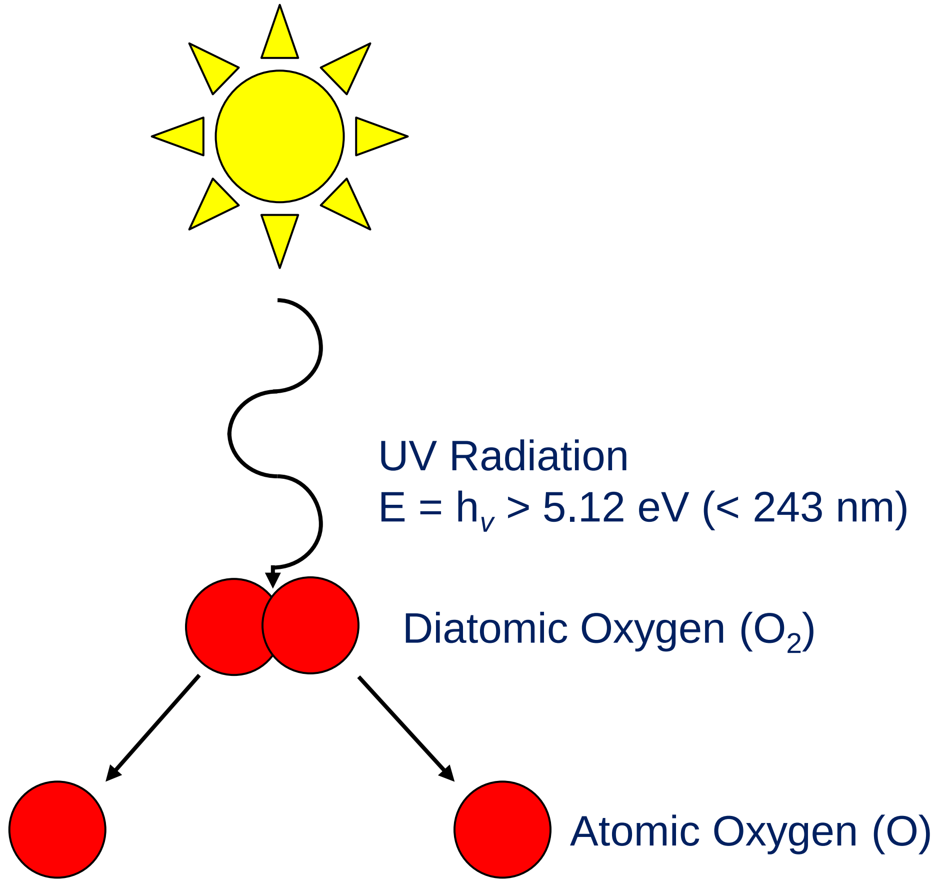
Atomic Oxygen Environment and Effects Overview

Sharon K. R. Miller[1] and Bruce A. Banks[2]

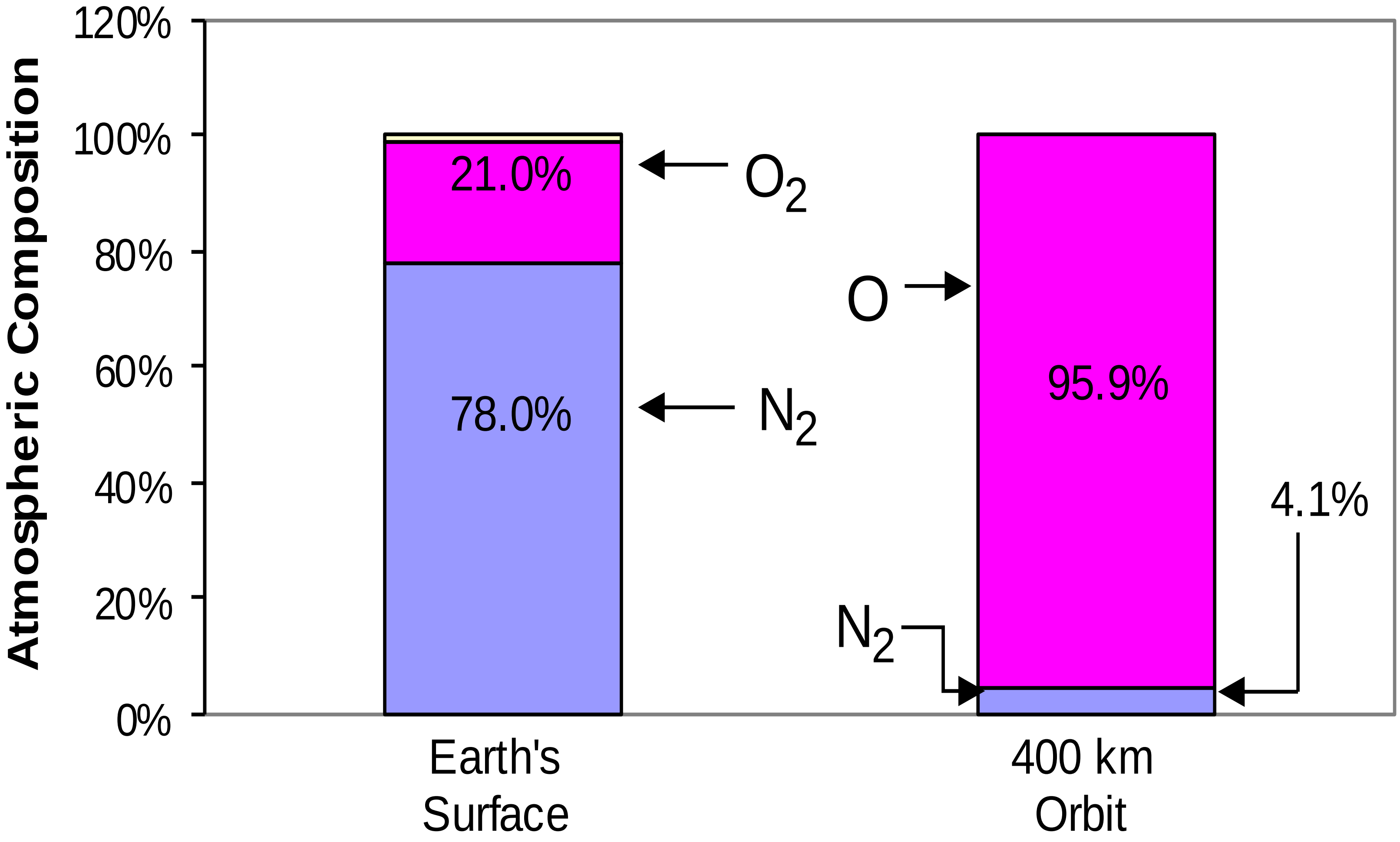
[1]NASA Glenn Research Center, Cleveland, OH 44135
[2]SAIC at NASA Glenn Research Center, Cleveland, OH 44135

Virtual Applied Space Environments Conference
November 1-5, 2021

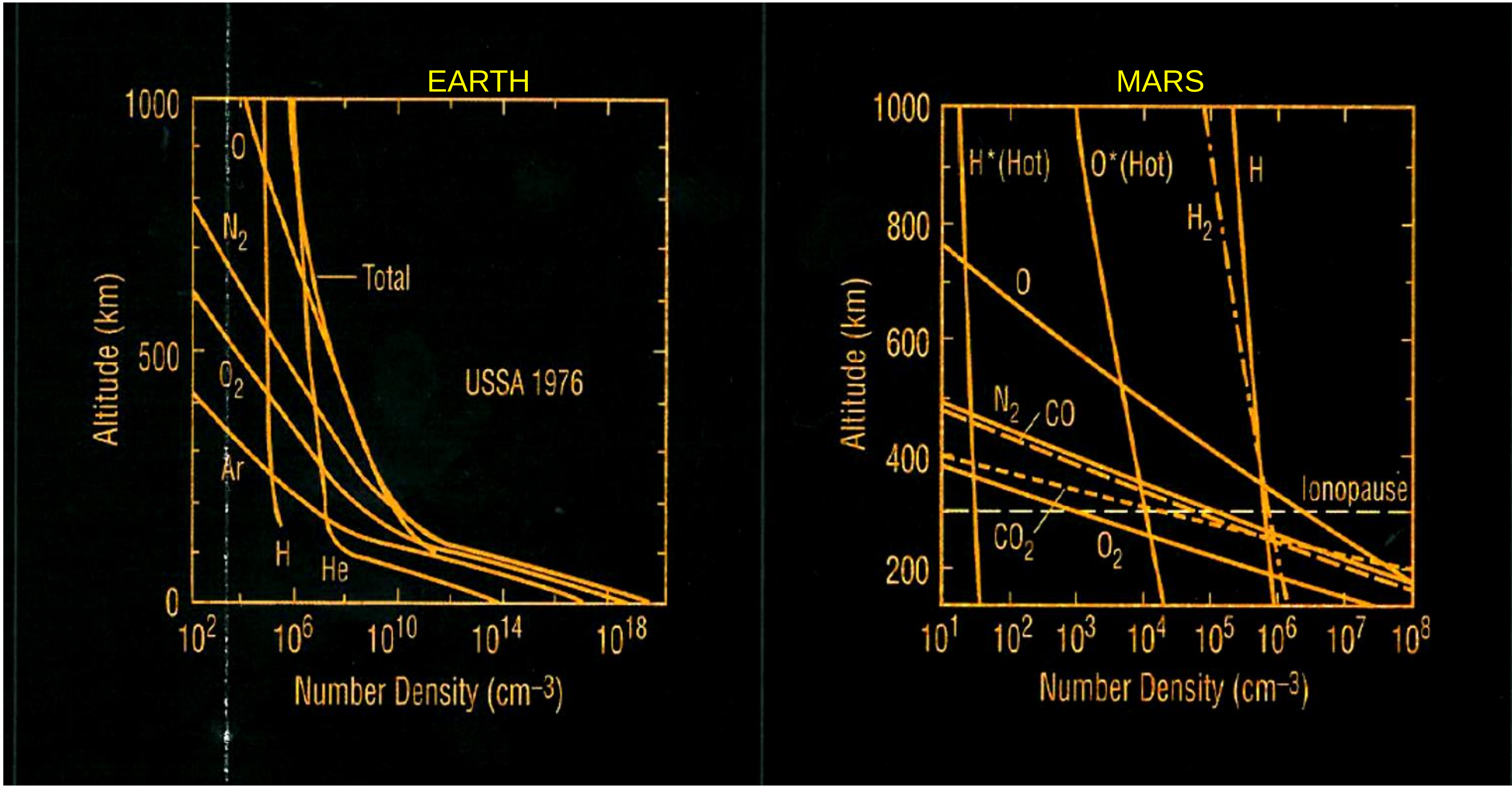
Atomic Oxygen Formation by Photodissociation



Atmospheric Composition



Atmospheric Composition Comparison Between Earth and Mars



Graphs Courtesy of NASA JPL

Composition of Mars Atmosphere

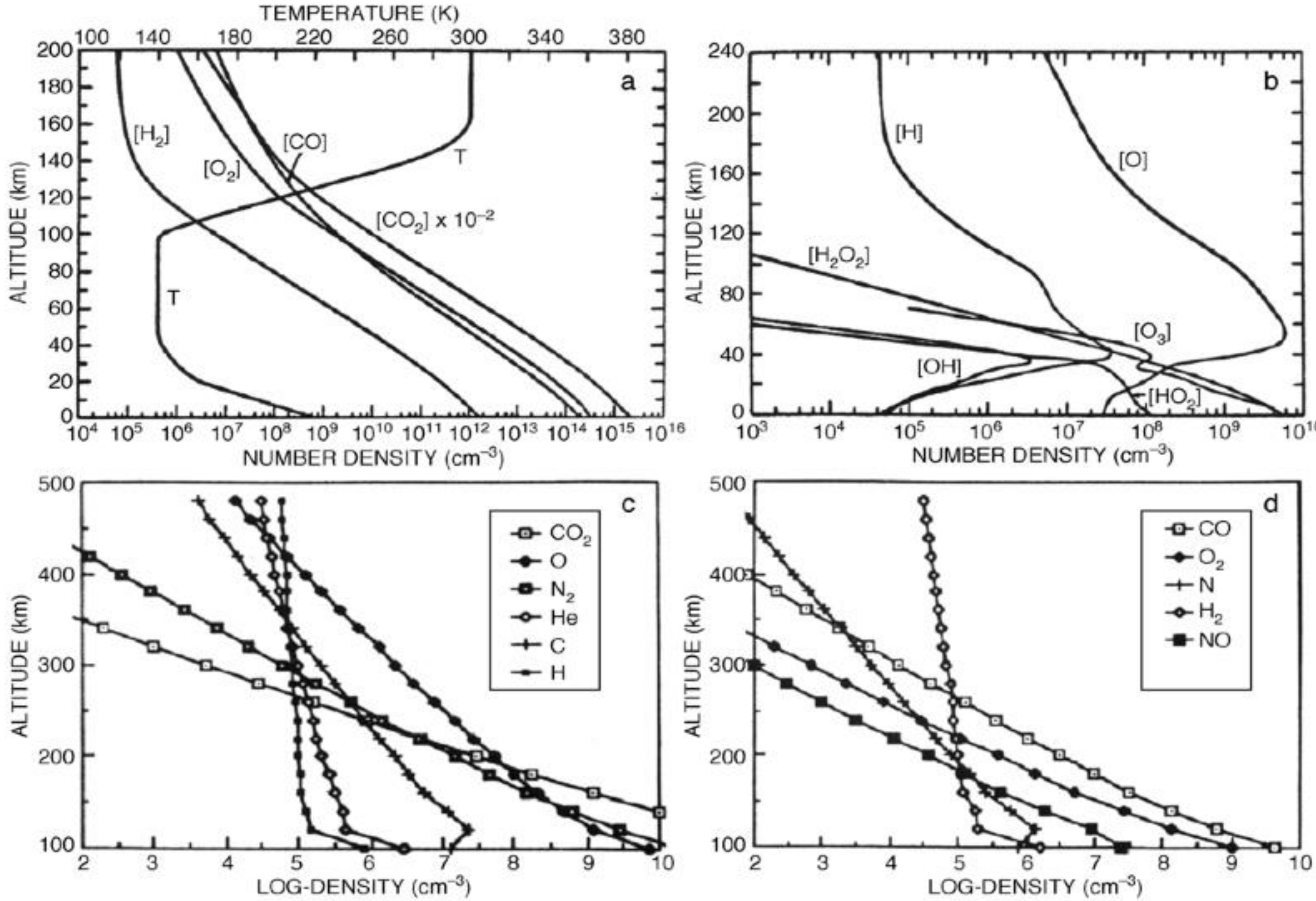
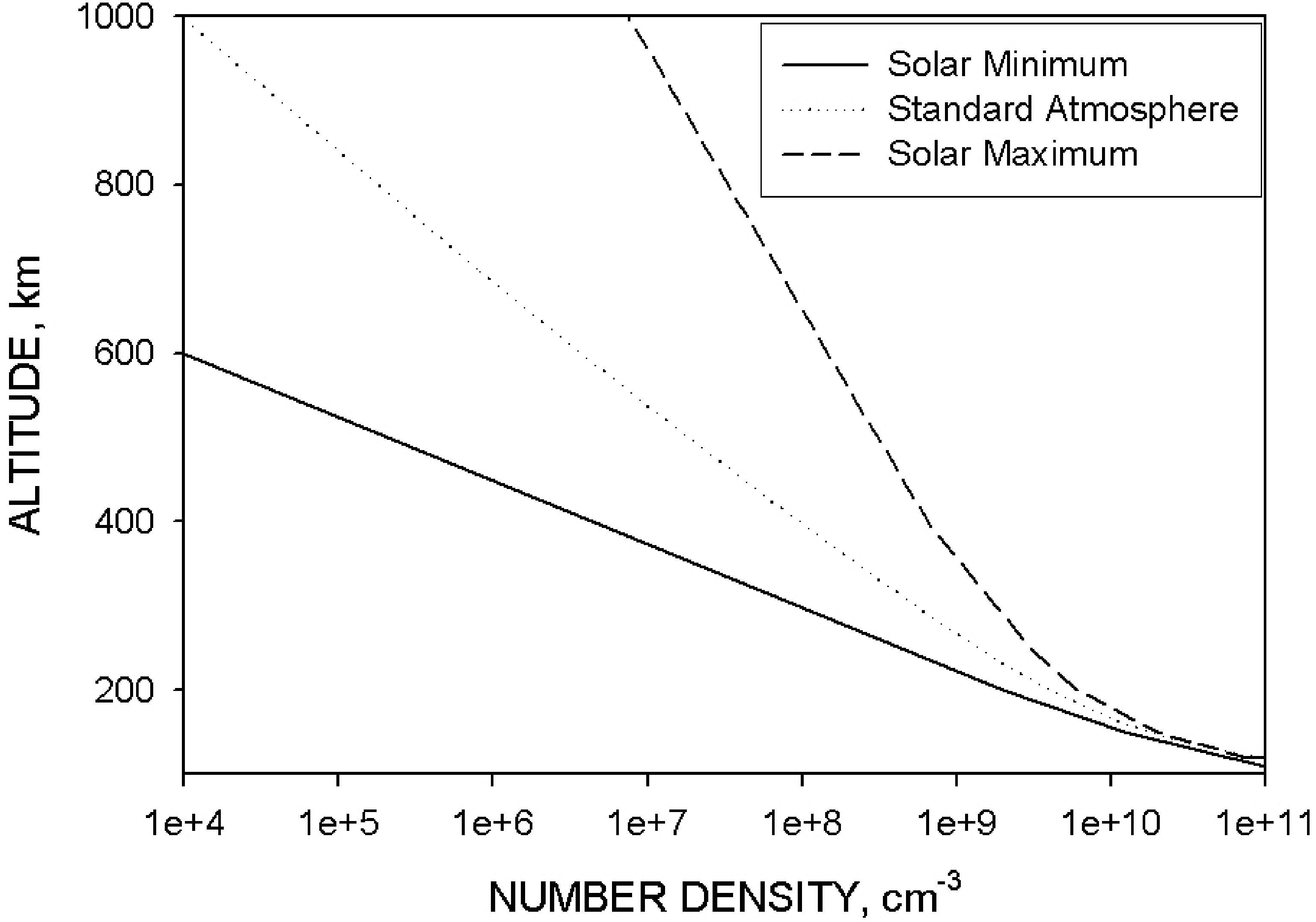


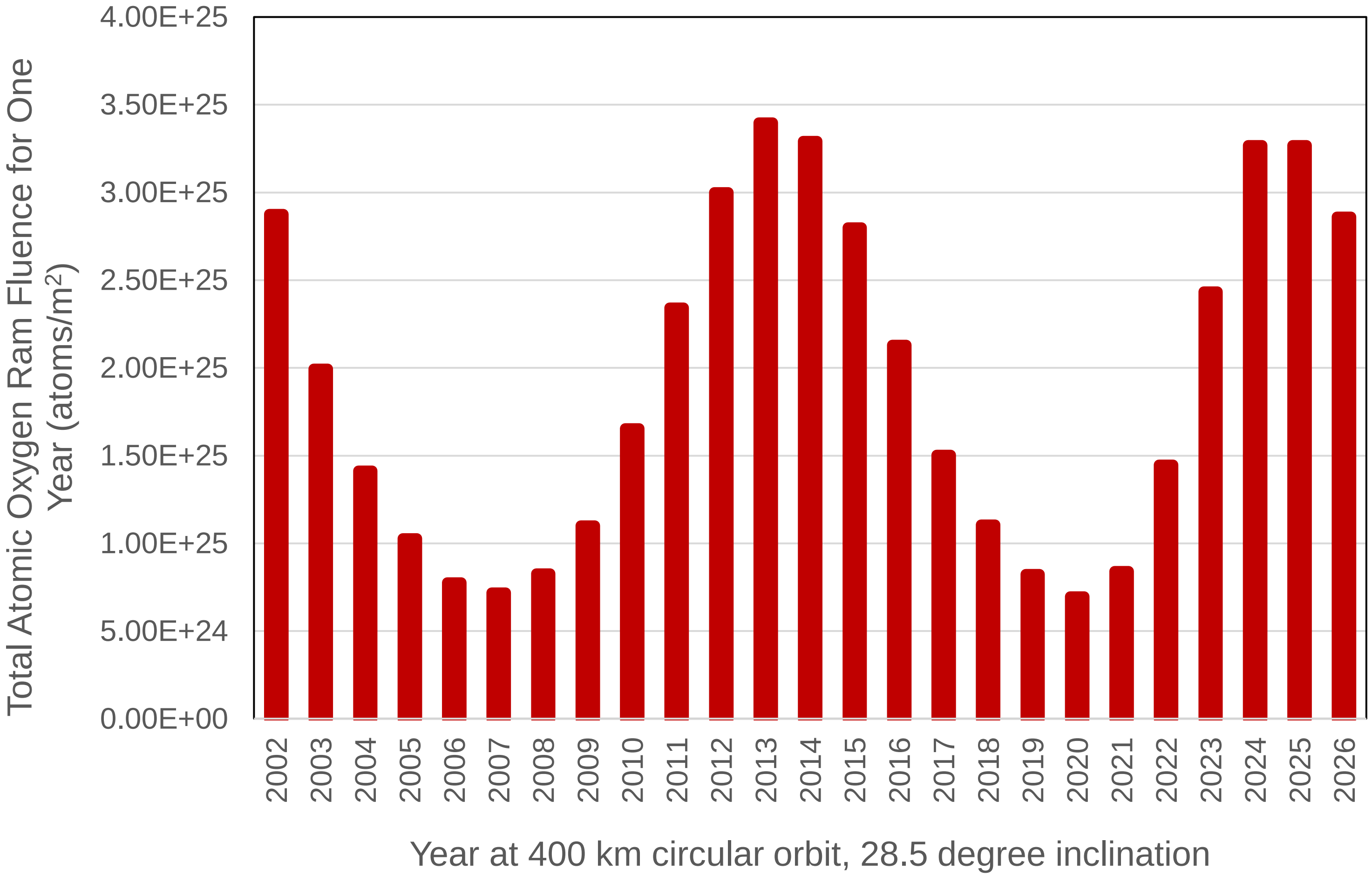
Figure 4-2. Martian Atmospheric Density Profiles for Various Constituents. a) CO_2, CO, O_2, and H_2 in an altitude range between 0 and 200 km, b) O, H, OH, H_2O_2, and O_3 from 0 to 240 km, c) CO_2, O, N_2, He, C, and H between 100 and 500 km and d) CO, O_2, N, H_2, and NO between 100 and 500 km.

Graphs Courtesy of Hank Garrett at NASA JPL

Atomic Oxygen Earth Atmosphere Number Density Dependence Upon Solar Activity

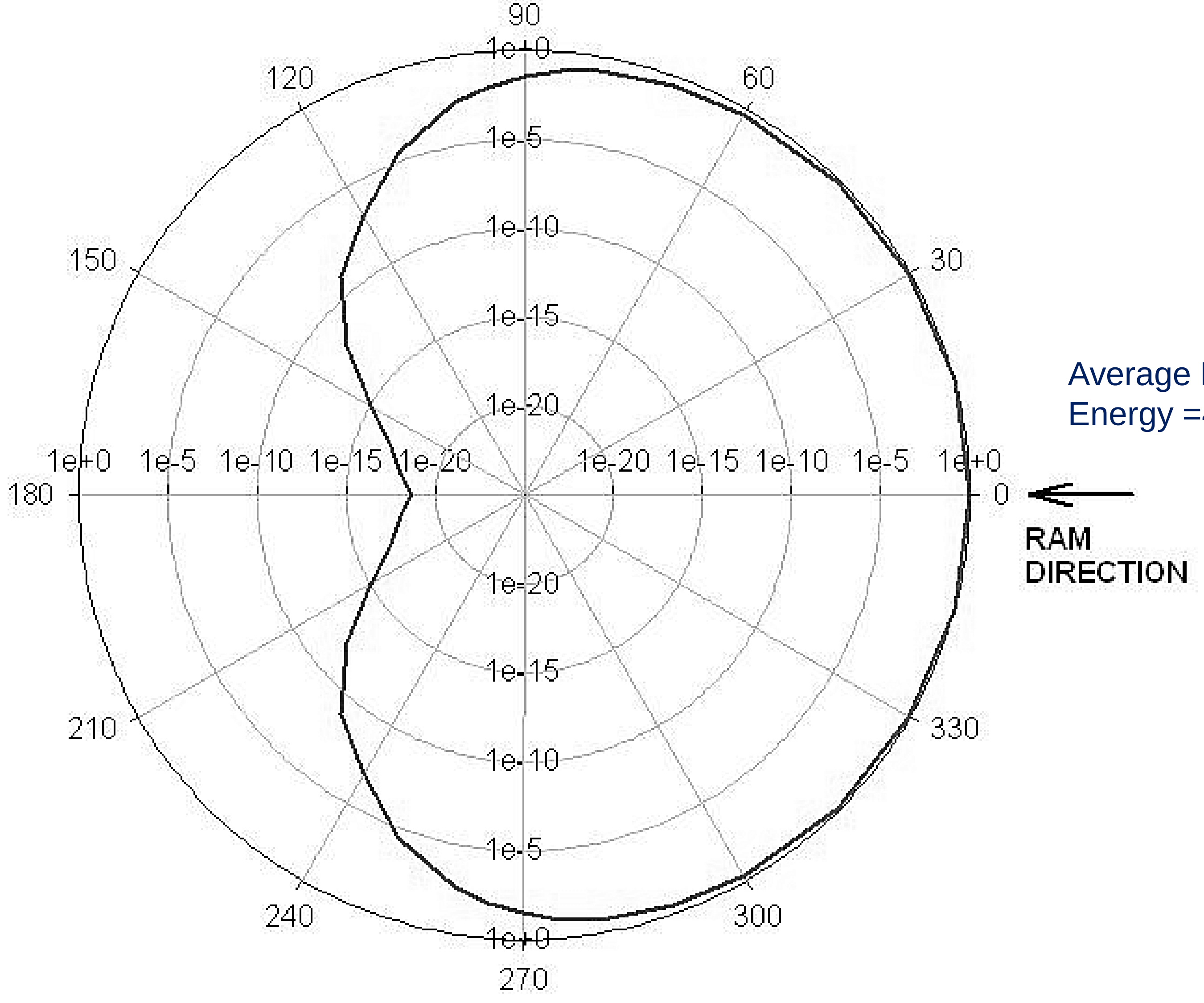


Solar Cycle Caused Variation in Level of Atomic Oxygen in Low Earth Orbit at 400 km



Logarithmic Polar Plot of Atomic Oxygen Arrival Flux

(400 km Earth orbit at 28.5º inclination and 1000 K thermosphere)



Average Ram Energy =4.5 eV

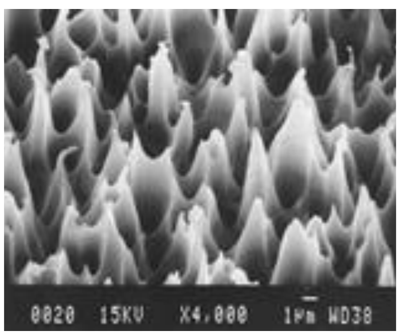
What Can Atomic Oxygen Do to Spacecraft?

Prior to Flight

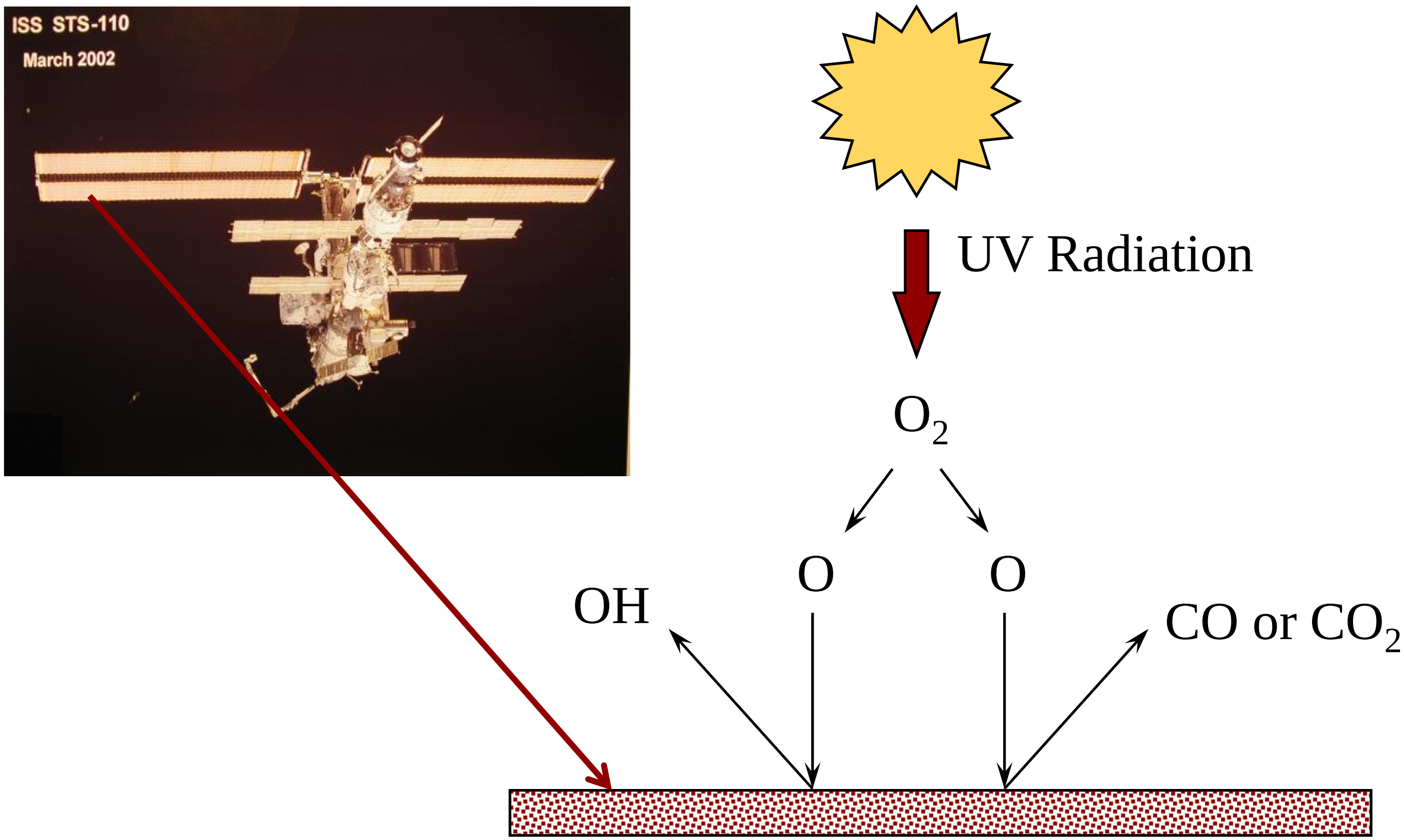
After 5.8 years in LEO

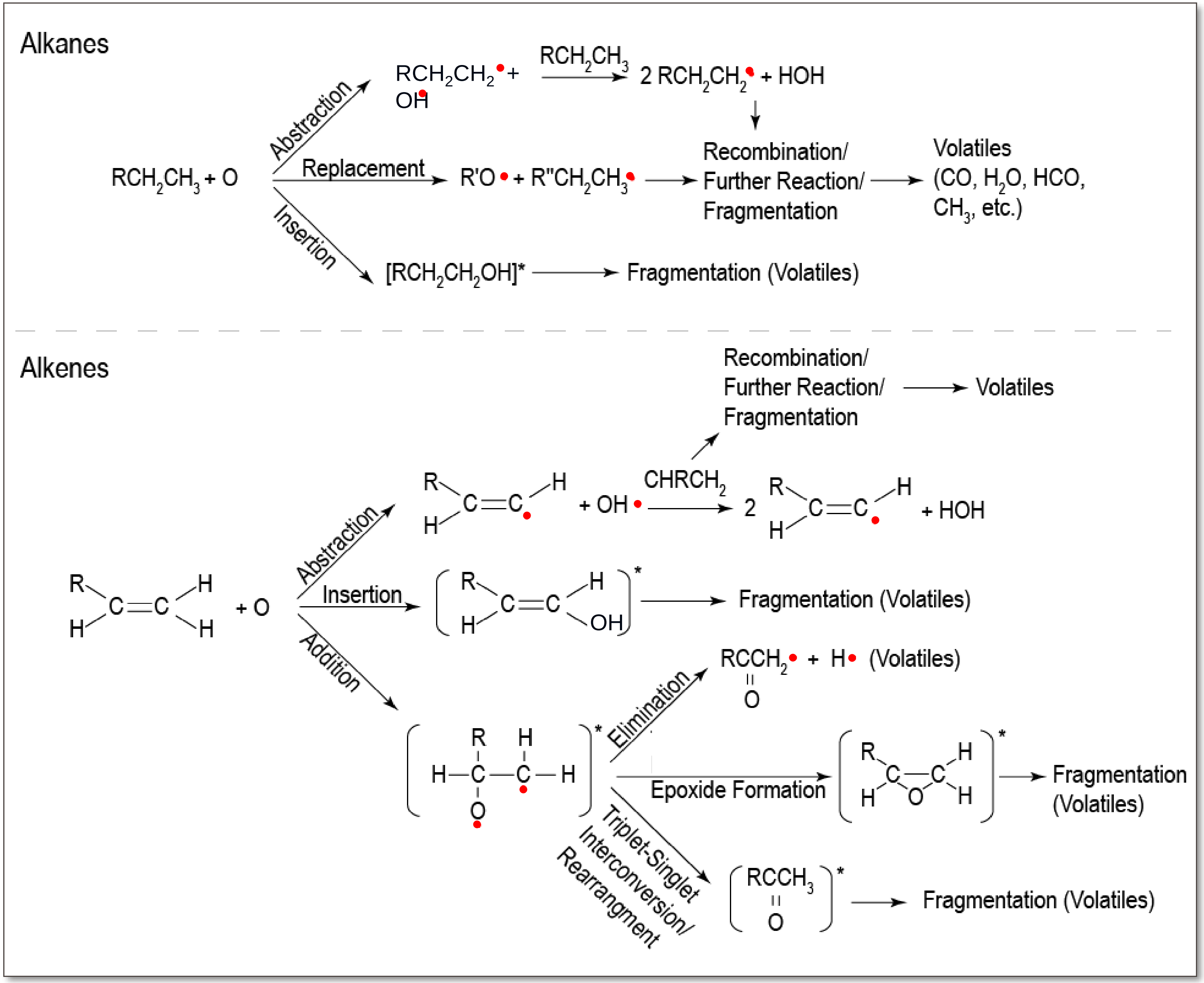
LDEF Spacecraft CTFE after

8.99 x 10^{21} atoms/cm^2



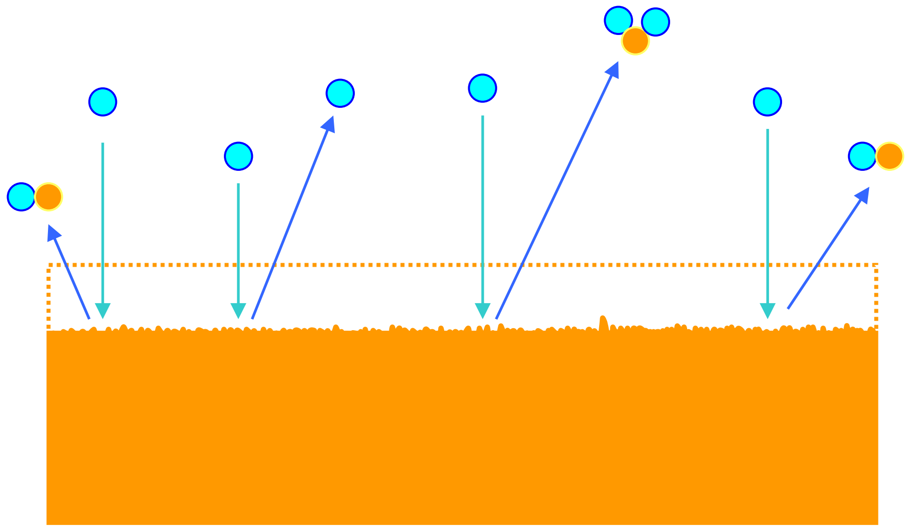
Basic Atomic Oxygen Interaction with Organic Surfaces





de Groh, K. K., Banks, B. A., Miller, S. K. R., and Dever, J. A., Degradation of Spacecraft Materials (Chapter 28) in Handbook of Environmental Degradation of Materials, Myer Kutz (editor), William Andrew Publishing, 2018.

Atomic Oxygen Erosion Yield (E_y)



E_y is the **volume loss** per incident **oxygen atom**

(cm^3/atom)

Ey based on Mass Loss Measurements

Erosion Yield (E_y) of Sample

$$E_y = \frac{\Delta M_s}{A_s \rho_s F_k}$$

where:

- **ΔM_s = mass loss of polymer sample**
- **A_s = area of polymer sample**
- **ρ_s = density of sample**
- **F_k = AO fluence measured by Kapton H witness samples**

Atomic Oxygen Fluence

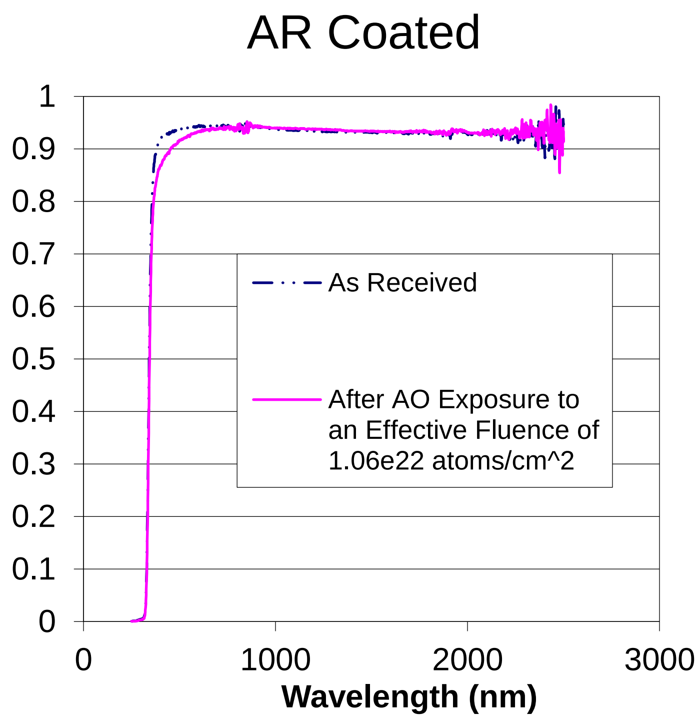
$$F_k = \frac{\Delta M_k}{A_k \rho_k E_k}$$

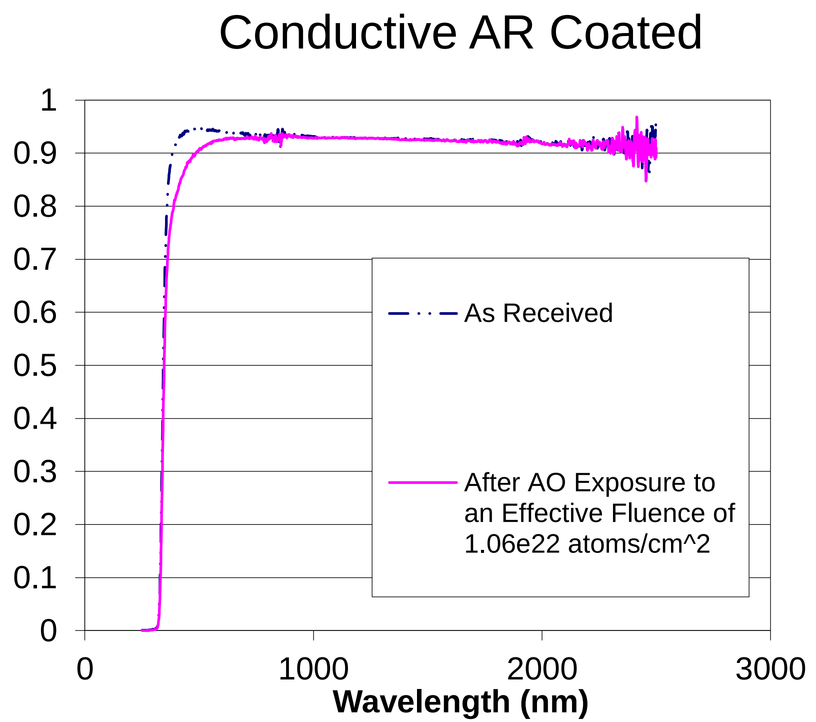
where:

- **ΔM_k = mass loss of Kapton H witness**
- **A_k = area of Kapton H witness**
- **ρ_k = density of Kapton H sample ($1.427\ grams/cm^3$)**
- **E_k = erosion yield of Kapton H ($3.0 \times 10^{-24}\ cm^3/atom$)**

Chart From Kim K. de Groh, NASA GRC

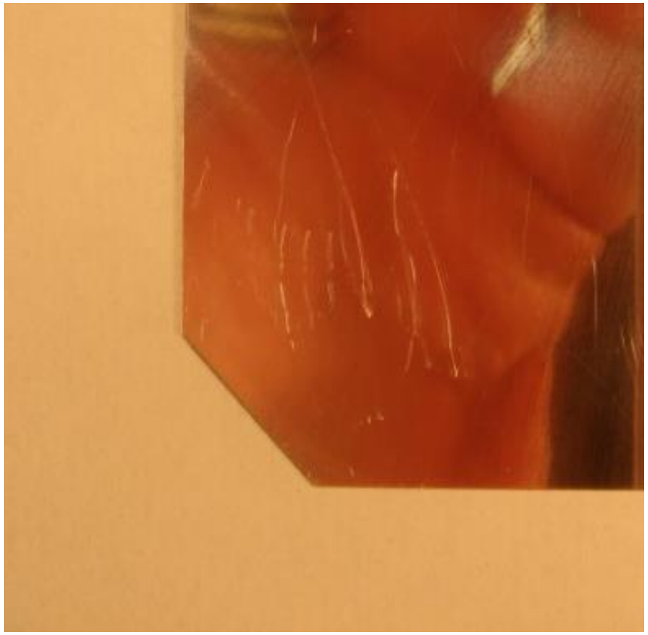
Total Transmittance as a Function of Wavelength for Coverglass Prior to and After Exposure to Atomic Oxygen



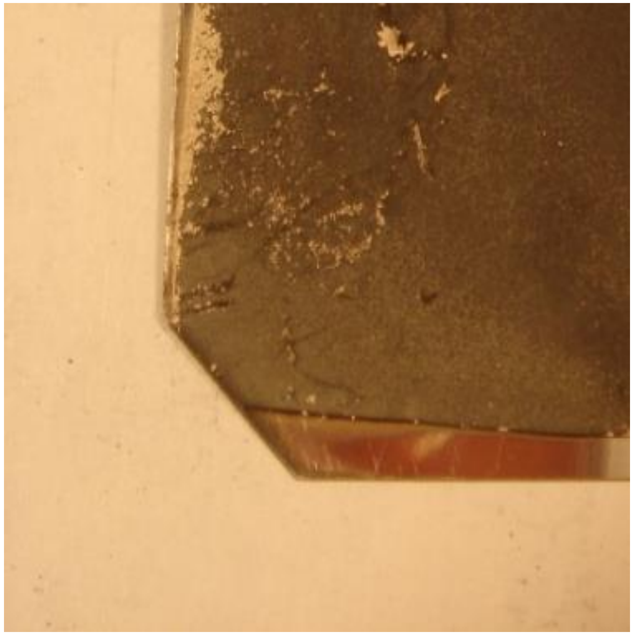


Mirrored Silver Back of Solar Cell Prior to and After Exposure to Atomic Oxygen

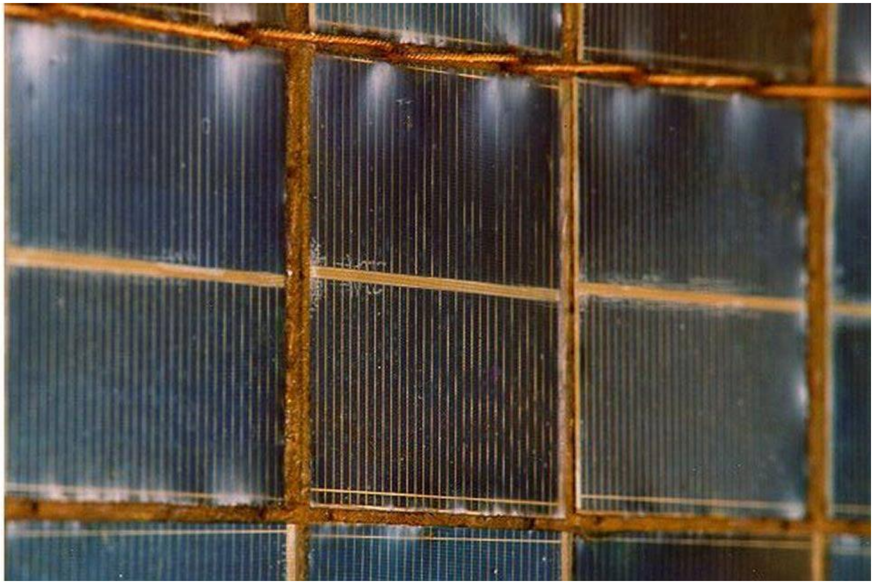
As Received



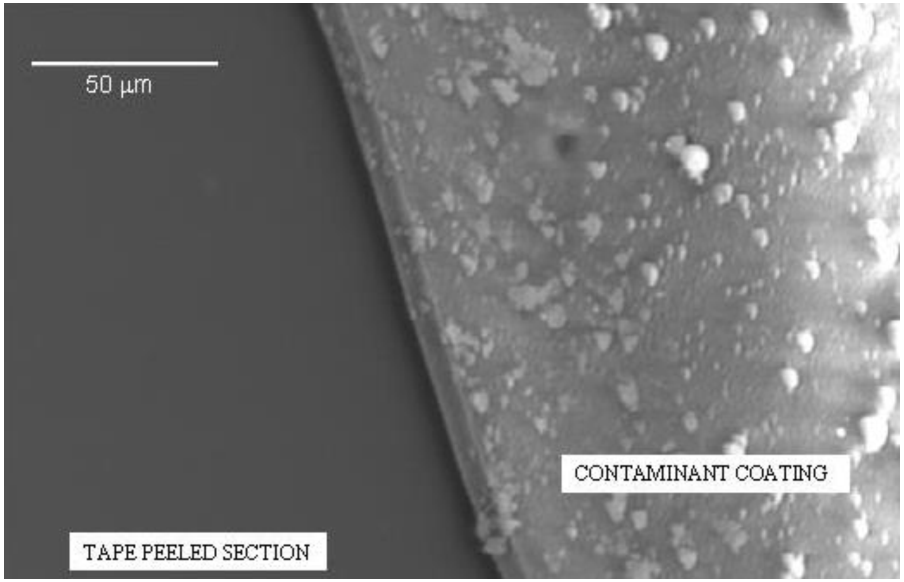
After Exposure to an AO Effective Fluence of $2x10^{21}$ atoms/cm^2



Oxidized Silicone Contamination on the MIR Solar Array After 10 Years in LEO



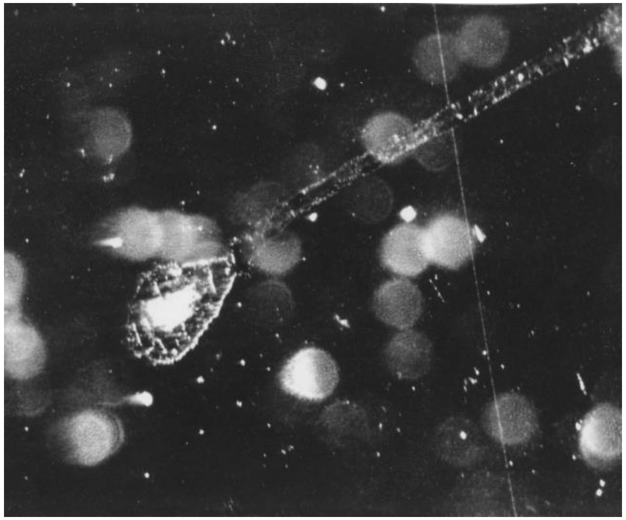
Frosty deposits on solar cell cover glasses



~ 4.6 micron thick silica deposits

Oxidative Cracking of Silicone

DC 93-500 Silicone
Exposed to LEO Atomic Oxygen on STS-46
Fluence = 2.3×10^{20} atoms/cm^2



Pre-flight

Post-flight

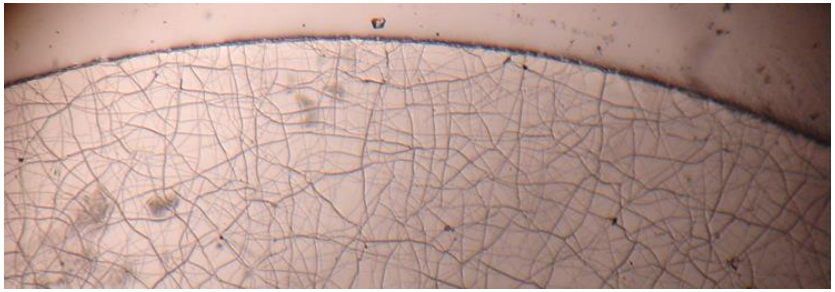
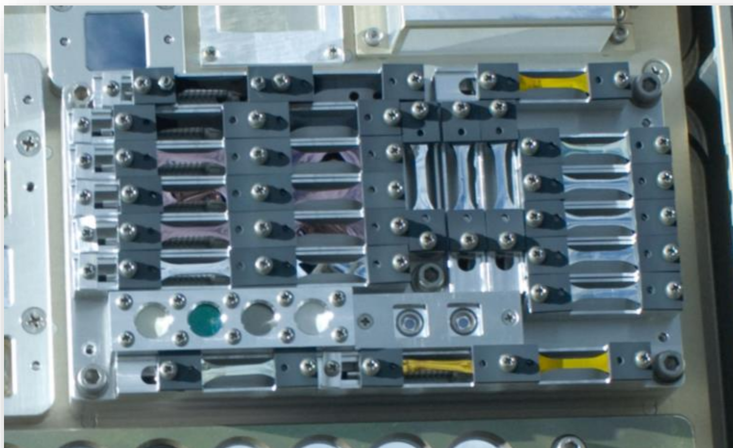


Chart From Kim K. de Groh, NASA GRC

Stress Dependent Atomic Oxygen Erosion of Black Kapton XC

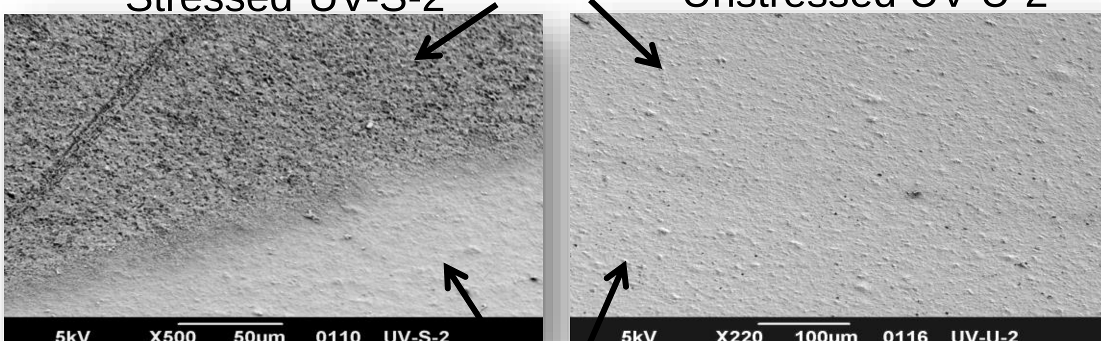
Polymers Exposed Under Stress on Materials International Space Station Experiment (MISSE) 6



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

- Stress level: Force/Area = ~4000psi (2.76e7 N/m^2)
- Strain = Stress/Modulus = 4000 psi/480000 psi (3.3e9 N/m^2) = ~0.008
- For Kapton XC this represents ~3 % of the maximum strain and ~24% of the tensile strength

Stressed UV-S-2 | Exposed | Unstressed UV-U-2



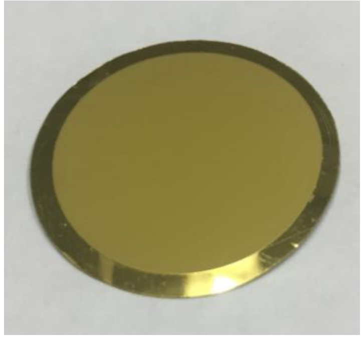
Under Mount

Kapton XC experienced a factor of 4 higher erosion rate under tension

Comparison of Simulated LMO and LEO Atomic Oxygen Erosion

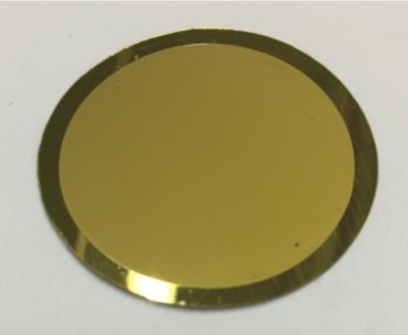
Polyimide (BPDA) – Upilex

Pure O_2



5.89E20 atoms/cm^2
Erosion yield = 2.37E-24 cm^3/atom

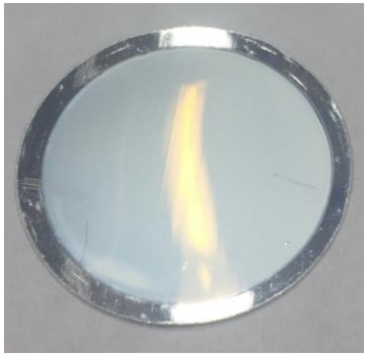
Mars Gas



3.29E20 atoms/cm^2
Erosion yield = 2.55E-24 cm^3/atom

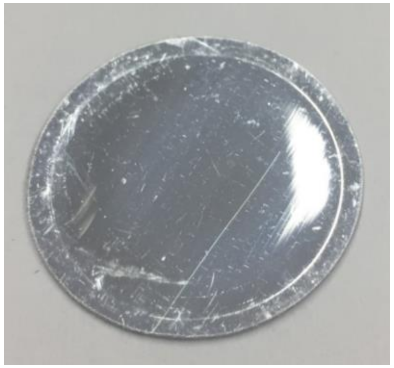
Aluminized Fluorinated Ethylene Propylene – FEP Teflon

Pure O_2



5.97E20 atoms/cm^2
Erosion yield = 4.85E-24 cm^3/atom

Mars Gas

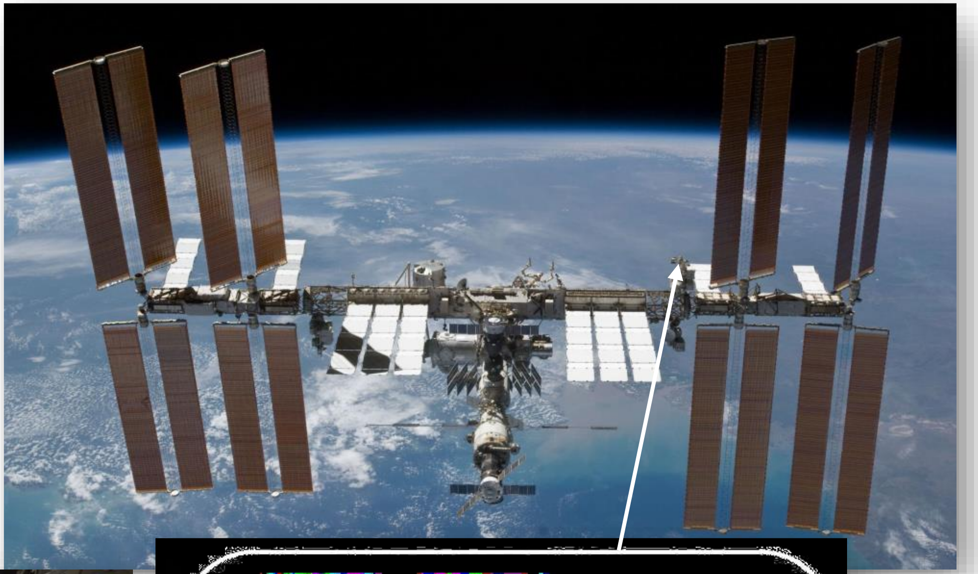


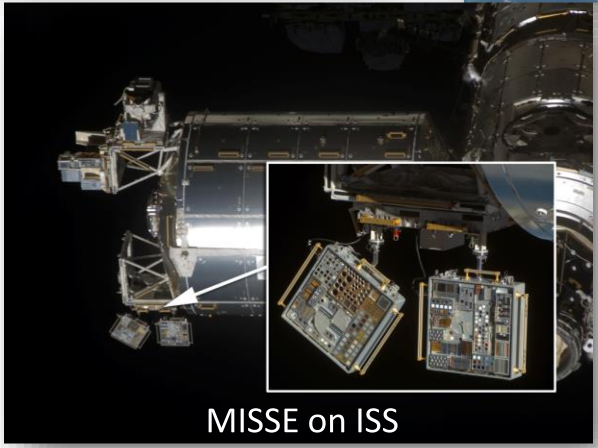
3.41E20 atoms/cm^2
Erosion yield = 4.63E-24 cm^3/atom

Material Tests in Low Earth Orbit (LEO) for Environment Interactions

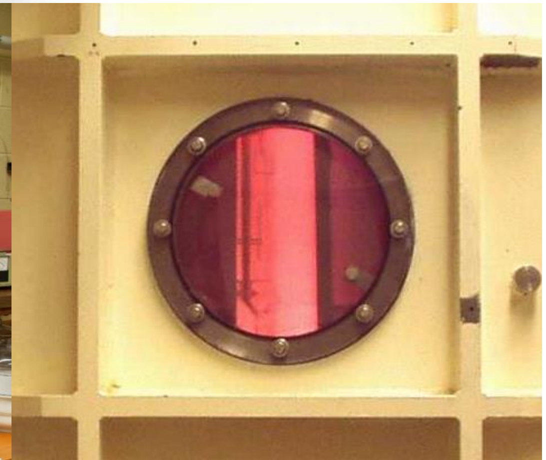
Long Duration Exposure Facility (LDEF)

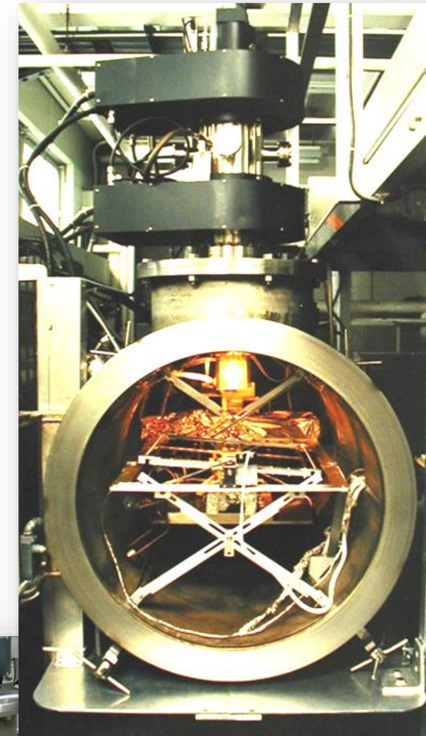
Materials International Space Station Experiment (MISSE)

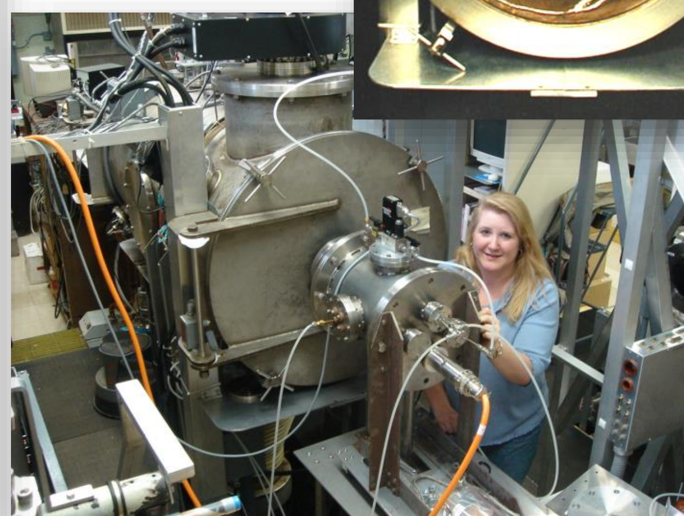




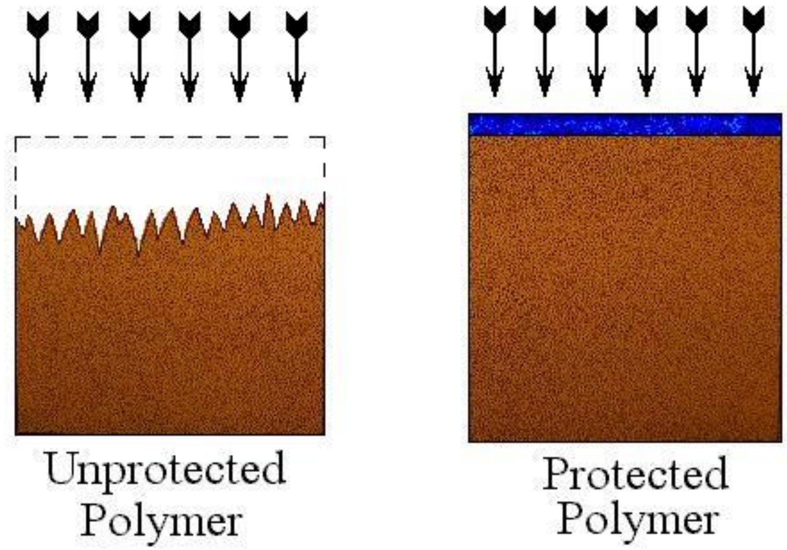
Material Testing in an Atomic Oxygen Environment Using Ground-Based Systems



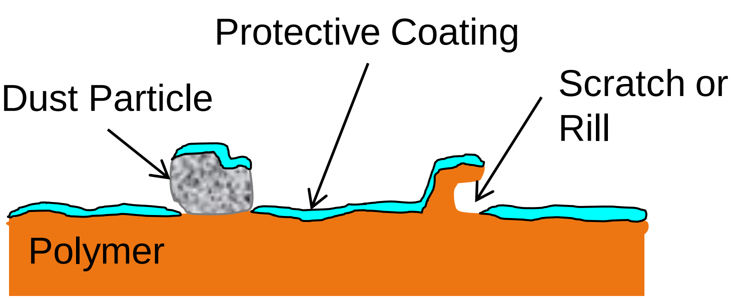




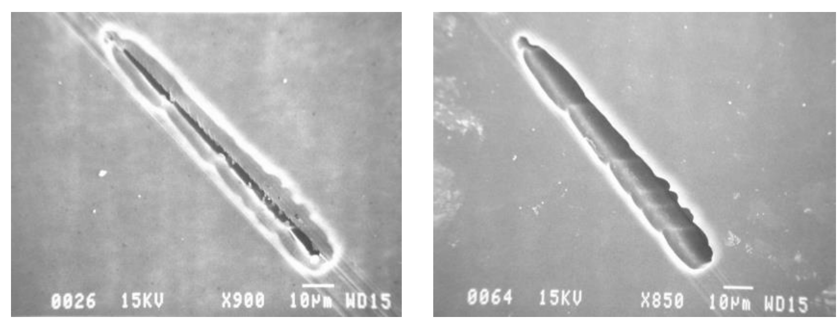
Atomic Oxygen Mitigation Using Protective Coatings



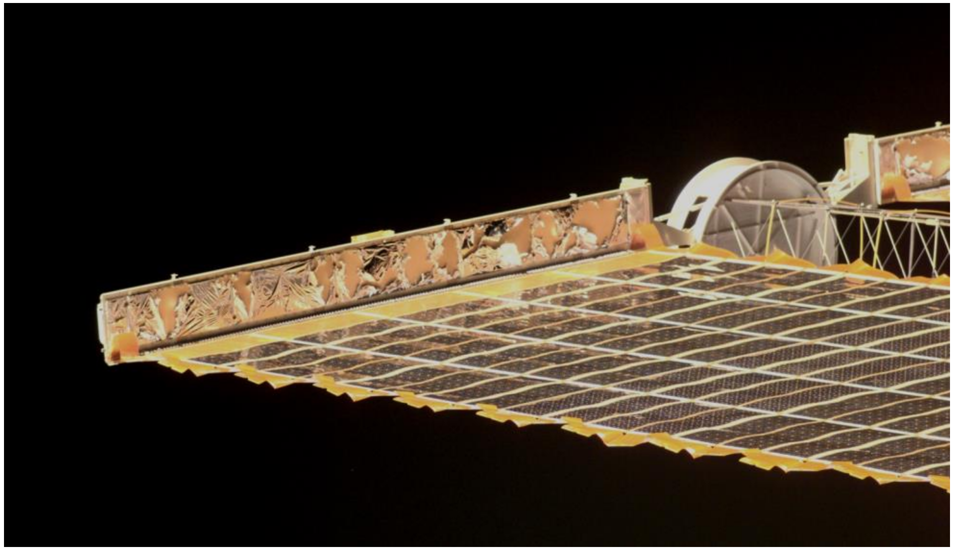
Imperfections in Thin Film Coatings

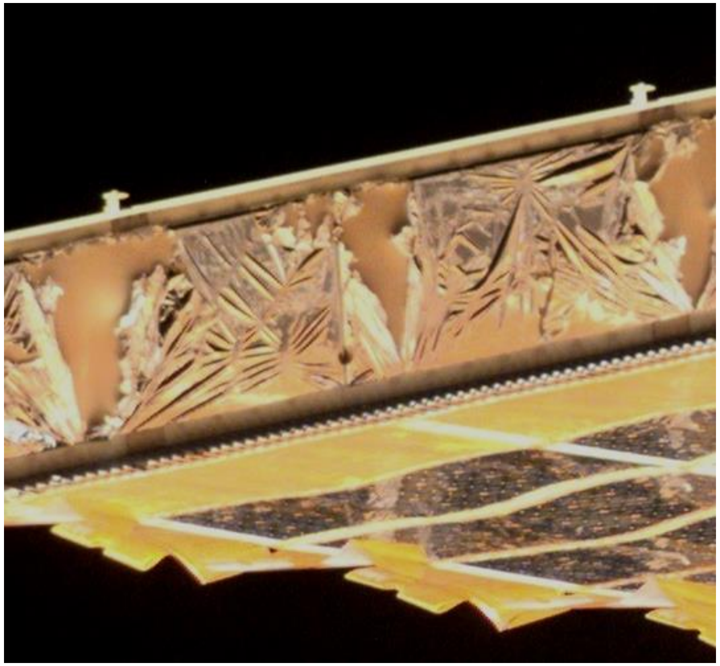


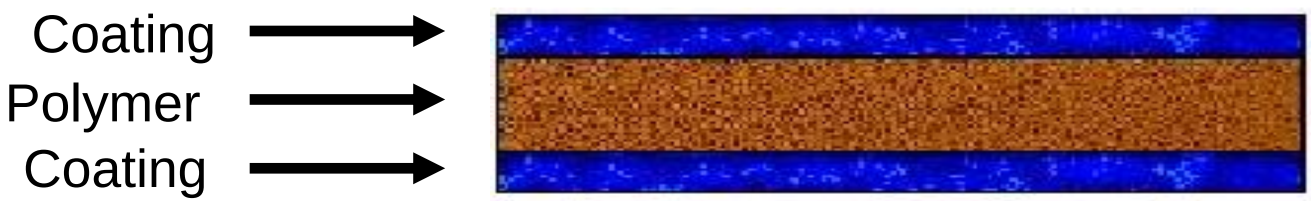
Aluminized Kapton Flown on LDEF



Blanket Box Cover Failure of Aluminized Kapton Observed on ISS

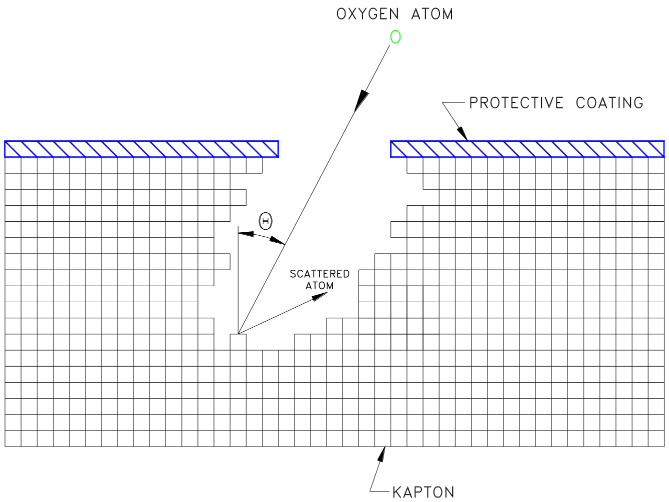


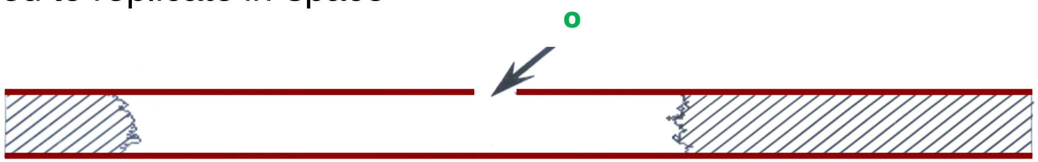




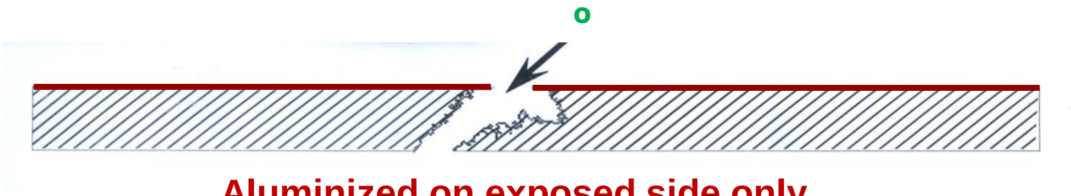
Monte Carlo Computational Model Predictions

- 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





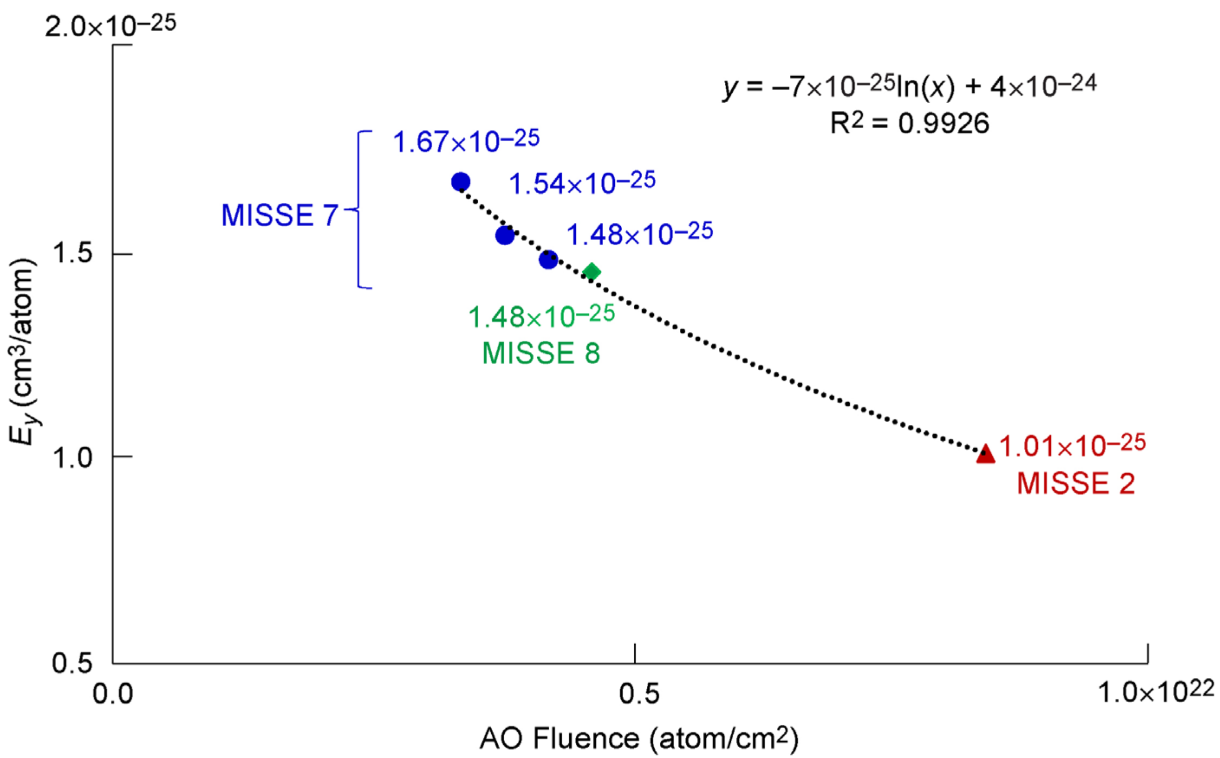
Aluminized on both sides

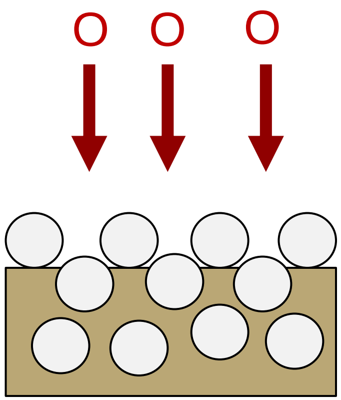


Aluminized on exposed side only

Atomic Oxygen Mitigation Using Fillers

Erosion Yield Versus Atomic Oxygen Fluence for White Tedlar

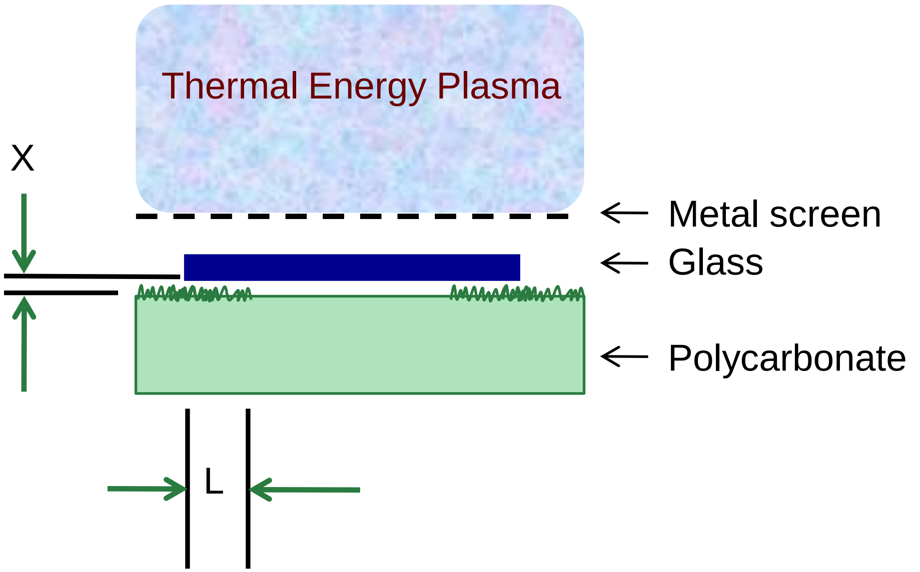




Kim K. de Groh and Bruce A. Banks, Atomic Oxygen Erosion Data from the MISSE 2-8 Missions, May 2019, NASA TM-2019-219982

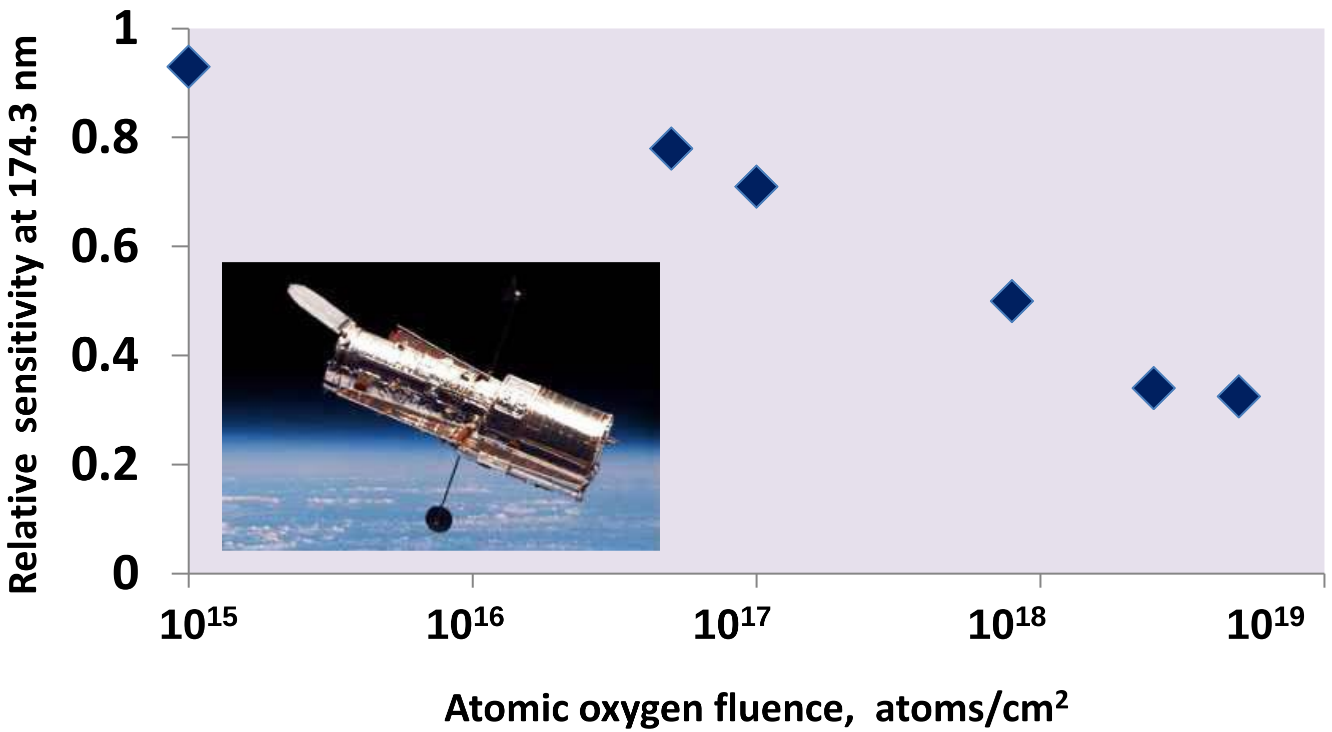
Atomic Oxygen Scattering

12 inch diameter
polycarbonate window



L/X $\cong$ 165

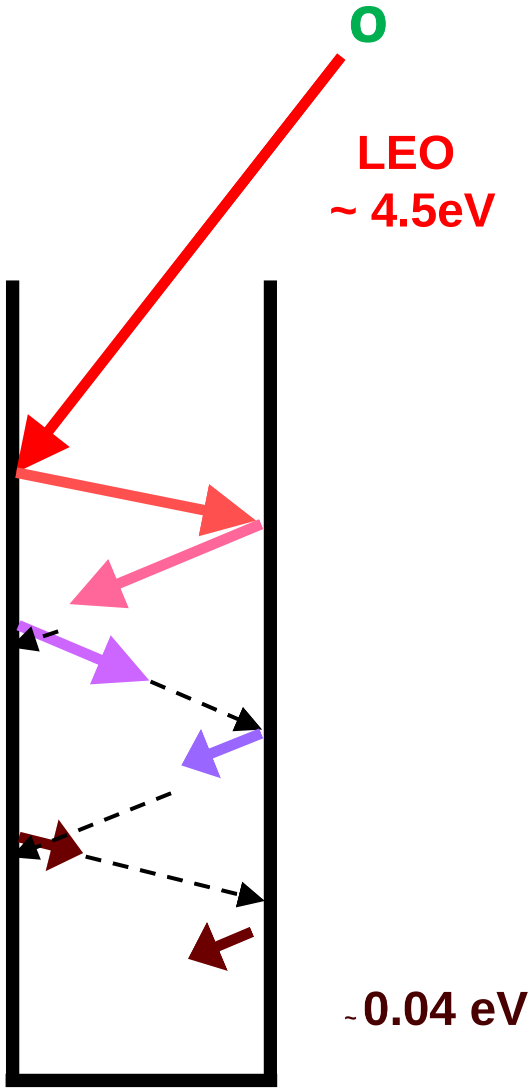
Change in Sensitivity of Cosmic Origins Spectrograph on Hubble Space Telescope



Experienced a far UV sensitivity decline ranging from 3-15%/year

(based on data from June 2009 through mid-February 2010)

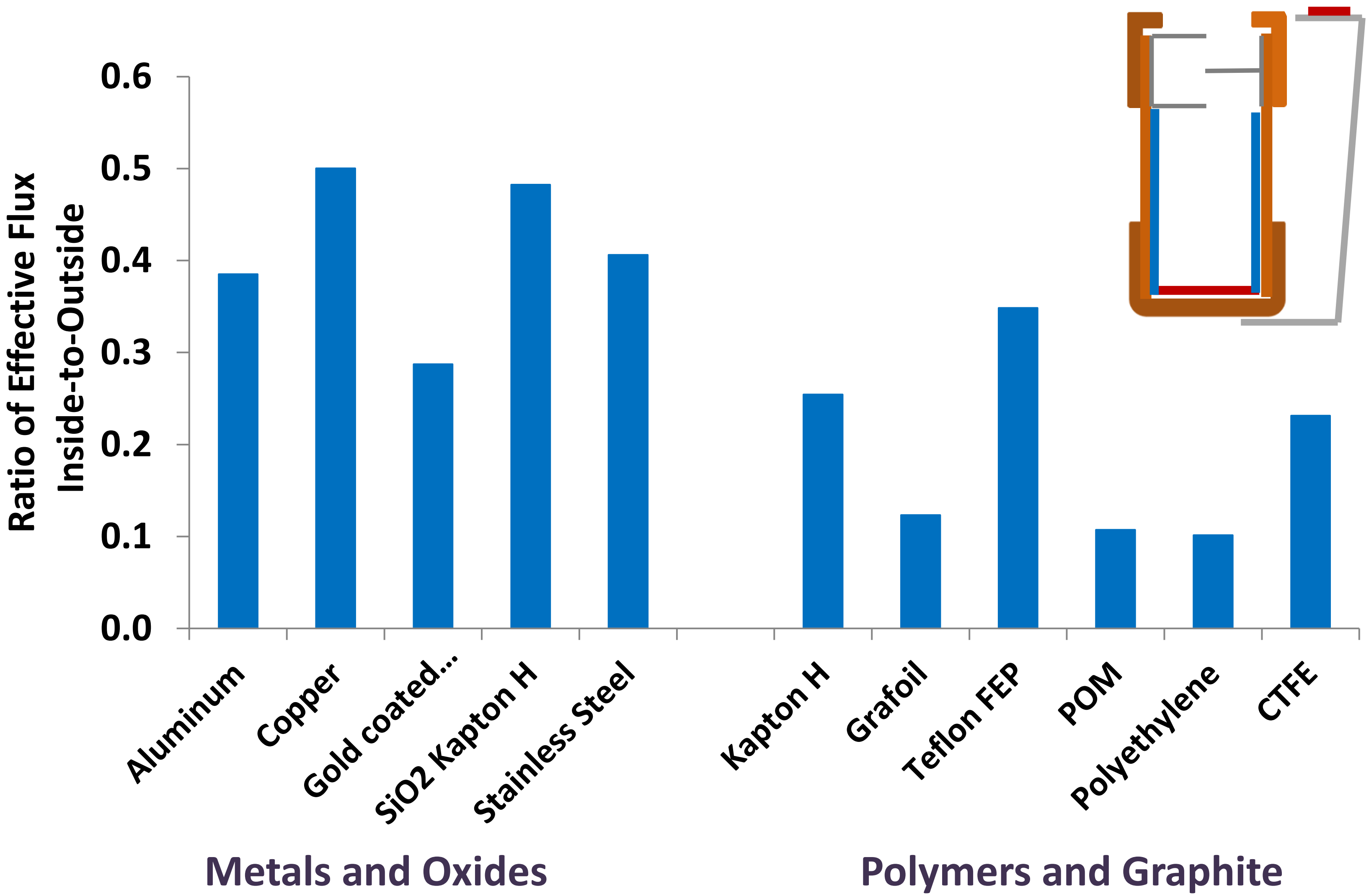
Scattering and Thermal Accommodation of Low Earth Orbital Atomic Oxygen



Possible Events Upon Impact:

- Reaction
- Recombination
- Scattering
- Partial thermal accommodation
- Ejection out the entrance

Atomic Oxygen Mitigation Using Getters



Summary

- Atomic oxygen is the most predominant specie in LEO and LMO
- 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, other gases…)
- Atomic oxygen mitigation techniques include protective coatings, fillers, modified surface chemistry and getters
- 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

NASA