Atomic Oxygen Environments, Effects and Mitigation

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Acknowledgments

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Atomic Oxygen in Low Earth Orbit

Photodissociation of O_2

UV Radiation

$E = h_\nu > 5.12$ eV (<243 nm)

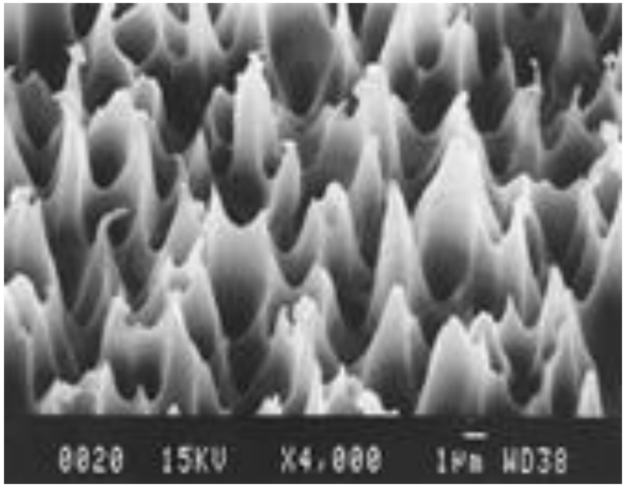
O_2 Diatomic Molecule

Atomic Oxygen

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

LDEF Spacecraft CTFE after

8.99×10^{21} atoms/cm^2

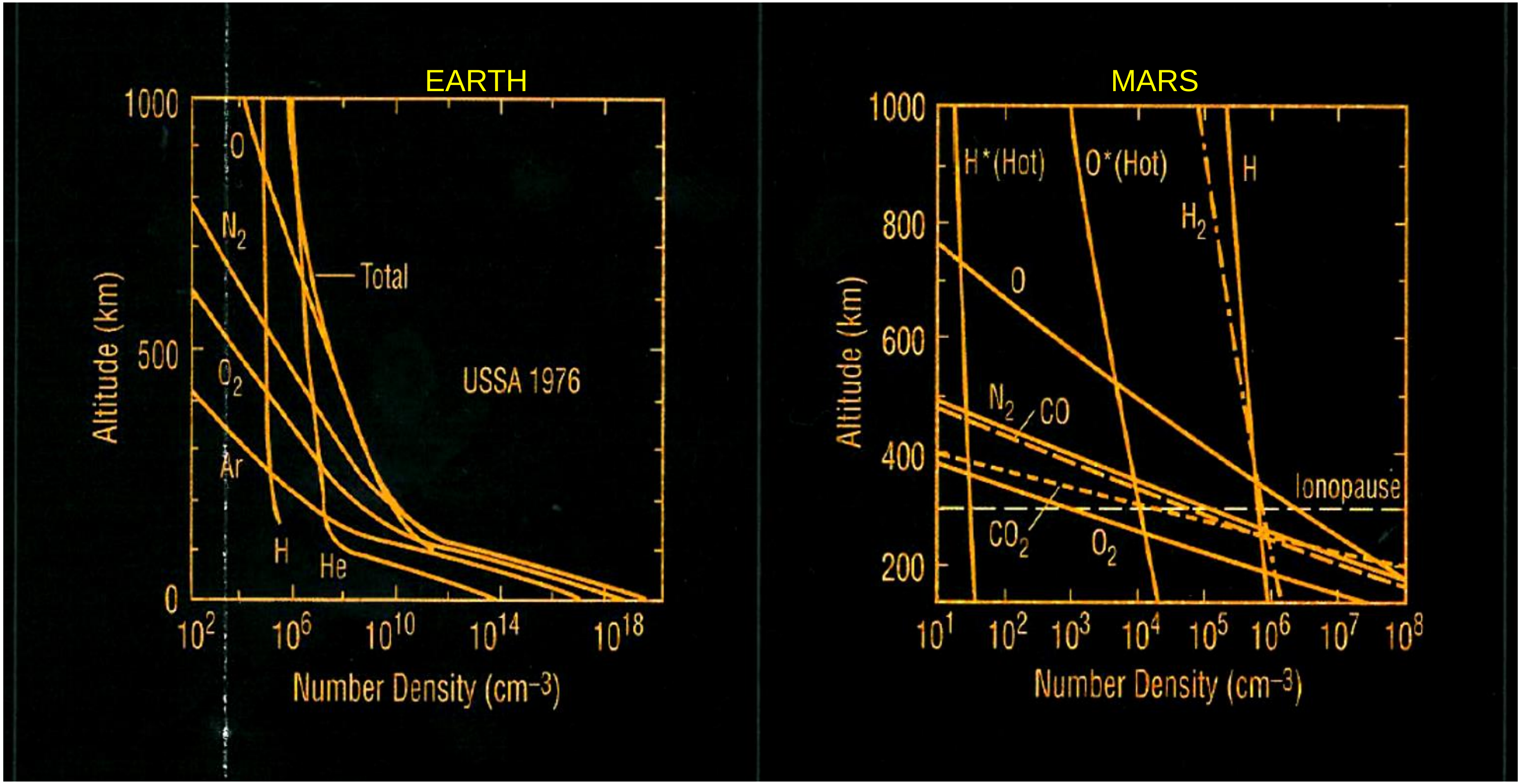


Polychlorotrifluoroethylene (CTFE)

Atomic Oxygen Effects

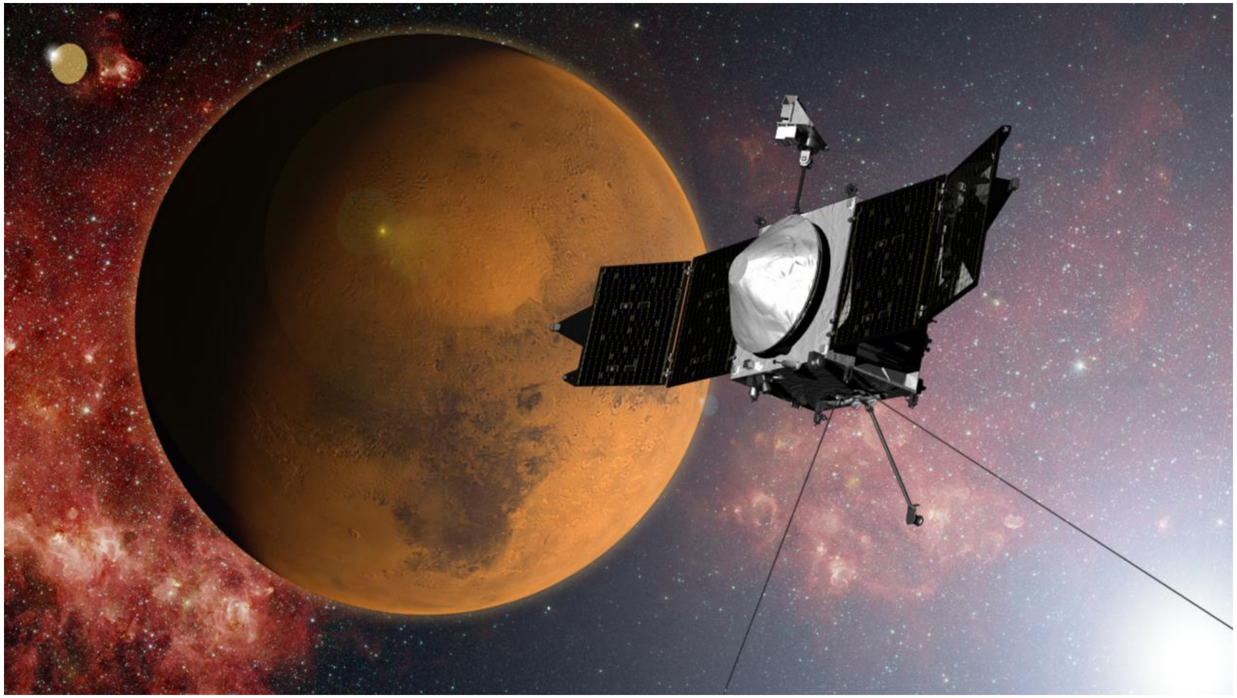
- Extent of damage dependent on:
  - Quantity arriving
  - Atom energy
  - Material reactivity (can vary with temperature, radiation, contamination, mechanical loading)
- Reaction can cause changes in:
  - Mechanical properties
  - Electrical properties
  - Optical properties
  - Thermal properties
  - 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



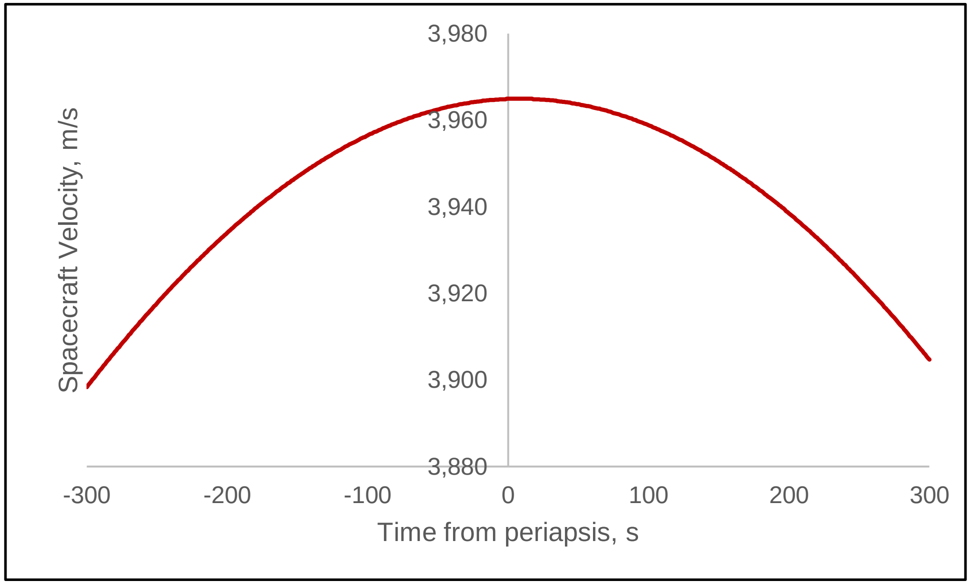
- Mars Atmospheric and Volatile Evolution Mission
- Launched in November, 2013 to understand the role the loss of volatiles from the atmosphere to space has played in the history of Mars atmosphere and climate
- Insertion into Mars orbit September, 2014

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

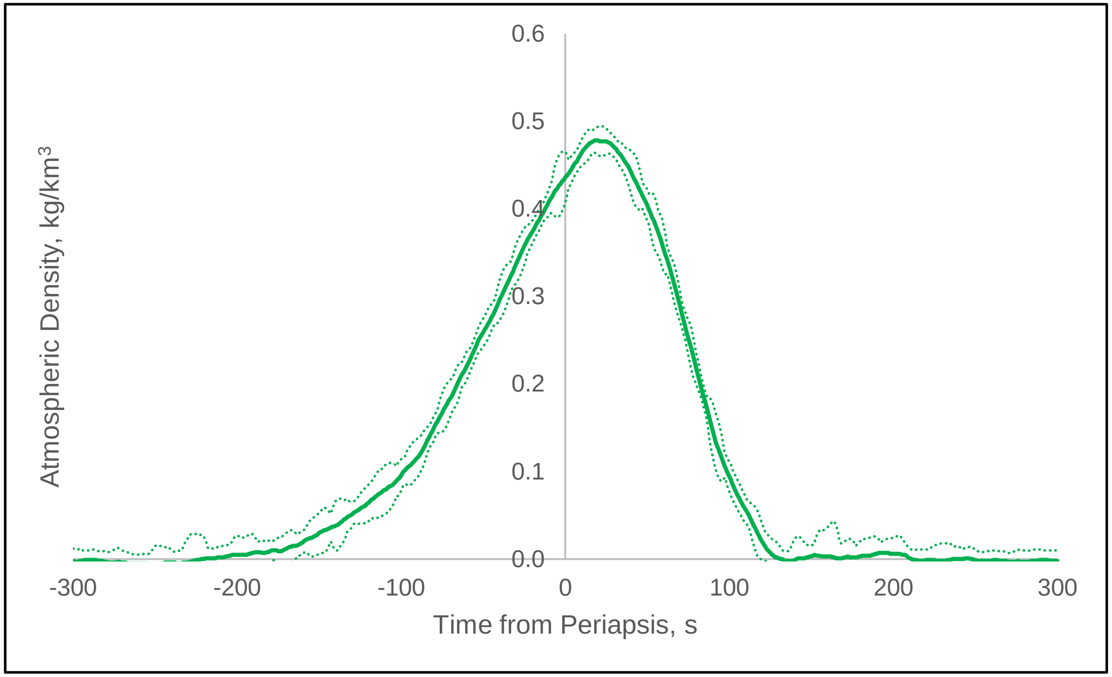
- Highly elliptical orbit
- Apoapsis: 6000 km, Periapsis: 160 to 180 km, 60 degree inclination
- At periapsis, the atmosphere is predominantly O, CO, CO_2, N_2, and O_2
- Maximum ram velocity of ~4 km/sec



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

R. Zurek, R. Tolson, and D. Baird, “Mars Atmosphere and Volatile Evolution (MAVEN) Mission ACC Software Interface Specification, Rev. 1, March 30, 2015.

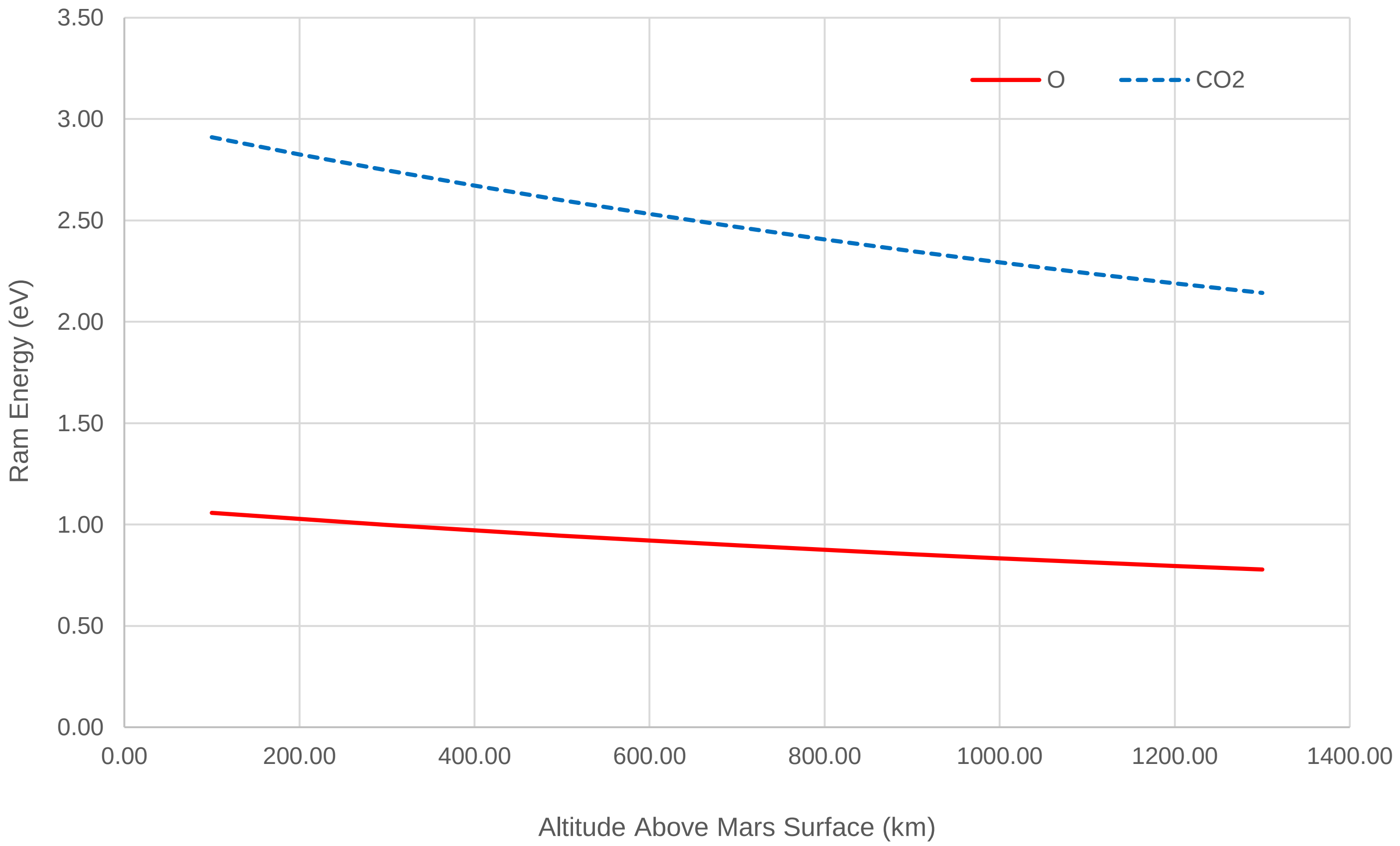
MAVEN Environment



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

R. Zurek, R. Tolson, and D. Baird, “Mars Atmosphere and Volatile Evolution (MAVEN) Mission ACC Software Interface Specification, Rev. 1, March 30, 2015.

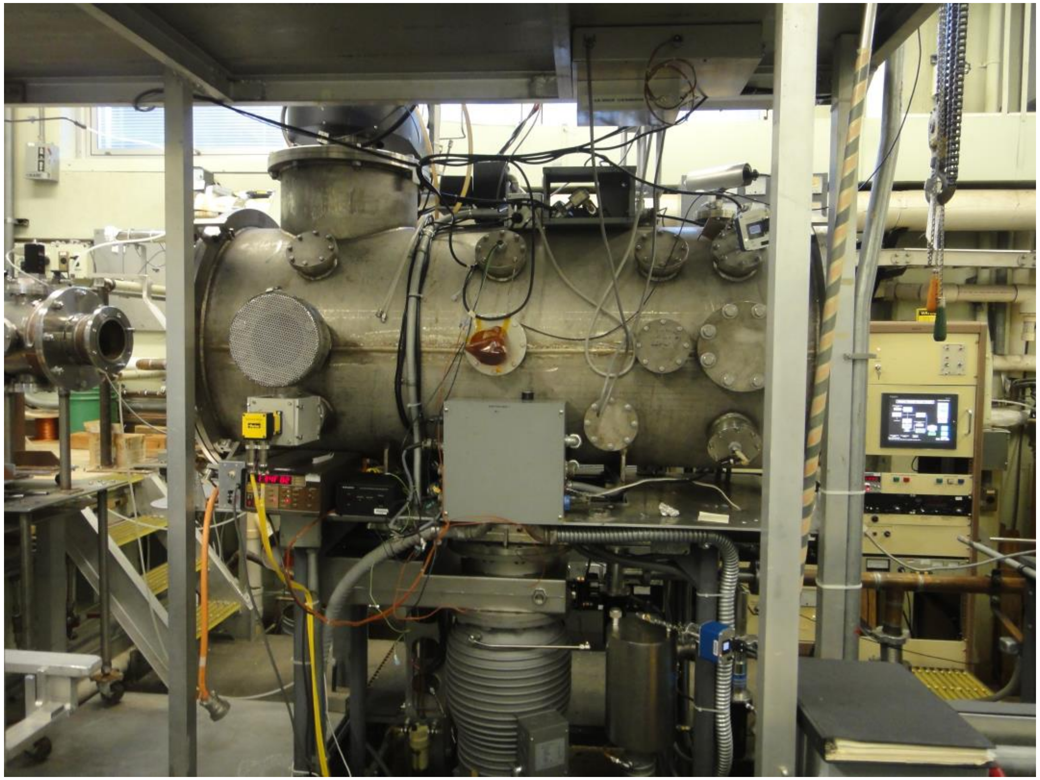
MAVEN Atmosphere Ram Energy

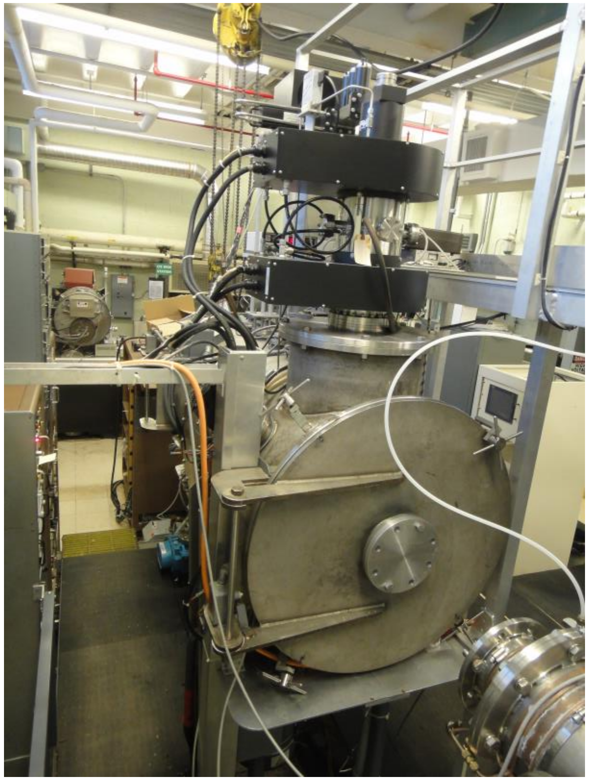


Understanding the Differences Between LEO and LMO

- 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% CO_2, 11.9% N_2, 10% O_2, 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 (cm^3 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 ^{o}C

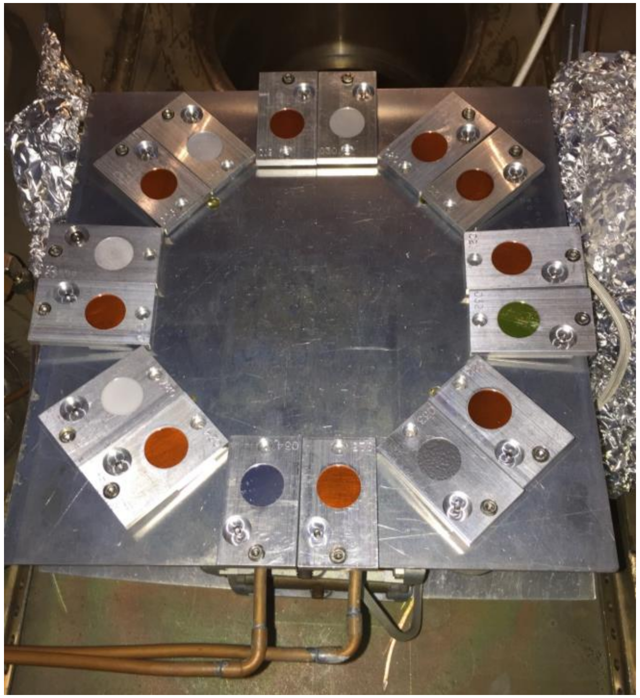
Atomic Oxygen Directed Beam System

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

$$F_E = \frac{4*(\Delta m_K)}{\rho_K*\pi*D^2*E_{yK}}$$

Where: F_E = effective atomic oxygen fluence (atoms/cm^2)
Δm_K= change in mass of Kapton H (g)
ρ_K = density of Kapton H (1.4273 g/cm^3)[1]
D = diameter of area exposed (2.228 cm)
E_{yK} = erosion yield of Kapton H (3x10^{-24} cm^3/atom)[2]
F_E for SLEO = 5.79E20 atoms/cm^2 ,
F_E for SLMO = 3.17E20 atoms/cm^2

$$E_y = \frac{4*\Delta m}{\rho*\pi*D^2*F_E}$$

Where: F_E = effective atomic oxygen fluence (atoms/cm^2)
Δm = change in mass of the material (g)
ρ = density of the material (g/cm^3)
D = diameter of area exposed (2.228 cm)
E_y = erosion yield of the material (cm^3/atom)

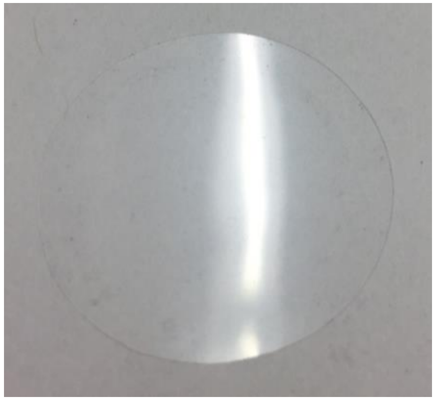
[1] de Groh, K. K., Banks, B. A., McCarthy, C. E., Rucker, R. N., Roberts, L. M. and Berger, L. A., "MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station," High Performance Polymers 20, 2008, pp. 388-409.

[2] American Society for Testing and Materials (ASTM), Standard Practices for Ground Laboratory Atomic Oxygen Interaction Evaluation of Materials for Space Applications, ASTM E 2089-00, 2000.

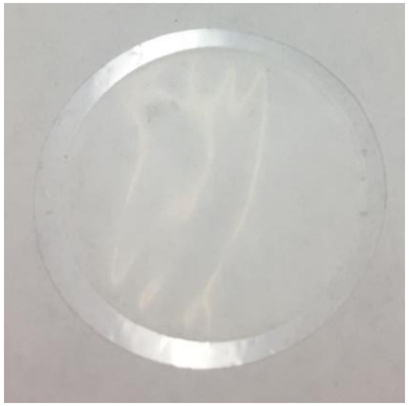
Material	**Erosion Yield Comparison Between Simulated LEO, Simulated LMO and ISS LEO**						
	Density[1] (g/cm^3)	***E_y Simulated LEO (SLEO) (cm^3/atom)***	***E_y Simulated LMO (SLMO) (cm^3/atom)***	***E_y ISS LEO (LEO)[1] (cm^3/atom)***	***E_y SLEO/ E_y LEO***	***E_y SLMO/ E_y LEO***	***E_y SLMO/ E_y SLEO***
Polyimide Kapton H	1.427	3.03E-24	3.11E-24	3.00E-24	1.01	1.04	1.03
Polyimide Upilex-S/Aluminum	1.387	2.37E-24	2.55E-24	9.22E-25	2.57	2.76	1.07
FEP Teflon/Aluminum	2.144	4.85E-24	4.63E-24	2.00E-25	24.27	23.13	0.95
Pyrolytic Graphite	2.220	6.42E-25	6.69E-25	4.15E-25	1.55	1.61	1.04
Polymethyl methacrylate	1.163	5.99E-24	1.14E-23	>5.6E-24	<1.07	<2.03	1.90
Polyethylene terephthalate	1.393	3.78E-24	3.82E-24	3.01E-24	1.25	1.27	1.01
Polyoxymethylene	1.398	3.73E-23	3.43E-23	9.14E-24	4.08	3.75	0.92
Polycarbonate	1.123	5.35E-23	3.59E-24	4.29E-24	12.48	0.84	0.07

[1] de Groh, K. K., Banks, B. A., McCarthy, C. E., Rucker, R. N., Roberts, L. M. and Berger, L. A., “MISSE 2 PEACE Polymers Atomic Oxygen Erosion Experiment on the International Space Station,” High Performance Polymers 20, 2008, pp. 388-409.

Polymethylmethacrylate – PMMA



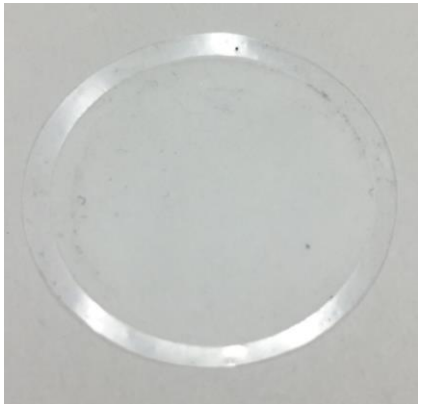
As Received



SLEO

F_E = 5.79E20 atoms/cm^2

E_y = 5.99E-24 cm^3/atom

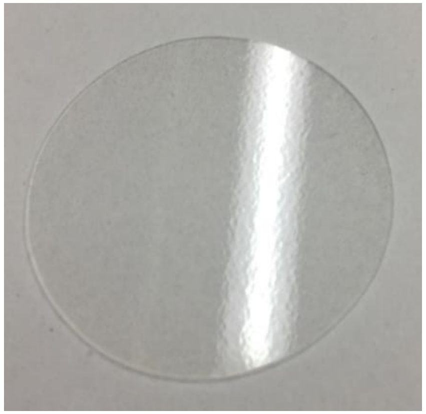


SLMO

F_E = 3.17E20 atoms/cm^2

E_y = 1.14E-23 cm^3/atom

Polycarbonate - PC



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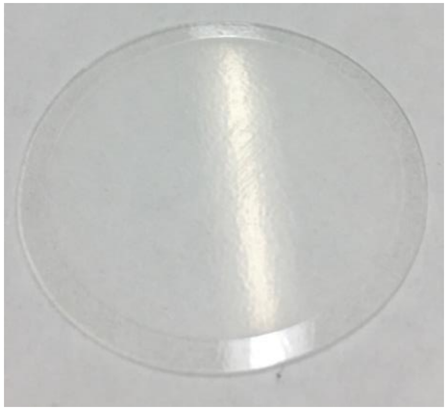
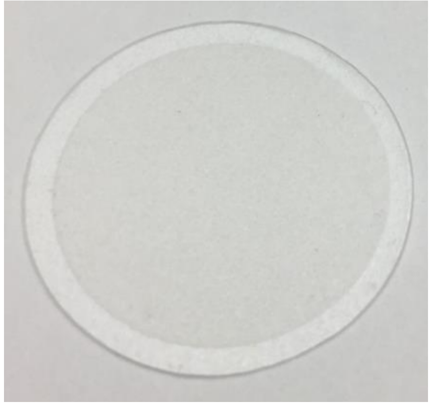


SLEO

F_E = 5.79E20 atoms/cm^2

E_y = 5.35E-23 cm^3/atom



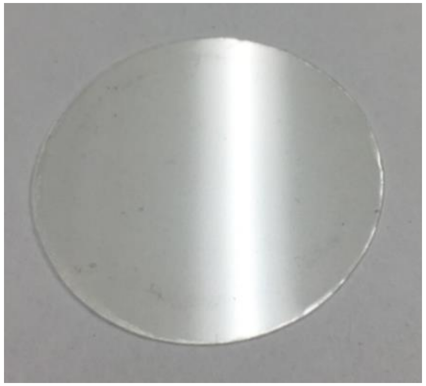
SLMO

F_E = 3.17E20 atoms/cm^2

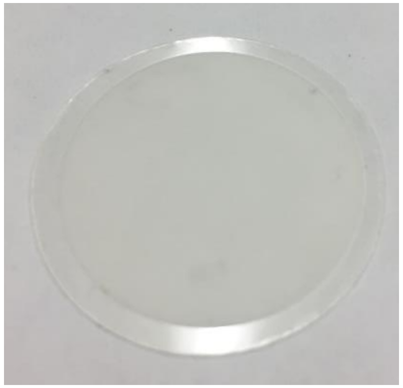
E_y = 3.59E-24 cm^3/atom

Material	**Comparison of Solar Absorptance for Simulated LEO and LMO**				
	α_S ***As Received***	α_S ***After SLEO Exposure***	***% Change (from Received to After SLEO)***	α_S ***After SLMO Exposure***	***% Change (from Received to After SLMO)***
Polyimide Kapton H	0.336	0.341	1.49	0.339	0.89
Polyimide Upilex-S/Aluminum	0.409	0.509	24.45	0.492	20.29
FEP Teflon/Aluminum	0.141	0.154	9.22	0.147	4.26
Pyrolytic Graphite	0.741	0.937	26.45	0.890	20.11
Polymethyl methacrylate	0.013	0.011	-15.38	0.006	-55.38
Polyethylene terephthalate	0.061	0.065	6.56	0.060	-1.64
Polyoxymethylene	0.082	0.044	-46.34	0.094	14.63
Polycarbonate	0.108	0.097	-10.19	0.107	-0.93

Polyethylene terephthalate – PET



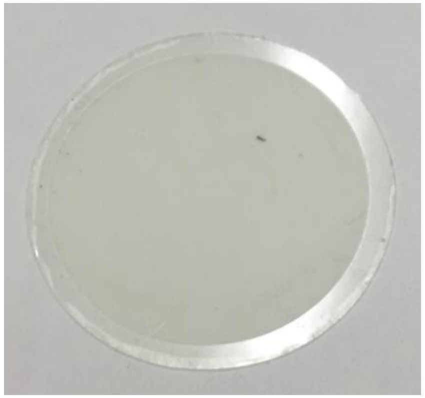
As Received



SLEO

F_E = 5.79E20 atoms/cm^2

E_y = 3.78E-24 cm^3/atom



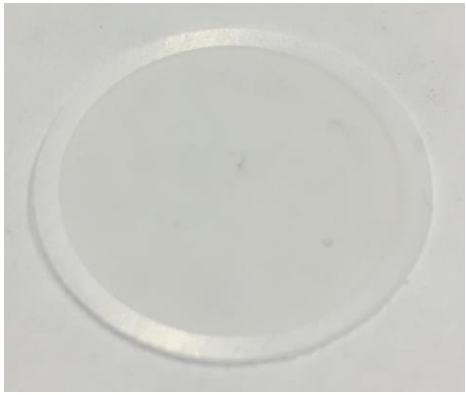
SLMO

F_E = 3.17E20 atoms/cm^2

E_y = 3.82E-24 cm^3/atom

Polyoxymethylene - POM

As Received



SLEO

F_E = 5.79E20 atoms/cm^2

E_y = 3.73E-23 cm^3/atom

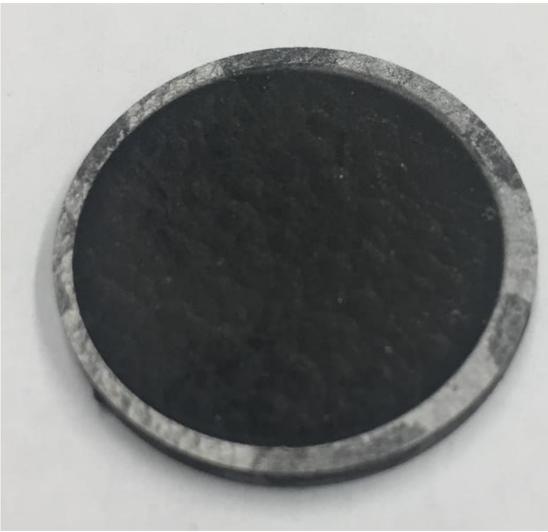
SLMO

F_E = 3.17E20 atoms/cm^2

E_y = 3.43E-23 cm^3/atom

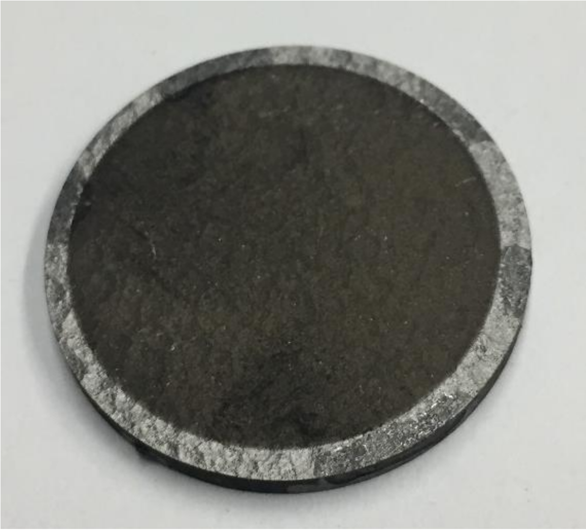
Material	**Comparison of Thermal Emittance for Simulated LEO and LMO**				
	ε_{T300} ***As Received***	ε_{T300} ***After SLEO Exposure***	***% Change (from Received to After SLEO)***	ε_{T300} ***After SLMO Exposure***	***% Change (from Received to After SLMO)***
Polyimide Kapton H	0.828	0.832	0.48	0.825	-0.36
Polyimide Upilex-S/Aluminum	0.835	0.848	1.56	0.834	-0.12
FEP Teflon/Aluminum	0.792	0.754	-4.80	0.775	-2.15
Pyrolytic Graphite	0.522	0.642	22.99	0.507	-2.87
Polymethyl methacrylate	0.589	0.338	-42.61	0.508	-13.75
Polyethylene terephthalate	0.803	0.814	1.37	0.798	-0.62
Polyoxymethylene	0.874	0.698	-20.25	0.849	-2.86
Polycarbonate	0.870	0.860	-1.15	0.860	-1.15

Pyrolytic Graphite



SLEO

F_E = 5.79E20 atoms/cm^2
E_y = 6.42E-25 cm^3/atom



SLMO

F_E = 3.17E20 atoms/cm^2
E_y = 6.69E-25 cm^3/atom

Summary of Results

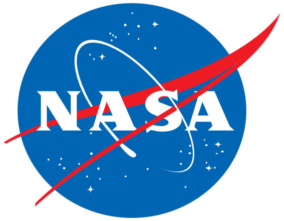
- Kapton H, Upilex-S/Al, FEP Teflon/Al, pyrolytic graphite, PET and POM: good agreement between simulated LEO (SLEO) and simulated LMO (SLMO) erosion yields
- PMMA erosion yield nearly double in SLMO compared to SLEO
- Polycarbonate erosion yield SLMO 0.07 times SLEO
- SLEO erosion yield is in general 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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