

Properties and Improved Space Survivability of POSS Polyimides

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Outline



- Lower Earth Orbit Environment
- Assessment of state-of-the-art Space Polyimides.
- POSS: Polyhedral Oligomeric Silsesquioxane
- POSS Kapton Polyimides
- Ground Based Tests: Atomic Oxygen (AO) Erosion Studies
- Self Forming / Self Healing Silica Passivation Layer
- Modeling and Simulation of AO attack on POSS
- Flight Tests: MISSE 4, 5, 6
- Thermal and Mechanical Properties
- Summary and Conclusions
- Acknowledgments



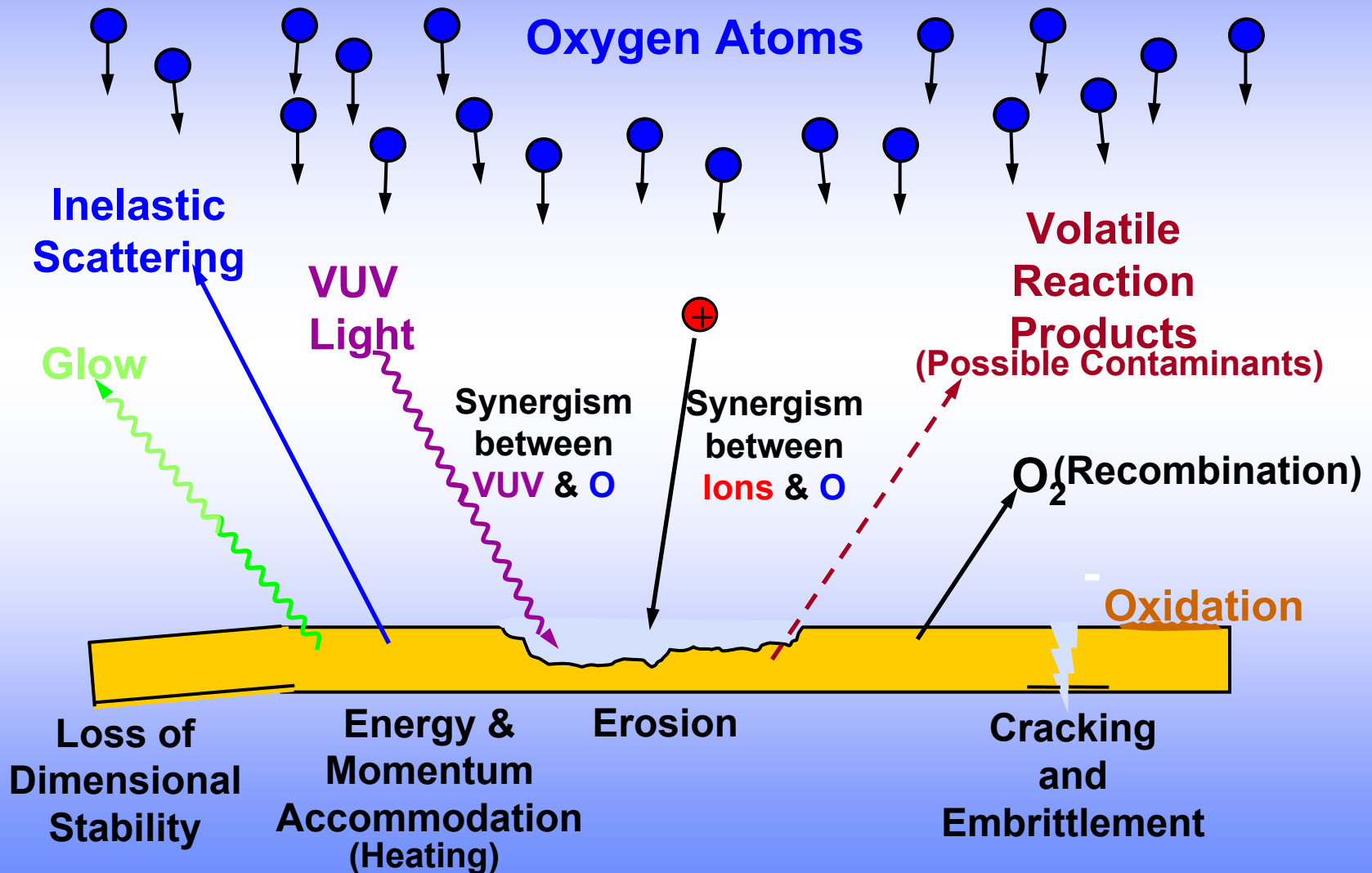
Lower Earth Orbit Environment



- **Atomic Oxygen (AO) Erosion of Kapton in LEO is a serious threat to spacecraft durability.**
- **As a space vehicle orbits the Earth at orbital speed (7.8 km/sec at low altitudes) it undergoes energetic collisions with atoms and molecules in the orbital environment.**
- **AO is the dominant species in the outer ionosphere from 200-700 km, becoming as much as 90 % of the atmosphere at 500 km, a typical altitude for the International Space Station and future space platforms.**



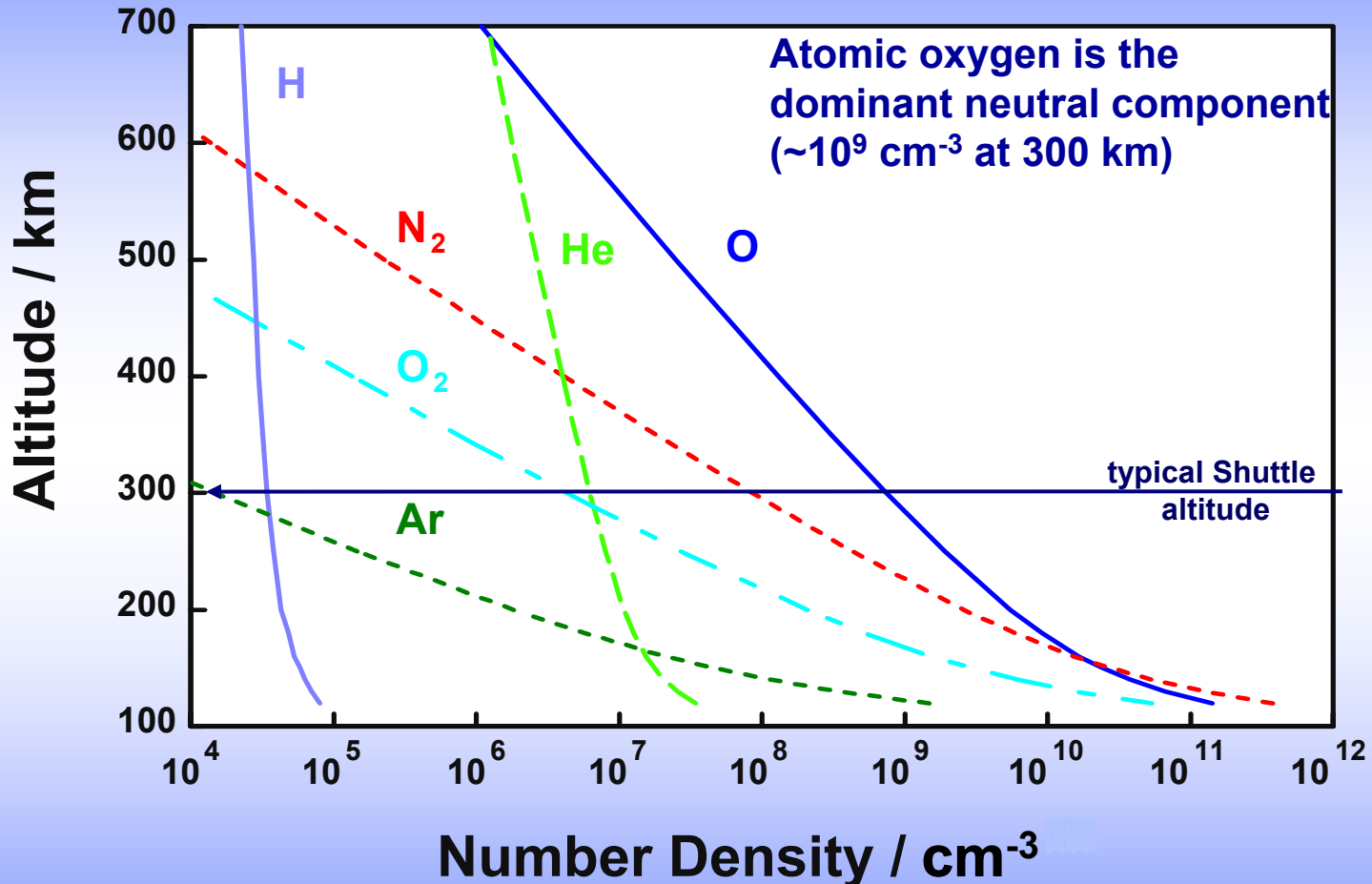
Atomic Oxygen and Synergistic Effects on Materials



Courtesy of Dr. Timothy Minton, Montana SU



Neutral Composition of Earth's Upper Atmosphere



Roble, in The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory, Geophysical Monograph 87, pp 1 – 21, 1995.

Courtesy of Dr. Timothy Minton, Montana SU



Technical Problem

Atomic Oxygen in Lower Earth Orbit



LEO Environment (Altitudes of 200 to 1500 km)

- Atomic Oxygen (AO): $\sim 10^6 - 10^8$ atoms/cm³, up to 90 % of the atmosphere at 500km (typical altitude for international space station).
- Actual AO flux on spacecraft $\sim 10^{12} - 10^{14}$ atoms/cm²•s
- **AO Collision energy $\sim 5\text{eV}$ (7.8 km/sec)** (C-C bond energy ~ 4 eV, C-N $\sim 3\text{eV}$, **Si-O $\sim 8.3\text{eV}$**)
- Low-energy and high energy charged particles.
- Thermal cycling -50 to 150°C
- Solar VUV and UV radiation ($\sim 100 - 400$ nm)
- Bond scission and radical formation can lead to embrittlement.

Bond	Dissociation Energy (EV)	λ (nm)	Material
-C₆H₄-C(=O)-	3.9	320	Kapton®
C-N	3.2	390	Kapton®
Si-O	8.3	150	Nanocomposite

Satellites & Space Systems





State-of-the-Art Space Polyimides



- **Kapton H Protected by a sputtered on Silica layer (SiO_2).**
- **Inherent problems in protective Silica layer:**
 - **Defects from surface anomalies occurring during deposition process.**
 - **Cracks and microdefects** due to micrometeoroid and debris bombardment in LEO. **Underpinning Effect.**
- **Results:**
 - **Exposure of underlying Kapton layer.**
- **Lifetime of Kapton H protected by sputtered on silica layer:**
 - **Example:**
 - **Hubble Space Telescope:**
 - **Altitude = 610 km.**
 - **AO fluence exposure: 7.59×10^{20} atoms/cm² for 3.6 years.**
 - **Revisited every 2-3 years for maintenance including replacement of**
 - **solar arrays and patching of multilayer insulation blankets.**



AO undercutting of Aluminized-Kapton Multilayer Insulation flown on LDEF

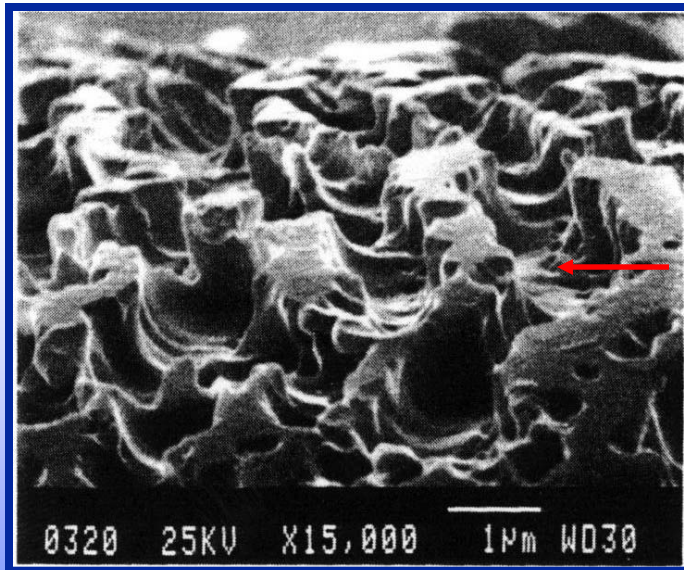


LDEF Satellite:

Long Duration Exposure Facility.

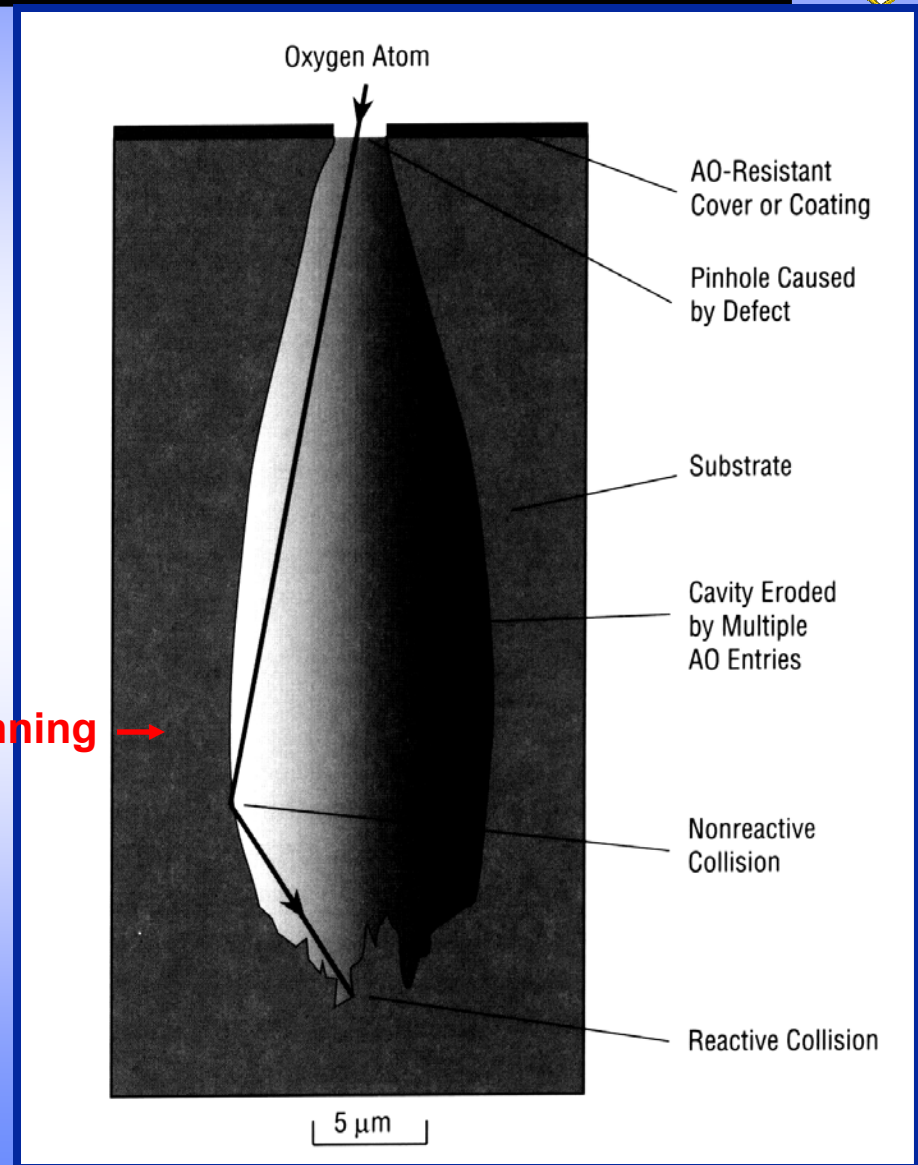
Total AO Exposure: 9×10^{21} atoms/cm²

Depths of >0.0127 cm (> 5 mils) of Kapton sheets were eroded away after 5.8 yrs in LEO on the ram AO surface of the LDEF



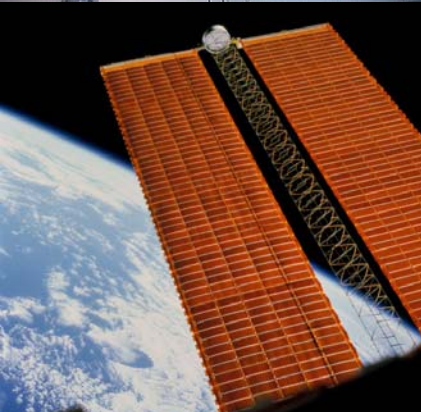
Underpinning Effect

Scanning Electron Micrograph Of Kapton MLI Surface.

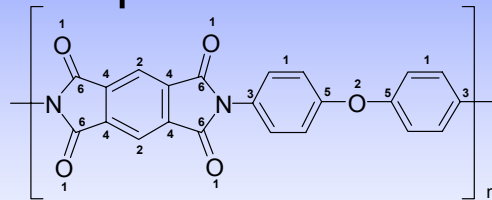




Goal

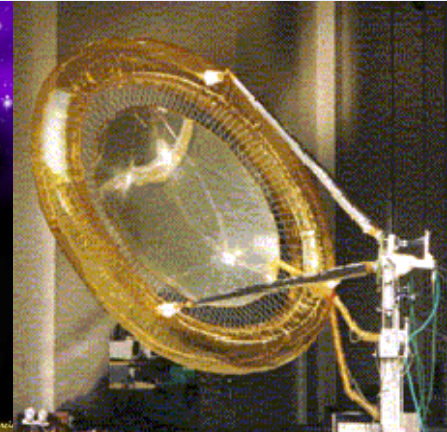
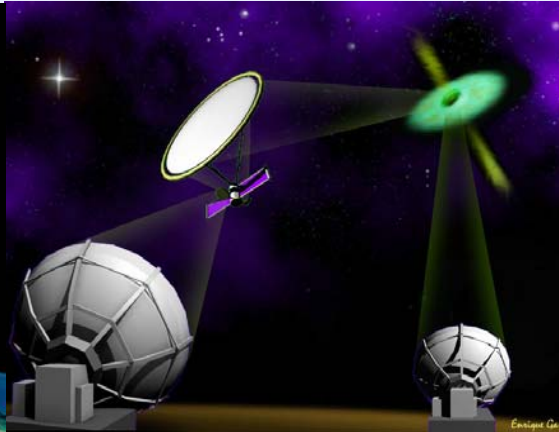
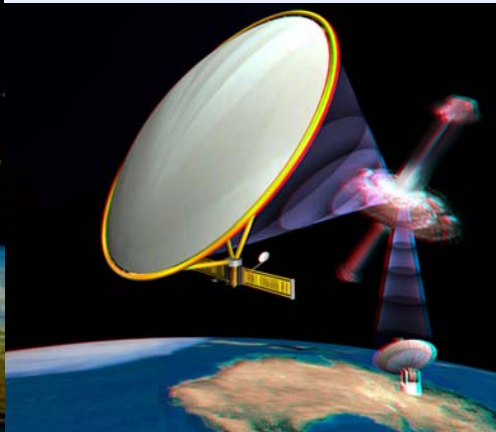


Kapton



Our goal is to create an efficient drop-in replacement for Kapton that:

1. Has increased space survivability due to **resistance to atomic oxygen**, thermal cycling, solar UV and VUV radiation, protons and electrons.
2. Is Self-Passivating and **Self-Healing** based on hybrid organic/ inorganic nanocomposite incorporation
3. Has superior optical properties, low solar absorptance, high thermal reflectance
4. Has excellent mechanical thermal properties.

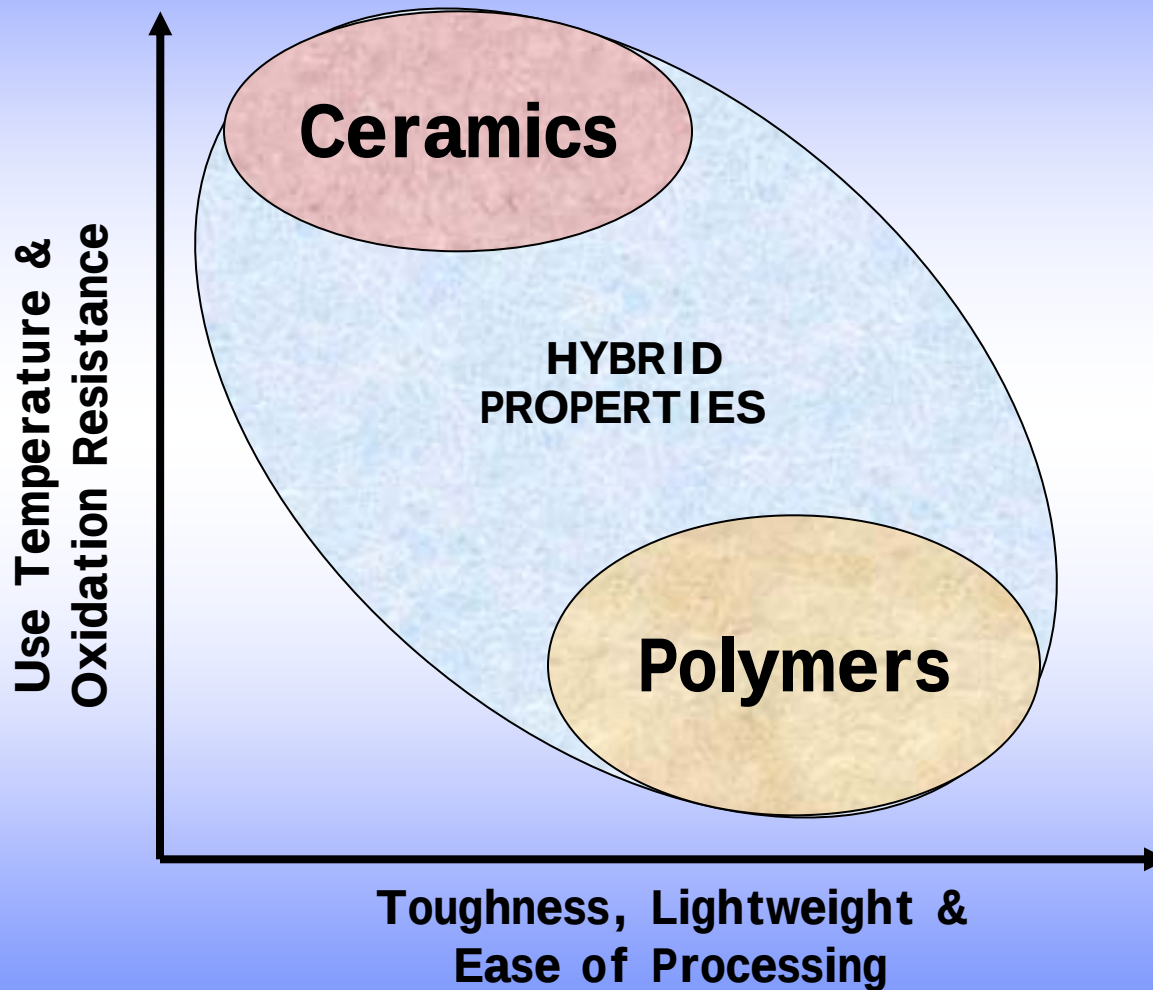




Hybrid Inorganic/Organic Polymers



Goal: Develop High Performance Polymers that REDEFINE material properties



•Hybrid plastics bridge the differences between ceramics and polymers



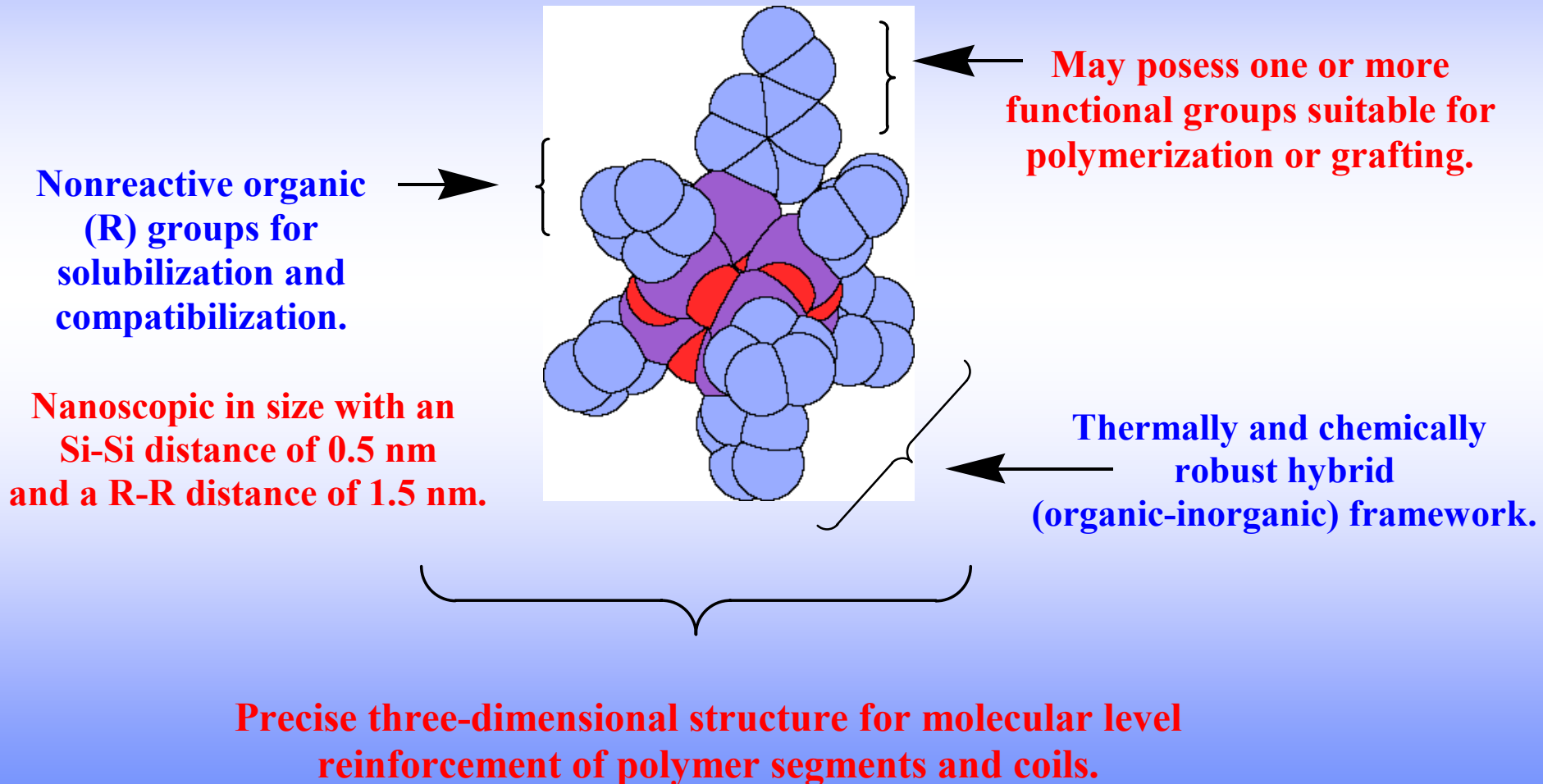
Why Use POSS?



- Multifunctionality – including no negative effects on processing (or can even get improvements)
- Properties previously not attainable (extended temp range, flame retardancy)
- Turnkey Utility
- Control of molecular architecture

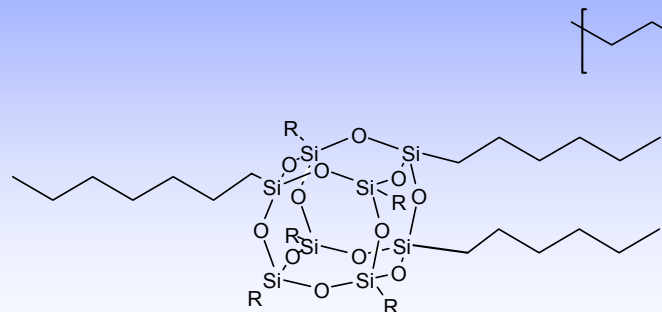


Anatomy of a POSS Nanostructure

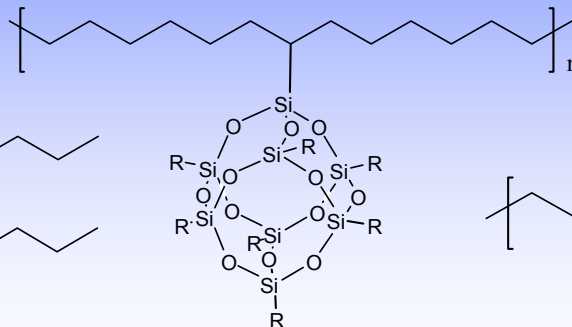




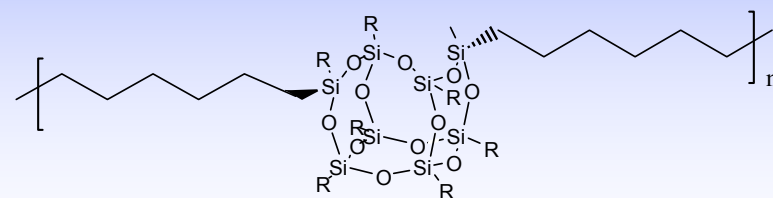
POSS Incorporation into Polymers



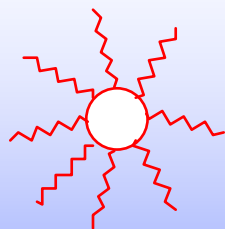
Cross-linker



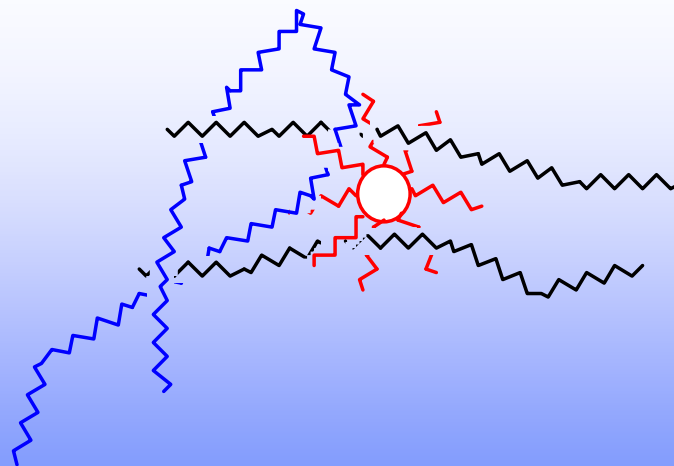
Pendant Polymer



Bead Copolymer

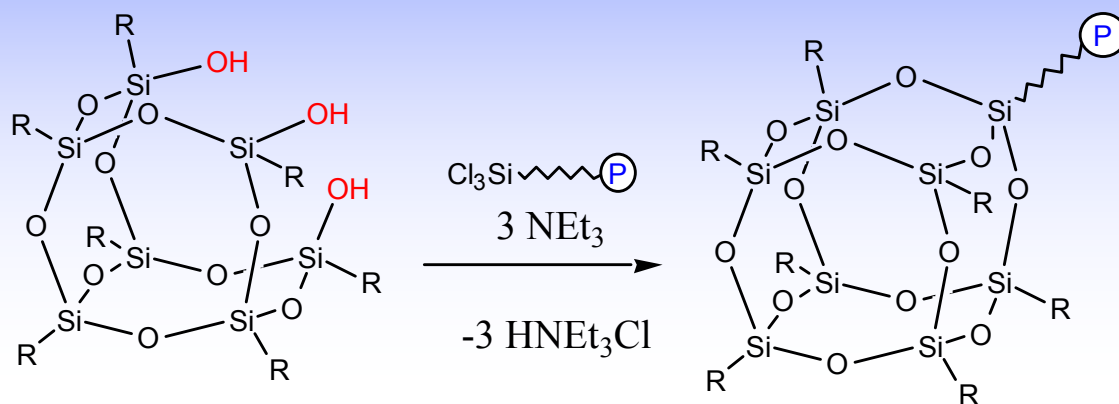
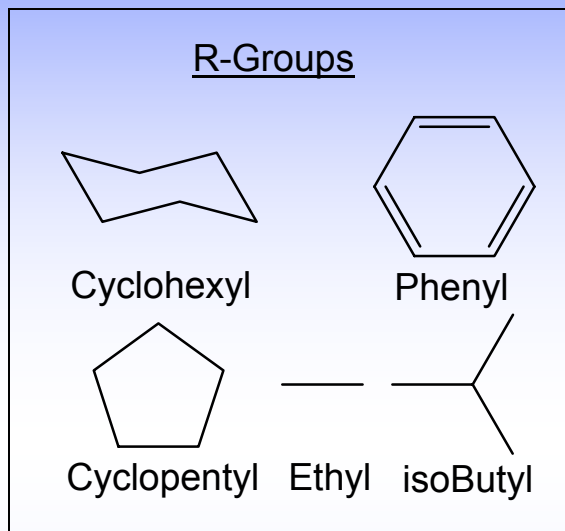


POSS Blending





New Polymer Feedstock Technology



Halides

Alcohols

Esters

Bisphenols

Nitriles

Amines

Isocyanates

Epoxides

Silanes

Silanols

Silylchlorides

Styryls

α -olefins

Acrylics

Norbornenyls

POSS-based macromers are available through either **Gelest** or **Aldrich**

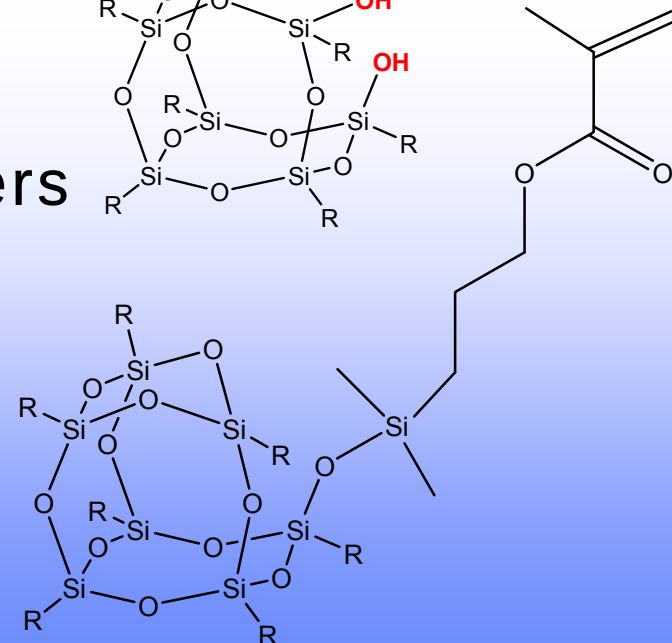
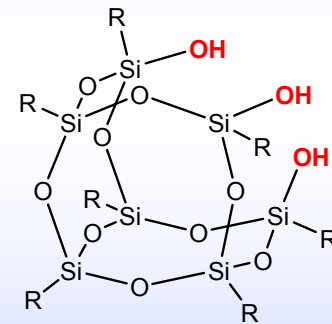
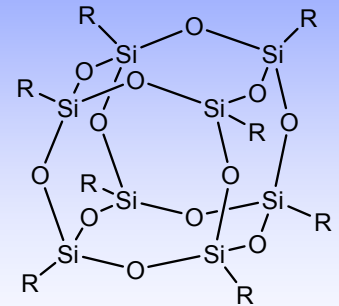
POSS technology is commercialized by **Hybrid Plastics** in Fountain Valley CA



POSS: Where We Were (1996)

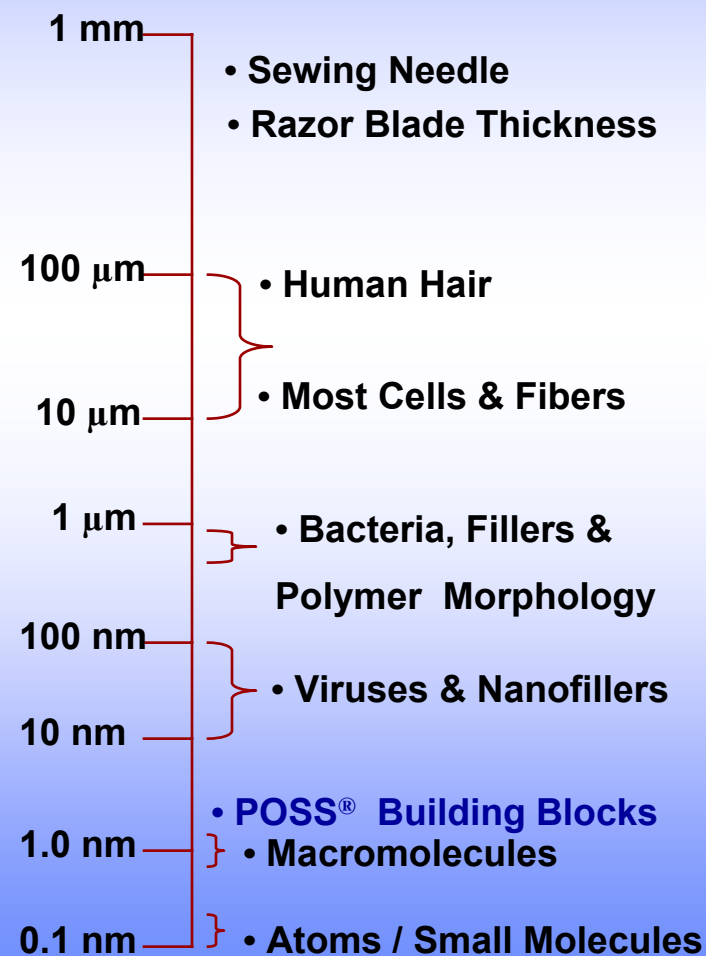


- Cost: \$5,000-\$10,000/lb
- Volume: ~20 lbs/yr
- Production time: min 11 days,
max 6 months
- Versatility: ~6 POSS feedstocks
~30 POSS macromers
- No successful POSS blends
- Made only by U.S. Government





Why POSS and Why Nano?



Field	Property	Critical Length
Electronics	Tunneling	1-100 nm
Optical	Quantum Well	1-100 nm
	Wave Decay	10-1000 nm
Polymers	Primary Structure	0.1-10 nm
	Secondary Structure	10-1000 nm
Mechanics	Dislocation Interaction	1-1000 nm
	Crack Tip Radius	1-100 nm
	Entanglement Rad.	10-50 nm
Therm-Mech.	Chain Motion	0.5-50 nm
Nucleation	Defect	0.1-10 nm
	Critical Nucleus Size	1-10 nm
	Surface Corrugation	1-10 nm
Catalysis	Surface Topology	1-10 nm
Biology	Cell Walls	1-100 nm
Membranes	Porosity Control	0.1-5 nm



Nanostructured™ POSS Chemicals

Physical Form of Products



Hybrid
Plastics™



Crystalline Solids

Wide melting range 24°C to 400°C+

Waxes

Liquids & Oils

Wide viscosity range 40cSt. to 400cSt

>120 POSS Monomers, Polymers and Feedstocks Available

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What Property Enhancements Can You Get From Using POSS?



increased T_g

increased T_{dec}

**oxidation
resistance**

**reduced
flammability**

**extended use
temperature range**

**altered
mechanicals**

**reduced
heat evolution**

**lower thermal
conductivity**

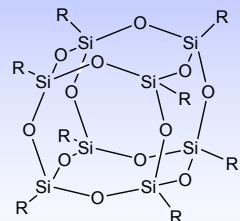
lower density



How to use POSS (Blends or Drop-In Nanofillers)

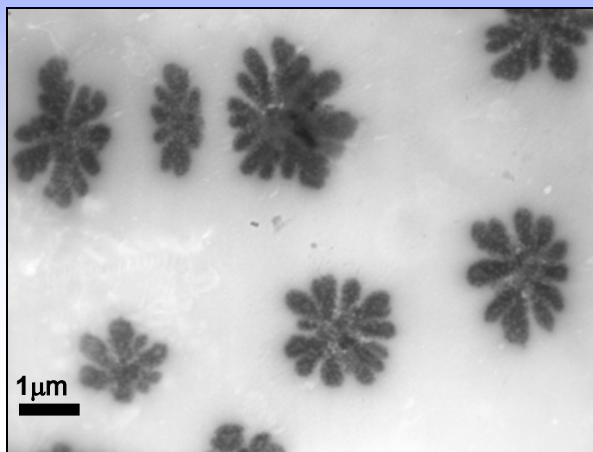


50 Wt % POSS Blends in 2 Million MW PS

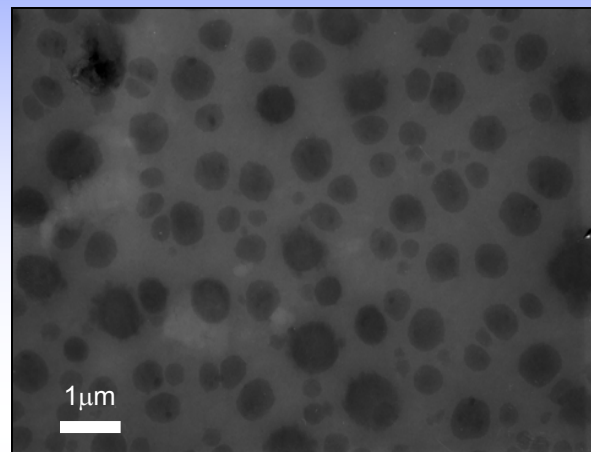


R = cyclopentyl

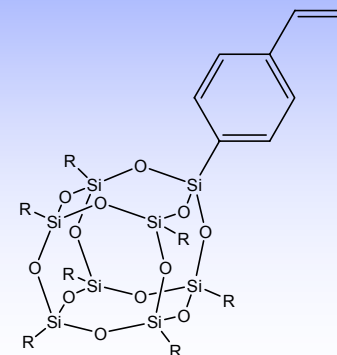
Cp₈T₈



Domain Formation

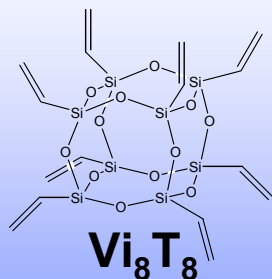


Partial Compatibility

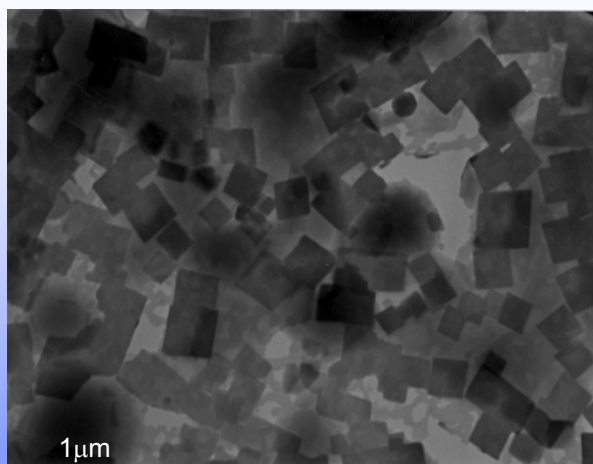


R = cyclopentyl

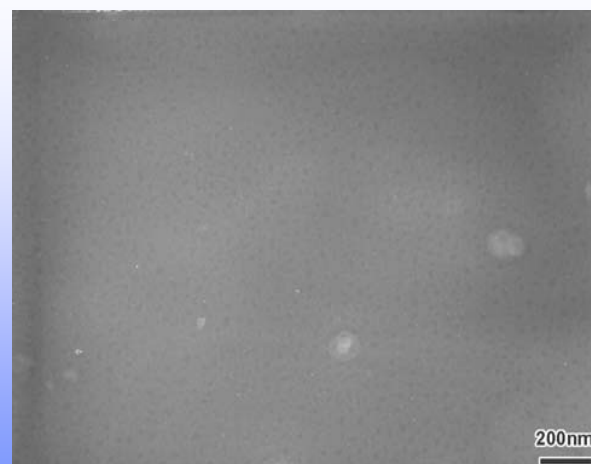
Cp₇T₈Styryl



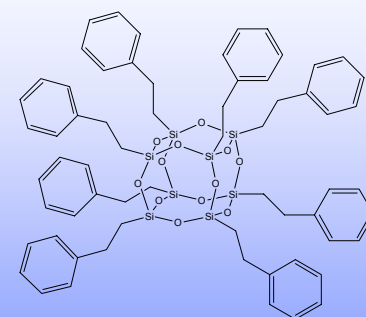
Vi₈T₈



Immiscible POSS Crystallites



**Complete Compatibility-
POSS Nanodispersion/Transparent**



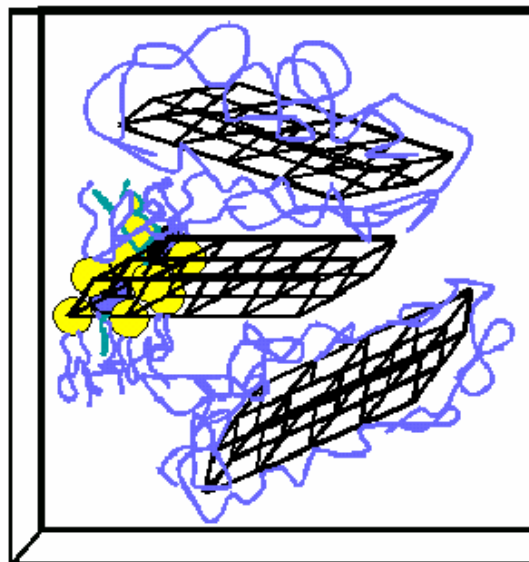
Phenethyl₈T₈



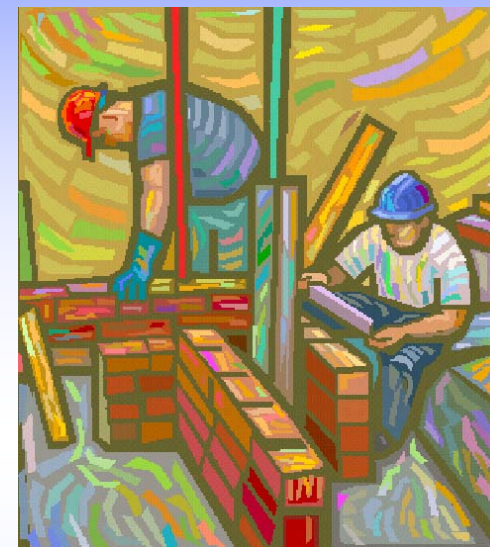
Coughlin Building Block Model (POSS Blends & Copolymers)



Bottom-up Approach
(Self-Assembly)



Top-down Approach

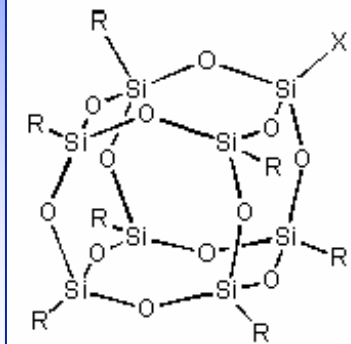


Bryan Coughlin-UMass

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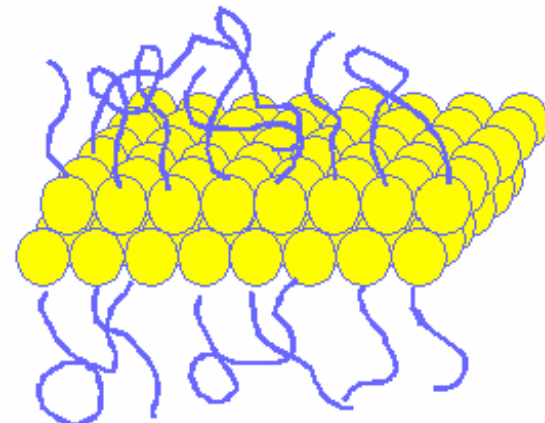
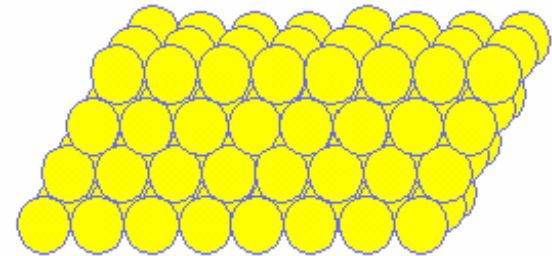
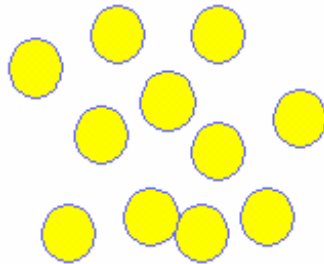
Coughlin Model Continued (building from the ground up)



≡

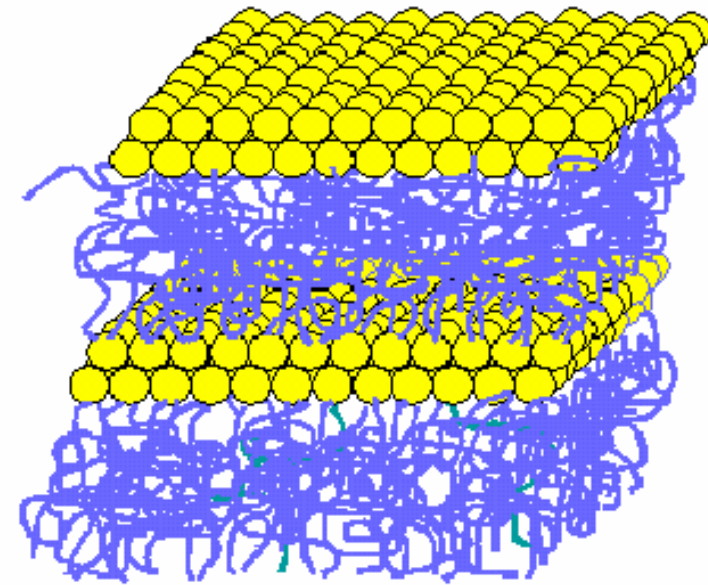
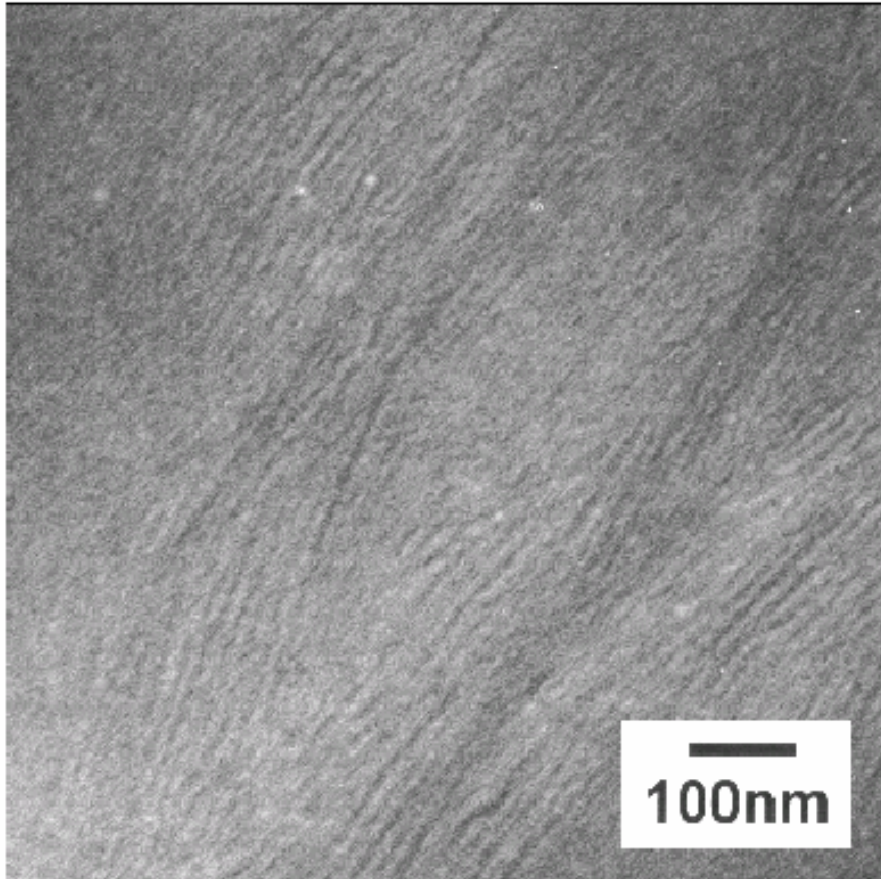


1. As a solid, POSS crystallizes





Nanoengineering with POSS

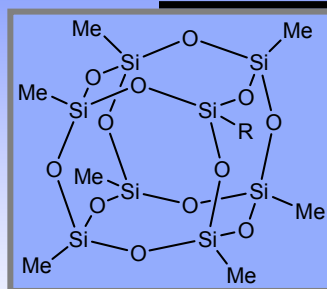


Bryan Coughlin-UMass

PBD-POSS4 (43wt%POSS)



Prof. Andre Lee i-PP/POSS Blends



	Dow data	Neat <i>i</i> -PP (processed)	<i>i</i> -PP blended 2 wt% Methyl ₈ T ₈	<i>i</i> -PP blended 5 wt% Methyl ₈ T ₈	<i>i</i> -PP blended 10 wt% Methyl ₈ T ₈
Tensile Strength @ Yield; ASTM D638	5000 psi (34.5 MPa)	4800 psi (33.0 MPa)	5000 psi (34.5 MPa)	5100 psi (35.1 MPa)	5200 psi (35.8 MPa)
Flexural Modulus (0.05 in/min); ASTM D790A	240,000 psi (1.655 GPa)	235,000 psi (1.620 GPa)	251,000 psi (1.730 GPa)	255,000 psi (1.757 GPa)	262,000 psi (1.80 GPa)
HDT @ 66 psi, as injected; ASTM D648	210 °F (99 °C)	210 °F (99 °C)	221 °F (105 °C)	239 °F (115 °C)	255 °F (124 °C)
Impact Izod @25C ASTM D256A	0.5 ft-lb/in	0.55 ft-lb/in	0.55 ft-lb/in	0.62 ft-lb/in	0.75 ft-lb/in

- **The above data (other than Dow's data) is an average of at least 10 samples for each test with acceptable S.D. of 5% or better.**

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Prof. Andre Lee

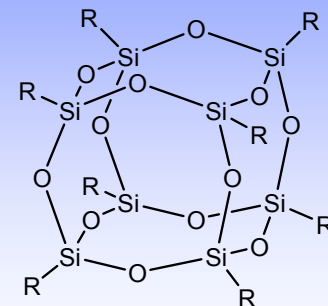


POSS: Where Are We Now (2004)

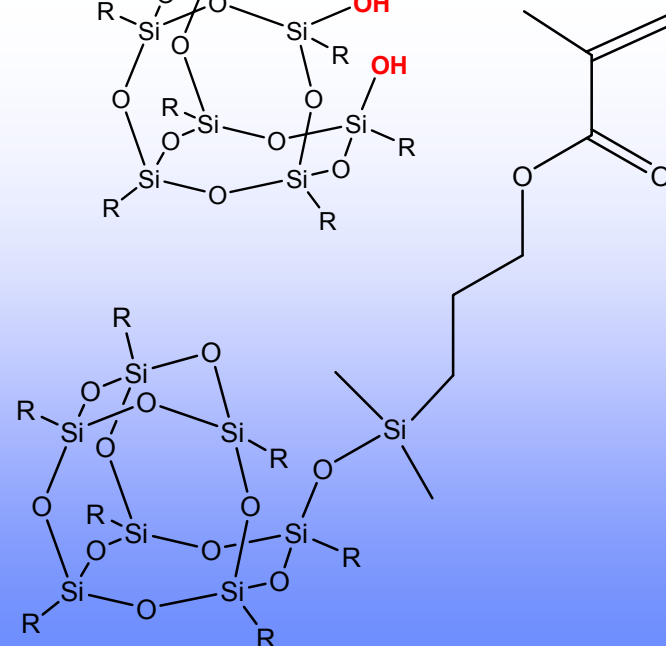
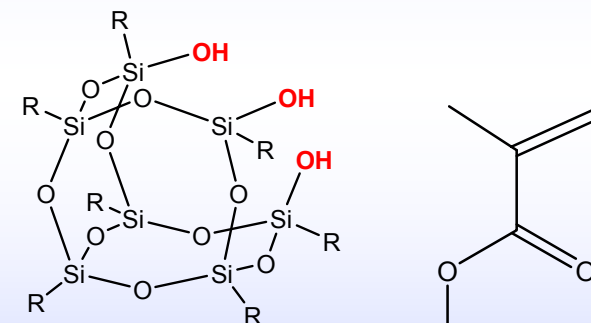
1996 data in red



- Cost: \$20-\$5000/lb (\$5000-\$1000/lb)
- Volume: Multi-ton (~20lb/yr)
- Production time: min 1 hour (11 days),
max 14 days (6 months)



- Versatility: >120 POSS (36 POSS)
monomers, feedstocks, polymers
- Many successful POSS blends
- Commercialized by Hybrid Plastics
www.hybridplastics.com





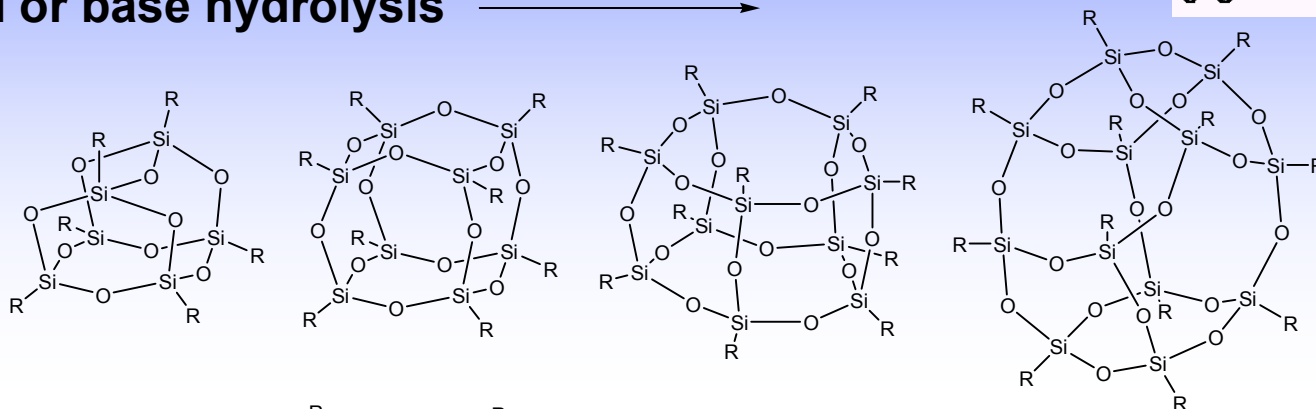
Polyhedral Oligomeric Silsesquioxanes (POSS)



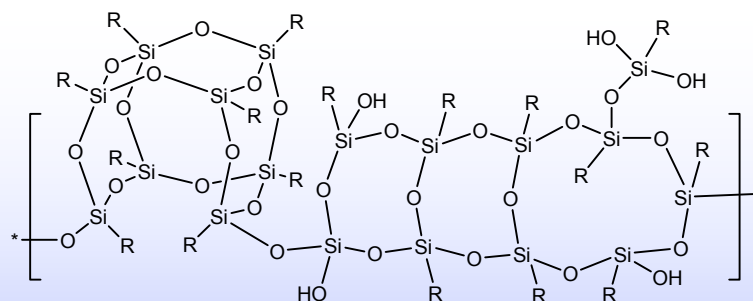
Hybrid
Plastics™

RSiX_3 acid or base hydrolysis $\longrightarrow$

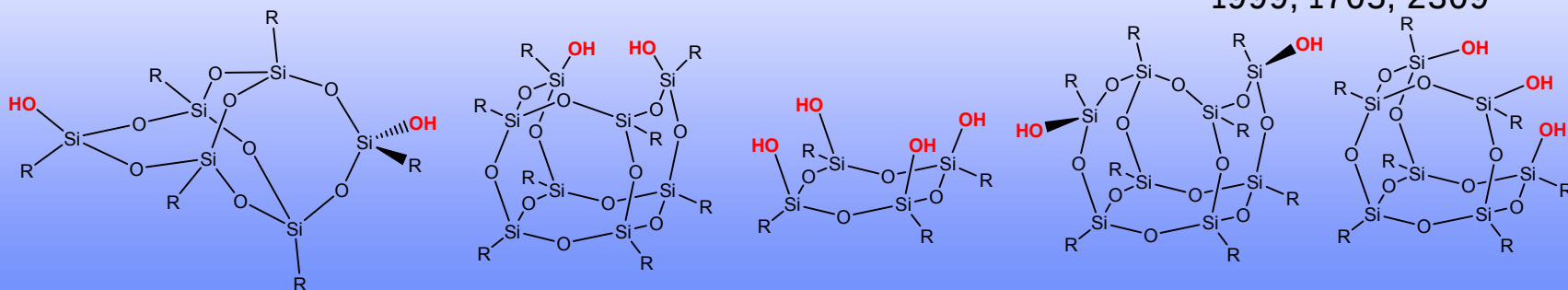
Blendables



Resin



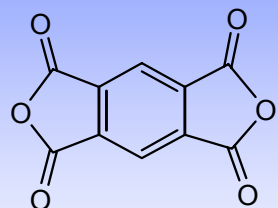
Brown & Vogt:
JACS, 1965, 4313
Feher et al:
JACS, 1989, 1741;
Organometallics, 1991,
2526; Chem Comm,
1999, 1705, 2309



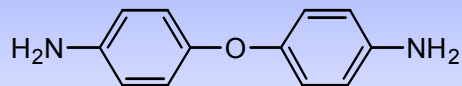
Incompletely condensed cages



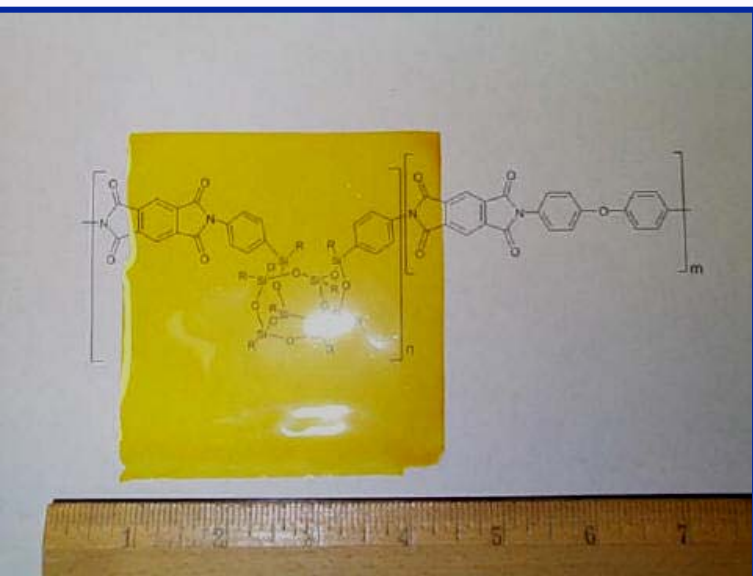
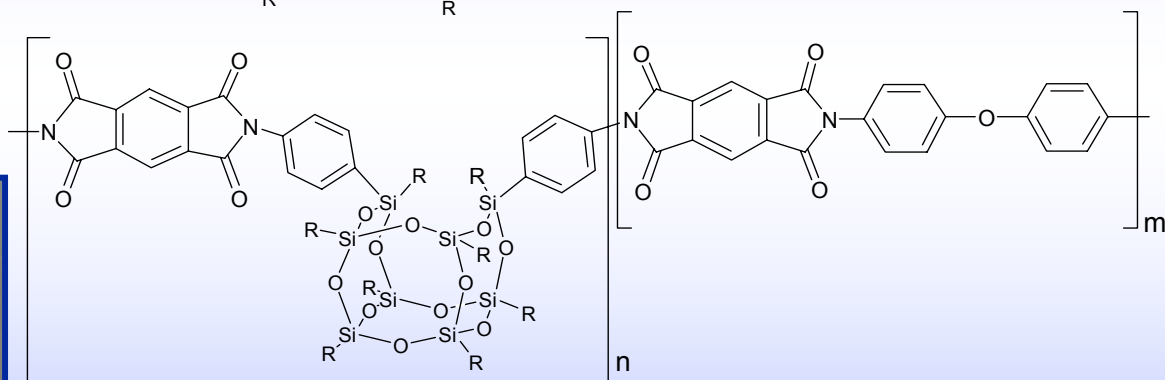
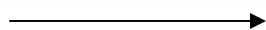
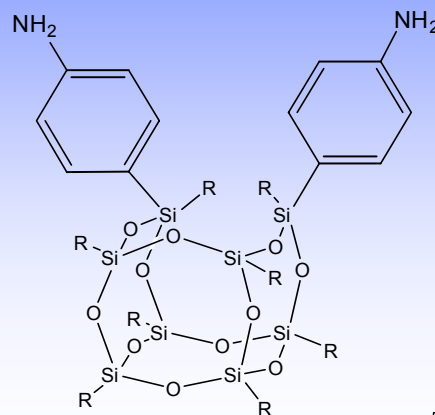
POSS-Kapton Polyimides



PMDA



ODA



- transparent films
- no aggregates formed

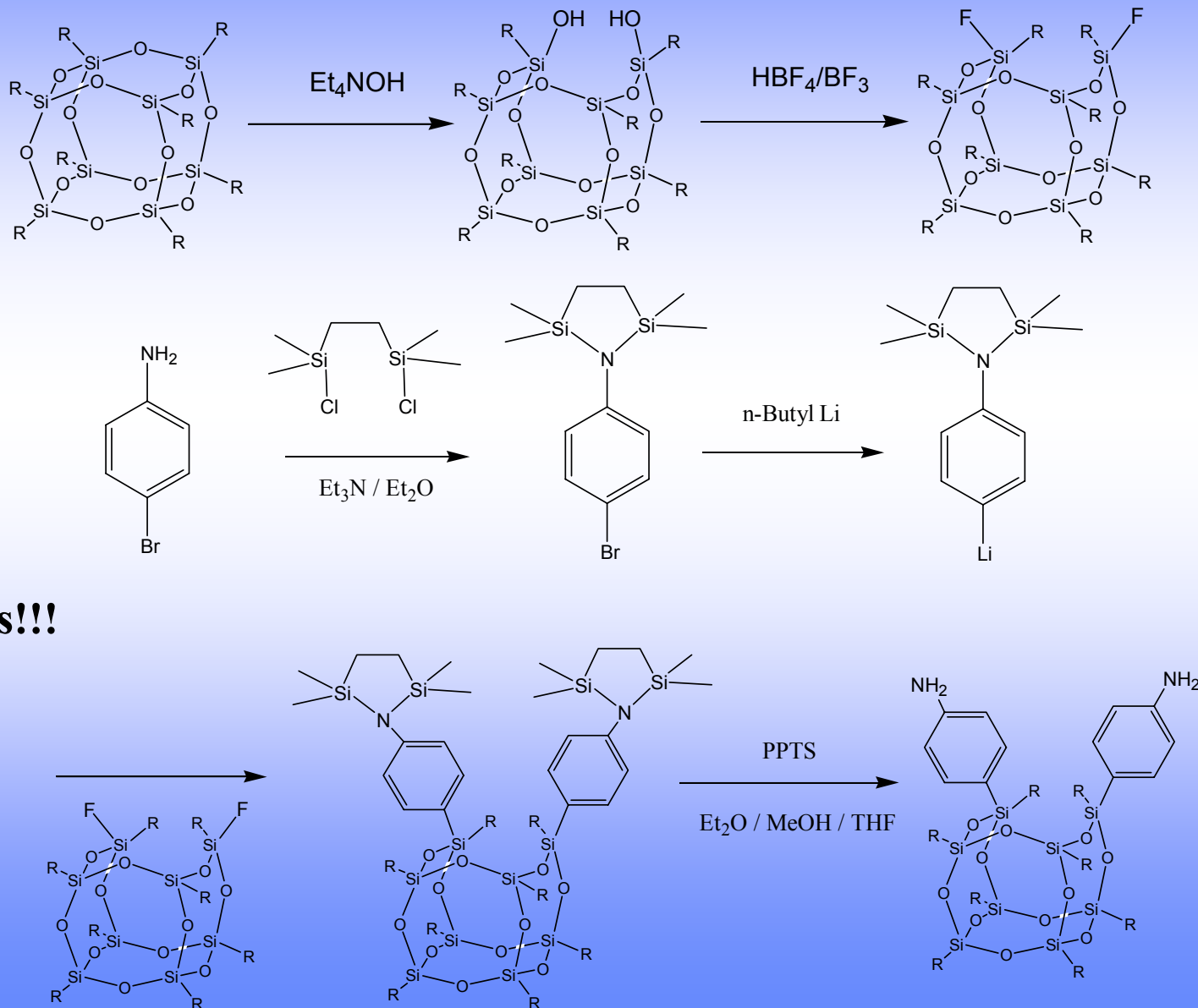


First POSS-Aniline Synthesis



**Multiple step
synthesis
Moisture and
air sensitive
Not amenable
to scale up**

**Yet Critical
for Development
of POSS Polyimides!!!**



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distribution unlimited.



Program Challenge: Synthesis of Cost Efficient POSS Diamines.

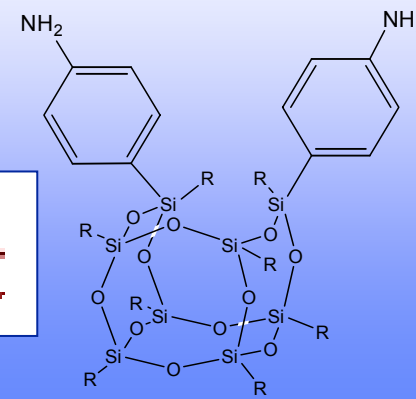


Make a cost efficient POSS Polyimide that is amenable to scale up and performs as well as current POSS Polyimide (POSSdi1 Polyimide).

This will involve:

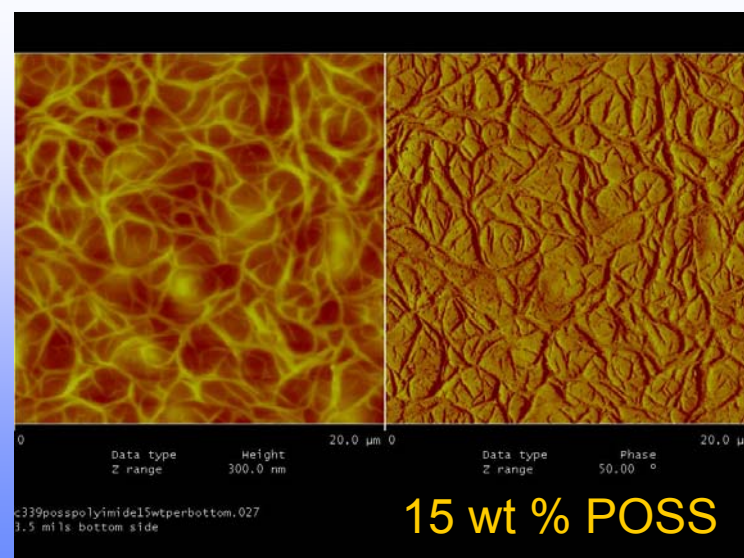
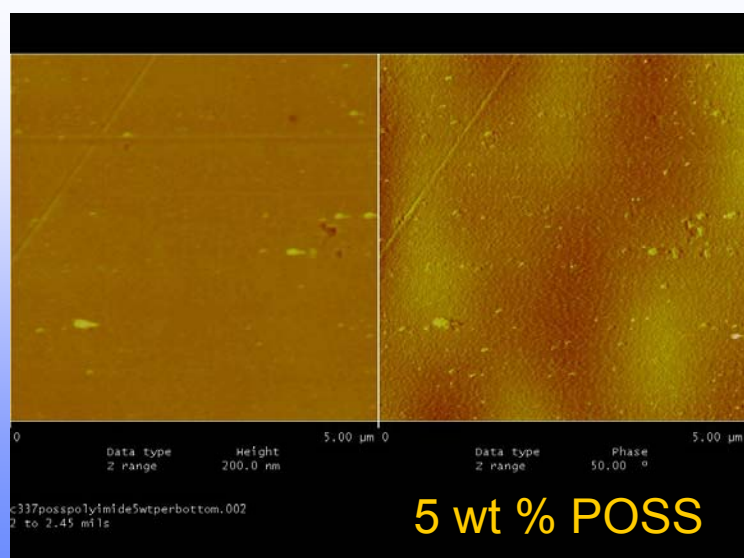
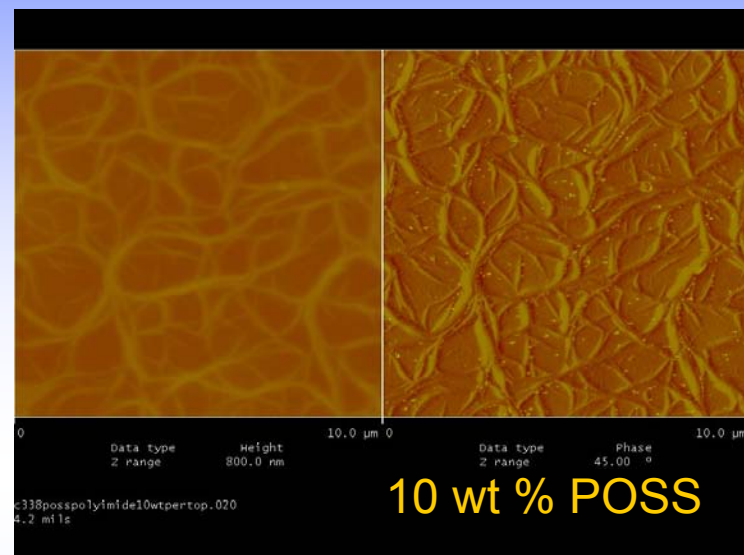
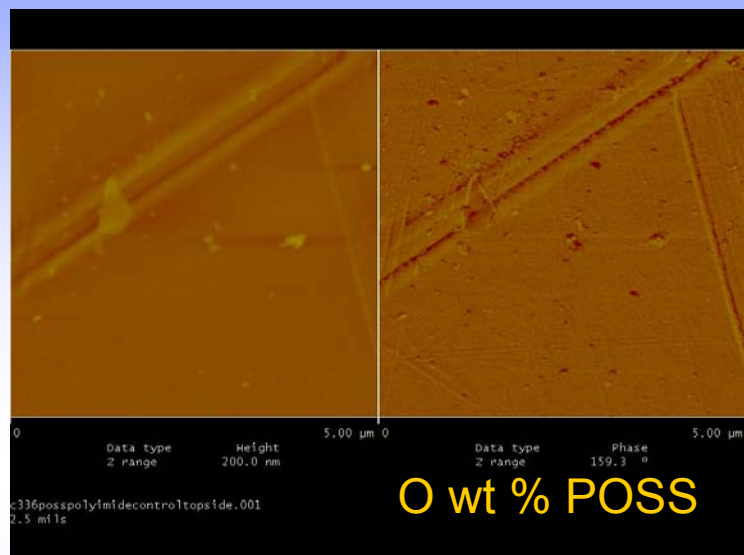
- Cost efficient synthesis of next generation POSS diamine monomers.
- Copolymerization of next generation POSS diamine monomers to form POSS Polyimides.
- Testing of thermal and mechanical properties and range of optical clarity.
- Imaging of POSS Polyimide films: Atomic Force Microscopy (AFM), Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM) with X-Ray mapping.
- Molecular modeling and simulation of oxygen atom, photon, electron, and proton attack on next generation POSS Polyimides.
- Simulated LEO and GEO exposure ground based testing.

UMassAmherst



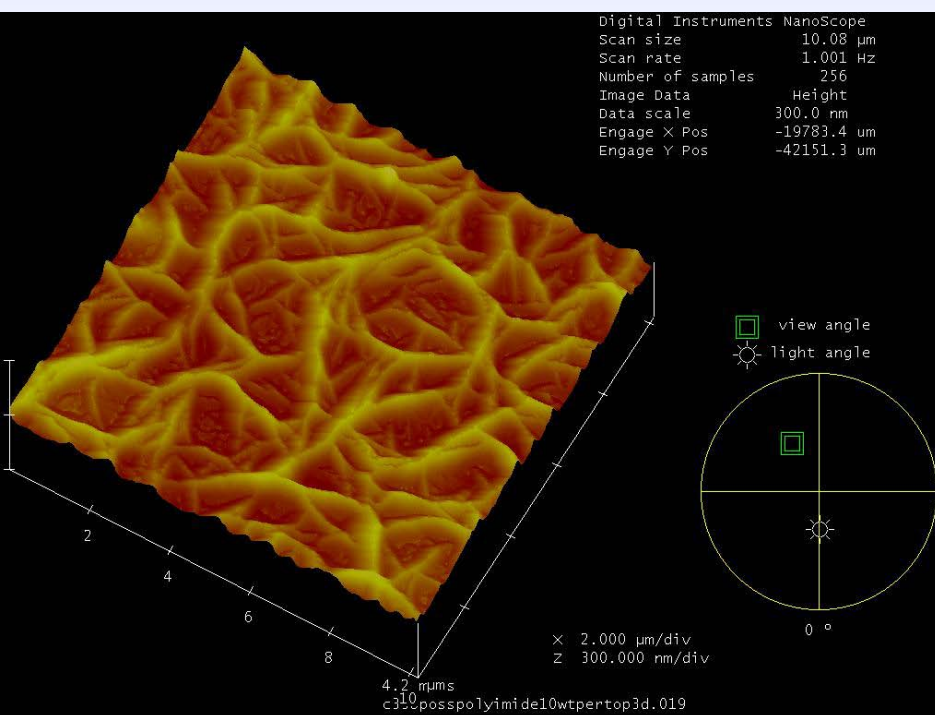


AFM Images of Unexposed Polyimides Copolymerized With Various Weight Percents of POSS

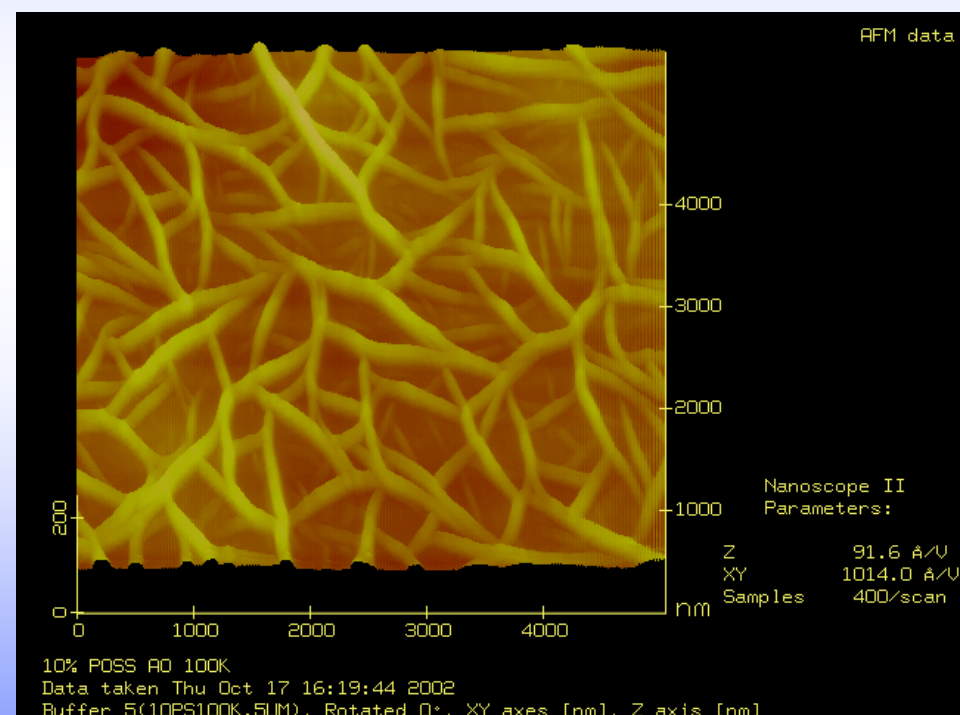




Three dimensional AFM Images 10 wt % POSS Polyimide Films



Unexposed



Exposed

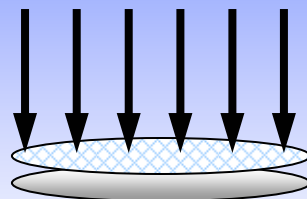


O-Atom Etching Experiment

Total AO fluence of 8.47×10^{20} atoms cm^{-2} (100,000 pulses)



Hyperthermal AO Beam

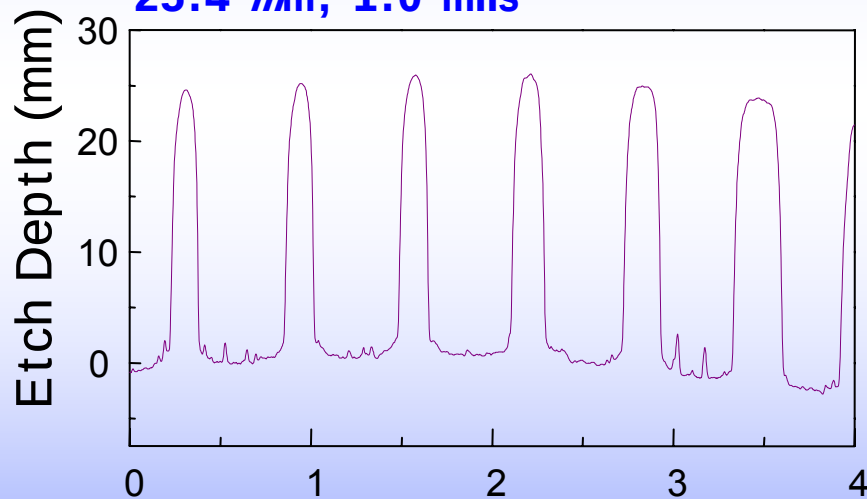


Screen
Sample

Kapton H Standard

Average etch depth:

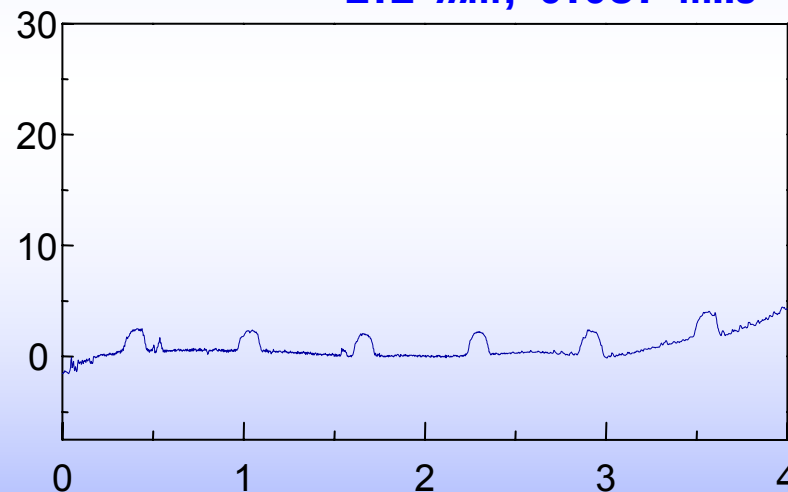
25.4 mm; 1.0 mils



Kapton 10 wt% POSS

Average etch depth:

2.2 mm; 0.087 mils



Scanning Length (mm)

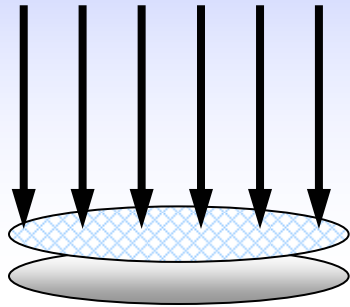
Significantly improved oxidation resistance due to a rapidly formed ceramic-like, passivating and **self-healing** silica layer preventing further degradation of underlying virgin polymer.



O-Atom etching experiment of POSS-Kapton polyimides

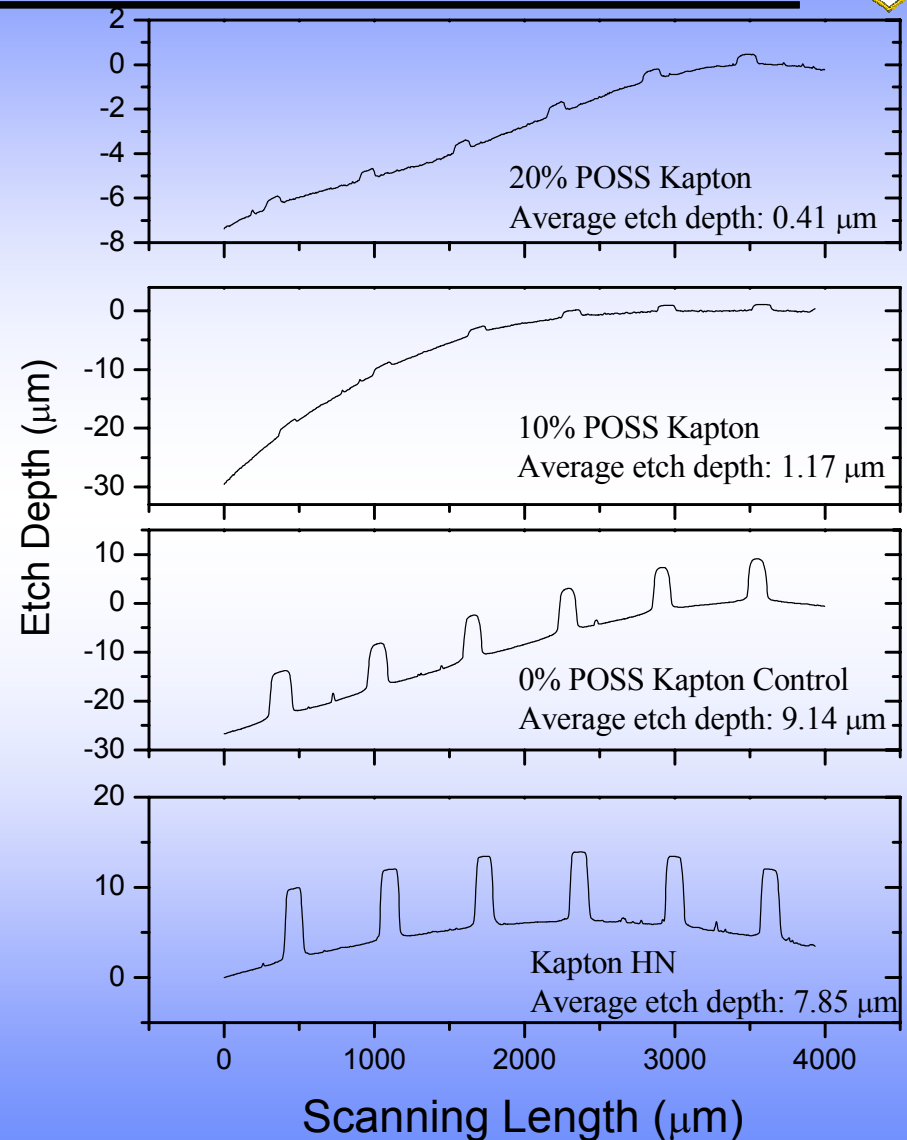
Total AO fluence of 2.62×10^{20} atoms/cm² (~ 3 Days in LEO)

Hyperthermal AO Beam



Screen
Sample

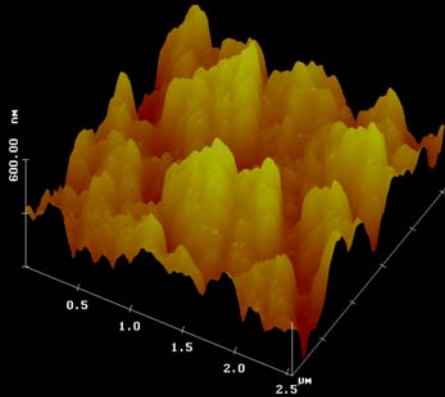
20 wt% POSS in Kapton results in over 20 time improvement in erosion resistance.





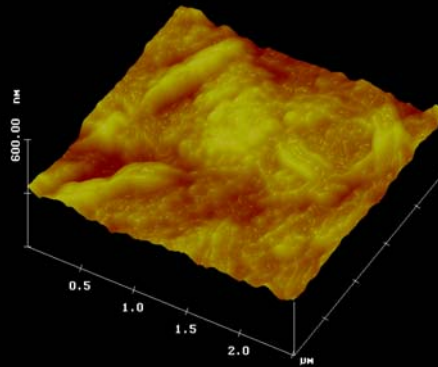
AFM Images of Unexposed POSS, 0%, 10%, and 20% POSS Polyimide Films

Pulses of Infrared AO Beam



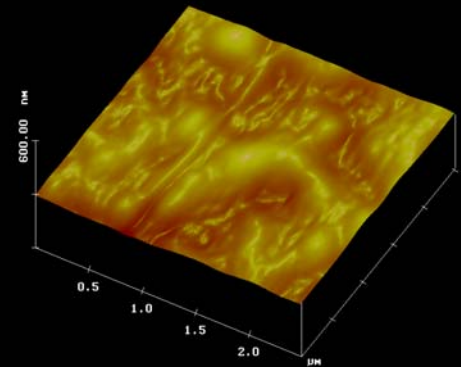
0% POSS

rms roughness:
11092 nm



10% POSS

rms roughness:
1.03 nm



20% POSS

rms roughness:
1655 nm



AFM Images of POSS Polyimides With increasing AO Flux.

(10 × 10 μm; z scale = 500 nm)



rms roughness →

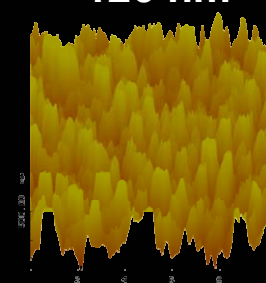
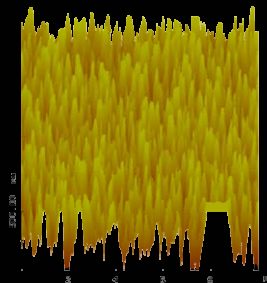
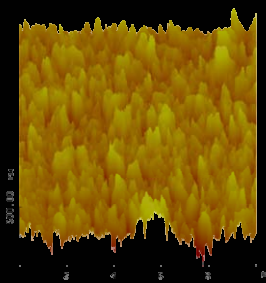
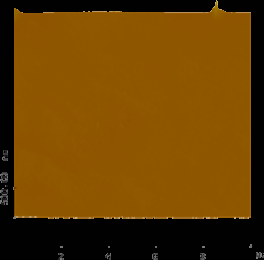
2.48 nm

70 nm

120 nm

126 nm

0 wt %
POSS Polyimide



rms roughness →

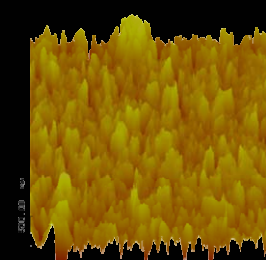
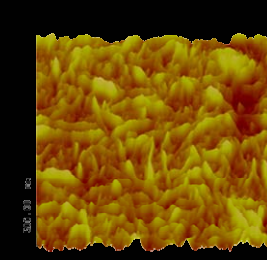
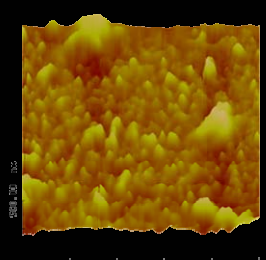
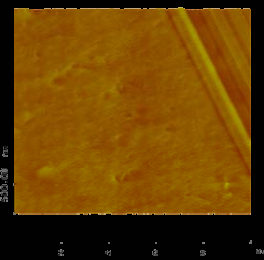
2.47 nm

22.4 nm

34.3 nm

78.9 nm

10 wt %
POSS Polyimide



rms roughness →

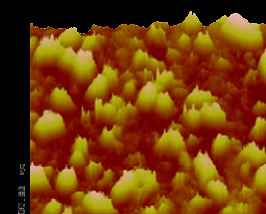
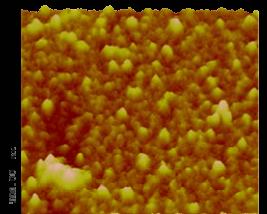
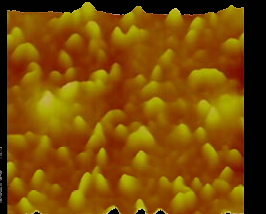
2.86 nm

17.2 nm

23.7 nm

39.1 nm

20 wt %
POSS Polyimide



AO fluence
(O atoms/cm²) →

0.0 cm⁻²

3.8×10^{19}

1.6×10^{20}

4.1×10^{20}

Note:

1×10^{20} O atoms/cm² is roughly equivalent to a spacecraft operating at 500 – 600 km orbit during nominal solar activity conditions for periods of at least 1 year.



X-ray Photoelectron Spectroscopy Analysis of POSS Polyimides



Surface Atomic Concentrations (%) determined from
XPS Survey Scans following Atomic Oxygen Exposure

Sample	Exposure (beam pulses)	Kapton-equivalent atomic oxygen fluence (10^{20} O atoms cm^{-2})	C	O	Si	N
0 wt% POSS polyimide	0	0	72	19.5	1	7
	6	~0.1	69	20	2	9
	100	1.63	69	24	1	6
	250	4.10	55	36	0	9
10 wt% POSS polyimide	0	0	77	16	2	5
	6	~0.1	73	18.5	5	3.5
	100	1.63	48	30	19	3
	250	4.10	20	56	23.5	0.5
20 wt% POSS polyimide	0	0	70	20	6	4
	6	~0.1	66	24	7	3
	100	1.63	20	54	25	0
	250	4.10	12	60	26	1



Erosion of POSS Polyimides by a Beam of Hyperthermal (5eV) O Atoms



Etch depths for 0, 10, and 20 wt % POSS Polyimide films as a function of O-atom fluence.

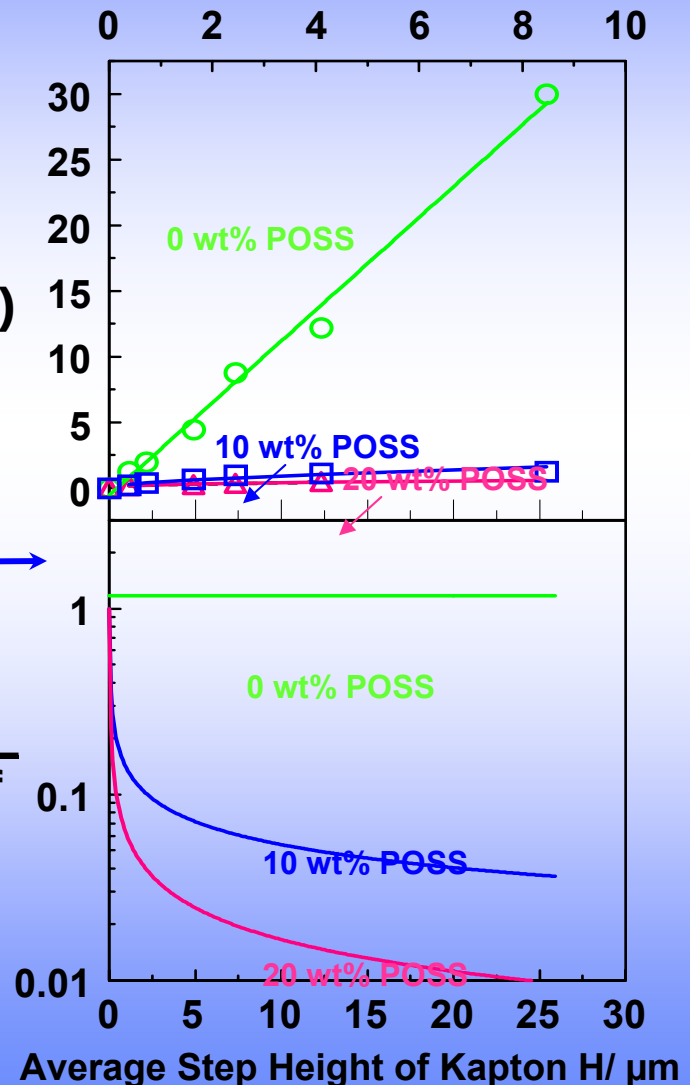
The erosion yields* of the 10 and 20 wt % POSS Polyimide samples were 3.7 and 0.98 percent, respectively, of the erosion yield for Kapton H at the highest fluence used in this experiment (8.5×10^{20} atoms cm^{-2}).

*Erosion Yield = $\frac{\text{erosion depth step height (cm)}}{\text{AO fluence atoms/cm}^3}$

Average Step Height of POSS Polyimide (μm)

Average Step Height of POSS Polyimide
Average Step Height of Kapton H

Kapton-Equivalent Fluence / 10^{20} O atoms cm^{-2}





Molecular dynamics calculations of $O(^3P)$ collisions (5 eV) with POSS ($Si_8O_{12}H_8$) cages

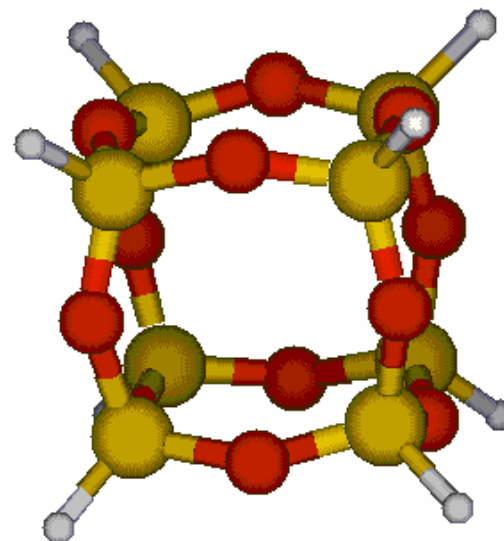


Possible Reaction Channels:

- H abstraction to give OH
- H elimination (O adds to the cage)
- Cage opening (O adds to the cage)

Number of trajectories	103
Impact parameter	7 a.u.*
Inelastic	63
H abstraction	3
H elimination	22
Cage opening	15

*(~Half diagonal of the Si_4 faces + 3 a.u.)

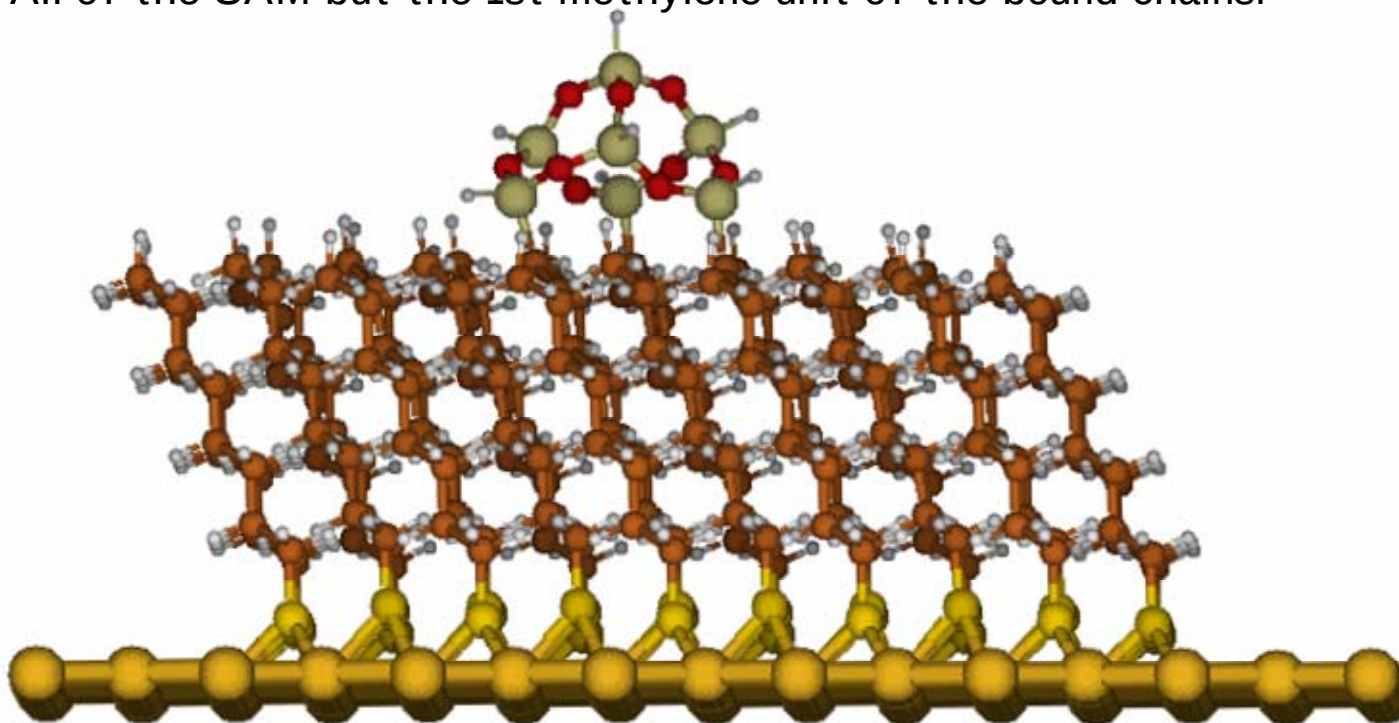




Model System: POSS Coated Alkane Thiol Self-Assembled Monolayer (SAM) on a Gold Surface.



- **Molecular dynamics** calculations of **O(³P) collisions** (5 eV) with “functionalized” **POSS**.
- **Method:** Classical trajectories with a **QM/MM** (quantum mechanics / molecular mechanics) **hybrid potential**.
 - QM part: O(³P), POSS cage and 1st methylene unit of the bound chains.
 - MM part: All of the SAM but the 1st methylene unit of the bound chains.



- **Results:** Of limited trajectories studied, similar mechanisms of O atom attack on POSS (Si₈O₁₂H₈) Cages were found to apply to the studies of the POSS coated SAM.



Molecular Modeling Objectives



1. **AO degradation pathways of polyimide** when exposed to 5 eV oxygen.
2. **Oxidation of POSS** cage by 5 eV AO.
3. Penetration of 5 eV AO through POSS and silica layers to **determine the SiO₂ layer thickness needed to quench reaction** with an underlying polymer layer.



MATERIALS INTERNATIONAL SPACE STATION EXPERIMENT



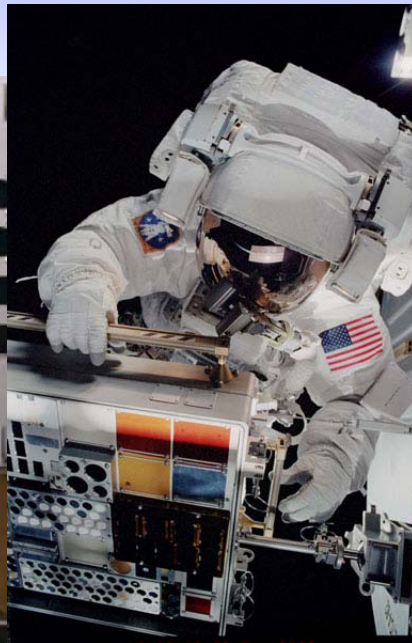
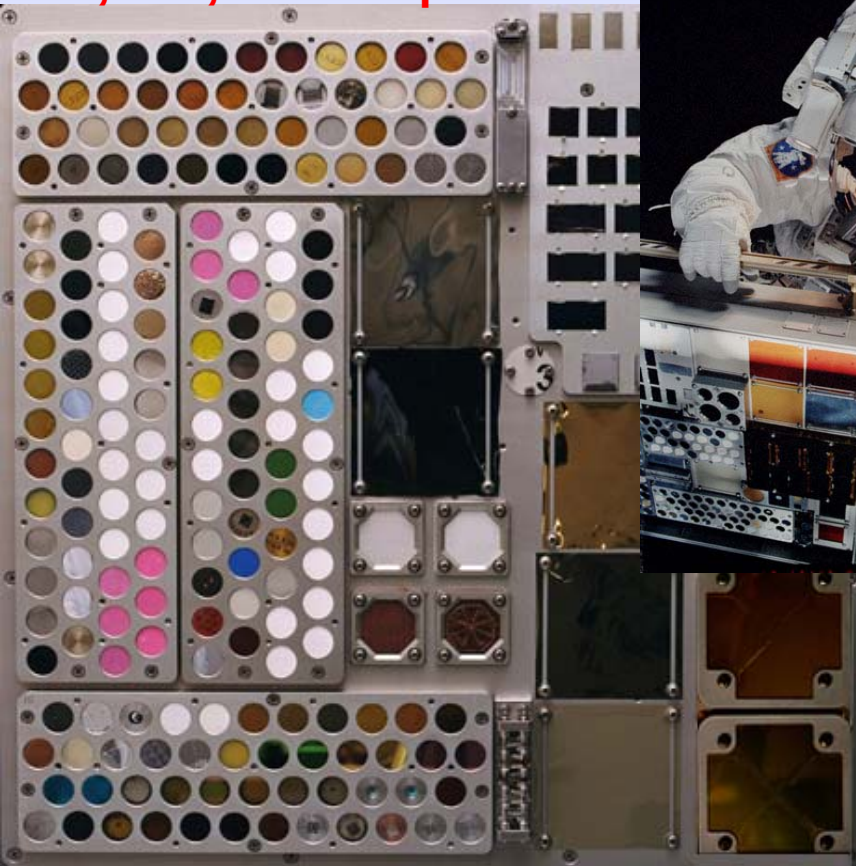


MATERIALS on the INTERNATIONAL SPACE STATION EXPERIMENT



POSS-Polymers Fly on STS 105 Discovery and are deployed on the International Space Station 16 Aug 2001, MISSE 4

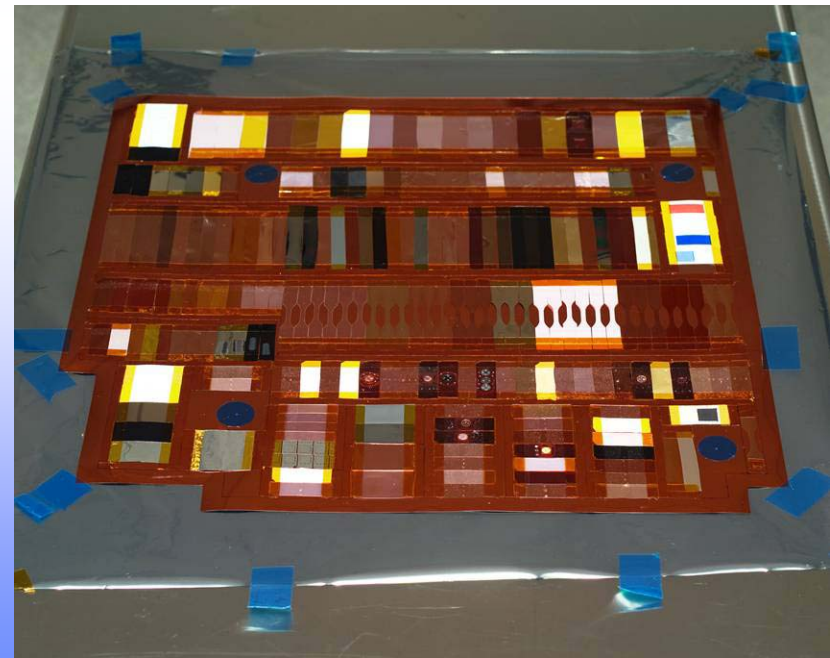
AO, UV, VUV exposure.



POSS-Polymers awaiting flight on ISS, MISSE 5

AO exposure only.

SALT Sprayed Samples!

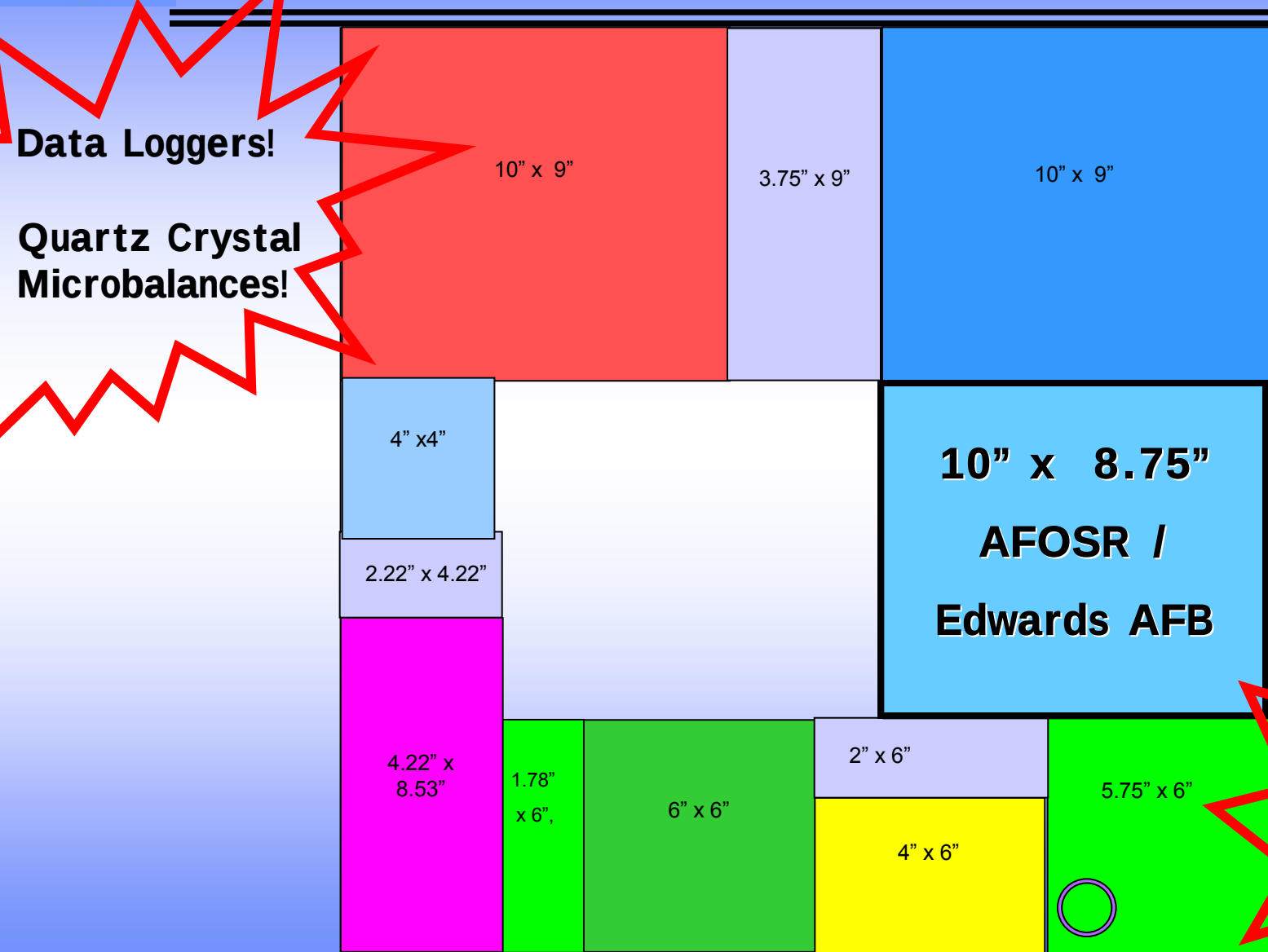


Footage courtesy of NASA

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MISSE-6 Experiment Tray Layout: AO and UV Side



Data Loggers!

Quartz Crystal Microbalances!

Same amount of space on "UV only" tray!

Effects of POSS on Thermal and Mechanical Properties of Polyimides



➤ **POSS Polyimides do not lose rigidity above the T_g .**

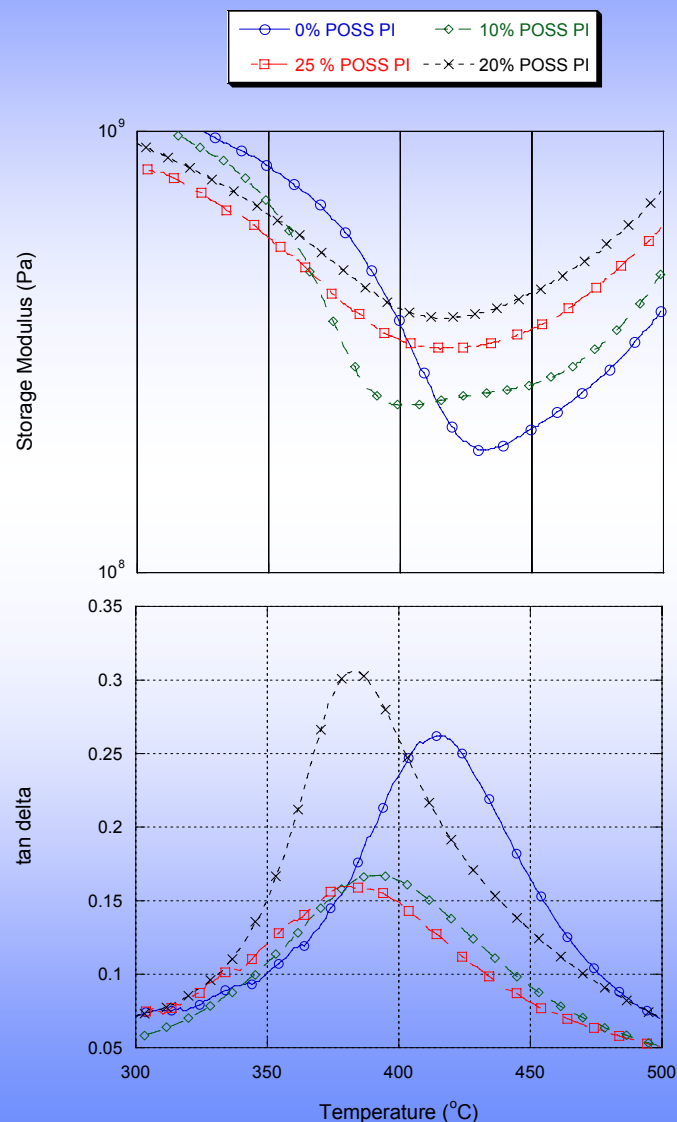
Room temperature modulus (stiffness) unaffected by POSS.

High temperature (430°C) modulus exhibits a maximum with POSS PI loading at 20 wt%:

@ 430°C , the modulus of 20 % POSS Polyimide doubles relative to 0 % POSS polyimide.

➤ **T_g of POSS polyimides is 5 - 10 % lower than polyimides (414°C).**

Tan δ peaks for the 20 and 25 wt% are lower intensity and broader indicating that at POSS loadings greater than 20 wt% there exists interactions between the POSS molecules strong enough to significantly affect polymer chain dynamics.





Acknowledgments



Polymer Working Group: Dr. Tim Haddad, Dr. Joe Mabry, Mr. Pat Ruth,
2Lt. Laura Moody, Mrs. Sherly Large, 2Lt. Amy Palecek.

Previous Group Members: Capt. Rene Gonzalez, Ph. D.

Branch Chief: Dr. Shawn Phillips

Collaborators:

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Dr. Alan Hopkins, Dr, Gary Steckle

Hybrid Plastics

University of Montana State; Dr. Tim Minton

Northwestern University: Dr. George Schatz



Summary and Conclusions



- **Our goal is to create an efficient drop-in replacement for Kapton that is:**
 - **Space survivable**
 - **Self passivating**
 - **Self healing**
 - **low in solar absorptance**
 - **Excellent in mechanical properties**
- **POSS Polyimides form a protective Si-O layer when exposed to Atomic Oxygen**
- **Modeling and Simulation Plan has shown that AO adds to the POSS molecule and does not pass through POSS.**
- **Thermal and Mechanical Testing indicate:**
 - **POSS Polyimides do not lose rigidity above the Tg.**
 - **Tg of POSS polyimides is 5 - 10 % lower than polyimides (414°C).**
 - **Analysis of $\tan \delta$ curves indicate that polymer chain dynamics are affected by the addition of POSS**
- **POSS-Polymers awaiting flight on ISS, MISSE 5 and scheduled to fly on MISSE 6.**



Abstract



Polyimides such as Kapton are used extensively in spacecraft thermal blankets, solar concentrators, and space inflatable structures. Atomic oxygen (AO) in lower earth orbit (LEO) causes severe degradation in Kapton resulting in reduced spacecraft lifetimes. One solution is that SiO_2 coatings impart remarkable oxidation resistance and have been widely used to protect Kapton.

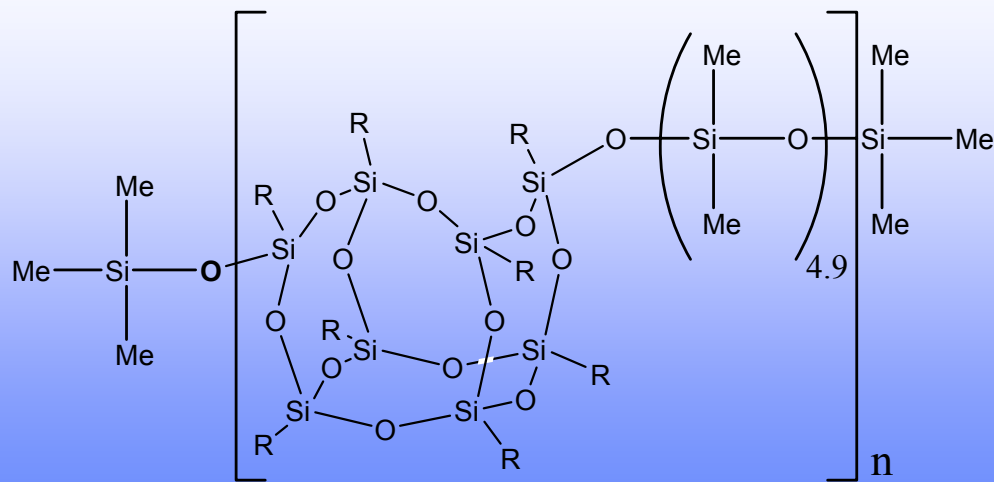
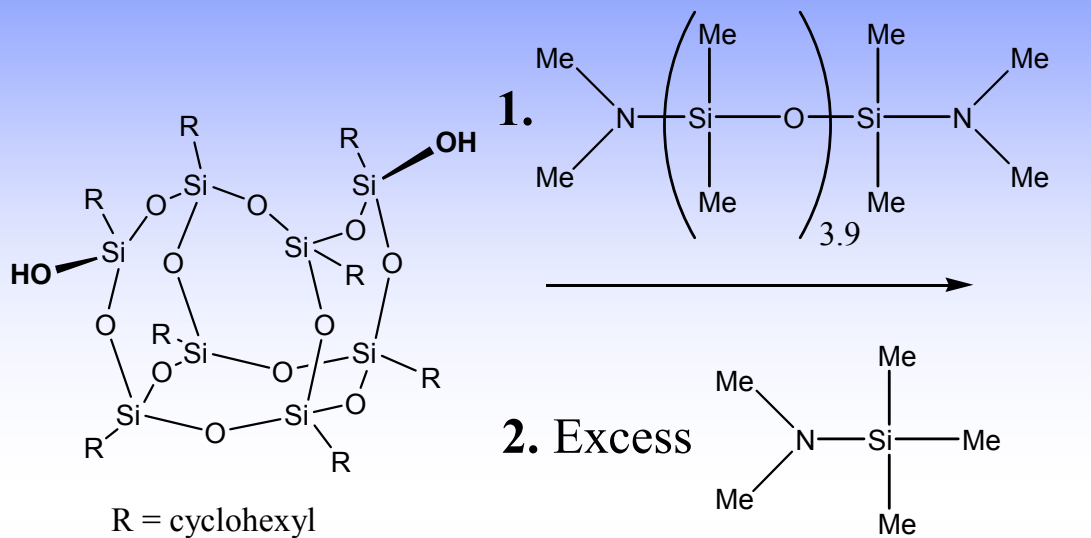
Imperfections in the SiO_2 application process and micrometeoroid / debris impact in orbit damage the SiO_2 coating leading to erosion of Kapton.

A self passivating, self healing silica layer protecting underlying Kapton upon exposure to AO may result from the nanodispersion of silicon and oxygen within the polymer matrix. Polyhedral oligomeric silsesquioxane (POSS) composed of an inorganic cage structure with a 2:3 Si:O ratio surrounded by tailor able organic groups is a possible delivery system for nanodispersed silica. A POSS diamine was copolymerized with pyromellitic dianhydride and 4,4'-oxydianiline resulting in POSS Kapton Polyimide. The glass transition temperature (T_g) of 5 to 20 weight % POSS Polyimide was determined to be 5 – 10 % lower than that of unmodified polyimides (414 °C). Furthermore the room temperature modulus of polyimide is unaffected by POSS, and the modulus at temperatures greater than the T_g of the polyimide is doubled by the incorporation of 20 wt % POSS.

To simulate LEO conditions, POSS Polyimide films were exposed to a hyperthermal O-atom beam. Surface analysis of exposed and unexposed films conducted with X-ray photoelectron spectroscopy, atomic force microscopy, and surface profilometry support the formation of a SiO_2 self healing passivation layer upon AO exposure. This is exemplified by erosion yields of 10 and 20 weight % POSS Polyimide samples which were 3.7 and 0.98 percent, respectively, of the erosion yield for Kapton H at a fluence of 8.5×10^{20} O atoms cm^{-2} .



POSS - Siloxane

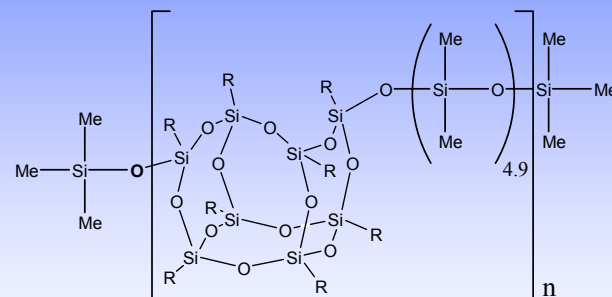
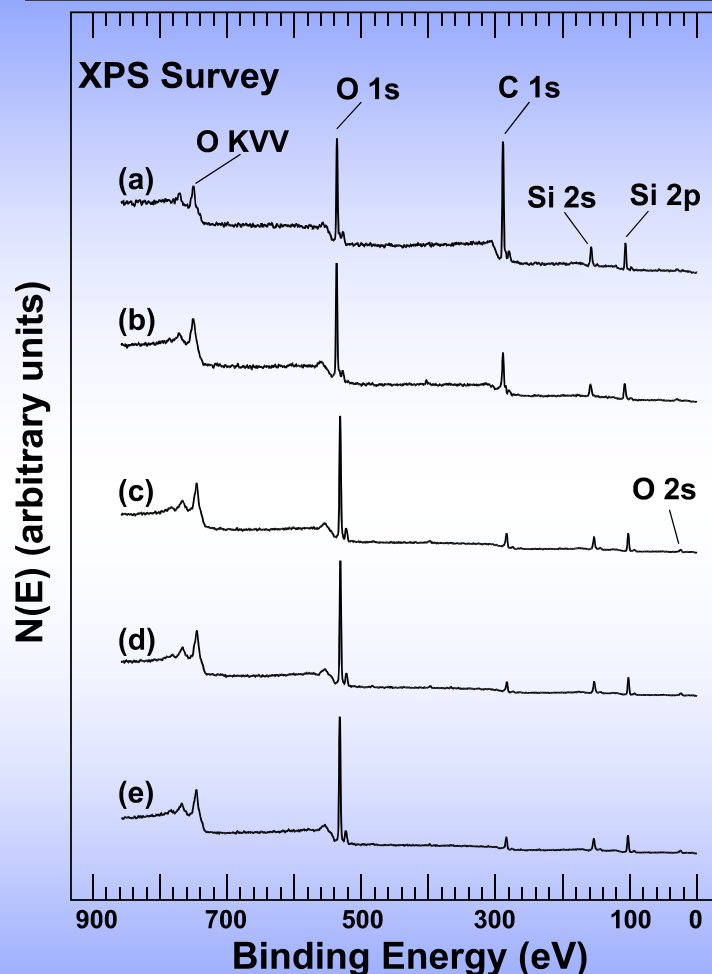


$n = 43$

POSS-PDMS Copolymer



POSS Siloxane



Composition, at %

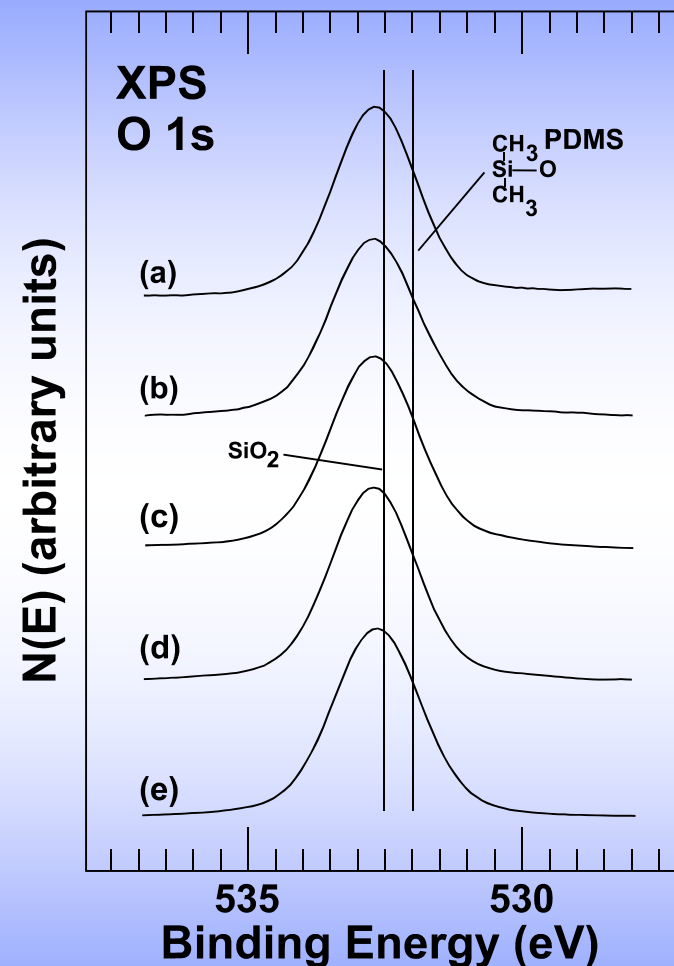
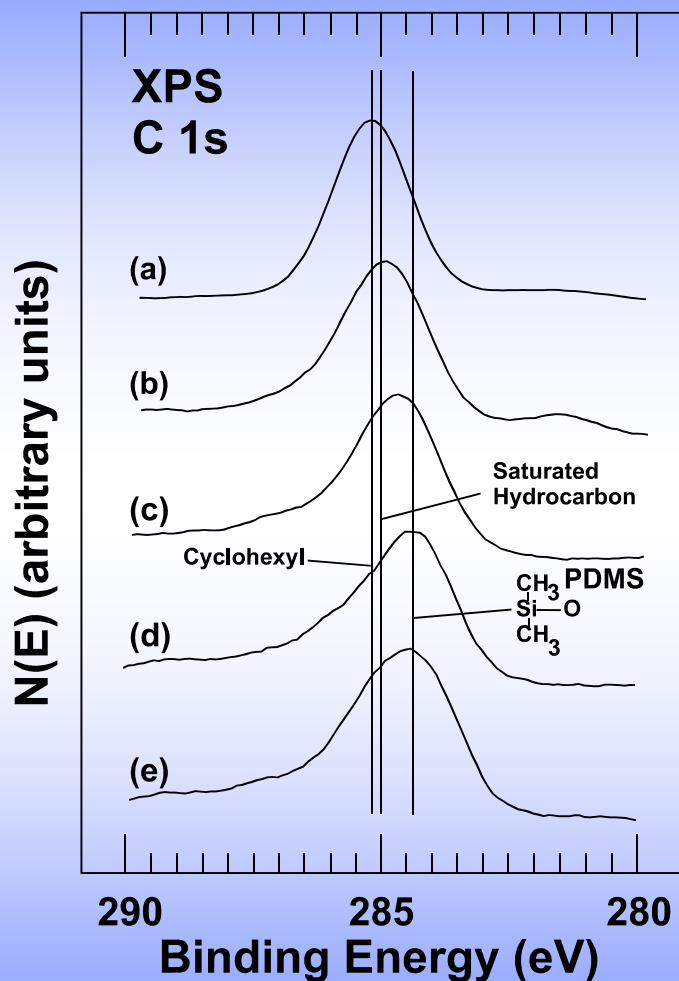
Sample Treatment	O	C	Si
As entered	18.5	65.0	16.6
2.0 hr	33.8	48.4	17.8
24.6 hr	49.1	22.1	28.8
63.0 hr	55.7	16.3	28.0
4.8 hr air	52.8	19.5	27.7

Gonzalez, R. I., Phillips, S. H., Hoflund, G. B., *J. of Spacecraft and Rockets*, Vol 37, No. 4, **2000**, pp. 463-467.

XPS survey spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.



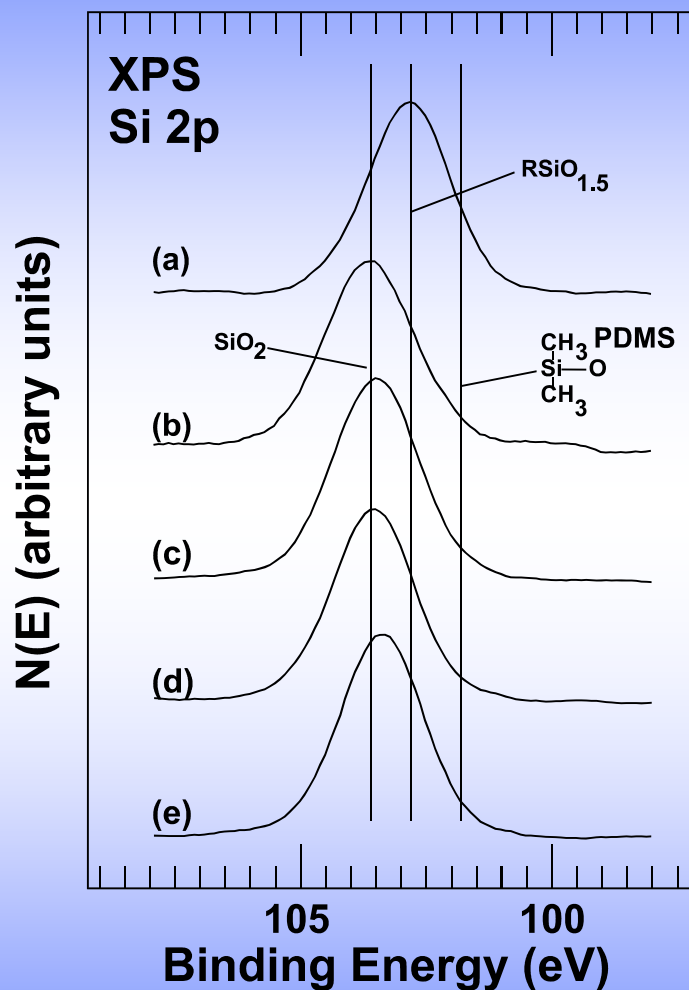
POSS PDMS



High Resolution C 1s and O 1s spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.



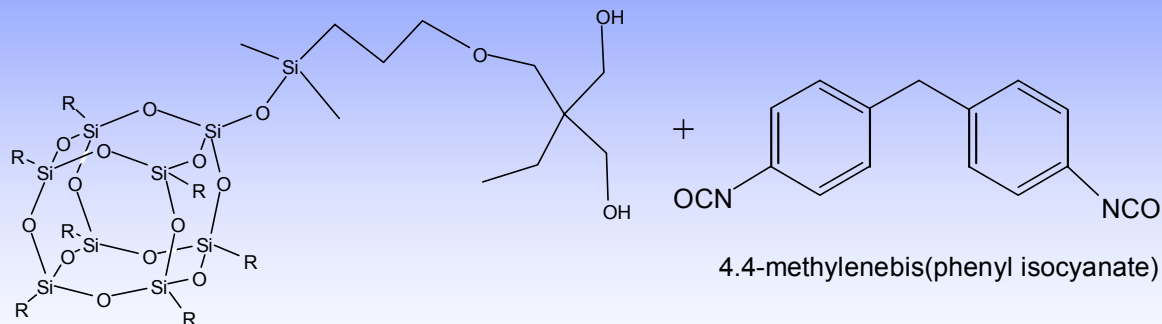
POSS PDMS



High Resolution Si 2p spectra obtained from a solvent-cleaned, POSS-PDMS film (a) after insertion into the vacuum system, (b), after a 2-hr (c) 24.6-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 4.75-hr air exposure following the 63-hr AO exposure.



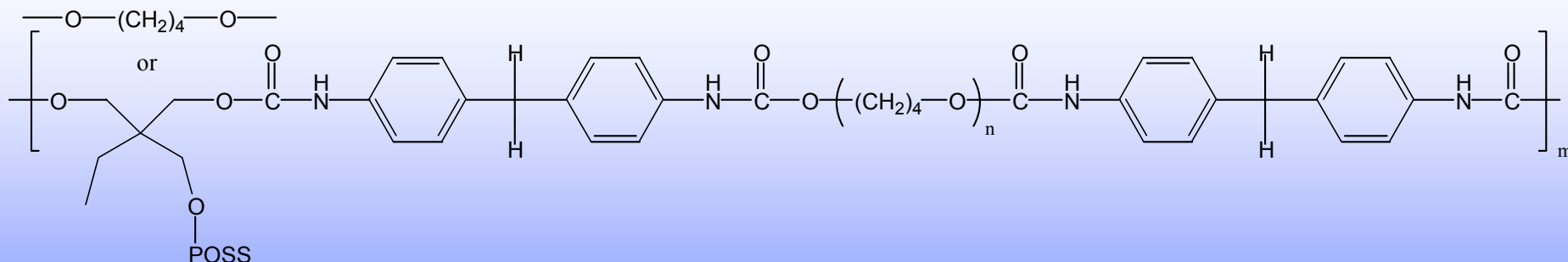
POSS-Polyurethane



4,4'-methylenebis(phenyl isocyanate)

R = cyclopentyl
POSS-TMP diol

Et₃N/DBTDL
PTMG (M_n=2000)
1,4-butanediol

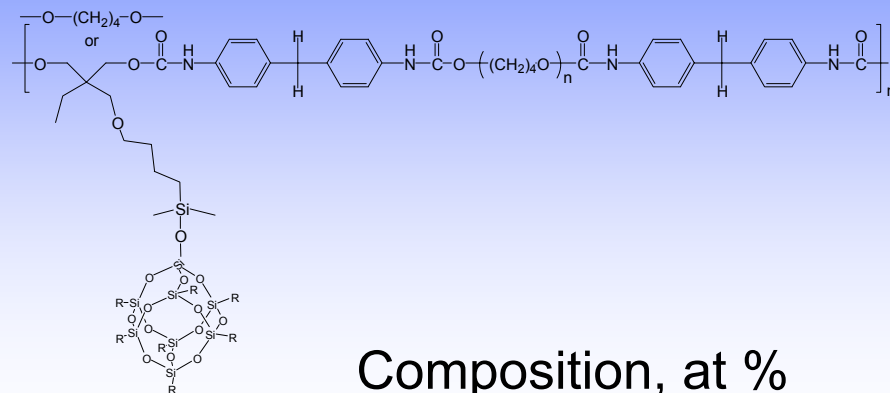
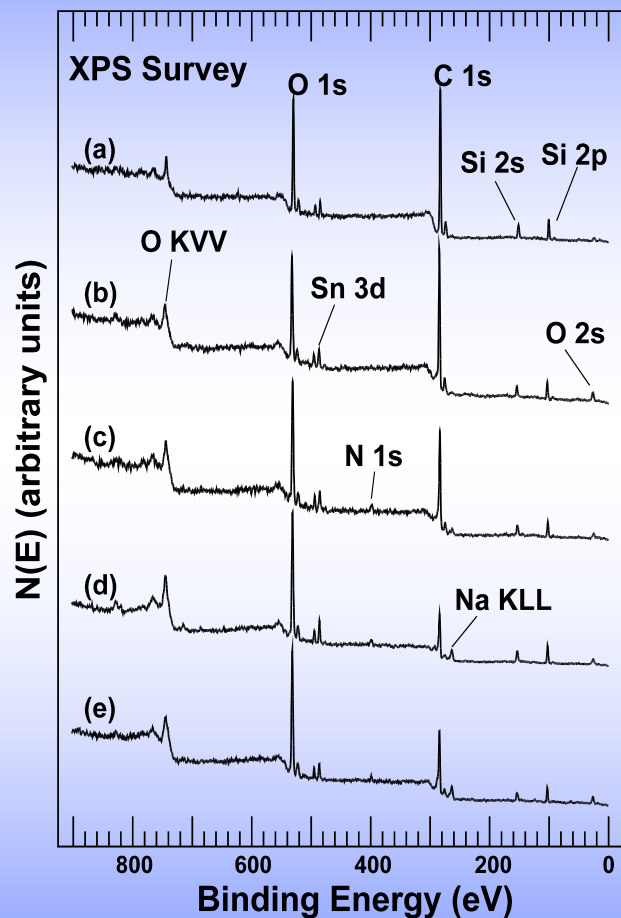


Fu, B.X., et al. *High Performance Polymers*, **2000**. 12(4): p. 565-571.

Fu, B.X., et al. *Polymer*, **2001**. 42(2): p. 599-611.

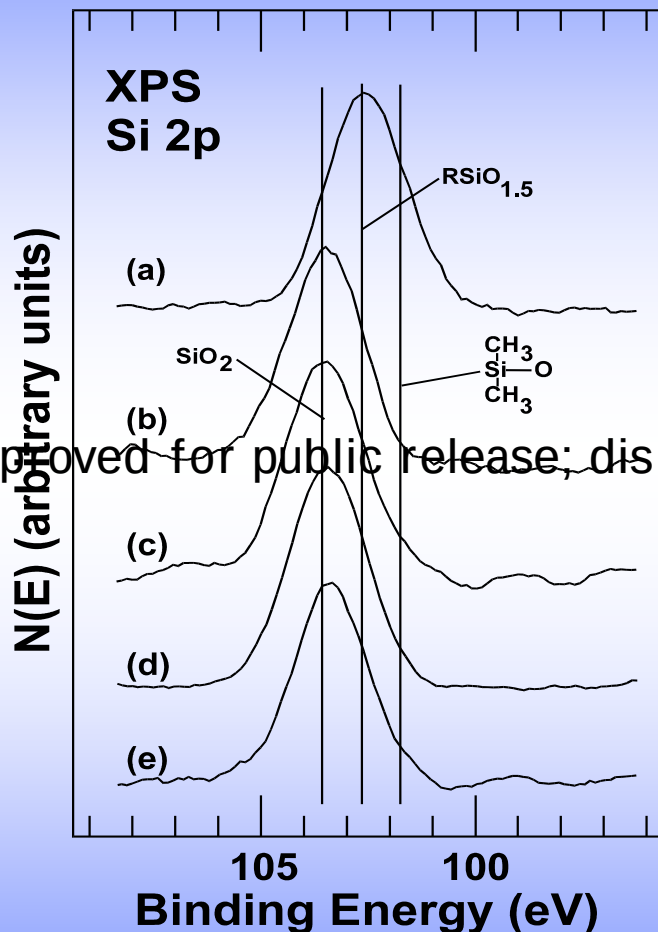


60 wt % POSS-Polyurethane



Sample Treatment	O	C	Si	Sn	Na	N
As entered	18.2	70.1	11.3	0.4	-	-
2.0-hr	17.5	70.2	11.2	0.7	0.4	-
24.0-hr	23.7	58.2	13.2	0.9	1.4	2.6
63.0-hr	35.3	37.3	20.4	1.3	3.0	2.7
3.3-h air	31.6	48.5	14.6	1.0	2.7	1.6

Phillips, S. H., Hoflund, G. B., Gonzalez, R. I., 45th International SAMPE Symposium, 2000, Vol. 45, No. 2, pp. 1921-1931.

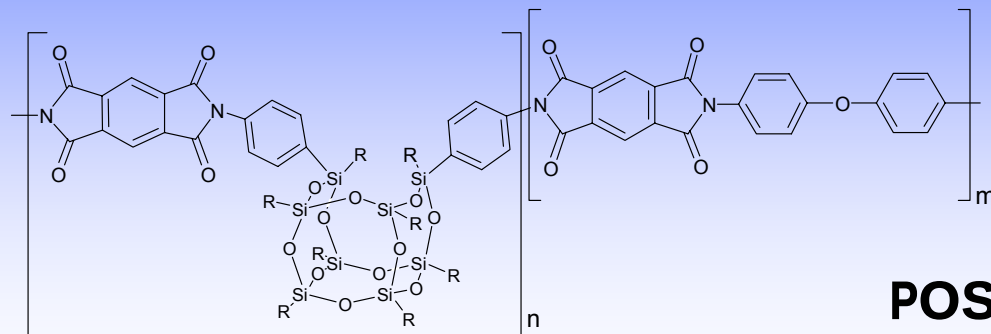


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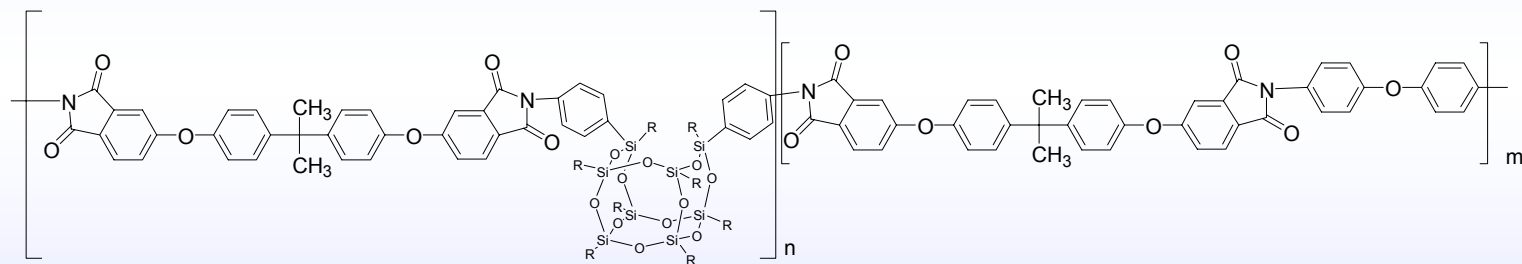
High Resolution Si 2p spectra from a 60 wt% POSS-PU (a) after insertion into the vacuum system, (b) after a 2-hr (c) 24-hr and (d) 63-hr exposure to the hyperthermal AO flux, and (e) 3.3-hr air exposure following the 63-hr exposure.



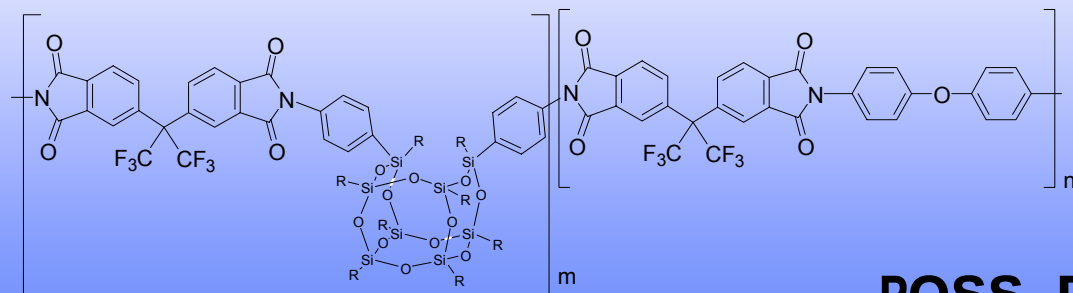
POSS High Performance Polyimides



POSS-Kapton polyimide



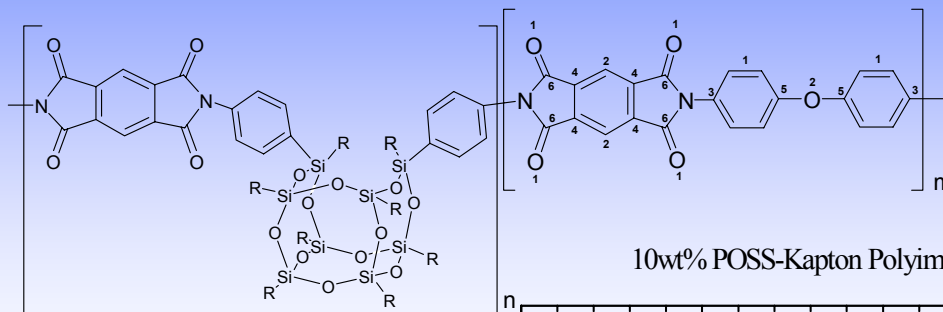
POSS processable ether-imide



POSS-Fluorinated colorless polyimide



POSS Polyimide



10wt% POSS-Kapton Polyimide

