GSFC· 2015

Contamination Control for Thermal Engineers

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NASA/GSFC/Code 546

Agenda

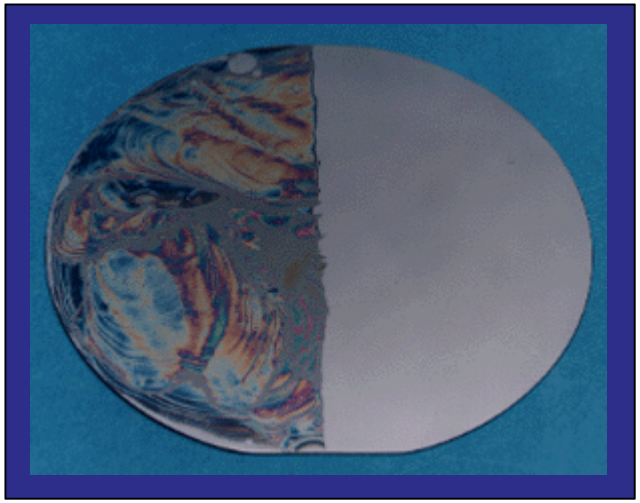
- Contamination Overview
- Effects of Contamination on Flight Hardware
- Contamination Requirements
- Design Methodology
- Integration and Testing
- Launch Site Support
- Contamination Control & Prevention

Contamination Overview

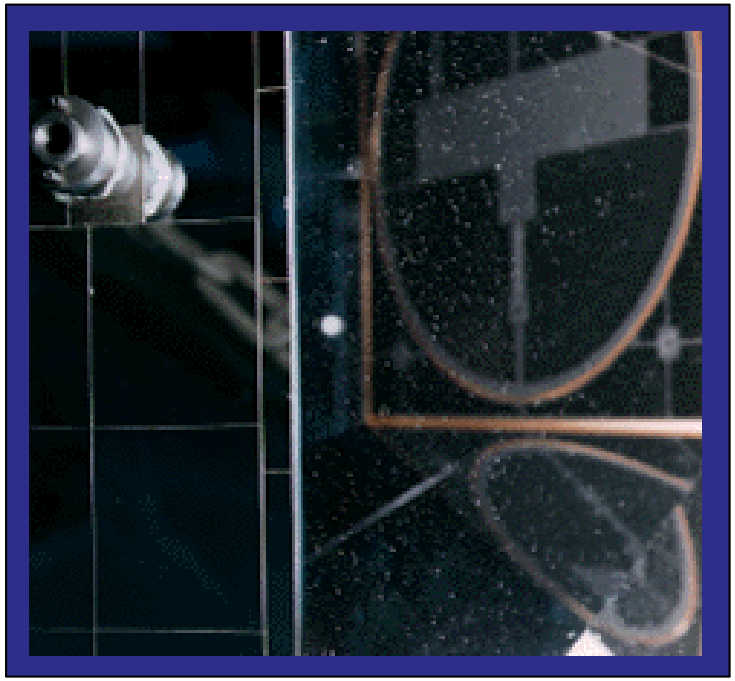
Contamination Overview

There are 2 types of Contamination

- **Particulate: dust, debris, skin cells, fibers**
- **Molecular: films, greases, skin oils, ice**



Molecular Contamination on a Si Wafer



Particulate contamination on Radiators

Contamination Overview (Cont)

In order to mitigate performance degradation of space flight hardware caused by contamination, a Contamination Control Program is established on the Mission.

- Understand the design: what are the critical components, what are their sensitivities, and their performance requirements
- How can the S/C & instrument design help mitigate contamination
- Establish a Contamination Control Program
- Implement contamination control protocols
- Clean, monitor, verify, and maintain cleanliness

Why do we Have Contamination Requirements?

- Meet Mission and Science Objectives
- Maintain Long-Term Hardware Performance
- Prevent Against Cross-Contamination Across the S/C
- Maintain Cleanliness Levels
- Why are Contamination Requirements Important?
- Meet Mission Success

MISSION SUCCESS!!!

Summary of Spacecraft Contamination Problems

Spacecraft	Contamination Problem
OGO-6 (1969)[a]	Excessive build-up on QCMs due to solar array outgassing.
Nimbus IV (1970)[a]	Water build-up on cooled detectors caused failure of a spectrometer early in the mission.
OSO-8 (1975)[a]	Lost 3 orders of magnitude in throughput at Lyman-Alpha after 9 days due to electronics box outgassing.
NOAA, TIROS, and DMSP (1970s)[b]	Thermal control problems due to outgassing and engine plume deposition.
RCA and GE Spacecraft (1970s) [b]	Thermal control problems due to contamination build-up on OSRs.
Skylab and Voyager (1970s)[a]	Visual observations of particle clouds on Skylab; star tracker interference due to particle clouds on both missions.
LES 8 and 9 (1970s)[a]	Plumes from retro rockets impinged on payloads during stage II separation.
SCATHA (1979)[a]	Continual accumulations of 200 Angstroms/year were permanently "fixed" due to photopolymerization.
SMM (1980)[a]	Improved version of OSO-8 Lyman-Alpha instrument lost 2 orders of magnitude in throughput at Lyman Alpha within 40 days.
SBUV (1980s)[a]	Accretion and photopolymerization of contaminants on scatter plate calibration system.
DE A&B (1981)[a]	Vent effluents deposited on solar-lit radiator surface, causing permanent deposition and high temperatures.
Landsat (1980s)[a]	Degradation of 500-600 nm channel shortly after launch, due to contaminant build-up.
IECM (1980s)[a]	Measured Shuttle contamination levels; used to identify problems with particle clouds and payload outgassing.
CMP (1980s)[a]	Measured contaminant accretions in the Shuttle bay; measured materials erosion rates due to atomic oxygen exposure.
SUSIM (1980s)[a]	Internal box outgassing caused arcing and electronics burn-out, and failure of the instrument mission.
HRTS/Sunlab (1980s)[a]	Immediate loss of 1200-1600 Angstrom bandwidth due to build-up of silicones, caprolactam, and DOP.
INSAT1B (1983)[a]	Visible range instrument degraded 40% (in throughput).
HST WFPC-1 (1990s)[a]	UV capability lost due to contamination build-up on cold CCDs combined with UV (from earth albedo) exposure.
HST WFPC-2 (1990s)[a]	WFPC2 had a pre-launch cleaning and bakeout procedures, careful design of venting paths to protect the optical bench area, and inclusion of Zeolite molecular adsorbers in the design, it still suffered a decrease in throughput of about 30% per month at 1700 Å and required monthly decontamination procedures.
Yohkoh SXT (1991)[a]	After more than 2 years in orbit, CCD still collected some contaminant which is believed to be water ice and required CCD decontaminated at 20°C every 3 months.
HST STIS (1998) [a]	STIS CCD sensitivity is dropping slowly across the order, but more rapidly below the Lyman alpha (<120 nm) and beyond 150 nm due to contamination similar to that which affected the first generation HST instruments.
HST NICMOS (1999) [a]	Debris on top of the detectors are anti-reflective paint scraped from the optical baffles. These paint flecks in each of the cameras and are characterized by small areas of reduced sensitivity. The largest example is found in camera 1 and affects approximately 35 pixels.
Proton (2002?)[c]	Proton's Block DM upper stage stranded the Astra 1K satellite in low Earth orbit due to either stray particles clogged manifolds or particles prevented a valve from sealing properly, allowing propellant to leak into the engine.
	"Boeing to replace Faulty Solar Panels", January 21, 2002, Space News –702-model solar array concentrations may be to blame for power failures.
Cassini (2002)[a]	Narrow-angle camera with blurry vision seen in star images. The problem was fixed by a series of gentle heating procedures.
Arabsat (2002)[b]	The failure caused a complete shutdown of one of Arabsat 3A's two solar array because the drive mechanism was contaminated by pollution of metallic origin.

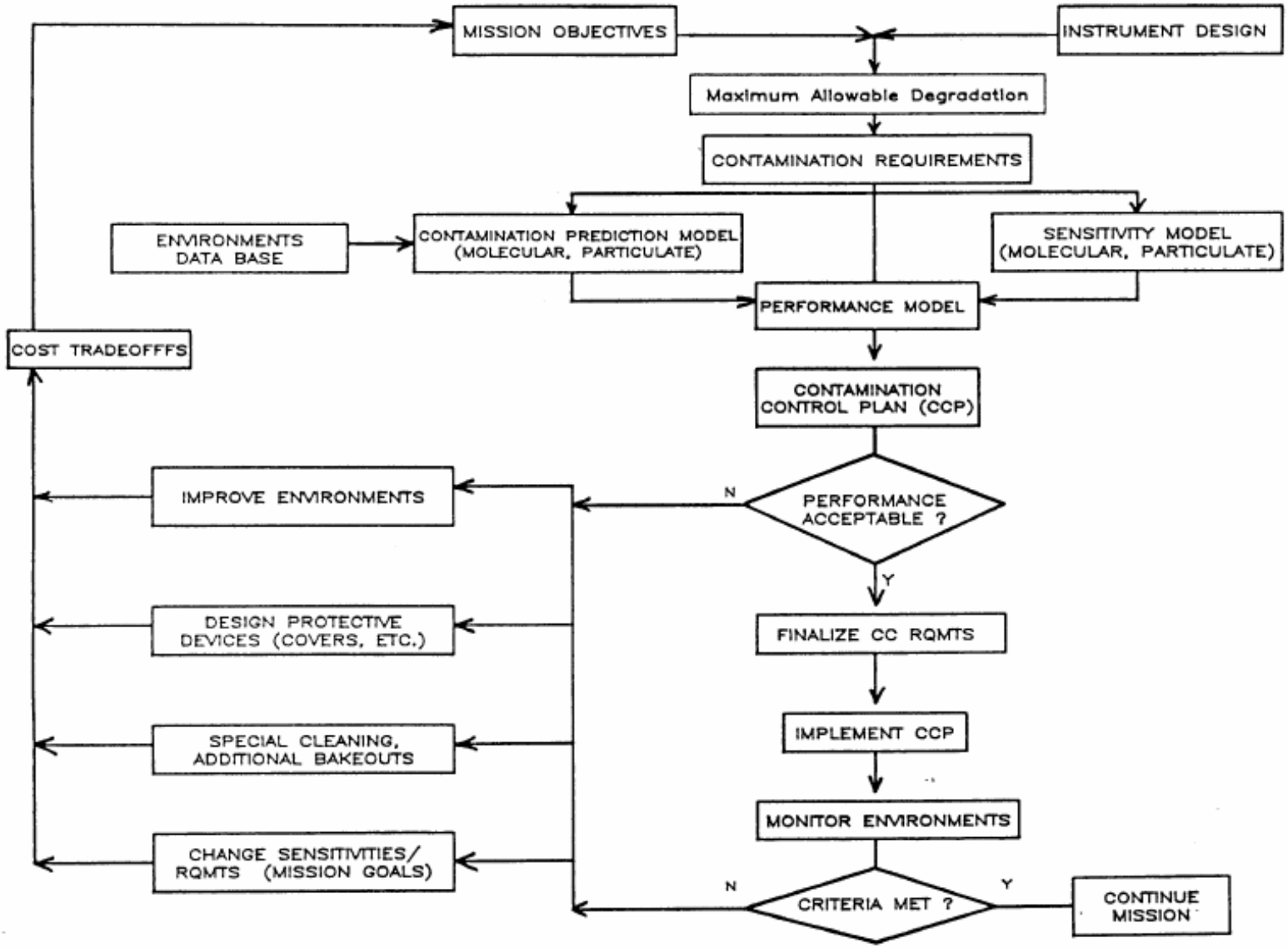
On-Orbit CC Issues

- "*Boeing to replace Faulty Solar Panels*", January 21, 2002, Space News
  - 702-model solar array concentrations may be to blame for power failures
- "*First Cassini Saturn Pictures Confirm Camera Problem Fixed*", November 18, 2002, Space News
  - Narrow-angle camera with blurry vision seen in star images
  - A series of gentle heating procedures fixed the problem
- "*Alcatel, Snecma Pinpoint Source of Arabsat Failure*", December 9, 2002, Space News
  - The failure caused a complete shutdown of one of Arabsat 3A's two solar array
  - Drive mechanism was contaminated by pollution of metallic origin
- **TIRS Instrument on LDCM has a 25 micron particle on its filter, 4% performance degradation**

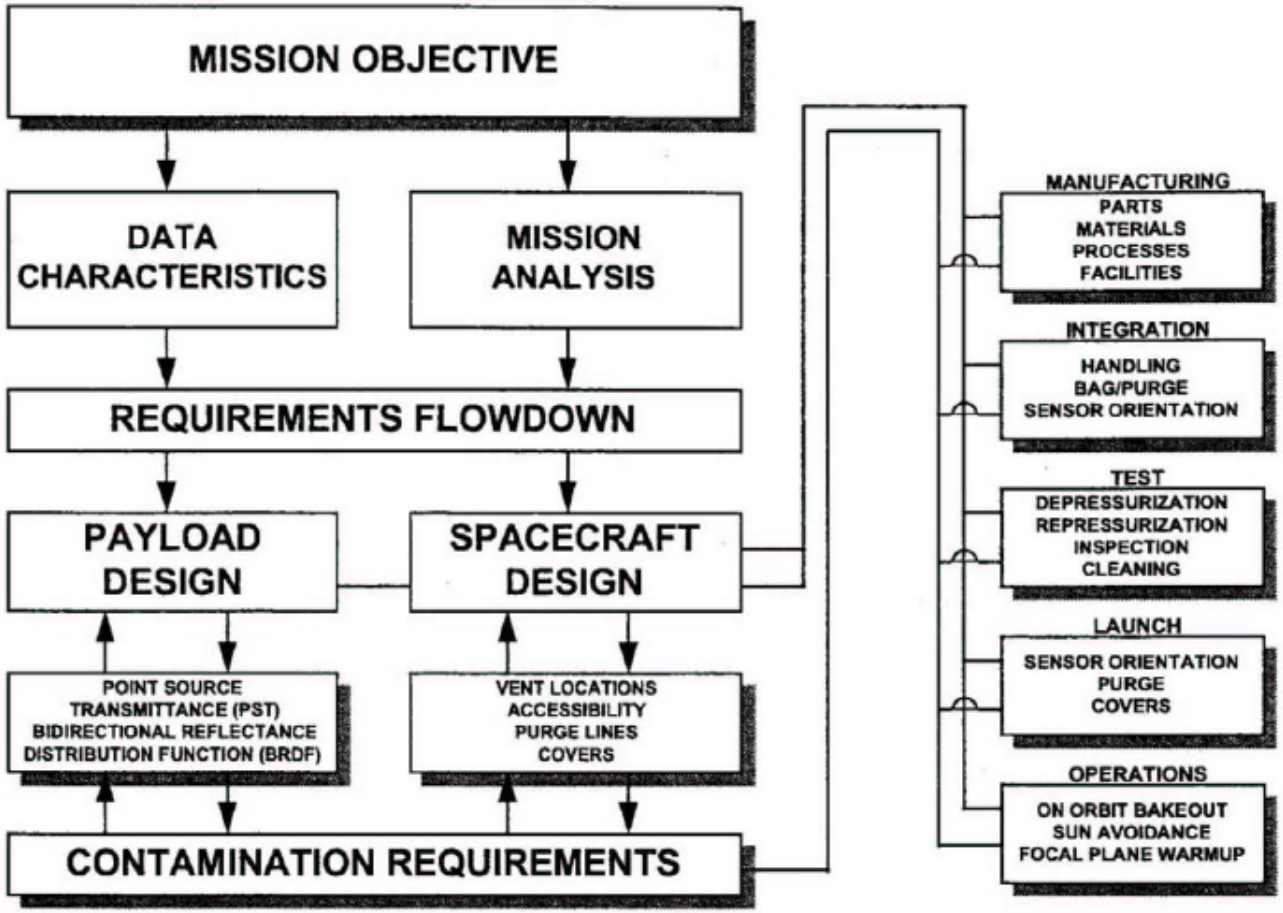
CC By Design

- Contamination control begins with conceptual design.
- Most contamination-sensitive surfaces or subassemblies may be identified at the start of a program, so that accommodating the needs of the sensitive elements may be incorporated into all phases of the program.
  - Protect the most contamination-sensitive surfaces
- The conceptual design must identify a configuration that isolates sensitive elements from contamination sources and permits assembly, test, inspection, and cleaning, with minimal impact to the system.
- It is far easier to design contamination control into the project from the start than it is to retrofit it in after the fact.
- Involving contamination knowledgeable personnel in the early stages of the design process is. the most effective way to accomplish this.
- If done properly, effective contamination control can be done at minimal cost, and inconvenience, to the program.

The Contamination Control Approach

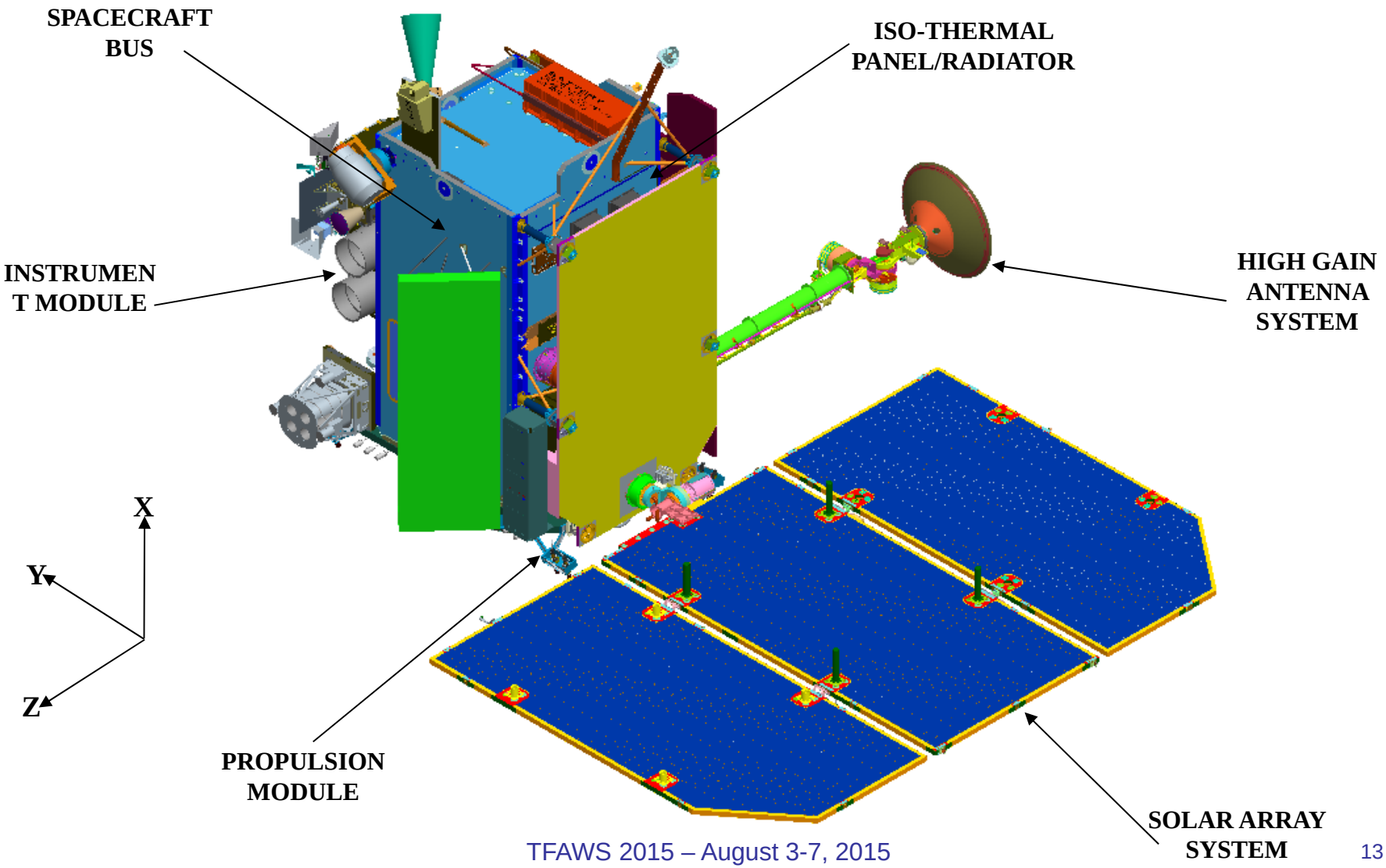


Contamination Control Flow Chart



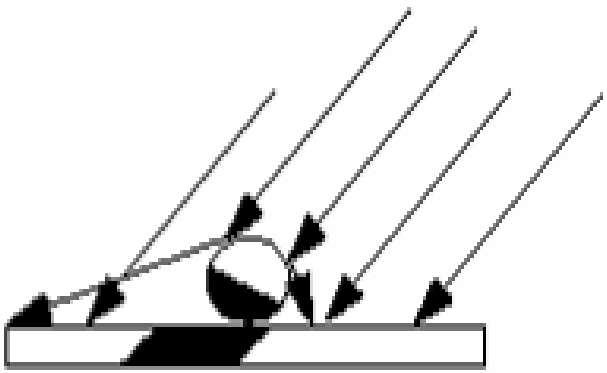
Contamination Effects

Satellite Example: Lunar Reconnaissance Orbiter



Contamination Effects on Hardware Performance

- Particle
  - Obscuration
  - Absorption
  - Scattering
  - Mechanical Interference, sticking, clogging
  - systems and moving mechanisms
  - If conductive, shorting



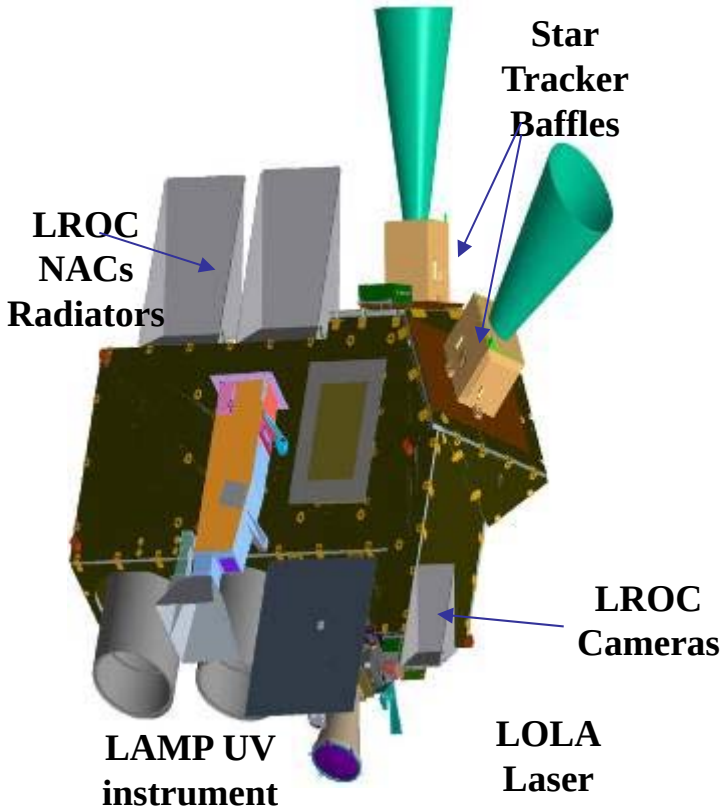
Particle on a surface causing obscuration and scatter.

- Molecular
  - Absorption (affects transmission, reflectance)
  - Scattering (dependent upon deposition pattern)
  - Sticking in mechanical mechanisms
  - Corrosion during ground operations can cause particulates

Impacts of Contamination Effects

Particle Effects:

- **Affects Signal Strength:**
  - **Reflective Mirrors/Detectors/ Micro-Channel Plates**
- **Scatter:**
  - **Optical Baffles/Mirrors/Lens**
- **Obscuration:**
  - **Radiators/ Thermal Coatings/Mirrors**
- **Absorption of Energy:**
  - **Solar Cells/ Thermal Coatings**



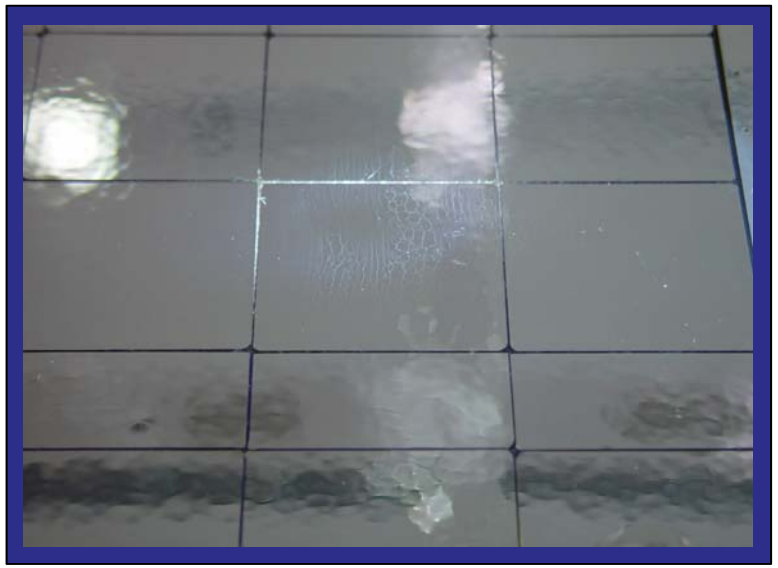
LRO Instrument Module

Impacts of Contamination Effects (Cont)

Molecular Effects:

- **Affects Signal Strength:**
  - Absorbed Laser Energy/Lens
- **Scatter & Obscuration :**
  - Optics/Mirrors/Lens
  - Radiators/ Thermal Coatings
- **Absorption of Energy:**
  - Solar Cells/ Thermal heating of Coatings/Lens/Optics
- **Synergistic Effects**

Laser and beam wordassociation1.net/action.html



Contamination Requirements

Introduction to Hardware Contamination Requirements

- **Sensitive hardware and instruments drive contamination requirements**
  - Not all hardware is sensitive to contamination, however all hardware still possess contamination requirements in order to avoid cross-contamination
- **There are 2 main types of contamination requirements on flight hardware**:
  - Surface cleanliness levels:
    - **Molecular requirements-** films, greases, skin oils
    - **Particulate requirements-** dust, debris, skin cells
    - Visibly Clean
  - Outgassing requirements:
    - Bake-outs are required in order to meet molecular outgassing flux levels

Hardware Contamination Requirements

Surface Particulate Cleanliness Levels per IEST-STD-CC-1246D

1. Particle Distribution:

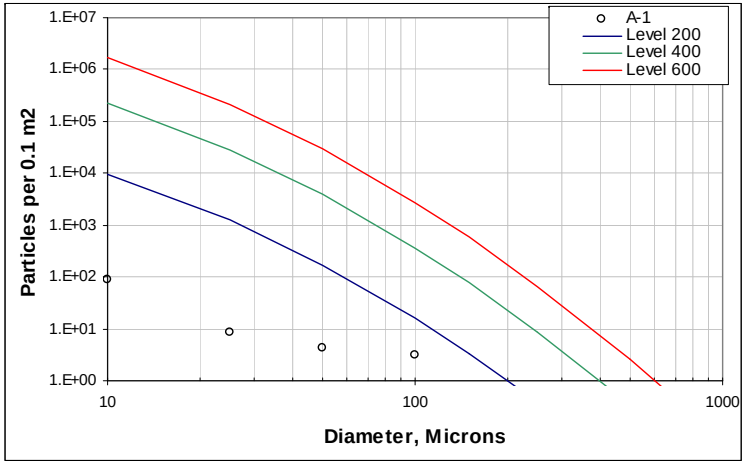
Size and Count yield

Cleanliness Level

$\text{Log } N = 0.926(\text{Log}^2 L - \text{Log}^2 X)$

N = Amount of Particles in $0.1m^2$

X = Particle Size L = Cleanliness Level



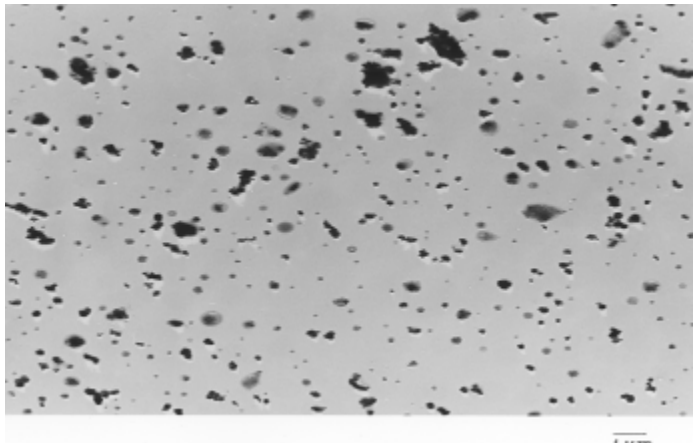
Log-Normal Distribution with Product Cleanliness Level (Dave Hughes)

2. Surface Obscuration:

Percent Area Coverage (PAC)

= Total Area of Particles*100

Total Surface Area

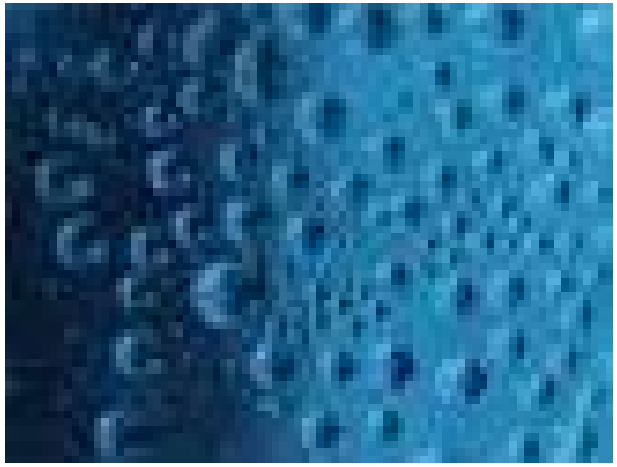


Particles on a surface using Image Analysis

Hardware Contamination Requirements (Cont)

Surface Molecular Cleanliness Levels per IEST-STD-CC1246D

Molecular NVR amount on a given surface area



Surface molecular contamination www.atp.ie/

Level	Limit, NVR mg/0.1m^2 (or µg/cm^2)
A/100	0.01
A/50	0.02
A/20	0.05
A/10	0.1
A/5	0.2
A/2	0.5
A	1.0
B	2.0
C	3.0
D	4.0
E	5.0
F	7.0
G	10.0
H	15.0
J	55.0

Molecular Thickness

- Generally, the contamination effect is directly related to molecular thickness
- If the density of the contaminant is known (1 g/cm^3 is a reasonable value), the cleanliness level can be converted to a contaminant thickness
- The thickness of a molecular contamination layer is typically expressed as Angstrom (Å)
- A requirement that a surface must be cleaned to level "C" means that molecular films can not exceed 3 mg per 0.1 m^2, or 3$\mu g/cm^2$, on that surface or 300 Å in thickness

On-Orbit Effects

On-Orbit Effects of Particulate Contamination

On orbit, particle movement and redistribution mechanisms differ from those normally encountered on the ground

- In space, there are fewer direct forces (wind, air flow disturbances, movement) to move particles around
- In space, movement and redistribution are caused primarily caused by
  - Launch ascent depressurization (Air rushes out of vents)
  - Greatly reduced gravitational forces (Everything “floats” -- No hiding dirt under the carpet or in the corner!)
  - Absence of air pressure
  - Charging

Information provided by Therese Errigo

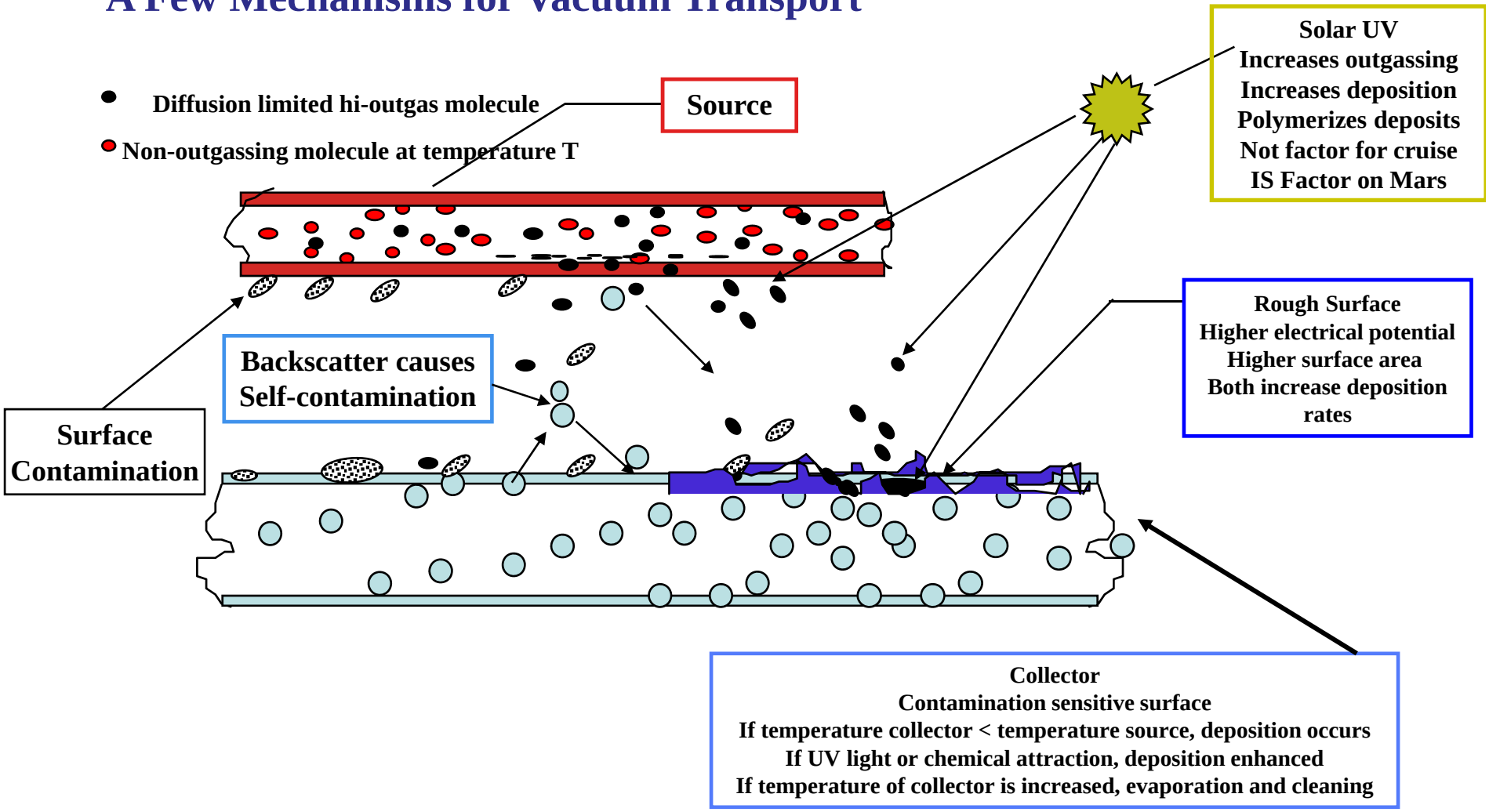
On-Orbit Effects of Molecular Contamination

- On-Orbit molecular effects are more of a concern than particulate (molecular transport analysis)
- On the ground, Non-Volatile Residue (NVR) or Molecular Contamination deposits result from two phenomena
  - contact with a contaminated or contaminating surface or material — contact transfer from fingerprints, adhesive tape, etc
  - condensation of airborne molecular organic contamination
    - volatile (gaseous) organic hydrocarbons (VOC): paint, adhesives, machine lubricating greases
- On orbit, NVR / molecular films result when materials outgas from one surface and deposit on another, usually cooler, surface.
- Contaminants inside electronic boxes can outgas and exit through the vents and deposit on colder surfaces. This is induced more due to the vacuum of space.

Information provided by Therese Errigo

Molecular Outgassing and Deposition

A Few Mechanisms for Vacuum Transport

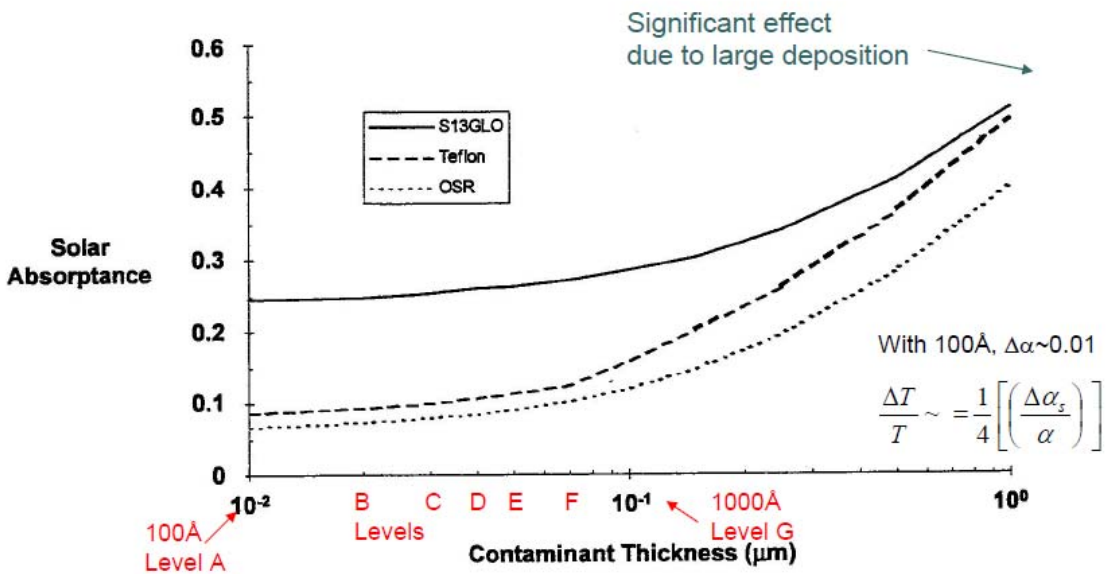


Information provided by Therese Errigo

Molecular Effects

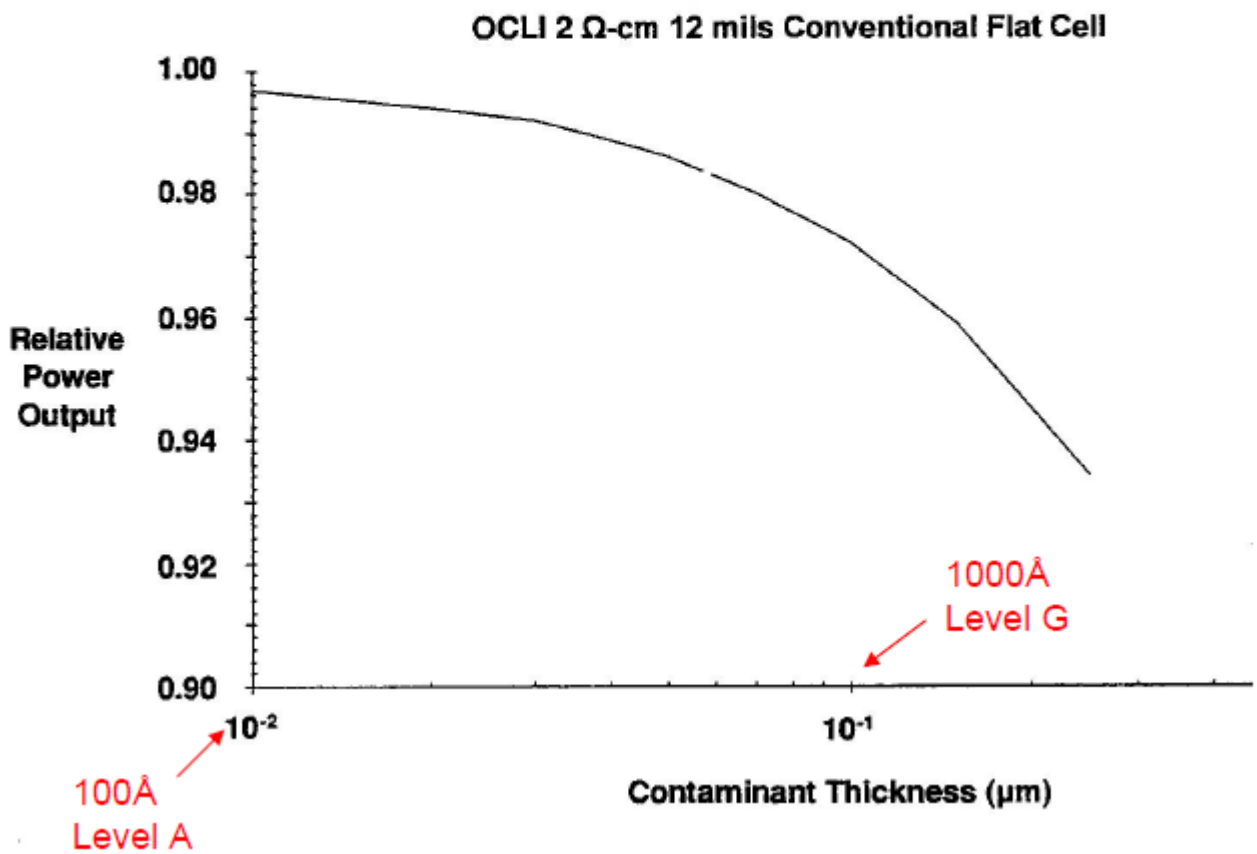
- Cleanliness level A corresponds to a contamination thicknesses of 100Å (or 0.01 μm, or 10 nm)
- Level A will have little effect on thermal control surfaces and solar arrays

Molecular Contamination Effects (thermal control surfaces)



Molecular Effects Continued

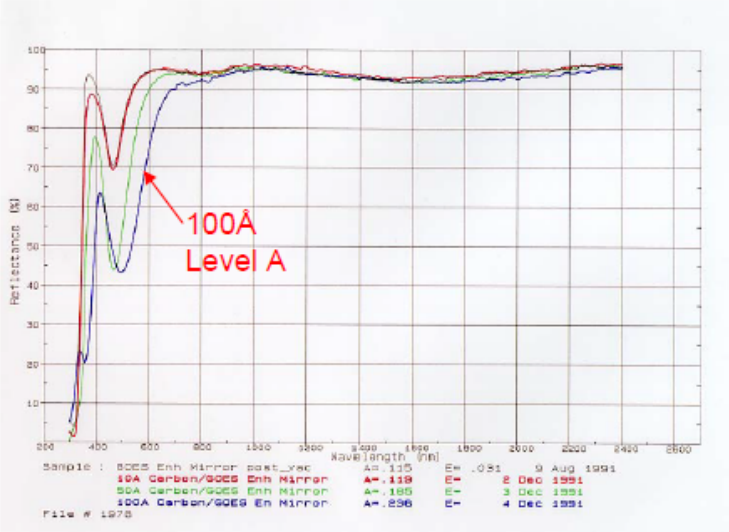
Molecular Contamination Effects (solar arrays)



Molecular Effects Continued

Molecular Contamination Effects

- Maintaining cleanliness level A is, relatively speaking, not that difficult
- This is an indication of the fact that optical surfaces are often the most susceptible to contamination



Molecular Sources

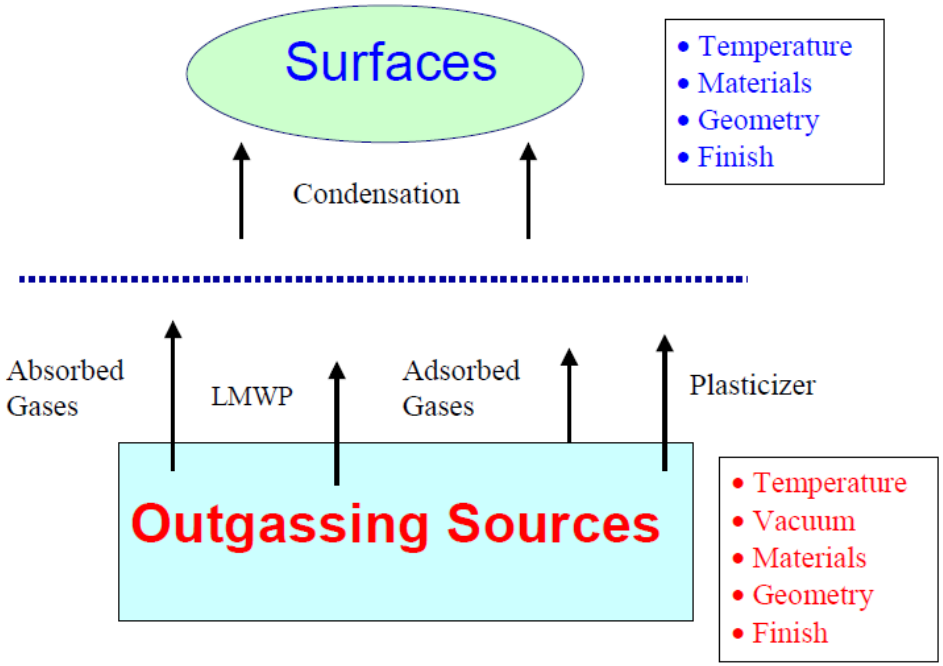
Contamination Sources

Structure	Epoxies, polycarbonates, polyurethanes, polyamines, polyimides, fluorocarbons
Encapsulation/Potting	Polyurethanes, epoxies, silicones
Conformal Coatings	Polyurethanes, epoxies, silicones
Adhesives	Polyurethanes, epoxies, silicones
Tapes	Polyesters, acrylics, polyamides, fluorocarbons
Others	Acetates, epoxies, acetals, polyamides

(Outgassing)

- Volatile chemicals, which may be simply excess chemicals left over from improper catalyst/resin ratios, improper curing, etc., can, over time, migrate to the surface and escape into the local environment
- This process, called *outgassing,* is responsible for the familiar odor of plastics or rubber

Outgassing



Material outgassing =
f (time, activation energy, temperature)

Diffusion

- The amount of mass loss due to diffusion ($t^{-1/2}$) can be represented by the relation

$$\frac{dm}{dt}(t,T) = C\,m\,\frac{e^{-E_a/RT}}{\sqrt{t}} \quad ...(d-1)$$

- kg/sec = $sec^{-1/2}$ · kg / $sec^{1/2}$
- C ($S^{-1/2}$) is a normalization constant that must be experimentally determined
- m (kg) is the amount of mass contributing to the outgassing
- E_a (kcal/mole) is the activation energy
- R (kcal K/mole) is the gas constant
- T (K) is the temperature
- t (s) is the time

Materials Outgassing Processes

- (ii) Diffusion is the homogenization that occurs from random thermal motions
  - Contaminants that diffuse to the surface of a material may have enough thermal energy to escape the surface forces and simply evaporate into the local environment
  - Diffusion has a mid-range temperature dependence and mid-range time constant
  - Diffusion is responsible for outgassing from organic materials and it is the mechanism that is the major source of outgassing on orbit

Time Dependence of Materials Outgassing

- Experimental data indicate that outgassing varies either
  - i) as an exponential function of time, or
  - ii) inversely as a power of time, or
  - iii) independently of time
- This depends on the mechanism responsible for the outgassing process

Outgassing Mechanisms

Mechanism	Time Dependence	Activation Energy (kcal/mole)	1/e Temperature Range $T=E_a/R$ (K)
Desorption	t^{-1} or t^{-2}	1-10	500-5000
Diffusion	$t^{-1/2}$	5-15	2500-7500
Decomposition	n/a	20-80	10,000-40,000

Note: 1/e = 0.367871
R = 1.987 cal/mole-K
$e^{-Ea/RT} = e^{-1} \Rightarrow E_a/RT=1 \Rightarrow T= E_a/R$

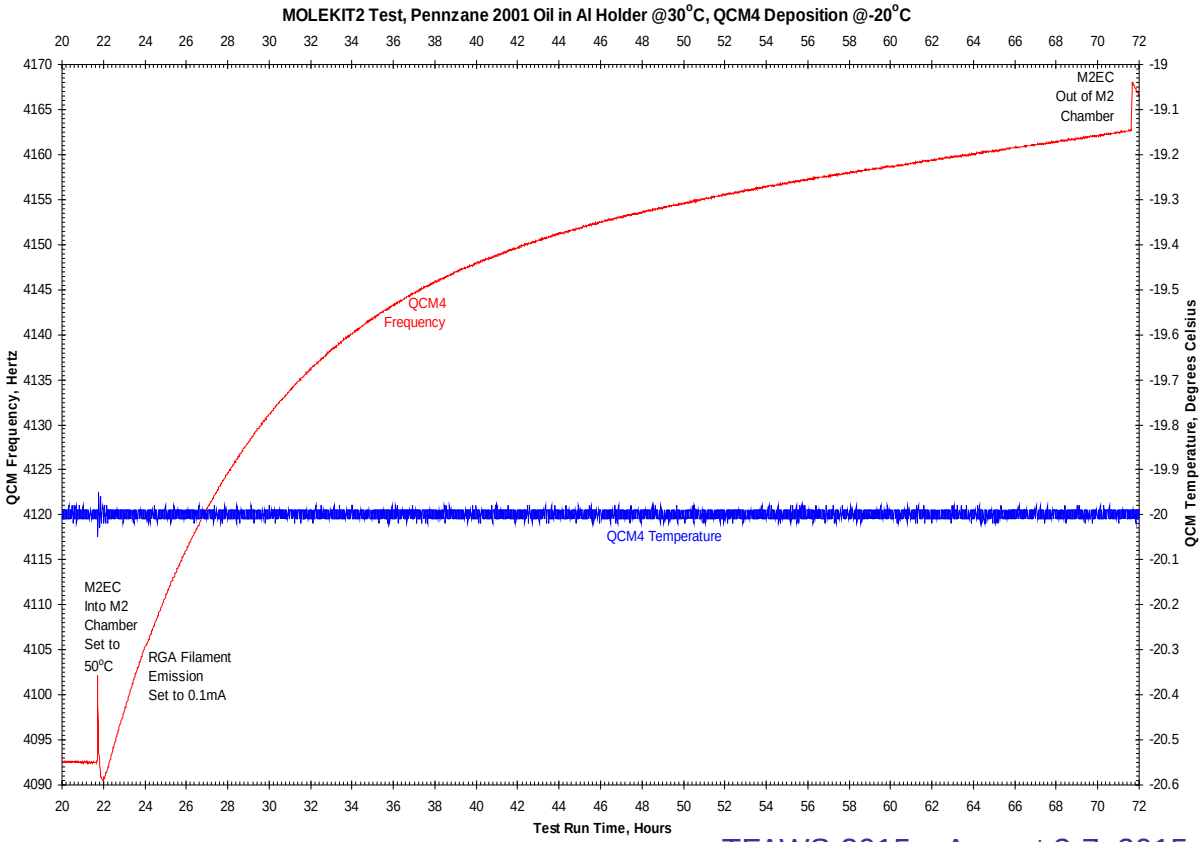
Materials Outgassing

- In addition to the time dependency, each process depends exponentially on a unique range of activation energies, E_a, (the energy required to initiate the process), and temperature, T, (the measure of the available thermal energy), according to the relation $e^{-Ea/RT}$
- The outgassing rate can be described as a reaction with its reaction rate determined by the Arrhenius Equation

$$k = A\, e^{-\frac{E_a}{RT}}$$

Hardware Contamination Requirements

Outgassing Requirements require hardware bakeouts in order to meet molecular flux levels. Molecular flux levels are derived through molecular transport analysis based on field of view to sensitive components, chemical constituent of hardware, and the amount of outgassing species.



Example of ambient air offgassing
www.glare-x-plus.com

Outgassing

Material	Most Abundant Outgassed Species (During isothermal 30°C tests)
3M No.59 tape	H_2O, acrylic ester
3M No. 5 tape	H_2O, methyl ester
Metex Card P/N ME6	Methyl and phenyl silicones, H_2O, ester
Technit EMC-034 Sponge Neoprene Per MIL-R-6130 Type II	Hydrocarbons (C_1-C_{16}), H_2O
Cho-Seal 1215 – bonded to aluminum	Methyl and phenyl silicones, H_2O
Technit P/N 45-09802	Methyl and phenyl silicones, H_2O
Polastrip P/N 14-024	Phenyl and Methyl silicones, H_2O, ester
Silastic 501 RT cure	Dimethyl silicones, H_2O
RTV 112 RT cure	Methyl and phenyl silicones, H_2O
Silastic 140 RT cure	Methyl and phenyl silicones, H_2O
RTV 90 RT cure	Dimethyl silicones, H_2O
Natvar 400 vinyl tubing	Aliphatic and aromatic esters, H_2O

Other Contamination Sources

- Thruster plumes are a potentially serious threat if the backflow is capable of reaching sensitive surfaces
- Deploying or operating mechanisms, releasing covers, dumping waste, or conducting proximity operations are all potential sources of contamination once on orbit, especially on manned spacecraft

Hardware Contamination Requirements (Cont)

Surface Visibly Clean Levels per JSC-SN-C-0005

A visually clean surface free of physical debris as seen without optical aids (except corrected vision)

Visual Inspection

VC Level	Incident Light Level	Observation Distance	Remarks
Standard	≥ 50 foot-candles	5 to 10 feet	(2) (3) (5)
Sensitive	≥ 50 foot-candles	2 to 4 feet	(2) (3) (5)
Highly Sensitive Plus UV	≥ 50 foot-candles	6 to 18 inches	(3) (4)

Contamination Modeling

- Thruster Impingement: Plume Analysis
- Atomic Oxygen Effects
- Mass Transport Analysis
- Particle Redistribution Analysis
- Venting Analysis
- MOLKIT Analysis

S/C Design Methodology

Material Screening

Material Screening Criteria per ASTM E595

- Low Outgassing: Total Mass Loss (TML) <1%, Collected Volatile Condensable Materials (CVCM) < 0.1%
- Water Vapor Regain (WVR) considered

- In ASTM E 595 test, a sample of the material is held at a temperature of 125°C for 24 h at a pressure of less than 7 x 10^{-3} Pa (or 5.0 x 10^{-5} torr)
  - 1 Pa = 1 N/m^2 = 7.5 x 10^{-3} torr
- Comparing the initial and final mass of the sample yields the change in mass, Δm, which is known as the TML

- "*Outgassing Data for Selecting Spacecraft Materials*", NASA Reference Publication 1124, Rev 4, June 1997
- http://outgassing.nasa.gov/, July 03, 2002

MATERIAL	DATA REFERENCE	MFR CODE	%TML	%CVCM	%WVR	CURE TIME	CURE TEMP	ATMOS	APPLICATION
CHEMGLAZE A276 HIGH GLOSS WHITE POLYURETHANE/F	GSC12244	HCC	1.87	0.14	0.20	28D	25	AIR	PAINT
CHEMGLAZE A276 HIGH GLOSS WHITE POLYURETHANE/F	GSC12247	HCC	0.99	0.08	0.19	15D	25	AIR	PAINT
						48H	96	E-6	
CHEMGLAZE A276 LOT FEA	GSC16697	LOR	4.65	0.02	0.47	14D	25	AIR	PAINT
CHEMGLAZE A276/9974 OVER 9924 PRIMER/F	GSC18262	HCC	4.89	0.02	0.38	21D	25	AIR	PAINT
CHEMGLAZE A276/A170 FLAT AGT/CAT 9986/PRIMER 9924/F	GSC15504	GSC	3.92	0.31	0.53	28D	25	AIR	PAINT
CHEMGLAZE A276/A170 FLAT AGT/CAT 9986/PRIMER 9924/F	GSC15506	GSC	3.19	0.26	0.51	7D	25	AIR	PAINT
						24H	50	E-6	
CHEMGLAZE A276/A771/9951 AS 10/1 PBW/20% BV BLUE	GSC20770	HCC	4.23	0.05	0.30	5D	25	AIR	PAINT
CHEMGLAZE A276/A771/9951 AS 20/3 PBW/20% BV BLUE	GSC20773	HCC	3.96	0.07	0.25	5D	25	AIR	PAINT
CHEMGLAZE A276/OVER SUPER KOROPON PRIMER - FREE FILM	GSC17640	MSF	3.77	0.16	4.70	90D	25	AIR	PAINT COMPOSITE
CHEMGLAZE A276/PRIMER 9924 FREE FILM	GSC17808	HCC	2.32	0.07	0.54	7D	25	AIR	PAINT COMPOSITE
CHEMGLAZE A276E HIGH GLOSS WHITE POLYURETHANE	GSC15456	HCC	2.29	0.05	0.62	14D	25	AIR	PAINT
CHEMGLAZE A288 OVER 9924 PRIMER/F	GSC18264	HCC	4.61	0.03	0.32	21D	25	AIR	PAINT
CHEMGLAZE A771 BLUE URETHANE	GSC18266	HCC	2.53	0.08	0.50	4D	25	AIR	PAINT
CHEMGLAZE A971 HIGH GLOSS YELLOW PAINT/F	GSC16392	HCC	1.70	0.04	0.35	30D	25	AIR	PAINT
CHEMGLAZE A971/PRIMER 9924 HIGH GLOSS YELLOW PAINT/F	GSC16394	HCC	2.36	0.02	0.43	30D	25	AIR	PAINT
CHEMGLAZE A971/PRIMER 9924 HIGH GLOSS YELLOW PAINT/F	GSC16422	HCC	0.77	0.03	0.26	7D	25	AIR	PAINT
						72H	90	E-6	
CHEMGLAZE H322 BLACK CONDUCTIVE PAINT POLYURETHANE	GSFC8066	HCC	1.92	0.07	0.31	20M	121	AIR	COND PAINT
CHEMGLAZE H322 BLACK CONDUCTIVE PAINT POLYURETHANE	GSFC8069	HCC	0.86	0.09	0.31	30H	121	AIR	COND PAINT
CHEMGLAZE H322 POLYURETHANE FORMERLY TS 1960-71	GSFC3193	HCC	1.35	0.15		24H	121	AIR	COND PAINT
CHEMGLAZE IC5241-64/PRIMER IC5002-16 WHITE PAINT/F	GSC16604	HCC	5.70	0.23	1.08	14D	25	AIR	PAINT COMPOSITE

Information provided by Therese Errigo

Outgassing Parameters of Typical Spacecraft Materials

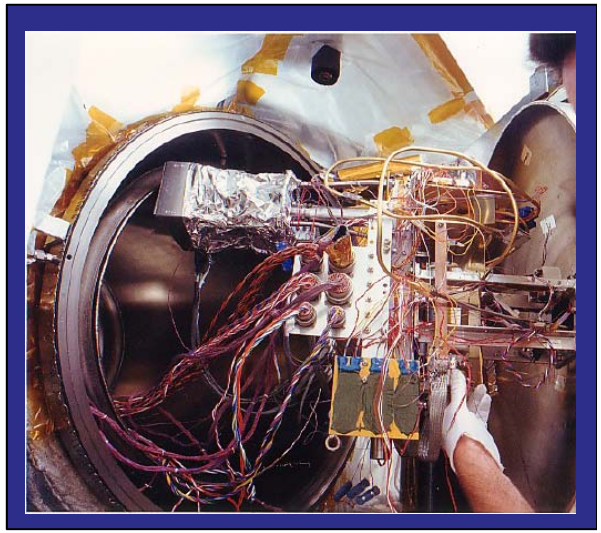
Nonstandard conditions

standard conditions

Material	TML (%) at 75°C	TML (%) at 125°C	CVCM (%)
Adhesives			
R-2560	1.58	1.53	na
RTV-566	0.11	0.26	0.02
DC 93-500	0.07	0.08	0.05
DC 6-1104	0.29	0.58	0.03
Films			
Kapton FEP	n/a	0.25	0.01
Kapton H	n/a	1.17	0.00
Mylar	n/a	0.32	0.04
FEP Teflon	n/a	0.77	0.35
Oils & Greases			
Brayco 815X	n/a	0.25	0.01
Braycote 803	n/a	0.24	0.13
Krytox 143AD	n/a	28.54	5.71
Vakote MLD73-91	0.40	n/a	n/a
Paints & Coatings			
S13GLO	n/a	0.30	0.03
Chemglaze Z306	2.40	2.52	0.07
DC Q9-6313	0.40	0.39	n/a
Aremco 569	2.28	3.58	n/a
LMSC 1170	1.88	2.89	n/a
YB71	n/a	2.48	0.00
Z93	n/a	2.60	0.00

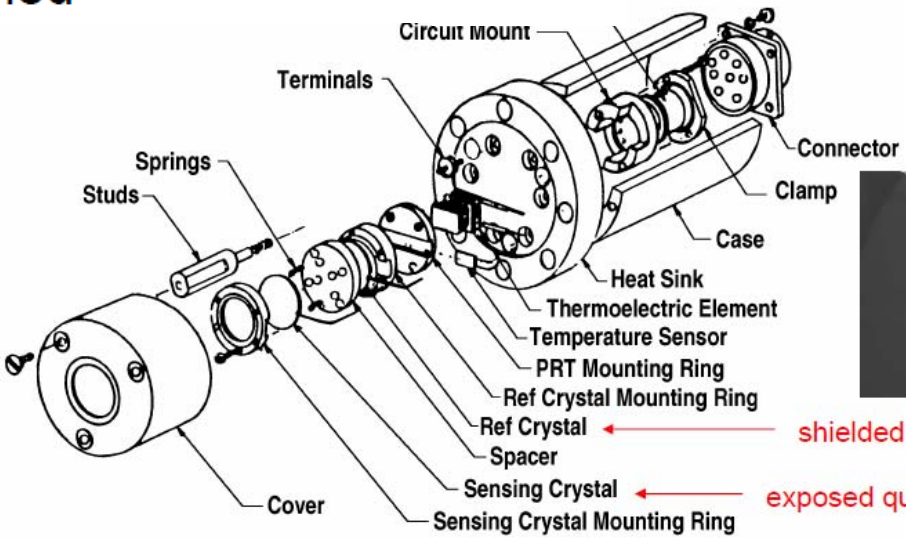
Material Screening Continued

- ASTM E 1559: Measure molecular outgassing with TQCM (MOLKIT)
  - *Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials*
  - ASTM E 595 screening test maintains the outgassing source and collector at fixed temperatures, it does not provide complete insight into the outgassing characteristics of a material
    - 125°C and 25°C; 24 hours
  - It is often necessary to conduct more detailed tests to determine outgassing characteristics over a wider temperature range and determine relevant time dependencies
  - ASTM E 1559 is capable of determining both the total mass flux evolved by a material when exposed to a vacuum environment and the deposition of the outgassed flux on surfaces held at various specified temperatures



QCMs

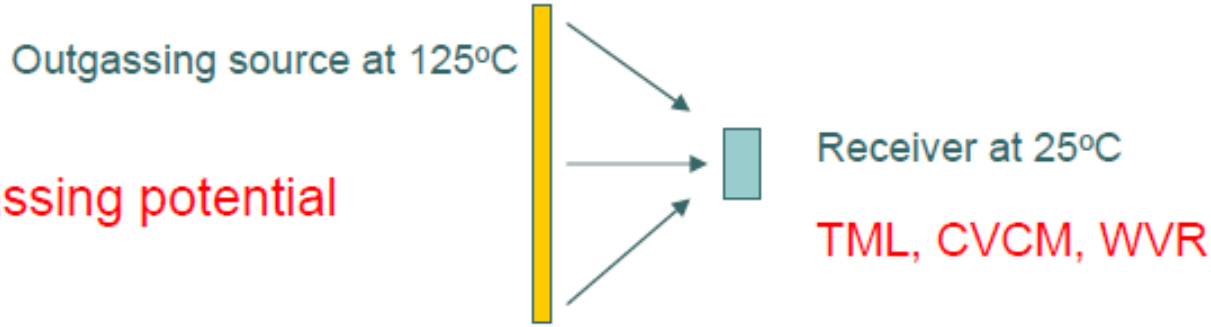
- ASTM E 1559 utilizes Quartz Crystal Microbalances (QCMs) to make measurements of outgassed matter at different temperatures
- A QCM compares the resonance frequency of a shielded quartz crystal, which remains contamination free, with one that is exposed to the environment and experiences a deposition of contamination
- By calibrating the QCM, the amount of mass deposition can be determined



Outgassing Measurements

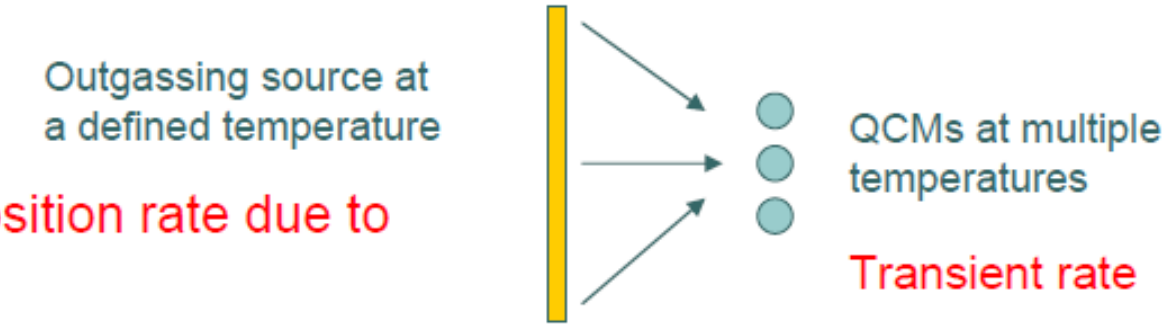
ASTM E 595

Measures the outgassing potential



ASTM E 1559

Measures the deposition rate due to outgassing



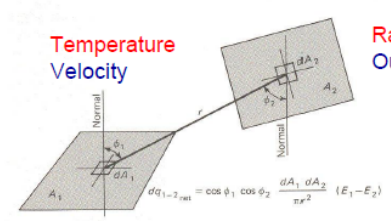
Contamination Transport

- The amount of contamination that is produced by a spacecraft is important, but the amount of contamination that reaches, and sticks to a sensitive surface is much more critical
- In general, transport processes are generally either line of sight or non-line of sight
  - The outgassing view factor bears a strong resemblance to the thermal view factor, or angle factor, used in radiative heat balance
    - Analogy
    - Use to derive source outgassing rate as well as estimate the surface deposition due to outgassing

Temperature
Velocity

Radiation receiver
Outgassing receiver

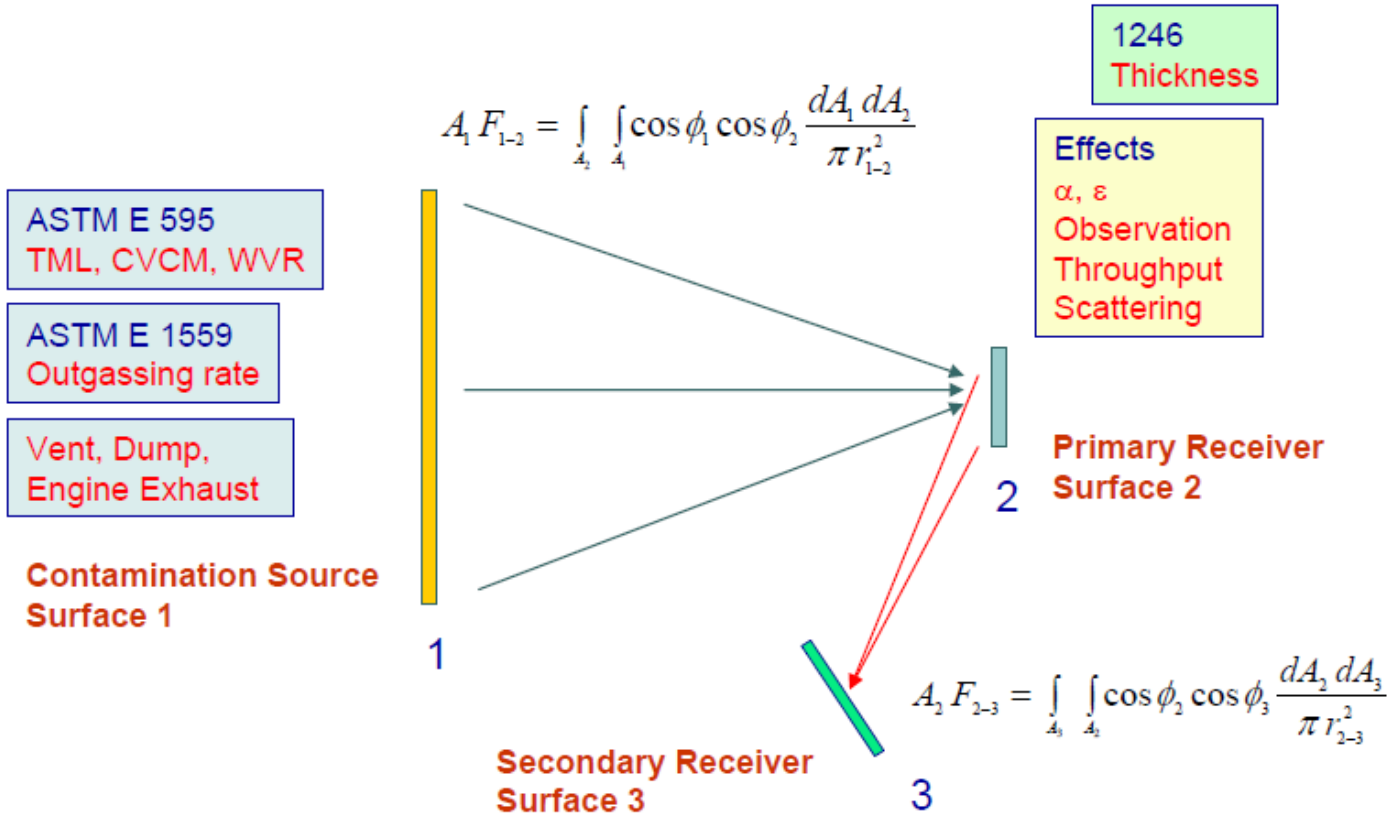
Radiation source, E
Outgassing source, M



	Radiation Heat Transfer	Material Outgassing Transport
	Spectral and directional distribution	*Lambertian distribution*
Radiance, L_1	L_1 (W m^{-2} sr^{-1})	
Exitance, M_1	M_1 (W m^{-2}) = π L_1 (W m^{-2} sr^{-1}) [M_1 presents emissive power $E_b = \pi\ I_b$ Total blackbody emissive power = π x Blackbody intensity]	M_1 (kg m^{-2} sec^{-1}) = (dm_1/dt) ($1/dA_1$) [M_1 presents outgassing rate OGR_{dA1}]
Transfer	q_{12} (W m^{-2}) = M_1 F_{12} [Total heat transfer from dA_1 to dA_2]	OGR_{12} (kg m^{-2} sec^{-1}) = OGR_{dA1} F_{12} [Outgassing transfer from dA_1 to dA_2]
Deposition		($\Delta x/\Delta t$) (m sec^{-1}) = M_1 F_{12} /ρ_c [Contamination thickness Δx on receiver]

$$A_1 F_{1-2} = \int_{A_2} \int_{A_1} \cos\phi_1 \cos\phi_2 \frac{dA_1\, dA_2}{\pi r_{1-2}^2}$$

Molecular Contamination Transport



Material Mitigations

- Low Particulating (minimize / avoid bare aluminum, woven textiles, Velcro)
- Avoid materials detrimental to your sensitive components (Silicones, Helium)
- Minimize quantity of organics (minimize thickness, bond lines)
- Bakeout under vacuum to reduce outgassing

On-Orbit Mitigations

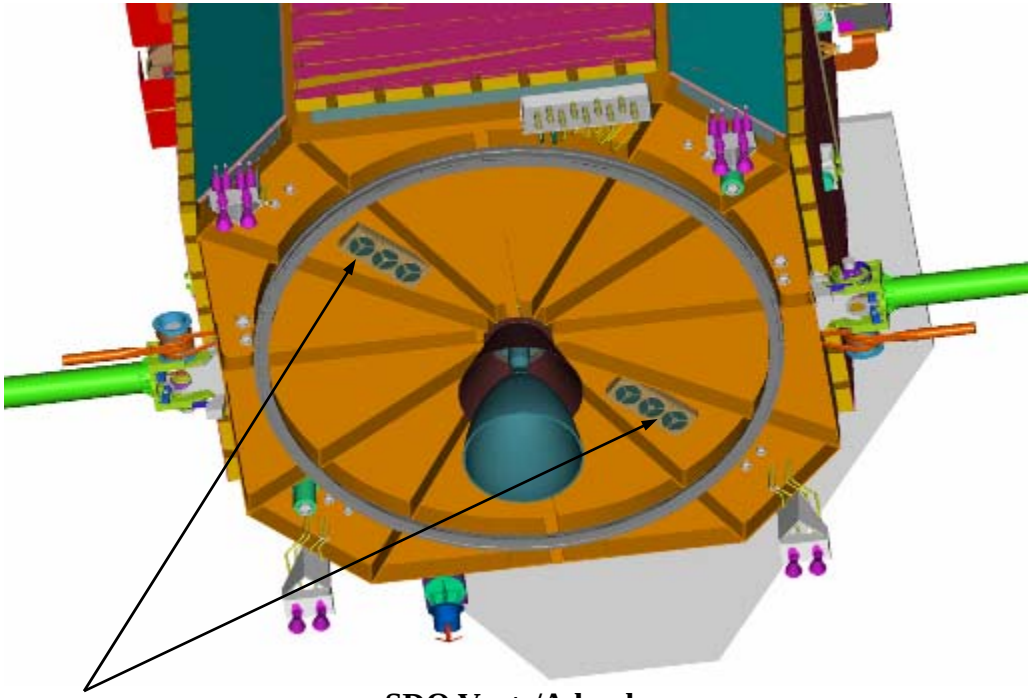
- On-orbit outgassing
- Vent control
- Protective cover
- Plume shield
- Decontamination
- Purge
- Collecting devices
- Operational control
- Modeling
- In-flight monitor

S/C Design Configuration

- Keep sources of organics out of line of sight of optics/inlets
- Get electronics out of optic cavities whenever possible
- Keep main apertures sealed
- Isolate hazards from sensitive items (e.g., barriers, baffles, doors, covers, vents, etc.) and direct venting into non-sensitive areas
- On-Orbit Deployable Covers/Doors
- Red-Tag Covers

Other S/C Design Methodologies

- Venting
  - direct effluent away from apertures/inlets
  - MLI flaps
- Minimize number of potential vents / unintentional vents; use directional venting
- Use molecular adsorbers
- Seal Honeycomb Edges
- Purge interface/Manifold on S/C for T-0 purging



SDO Vents/Adsorbers
are also cost saving to reduce bakeout time

Other S/C Design Methodologies

- Selection of Thermal Control Coatings
  - sources lower temperature than collectors (sensitive surfaces)
  - provisions to heat contaminated surfaces so they release condensed contaminates (decontamination heaters)
- UV
  - avoid / minimize UV impingement (direct sun or albedo) on optics or surfaces in line of sight or near of optics/sensitive surfaces; darken optics
- Atomic Oxygen
  - avoid use of silicones in orbits with significant atomic oxygen
  - Design with enough material to meet errosion rate, e.g. Kapton, Teflon
- Plume / vents
  - direct all thruster plume and backscatter away from sensitive surfaces
  - use high purity fuel
  - Plume analysis determines impact

Information provided by Therese Errigo

Contamination Effect on TCS

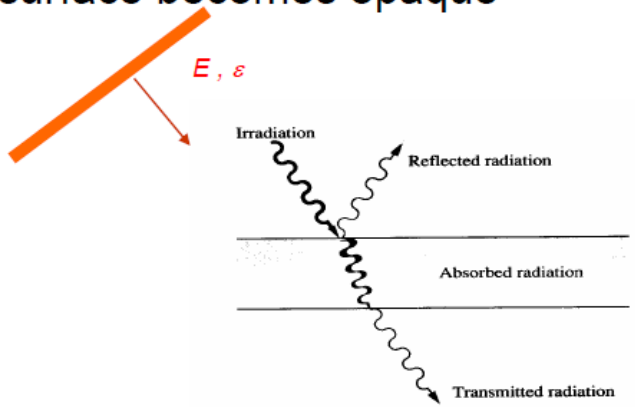
- Molecular contamination effect on TCS
  - Reflecting or radiating surfaces
  - Transmitting surfaces
  - Cryogenic surfaces and thin molecular films
- Particulate contamination effect on TCS

Reflecting or Radiating Surfaces

Emitting and Receiving Surfaces

Contamination affects thermal properties of emitting and receiving surfaces

As ρ (λ) approaches zero the surface becomes transparent, while as τ (λ) approaches zero the surface becomes opaque



G_{ref} and ρ (ρ = 0; transparent)

G_{abs} and α

G_{tran} and τ (τ = 0; opaque)

Surfaces		*f*	*g*
Emitting Surface	Emissive power, E (W/m^2)	Emission E_λ (W/m^2-μm)	ε
Reflecting Surface	Reflected irradiation, G_{ref} (W/m^2)	Spectral Irradiation, G_{ref} (W/m^2-μm)	ρ
Absorbing Surface	Absorbed irradiation, G_{abs} (W/m^2)	Spectral Irradiation, G_{abs} (W/m^2-μm)	α
Transmitting Surface	Transmitted irradiation, G_{tran} (W/m^2)	Spectral Irradiation, G_{tran} (W/m^2-μm)	τ

Notes: 1. The dummy variable "x" is wavelength λ (μm)
2. Directional, spectral property, P'_λ (λ, θ, ϕ, T)
3. Hemispherical, spectral property, P_λ (λ, T)

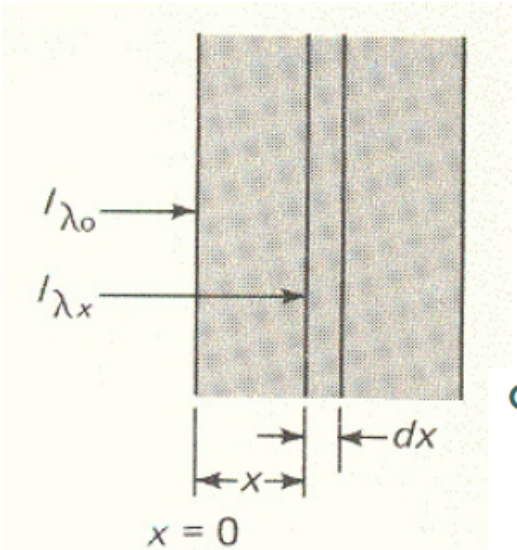
$$G_\lambda(\lambda) = \int^{2\pi} \int_0^{\pi/2} I_\lambda(\lambda,\theta,\phi)\cos\theta \sin\theta \, d\theta \, d\phi$$

Reflective Surfaces

- Consider the specific case of a surface that is designed to be totally reflective, such as a mirror or a thermal radiator, but is covered with a thin layer of a contaminant film
- The surface is a material that, (when clean), effectively satisfies the constraint $\tau(\lambda) = 0$
- The expression for the decrease in surface reflectance as a function of contamination thickness
  - $\rho^x(\lambda) = \rho(\lambda) \exp[-2\,\alpha_c(\lambda)\,x]$
  - The factor of 2 is because a ray of light would have to transverse the contaminant film, be reflected, and transverse the contaminant film a second time to avoid being absorbed.

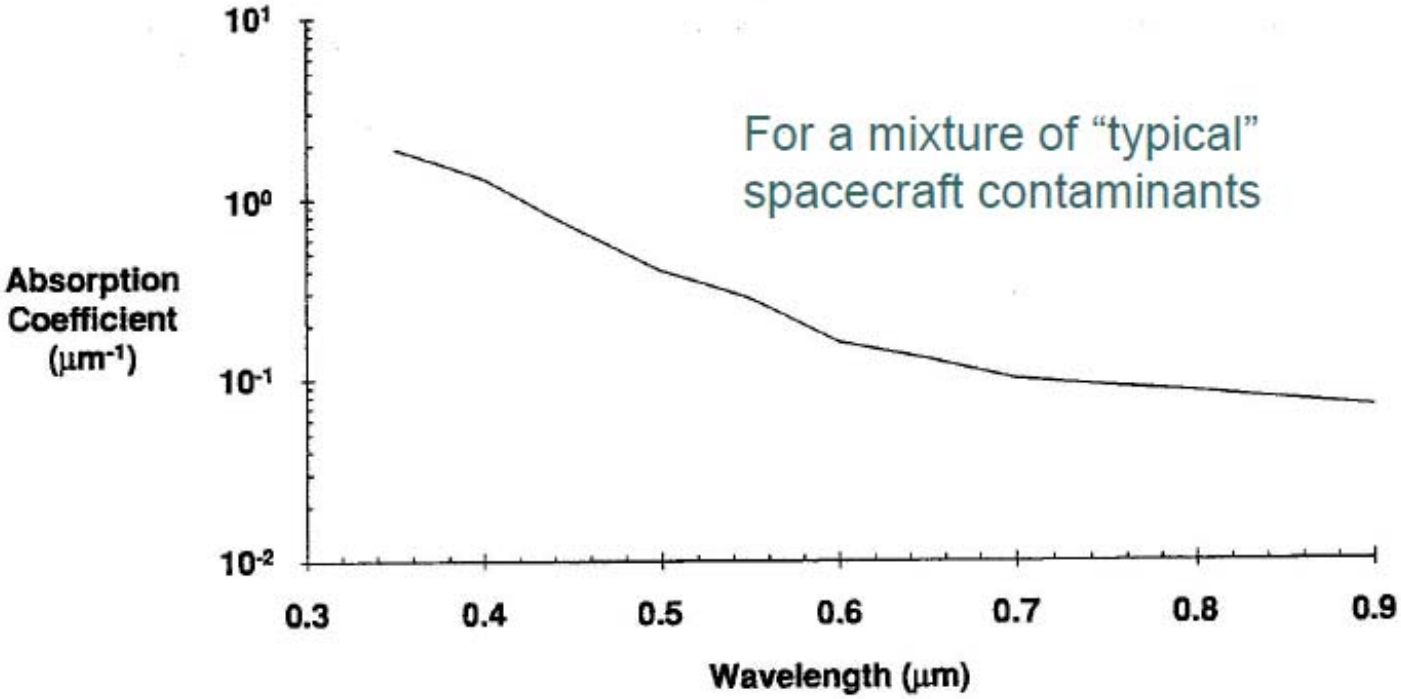
Absorption

- Consider the absorption on a receiving surface
- A monochromatic beam of radiation having an intensity of I_λ impinges on the layer of thickness *dx*



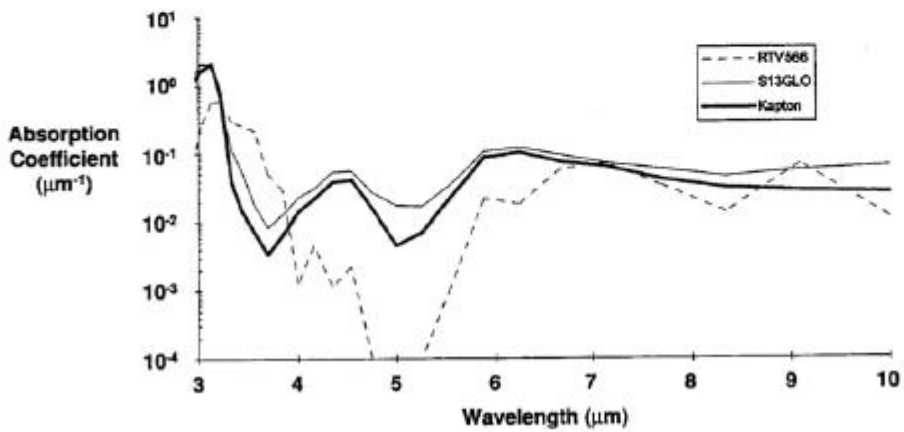
- From the definition of absorption, the absorptance of a contaminated surface is therefore given by
  - $\alpha^x(\lambda) = \alpha(\lambda)\{1 - \exp[-\alpha_c(\lambda)x]\}$
  - where $\alpha_c(\lambda)$ is defined as the experimentally determined absorption coefficient of the contaminating layer

Absorption Coefficient of Contaminants



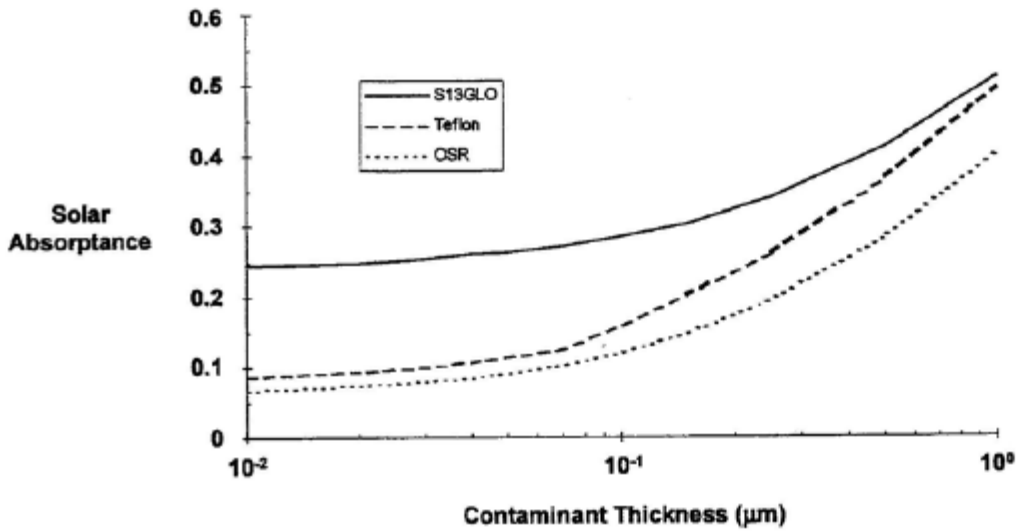
Absorption Coefficient of Contaminants

- The absorption profile of a single contaminant may be noticeably different, especially in different wavebands
  - This wavelength dependence will affect instruments operating in different wavebands



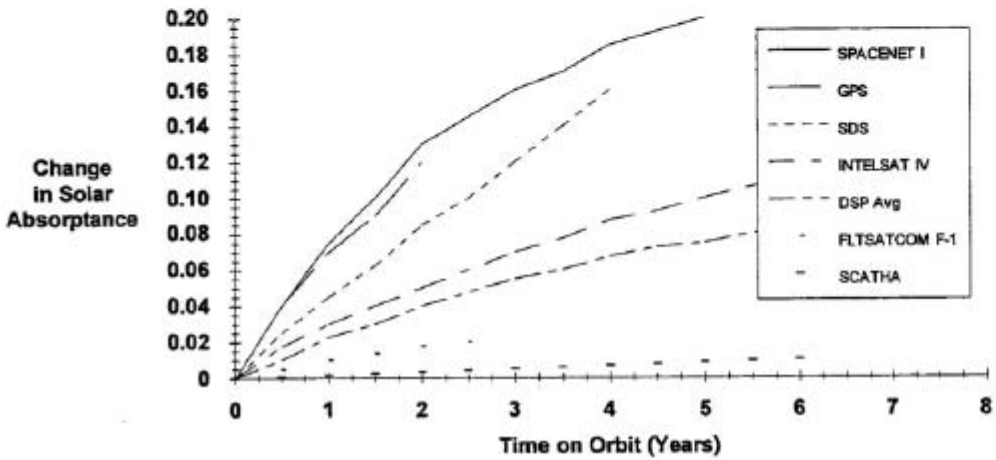
Absorption Coefficient of Contaminants

- A contaminant layer would increase the solar absorptance of a reflecting surface (possibly upsetting the thermal balance of the spacecraft)
  - $\Delta\alpha$ versus thickness



On-Orbit Solar Absorption Changes

- Historically, most spacecraft experience some degradation in α_s after reaching orbit
- Some spacecraft have end of life (EOL) increases in α_s as great as 0.15 - 0.20
  - ΔTemperature?



Contamination Effect on Equilibrium Temperature

If the value of either α_s or ε is altered by contamination, either molecular or particulate, the result will be a change in the equilibrium temperature of the surface given by

$$\frac{\Delta T}{T} = \frac{1}{4}\left(\frac{\Delta\left(\frac{\alpha_s}{\varepsilon}\right)}{\left(\frac{\alpha_s}{\varepsilon}\right)}\right) = \frac{1}{4}\left[\left(\frac{\Delta\alpha_s}{\alpha}\right) - \left(\frac{\Delta\varepsilon}{\varepsilon}\right)\right]$$

Molecular Contamination Effects on Emittance

- Molecular contamination will predominately be either transparent or opaque at radiating wavelengths
  - If transparent, the radiating surface is basically unaffected
  - If opaque, it takes over the job of the radiator
- Only if there is a significant decrease in the thermal conductivity leading to the radiating surface will the equilibrium temperature of the underlying surface be changed
  - Thermal conduction and thermal isolation
  - Specific temperature control

Effects on Surfaces

Effects on High-Emissive Surfaces

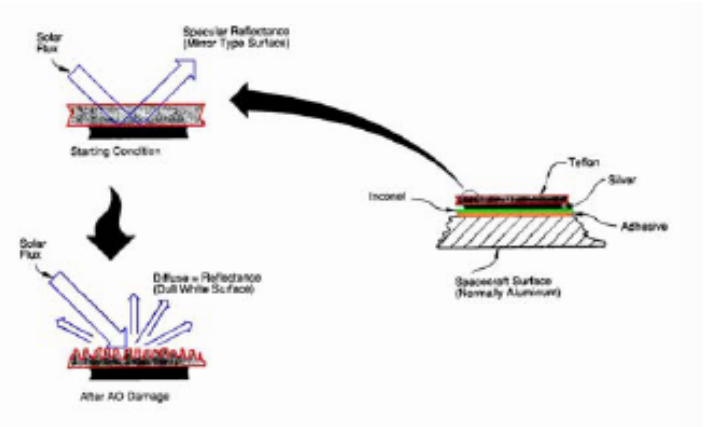
- For thin (< 1 μm) layers of molecular contamination this is not usually the case
  - 100 Angstroms (Å)
  - No significant decrease in the thermal conductivity
- Molecular surface contamination should have little thermal effect on high-emissivity surfaces at <300 K

Effects on Low-Emissive Surfaces

- The effects of molecular contamination on low-emissivity surfaces, such as polished metals, can be dramatic
- While molecules that are transparent to wavelengths >10 μm will not increase the surface emissivity, and therefore not decrease the surface temperature, molecules that are opaque at these wavelengths, which most molecules are, will increase emissivity and decrease temperature
- For many situations this can be desirable, if the extra energy is radiated to space and not to some other temperature-sensitive spacecraft surface

Effects on Specularity

- Note that an additional contamination concern in thermal control pertains to thermal radiator baffles that are highly specular
- These surfaces are used to shield the radiator from external heat sources and can cause significant backscatter into the radiator when illuminated by the Sun or Earth
- Often the thermal designer is more concerned with the baffles than with the initial radiator, since the radiator is protected from the Sun
  - Cooler radiator?



Effects on Transmitting Surfaces

Effects on Transmitting Surfaces

- If a contaminant film builds up the coverslide over a solar cell, less light will be transmitted to the cell and the power output of the cell will degrade according to the relation

$$DF(x) = \frac{\int S(\lambda) I_s(\lambda) e^{-\alpha_c(\lambda)x} d\lambda}{\int S(\lambda) I(\lambda) d\lambda}$$

- where $I_s(\lambda)$ (W/m) is the spectral response of the cell, a measure of how effectively the cell converts a particular wavelength of light into power

$$\int f(x)\, g(x)\, h(x)\, d\lambda$$

  - It will be seen that solar array degradation calculations should assume a photochemically deposited contaminant film that will be more absorptive
    - Photochemically enhanced deposition

Effects on Cryogenic Surfaces

Contamination on Cryogenic Surfaces

- The contamination issue associated with cooling any part of a spacecraft, especially an IR sensor, is that the average molecular residency times are exponential functions of temperature

$$\tau(T) = \tau_o e^{E_a/RT}$$

- On a cold surface, molecules with lengthy residence times, would stick to it
- On a warm surface, molecules would not stick to it

Contamination on Cryogenic Surfaces

- For example, water (the most common outgassing molecule from spacecraft surfaces) resides less than a microsecond, on average, at room temperatures, but will have a residence time on the order of the age of the universe (~10^{17} s) on a surface at a temperature of ~77K
  - Cold surfaces act as "getters" for most molecules that strike them

- The consequences of molecular contamination on cold spacecraft surfaces depend on the nature of the contamination and the sensitivity of the surface
- Molecules that do not scatter, reflect, or absorb IR photons at the wavelength of interest are of little concern
  - True of one-atom gas molecules (e.g. Ne, Ar), and often true of two-atom gas molecules (e.g. N_2, O_2)
  - One-atom molecules have no vibration modes, and two-atom molecules have only one vibration mode

Particulate Effects on TCS

Effects of Particles

- First, the dust will prevent some light from reaching the underlying surface [Obscuration]
  - Some effects of particulate contamination are therefore proportional to the surface obscuration, or the percent area coverage (PAC)
  - Solar arrays, thermal control surfaces, and optical surfaces may all be degraded due to surface obscuration
- Secondly, the particles may scatter light off of its original direction of travel [Scattering]
  - This is a critical concern for many optical systems

Reflecting of Thermal Control Surfaces

- The presence of particles on a thermal control surface will have the net effect of altering its effective solar absorptance and/or emissivity
- By design, many thermal control surfaces are chosen to have a low value of solar absorptance
- Particles, which would typically have a higher solar absorptance than the underlying surface, would block some light from reaching the radiator directly
  - α: White marble (0.46), red brick (0.75), gravel (0.29)
- Most of the obscured solar flux would be absorbed by the particles rather than reflected back to space

Reflecting of Thermal Control Surfaces

- As a result, the particles would seek a higher equilibrium temperature than the surface on which they are sitting
- The particles would then radiate and conduct more heat to the surface than they receive in return, and the end result would be an increase in the equilibrium temperature of the surface
- By inspection, the change in solar absorptance due to particles is given by

$$\alpha_s^x = \alpha_s + \Delta\alpha_s = \alpha_{s,surf}(1 - PAC) + \alpha_{s,part}(PAC)$$

Reflecting of Thermal Control Surfaces

$$\Delta\alpha_s = PAC\,(\alpha_{s,part} - \alpha_{s,surf})$$

- Where
  - $\alpha_{s,\,surf}$ and $\alpha_{s,\,part}$ refer to the solar absorptahce of the clean surface and particles
  - *PAC* is the percent area coverage of the particles
- How significant is this?
  - Level 400 is ~0.1% obscuration
  - $\Delta\alpha_s$ ~0.001

Reflecting of Thermal Control Surfaces

- Similarly, particles will also change the effective emissivity of a surface according to the relation

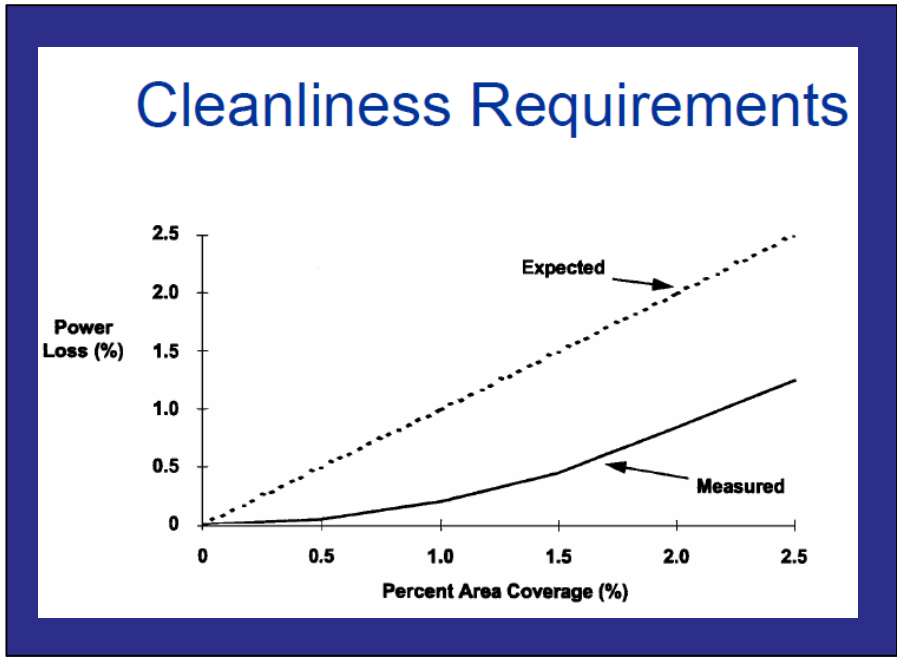
$$\varepsilon^{x} = \varepsilon + \Delta\varepsilon = \varepsilon_{surf}(1 - PAC) + \varepsilon_{part}(PAC)$$

$$\Delta\varepsilon = PAC\,(\varepsilon_{part} - \varepsilon_{surf})$$

- Consequently, it is seen that the effective increase in solar absorptance, emissivity, and equilibrium temperature is directly proportional to the *PAC*
- Note that the biggest concern is to be expected if black (highly absorptive) particles are deposited on white (highly reflective) surfaces, or if white (low-emissivity) particles deposit on black (high-emissivity) surfaces

Surface Obscuration Effects on Solar Arrays

- Because solar cells are nonimaging devices, surface obscuration at the wavelengths of interest (~0.4 - 1.1 μm) is the only effect of surface particles
- The power reduction is not exactly equal to the *PAC* of those particles
- Individual solar cells are less sensitive to surface particles than expected
- Experiments indicate that a 1 % *PAC* produces only a 0.2% power loss
- This is due to the fact that the contaminated cell not only produces less power, but also becomes a resistive load also (neglecting temperature effects, which can be important if the cells are not all at the same temperature)



Common Spacecraft Materials

Material	α_s	ε	α_s/ε	Material	α_s	ε	α_s/ε
Aluminum – polished	0.35	0.04	8.75	Kapton/Al	0.48	0.81	0.6
Beryllium – polished	0.4	0.05	8.0	In2O3/Kapton/Al	0.4	0.71	0.56
Copper – polished	0.28	0.13	2.2	Quartz Fabric/Tape	0.19	0.6	0.3
Stainless Steel – polished	0.5	0.13	3.85	OSR (quartz mirror)	0.06	0.81	0.07
Gold – on AL	0.26	0.03	6.5	FEP (5 mil)/Silver	0.11	0.8	0.14
Grafoil	0.66	0.34	1.9	FEP (2 mil)/Silver	0.08	0.62	0.13
Silicon Solar Cell				Black Paint			
- bare	0.82	0.64	1.3	- Epoxy	0.95	0.85	1.12
- Si cover	0.82	0.81	1.0	- Acrylic	0.97	0.91	1.07
- Si cover, blue filter	0.78	0.81	0.96	White Paint			
- Si cover, red filter	0.7	0.81	0.86	- Silicone (S13GLO)	0.20	0.90	0.22
				- Silicate (Z93)	0.15	0.91	0.16
				- Silicate (YB71)	0.10	0.91	0.11

Contamination Effect on Equilibrium Temperature

Sun-facing surfaces

- Sun-facing surfaces are often designed to be highly reflective to minimize the amount of heat that is absorbed by the spacecraft
  - designed to enhance reflection
  - α (small) + ρ (large) + τ (small) =1
- If the low initial value of α_s is increased by contamination, the heat load to the spacecraft will increase
  - $T = f(\alpha_s/\varepsilon)$
  - $\alpha_s \uparrow$ Temperature $\uparrow$
  - $\varepsilon \downarrow$ Temperature $\uparrow$

Deep-space-facing surfaces

- Deep-space-facing surfaces (and many Sun-facing surfaces as well) are often designed to be highly emissive, so that radiation heat loss to space is maximized and certain parts of the spacecraft (such as infrared focal plane detectors) can be passively cooled
- These surfaces radiate heat more effectively than they absorb it, these surfaces are usually called radiators
  - Contaminant lowers their effective emissivity, the heat loss will decrease and the "cold" parts of the spacecraft will warm up

$$Q_{out} = \varepsilon \, A_{tot} \, \sigma T^4$$

Thermal Control Hardware

Thermal Hardware

- Thermal Surface Finishes
- Insulation
- Radiators
- Heaters
- Mounting and Interfaces
- Louvers
- Heat Switches
- Phase-Change Materials
- Pump Fluid Loops
- Thermoelectric Coolers
- Heat Pipes

Thermal Control Hardware and Contamination

Thermal Control Hardware	Contamination Effect	
	Molecular	Particulate
Thermal Surface Finishes	α, ε	α, ε
Insulation	α, ε, k	α, ε, k
Radiators	α, ε	α, ε
Heaters	Performance	Performance
Mounting and Interfaces	k	k
Louvers	α, ε, performance	α, ε, performance
Heat Switches	k, performance	k, performance
Phase-Change Materials	Performance	Performance
Pump Fluid Loops	Performance	Performance
Thermoelectric Coolers	Performance	Performance
Heat Pipes	Performance	Performance
Others	Performance	Performance

Contamination Control and Prevention

Contamination Control during Assembly

Establish Contamination Control Plan (CCP)

General cleanliness should be maintained during manufacturing and assembly

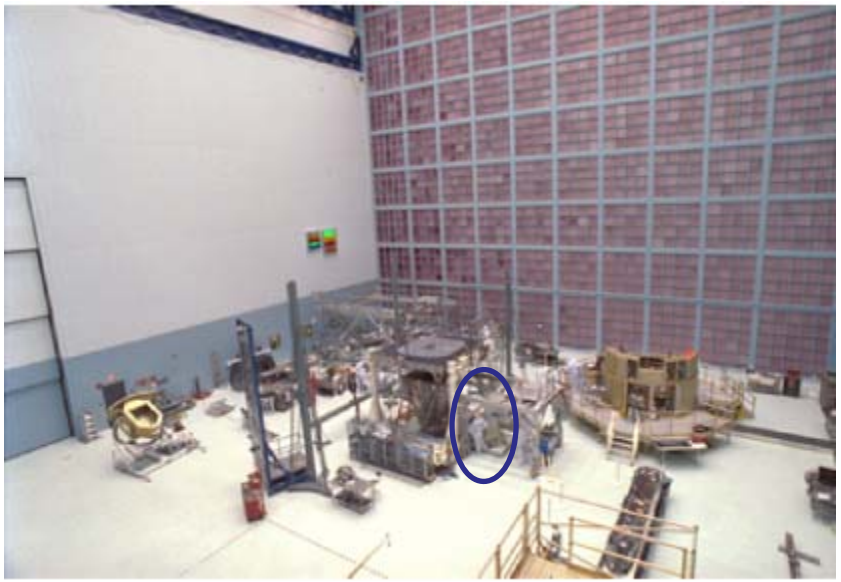
- Parts should be cleaned prior to assembly and as they become soiled
- Components should be cleaned prior to becoming inaccessible
- Machining/Welding/Soldering/Abrading: Should include vacuuming, wipe down
- Lubricant/Cutting Oils: Excess should be wiped
- Coatings Application: On a cleaned surfaces
- Assembly should be done in a clean area where possible and gloves should be worn

Facility and Personnel Requirements

Facility Requirements per FED-STD-209E or ISO-14644-1

Clean facilities help maintain cleanliness levels and standards

Cleanroom Garments help mitigate contamination



SSDIF
Building 29
Class 10,000/ISO 7
Temperature/Humidity Control
Full Cleanroom attire

Garmenting Requirements

Spacecraft Systems Development and Integration Facility (SSDIF)

Contamination Control Overview Environmental Testing

- Mechanical Tests (Additional Localized Covers for Sensitive Surfaces)
  - Vibration – Bag and Purge
  - Shock – Bag and Purge
  - Acoustic – Bag and Purge
  - Mass Properties – Perform in Cleanroom or Bag and Purge
  - Spin Balance (Launch Site) – Soft Covers for Apertures/Requires Class 10k Environment (Spacecraft Pursing)
- Thermal Vacuum Bakeout and Testing
  - Chambers Certified for Surface Cleanliness and Outgassing (TQCM, RGA, Cold Finger Analysis)
  - Use of Barriers (Bakeout Box, Tents, Bagging, Covers) to Prevent Particle Fallout
  - Scavenger Plate; Cold Finger
  - Slow Re-Pressurization
  - Use of Bakeout Boxes (Shroud Within a Shroud)
- EMI
  - Bagging/Purging to Greatest Extent Possible/Internal Covers for Optics
  - Class 10k Facility, Protect Apertures.

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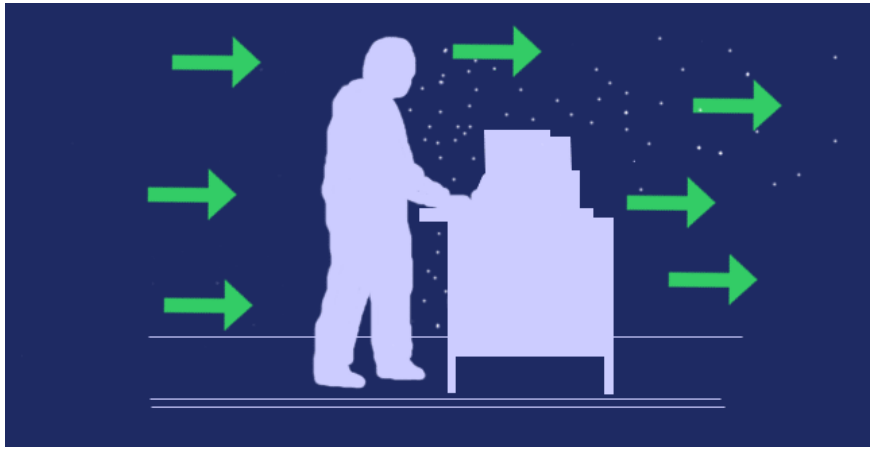
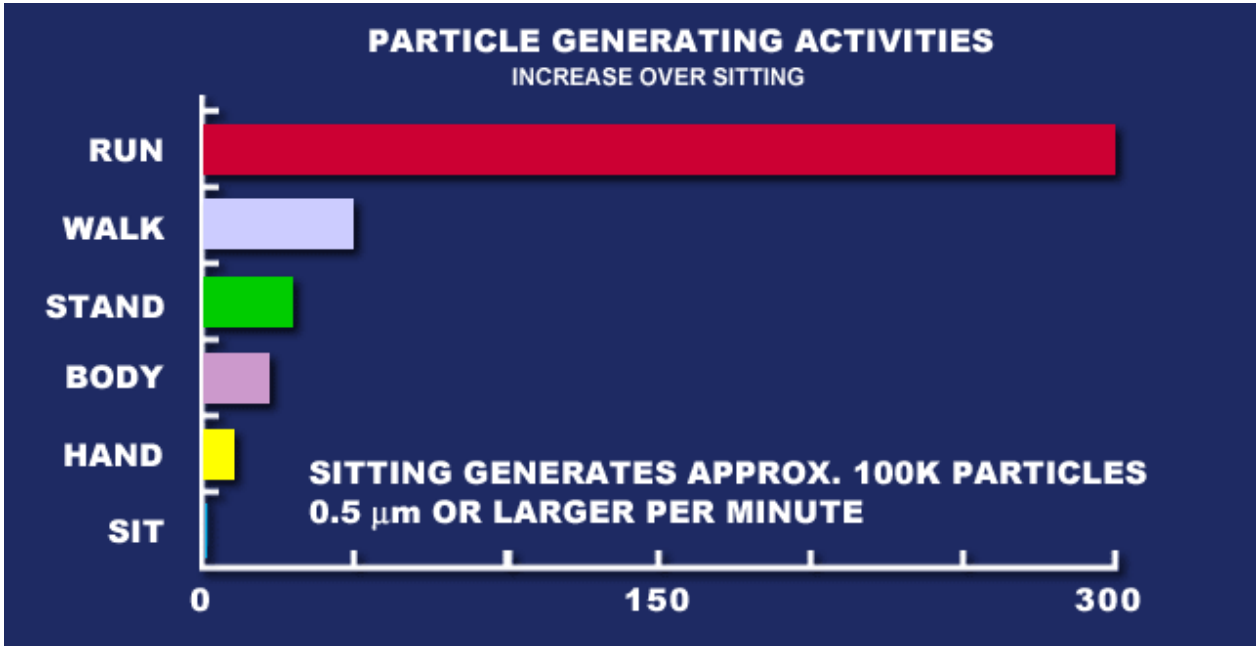
Facility Contamination Controls

- All equipment shall be cleaned before entering any cleanroom or cleantent
  - This includes GSE, ladders, scaffolds, dollies, tools
  - A precision cleaning area shall be provided
  - Before entering the clean area remove the outer bag in the anteroom and remove the inner bag in the cleanroom/cleantent.
  - Large items needing cleaning should be scheduled well ahead of time and coordinated with Contamination Control.
- Cleanroom paper must be used for all WOAs and papers entering a clean area
- Materials brought into the cleanroom shall be cleanroom compatible, if uncertain, contact Contamination Control
- Cleanroom doors and cleantent entrances should not be opened unless all hardware in the room/tent is in a safe configuration
- Access Restrictions: Required GSFC Code 540 Cleanroom Certification Course
- Manloading Restrictions
- Work downstream of airflow



Personnel Control Reminders

- Dust collects even within cleanrooms
- Fingerprints can not be completely removed by an alcohol wipe, and on many materials can etch the surface causing permanent changes to the surface properties.
- Particles that reside on a surface for a long period of time are harder to clean off.
- No make-up, perfume, or after shave are allowed in the clean area
- PEOPLE ARE DIRTY

Particle Generation