Materials and Processes for Space

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Overview

- ***Introduction***
- ***Space environment effects on materials***
  - *Pre-launch environment*
  - *Launch environment*
  - *External space environment*
  - *Internal environment (pressurised modules)*
- ***Materials used in space***
- ***Requirements and testing of space materials***
- ***Evaluation of materials***
- ***Processes for space***
  - *Classification*
  - *Most used processes*
  - *Electronics and surface protection*
- ***Selection of materials, parts and processes***

Some definitions

- *Material*
  A raw, semi-finished or finished purchased item (gaseous, liquid, solid) of given characteristics

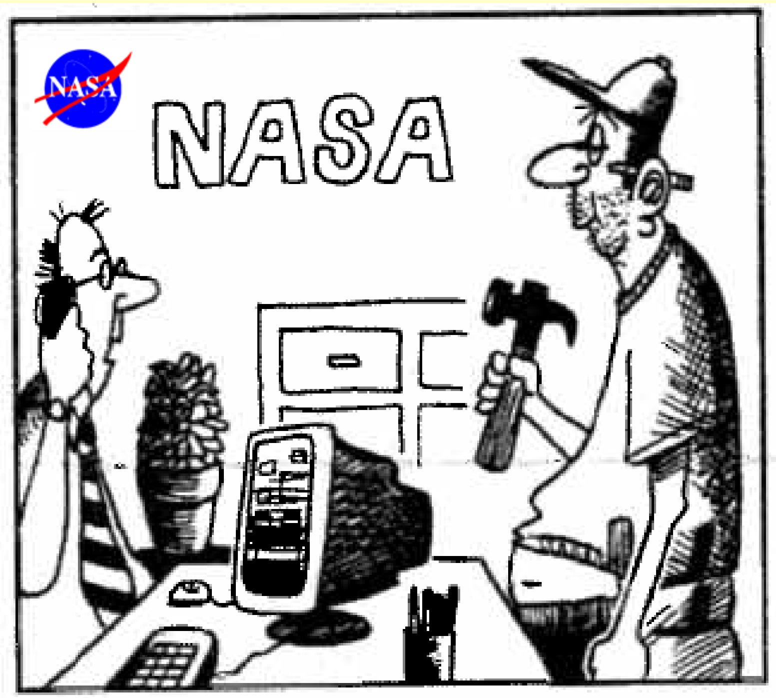
- *Process*
  A set of inter-related steps which transforms a material into a semi-finished product or a semi-finished product into a final product

- *Mechanical part*
  One or more elements which perform a function, mechanical, optical, thermal or electromechanical and not classified as EEE components as defined in ECSS-Q-60

- *Qualification*
  A set of data collected (typically test results) to demonstrate that a material or a process performs as intended with respect to technical requirements, with a sufficient margin and sufficient confidence

Space is special …

- We cannot spend two million dollars to repair the telescope Hubble, but here there is a guy that is willing to try to repair it for 40 dollars per hour.

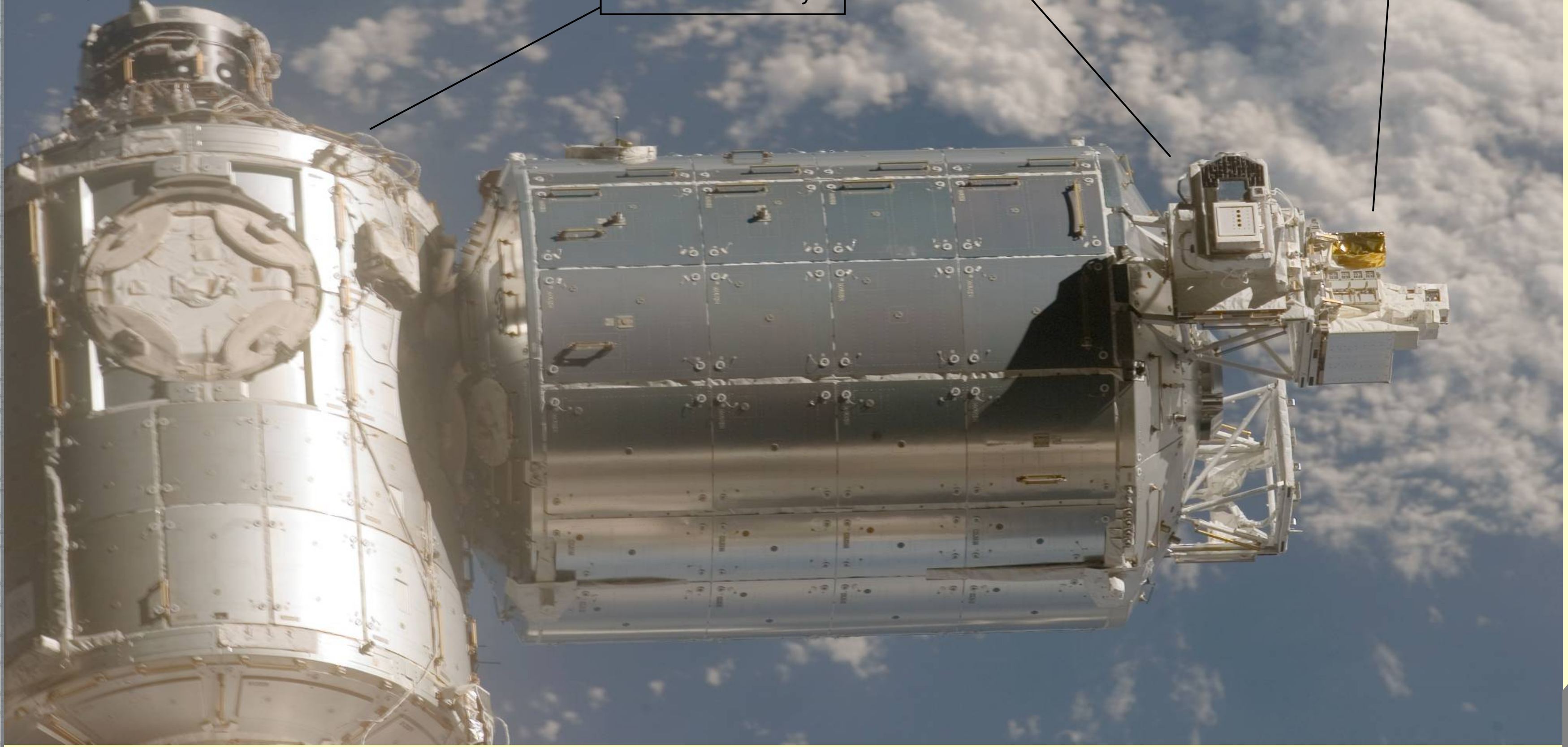


— Non possiamo spendere due milioni di dollari per riparare il telescopio Hubble, ma qui c'è un tizio che è disposto a fare un tentativo per quaranta dollari l'ora.

The International Space Station

The Columbus module (ESA)

- Module length 6.871 m
- Max diameter 4.477 m
- Max in orbit mass 21000 kg
- Facilities: Biolab, Fluid Science Laboratory, European Physiology Module, European Drawer Rack



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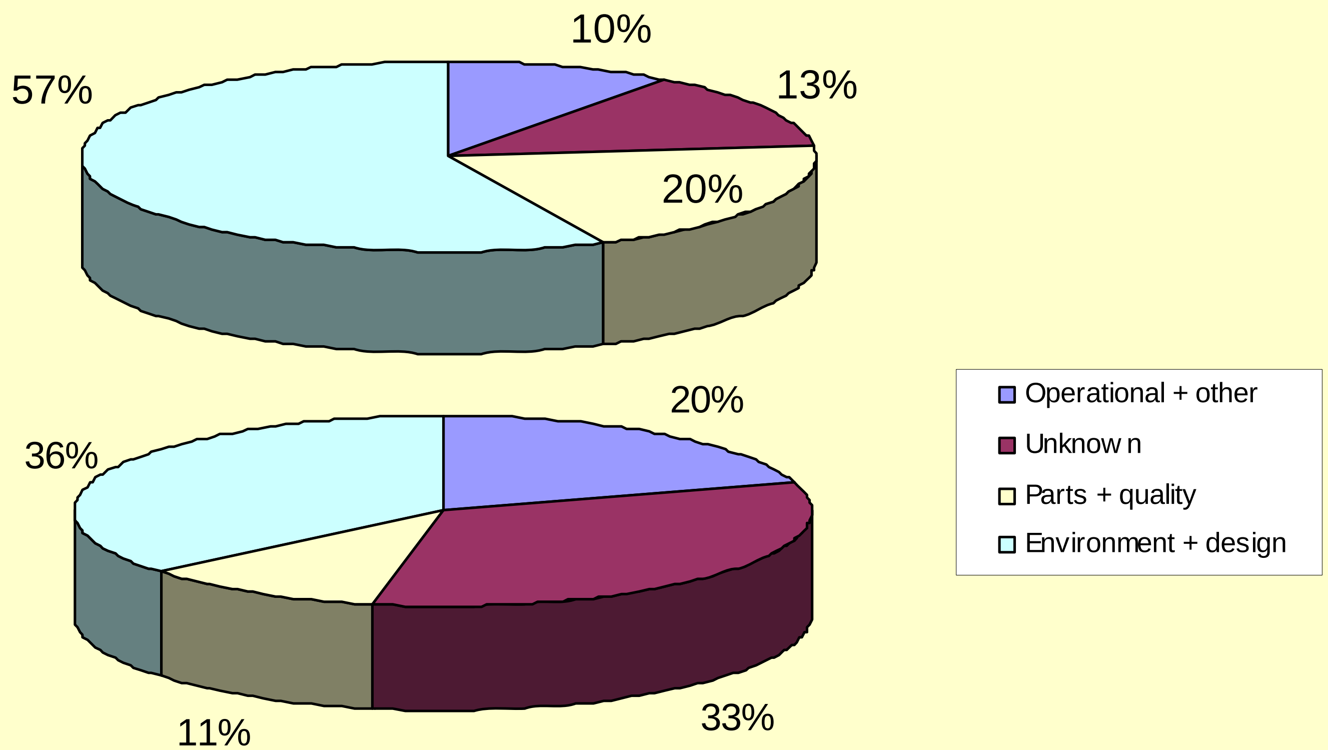
Space environment effects on materials

Spacecraft failure causes

Period 1977-1983

More recent



Sources: Hecht et al. (1985), Remez et al.(1996)

Space environment effects on materials

- Pre-launch environment

Before reaching space, space hardware is exposed to the ground environment. As the design of spacecraft is focused on surviving in the space environment, sometimes the effects of the ground environment are underestimated.

The design, manufacture, assembly, handling, transportation of a spacecraft, and its final integration into the launcher is a long process that can last between 5 and 10 years.

During this phase, corrosion, stress-corrosion cracking, ageing and materials degradation may damage the spacecraft.

Space environment effects on materials

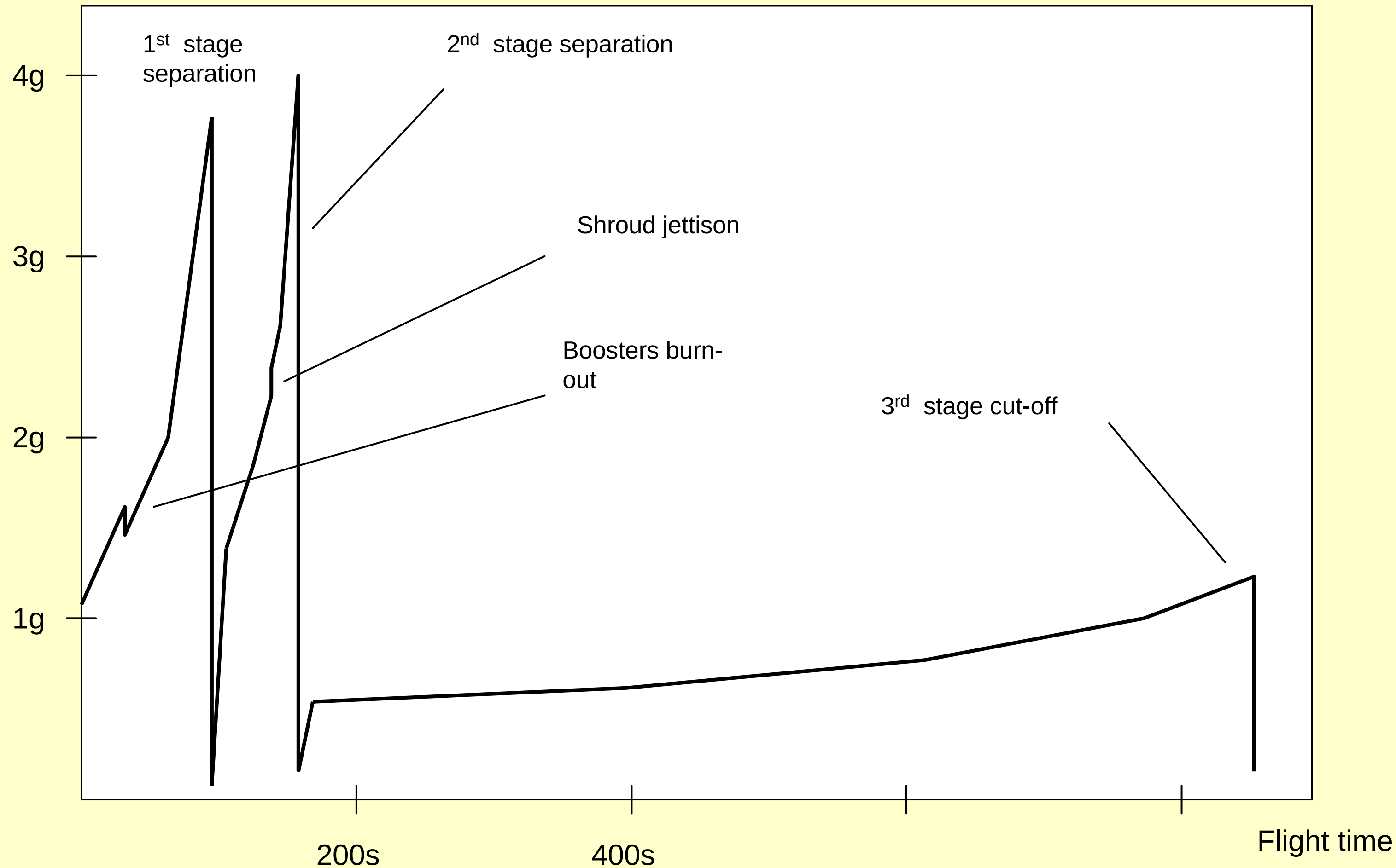
- Launch environment

  It is an extreme environment characterised by accelerations, vibrations, acoustic noise, shocks and rapid depressurisation. Materials are subjected to high stresses under static and fatigue loading.

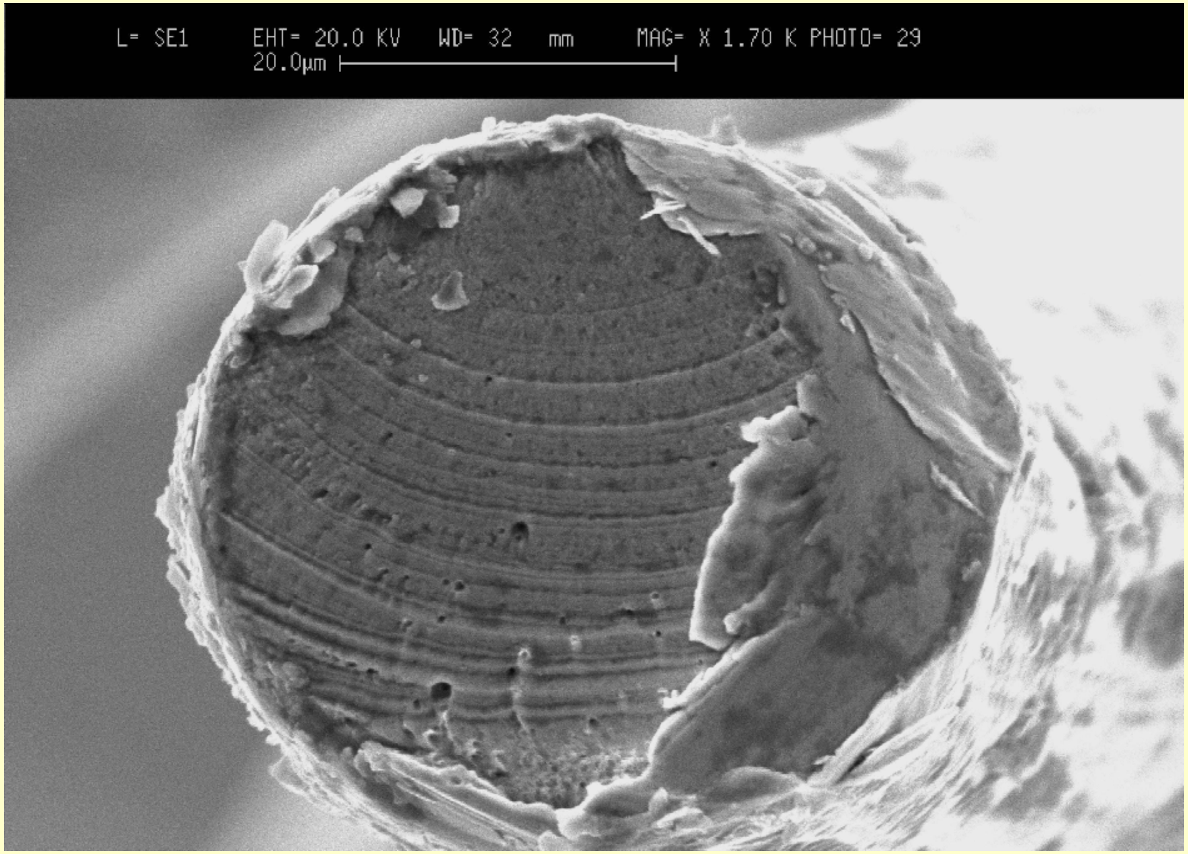
  Most launch pads are in a coastal environment, where the risk of corrosion and stress corrosion is higher.

Space environment effects on materials

Typical static acceleration profile of a three-stage launcher

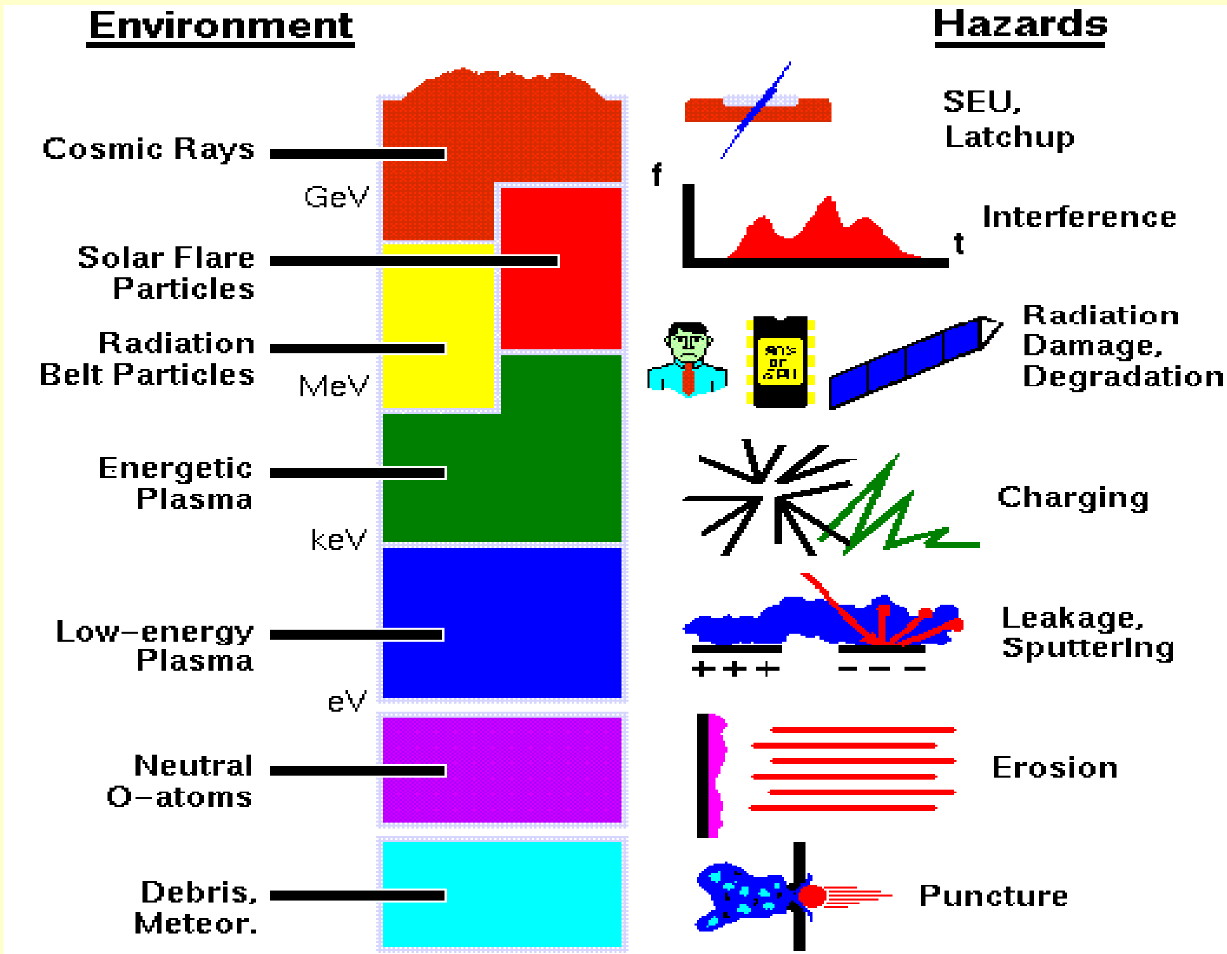


Space environment effects on materials (cont'd)

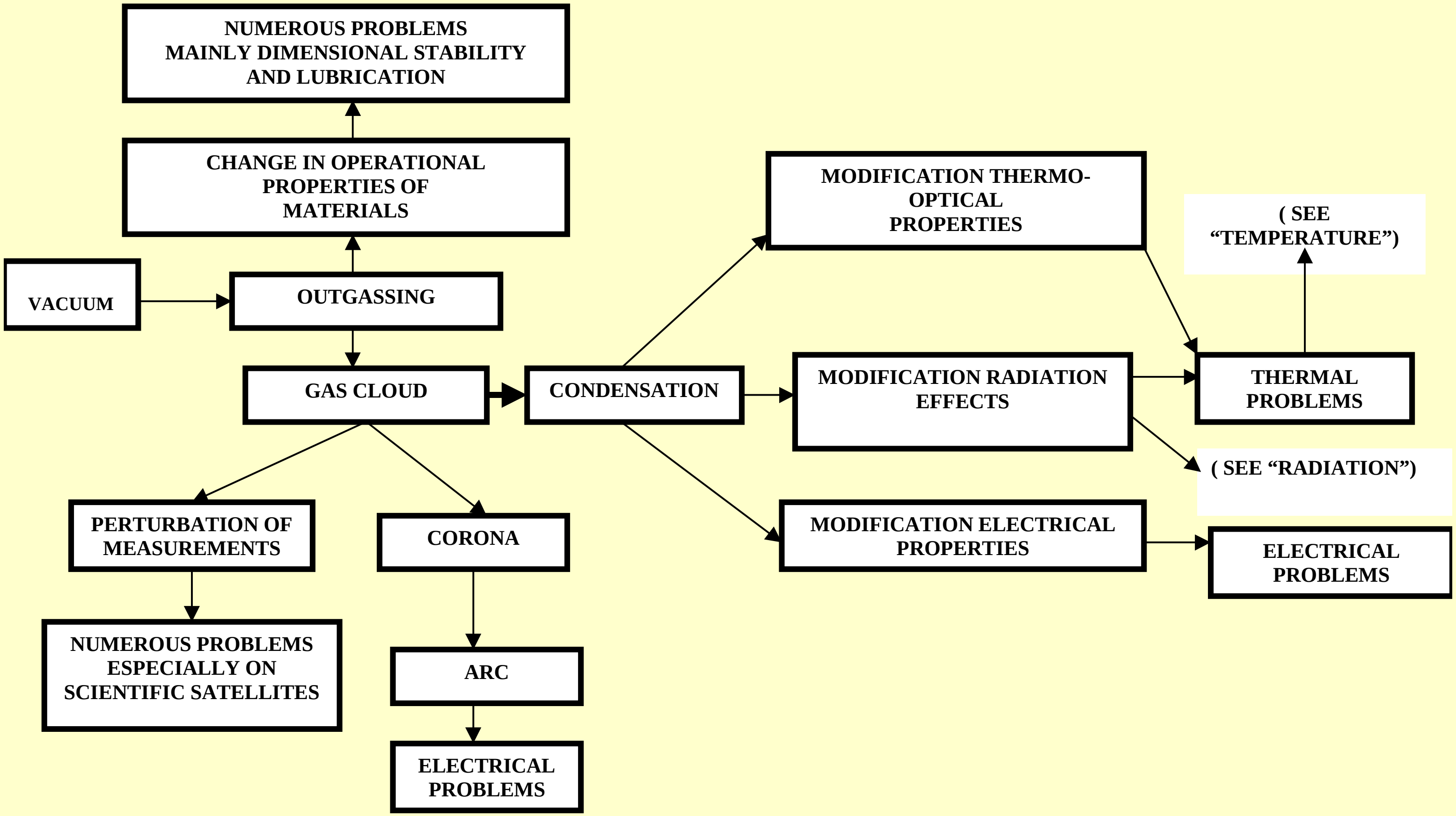


Failure by fretting fatigue of a 40µm steel wire occurred during vibration testing of a water pump assembly (Columbus).

Space environment and its effects



Space environment effects on materials (cont'd)

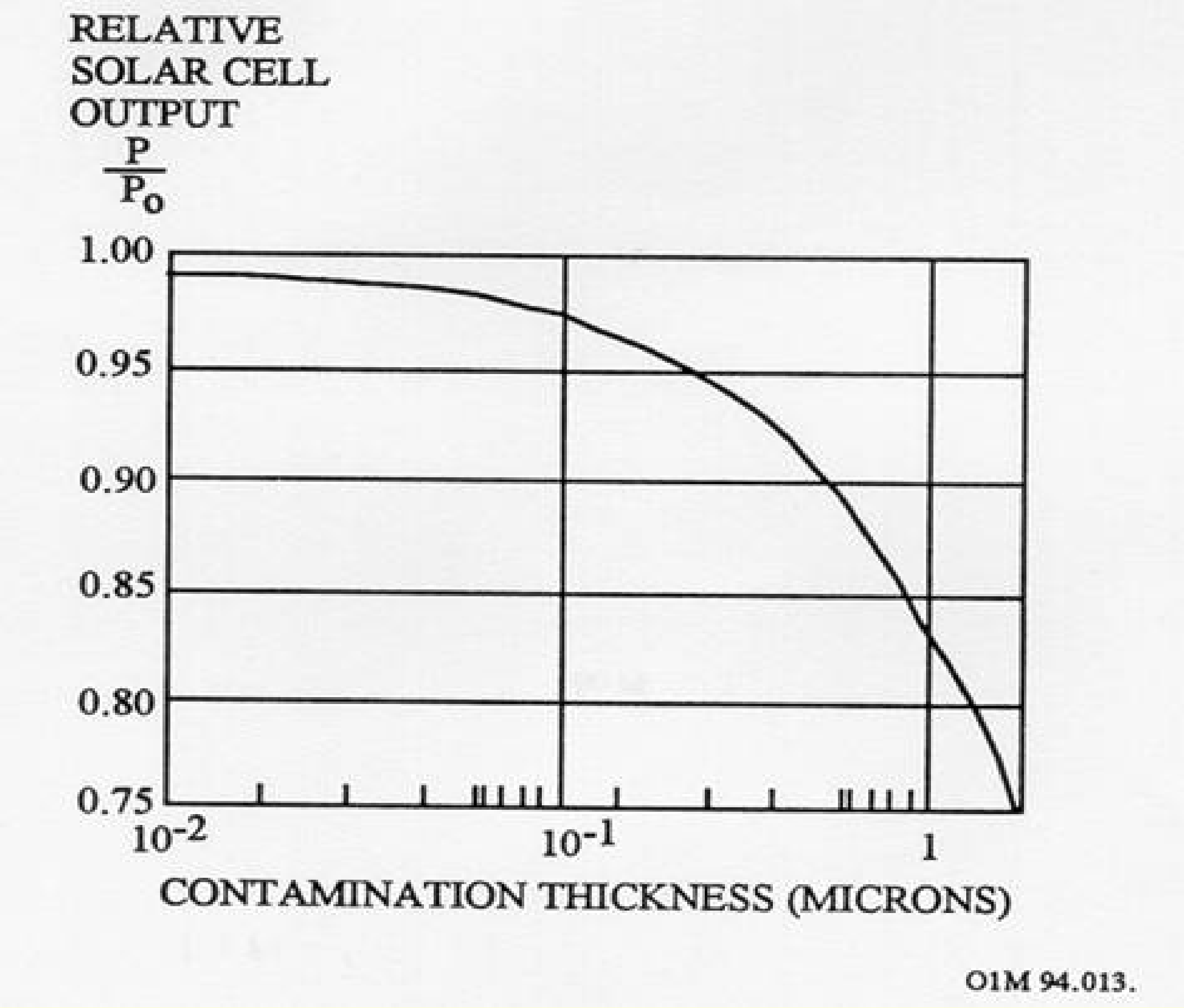


Space environment effects on materials (cont'd)

- Surface contamination: Surface contamination can be molecular or particulate
- Ground contamination: molecular and particulate contamination that occurred during manufacturing, assembly, testing, transportation and launch.
- In-orbit contamination: vacuum causes materials outgassing, venting of vapours and particulates. In-orbit contaminants include those generated on the ground and in space (e.g. EVA, thrusters, space debris). In microgravity conditions they deposit on electrically charged surfaces or condense on cold surfaces.

Contamination has a significant impact on the performance of optical sensors (partic. UV and IR sensors), solar arrays and thermal control surfaces. This phenomenon can occur at all altitudes.

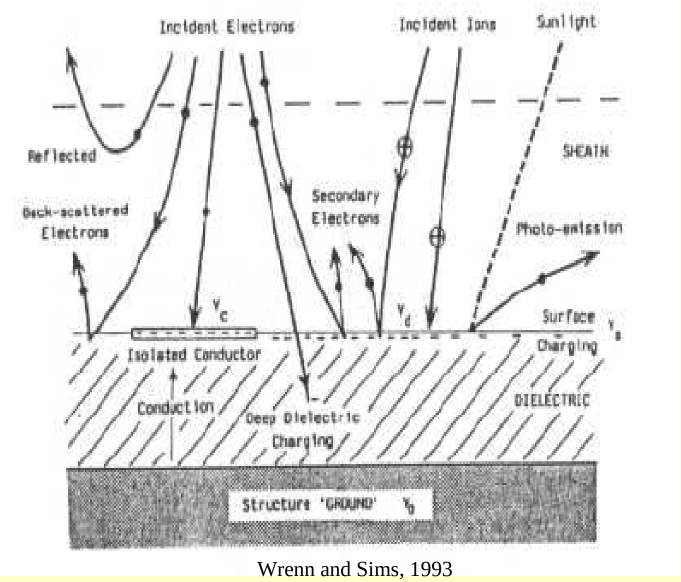
Effect of contamination on solar cell output



Space environment effects on materials (cont'd)

- Spacecraft charging

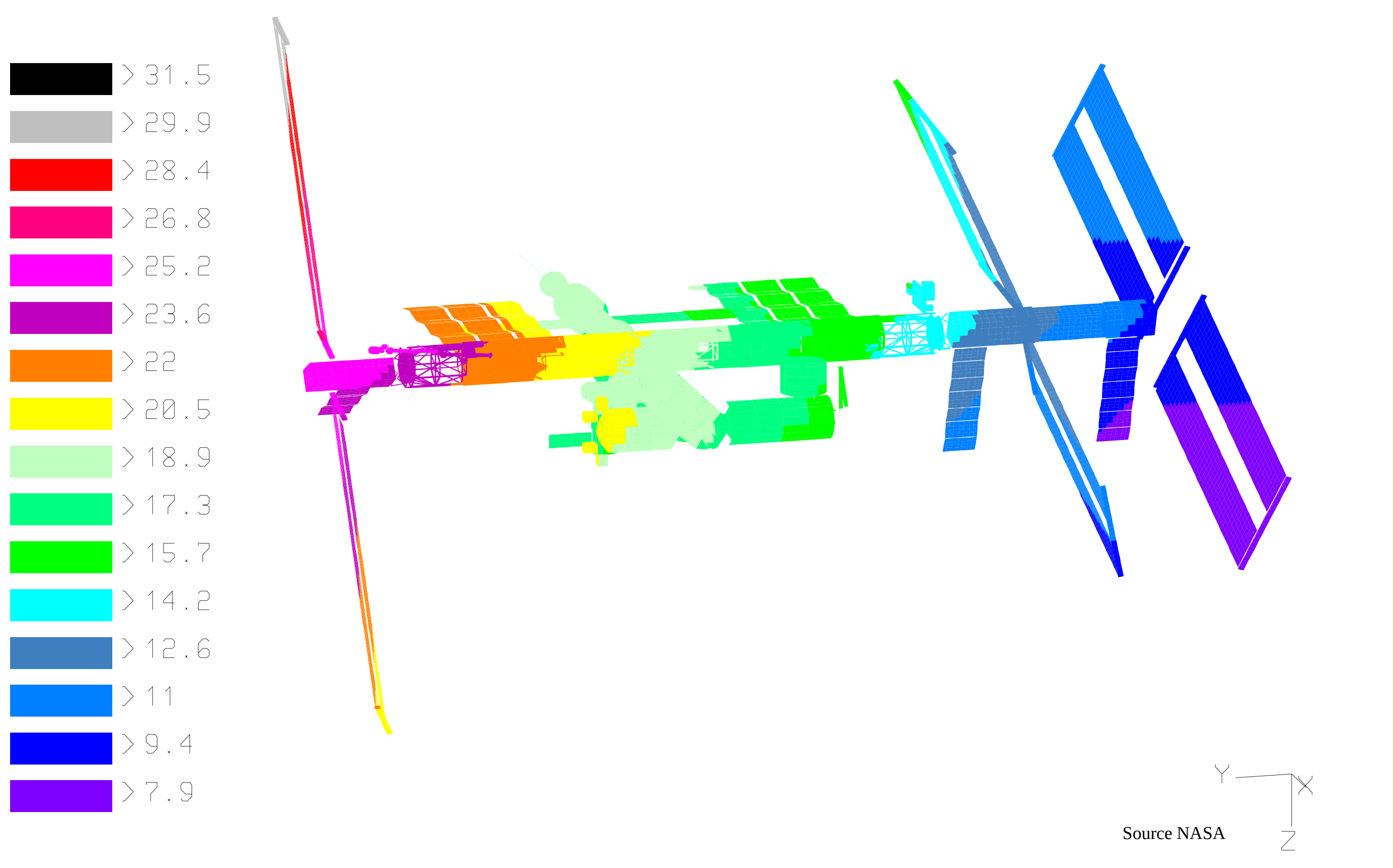
The plasma environment consists of charged particles such as electrons, ionised atoms and molecules. These particles deposit a charge on the spacecraft surfaces. Large potential differences, up to tens of thousands of volts, cause electrical discharge (corona) and arcing.



Wrenn and Sims, 1993

Discharging can damage spacecraft surfaces by altering thermal or electrical properties of materials. This phenomenon is more severe at 1000 km or higher altitudes. Elements affected include thermal blankets, optical coatings, paints and solar array triple junctions.

Example of ISS electrical potential with respect to the surrounding ionospheric plasma



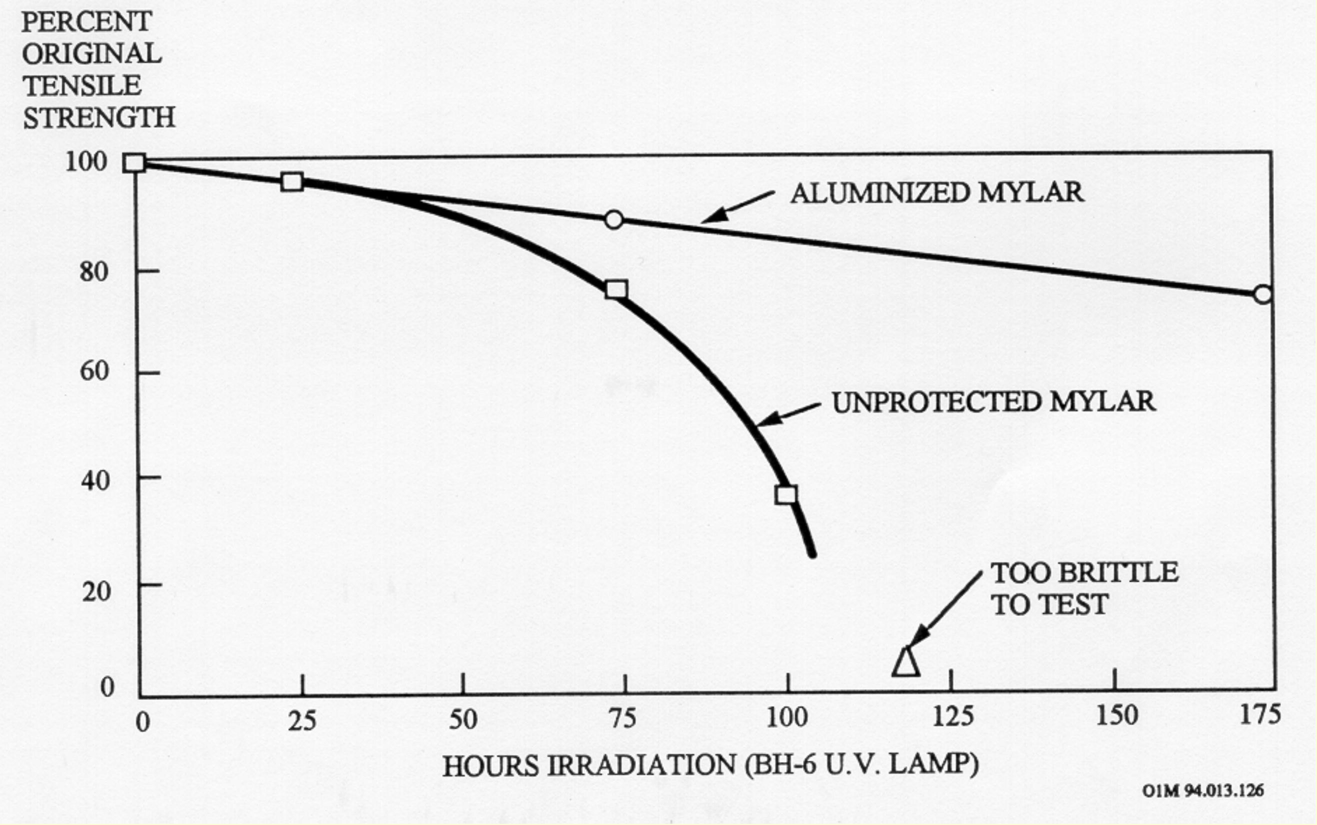
Source NASA

Space environment effects on materials (cont'd)

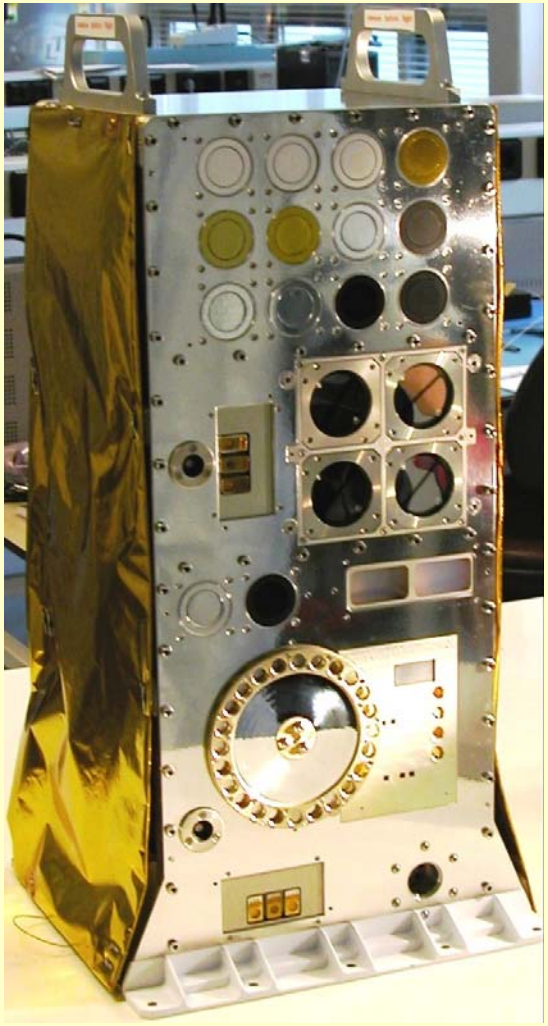
- Atomic oxygen produces enhanced erosion and degradation of spacecraft surfaces by the process of oxidation. This is a low altitude phenomenon (100-500 km), but it can affect any orbital configuration whose perigee is less than 500 km. Elements affected include optical coatings, paints and thermal blankets.

- Solar EUV (EXTREME ULTRAVIOLET) produces changes in the chemical and optical properties of various surfaces in the same way that UV radiation affects the paint on a car or a plastic garden chair. All altitudes and orbital configurations are affected, but low altitudes have higher degradation and erosion rates due to the "synergistic" effects with atomic oxygen. Spacecraft elements affected include optical coatings, paints, thermal blankets, etc.

Effect of UV radiation on Mylar tensile strength



Space environment effects on materials (cont'd)



• The ESA MEDET (Material Exposure and Degradation ExperimenT) will evaluate the synergistic effects of the low Earth orbit space environment on the optical and thermo-optical properties of spacecraft materials which will include windows, paints, thermal control foils, anodised surfaces and solar reflectors.

• The photo of MEDET ram face shows from top to bottom:

- Micro-calorimeters and illumination sensors,

- QCM (measure of contamination),

- SODAD (micro-particles impacts),

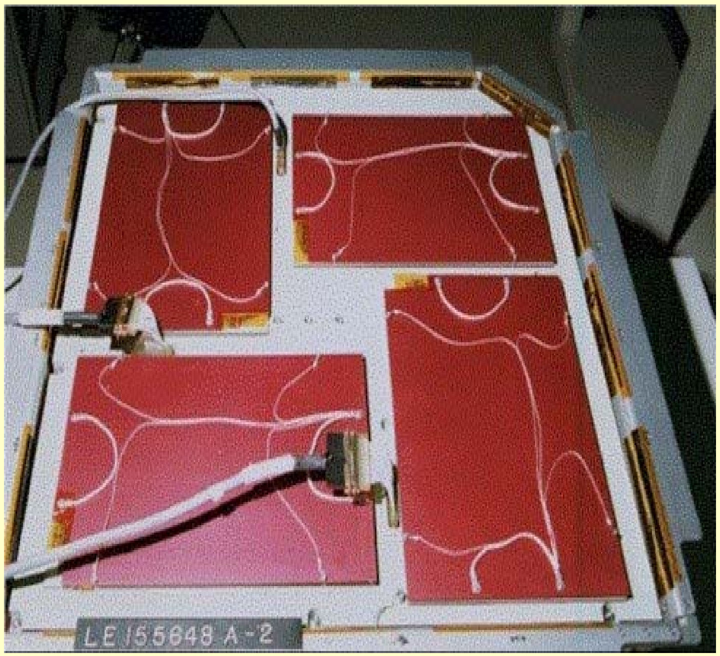
- Aerogel (collects micro-particles for analysis after return to earth),

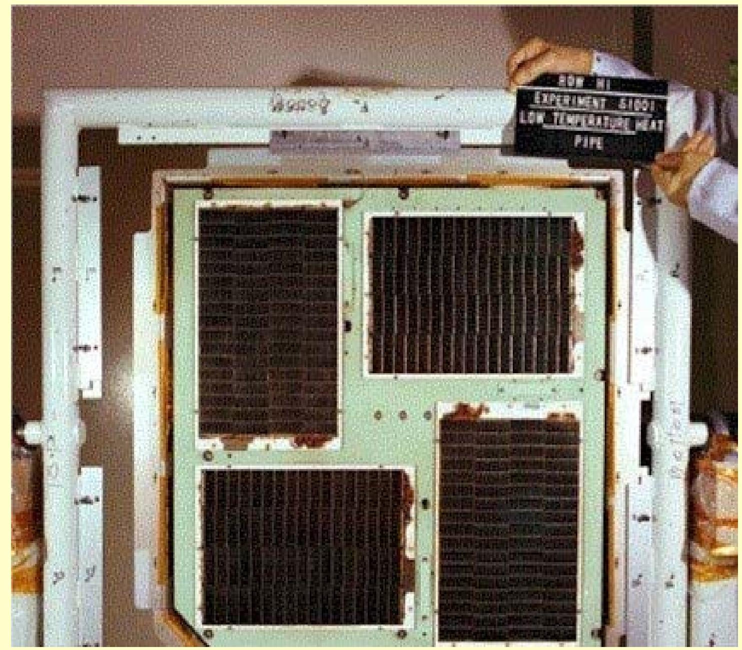
- Spectrometer wheel,

- STORM (atomic oxygen flux) and pressure gauge.

Space environment effects on materials (cont'd)

Pre- and post-flight photos of a low temperature heat pipe system flown on the NASA Long Duration Exposure Facility (LDEF).





The photos show the dramatic effect of atomic oxygen and EUV radiation on materials after 5.8 years in LEO. This can be seen by the change in colour of the surfaces.

Space environment effects on materials (cont'd)

- Long term exposure of materials to radiation in the Van Allen Radiation Belts (heavy ions He, O, N) and from high energy solar events can change the internal properties of various materials. Flexible thermal blankets can become brittle, dielectric material may become conductive, and optical windows such as cover glasses can become opaque. Here again all orbital configurations can be effected somewhat, especially orbits passing through the Van Allen Radiation Belts or the South Atlantic Anomaly (SAA).

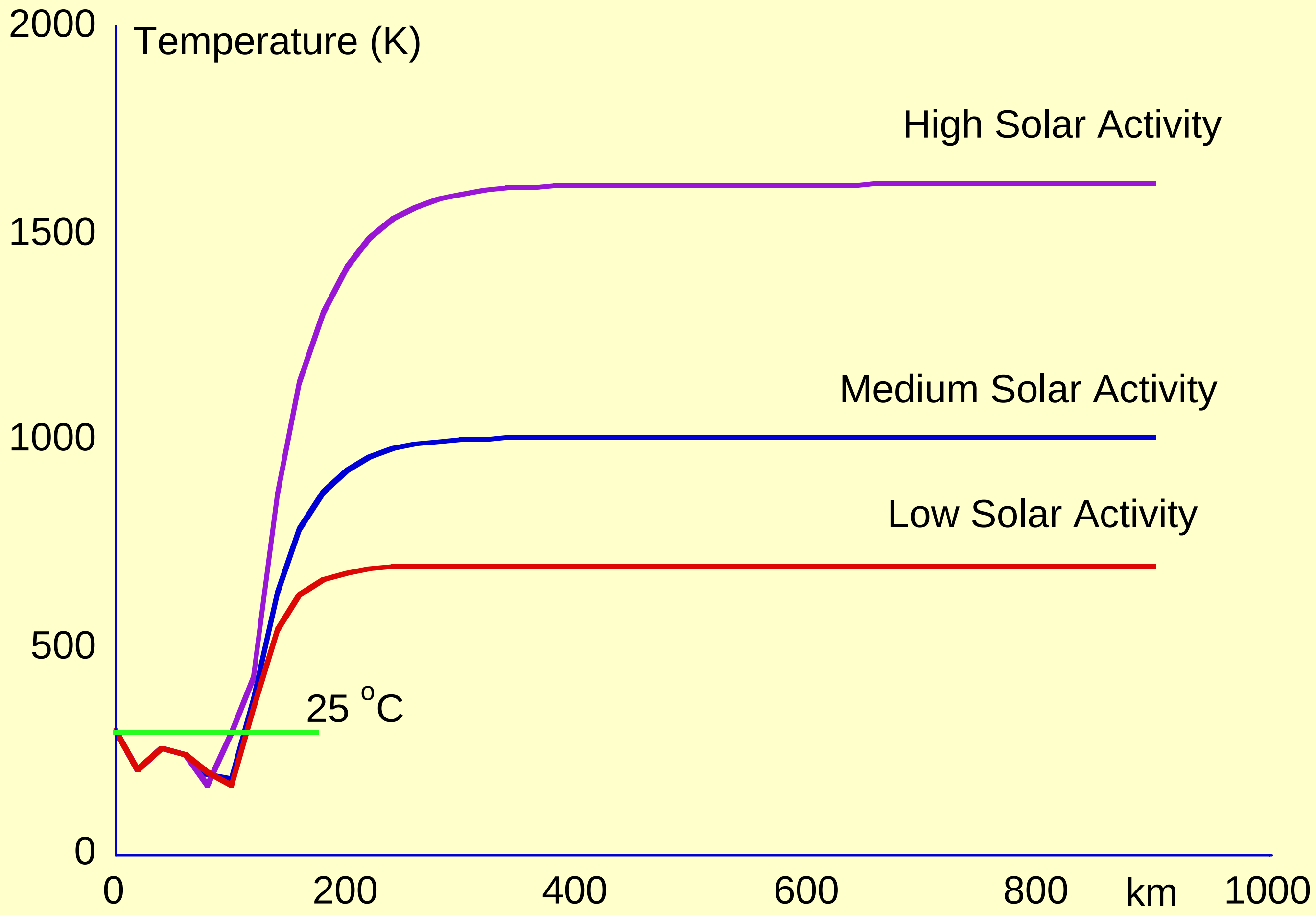
- The neutral upper atmosphere at lower altitudes (less than 1000 km) (O, He, H, N_2, O_2, Ar) impacts spacecraft at high speed (~ 8 Km/s) causing simple erosion and chemical reactions. Elements affected include optical coatings, paint, thermal blankets.

Space environment effects on materials (cont'd)

- Extreme temperatures

Spacecraft materials in the space environment are exposed to extreme temperatures and to thermal cycling. This also occurs to materials of cryogenic systems. At low temperatures materials can become brittle (eg. transition tough-to-brittle in metals) and at high temperatures they loose mechanical properties. Fatigue damage can occur as a result of thermal cycling.

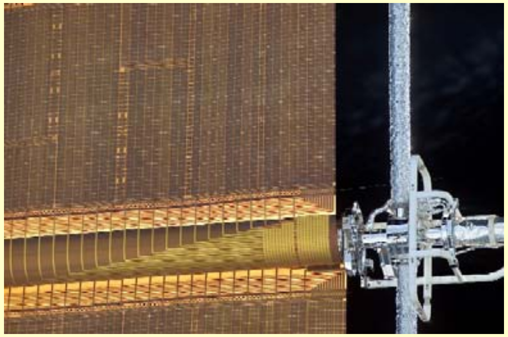
Temperatures in space as a function of altitude



Space environment effects on materials (cont'd)

- <u>Friction and wear</u>

In normal terrestrial conditions most contacting metallic surfaces are protected by oxide layers, oil or contaminants that ease sliding. Under vacuum, oxide layers and contaminants once disrupted or removed are unable to reform. For this reason, cold welding, galling and spalling increase wear and promote failures particularly in mechanisms such as solar arrays deployment assemblies, slip rings, pointing mechanisms.

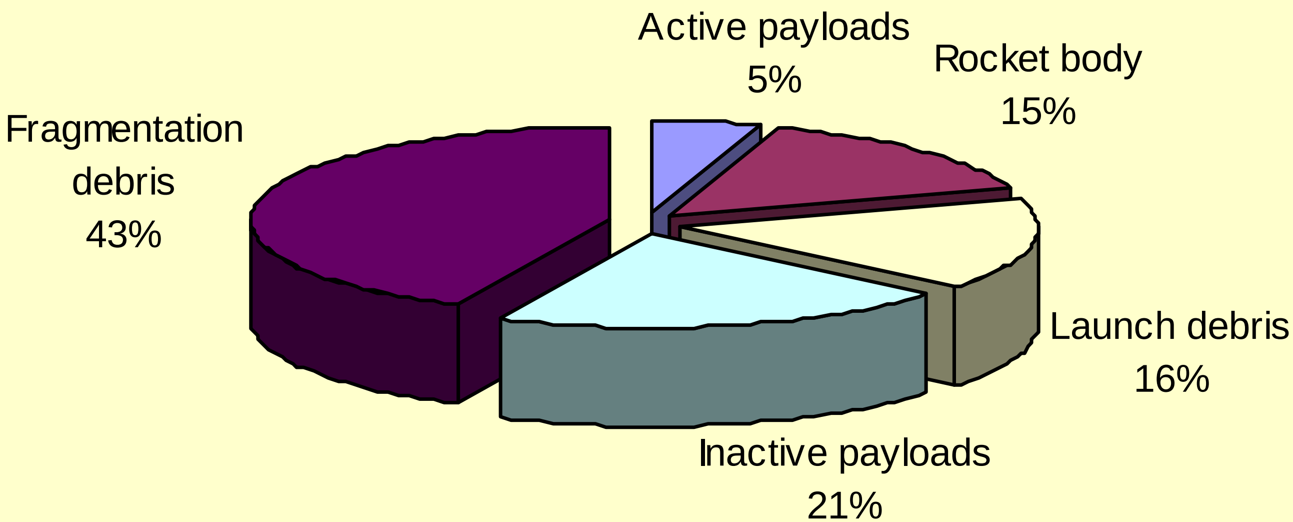


Space environment effects on materials (cont'd)

- Micrometeoroids and debris

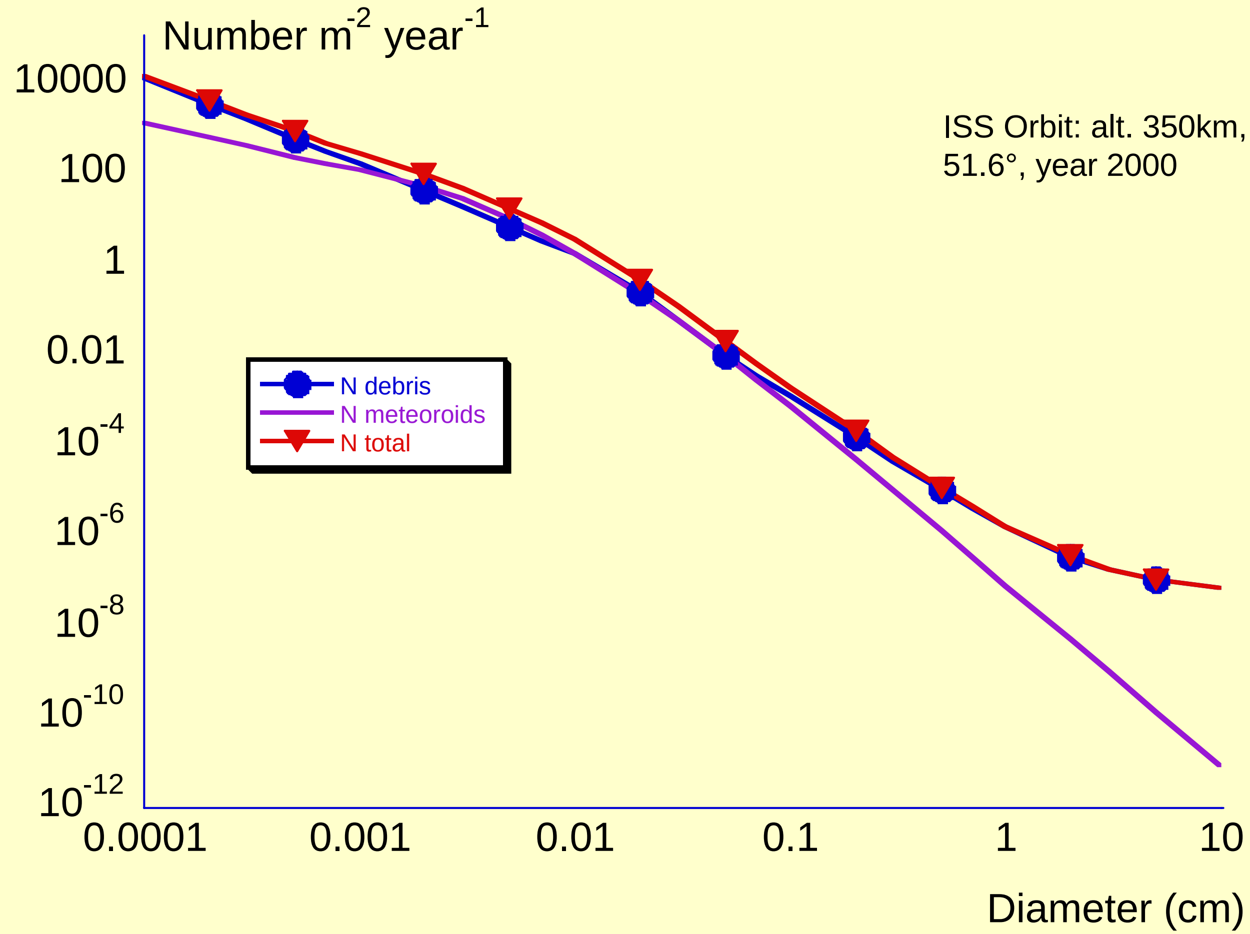
High velocity impacts pose a threat to safety and to the integrity of spacecraft. The impact of debris and micrometeoroids (~11 Km/s) typically produces craters, through holes and can generate debris. Damage can involve the loss of structural integrity and pressurisation, changes in thermo-optical properties, electrical conductive paths, erosion (synergistic effect with atomic oxygen) and contamination.

Source of catalogued debris population



Source: NASA Report (K.L. Bedingfield et. al)

Cumulative number of impacts in ISS orbit



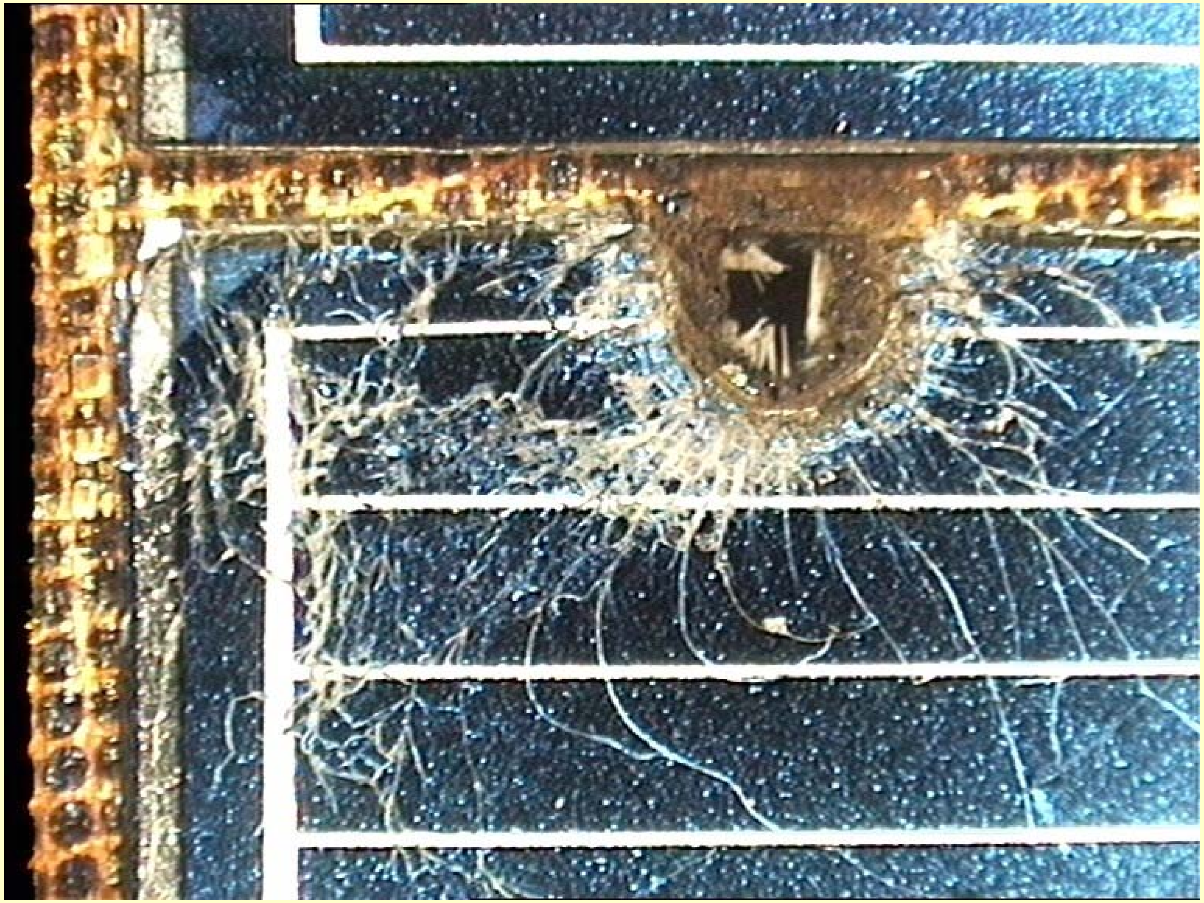
Space environment effects on materials (cont'd)

The image shows the results of an impact test between a small sphere of aluminium travelling at approximately 6.8 km/sec and a 18 cm thick aluminium block. The test simulates what can happen when a small space debris hits a spacecraft.

Space environment effects on materials (cont'd)

View of a few tenths of a millimetre hole made by an orbital debris in the panel of the Solar Max experiment (NASA).

Space environment effects on materials (cont’d)



Damage on Hubble Space Telescope (HST) solar array (hole size 2.5 mm). The HST solar array was retrieved in March 2002 after 8.25 years in space (NASA).

Space environment effects on materials (cont'd)

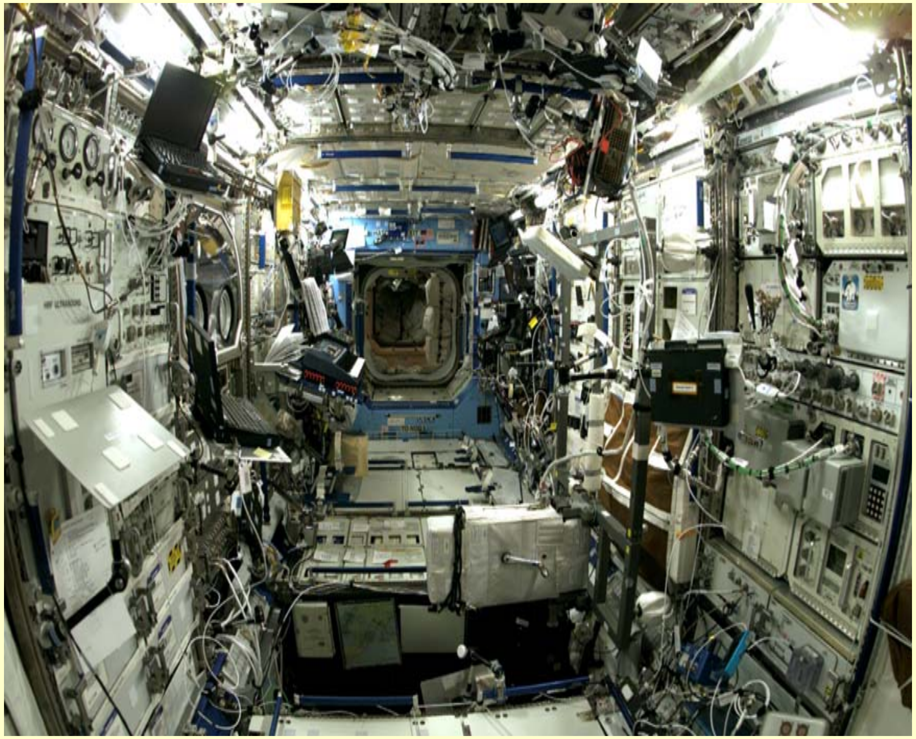
The effects of space environment can be reduced by design. For example:

- Appropriate materials – select materials and coatings that are stable under long exposure to space (vacuum, solar UV, erosion, etc)
- Treatment of materials – bake out materials and equipment to reduce outgassing during mission, use protective or conductive coatings
- Equipment configuration – direct gas purges and venting away from sensitive surfaces or equipment, shield sensitive optics, select radiation resistant materials and parts or shield them
- Design margins – use design margins to allow for degradation of thermal or optical surface properties (i.e. degradation of equipment performance over time)
- Spacecraft design and operation – select orbit configuration to reduce impacts, orient sensitive surfaces away from the direction of travel

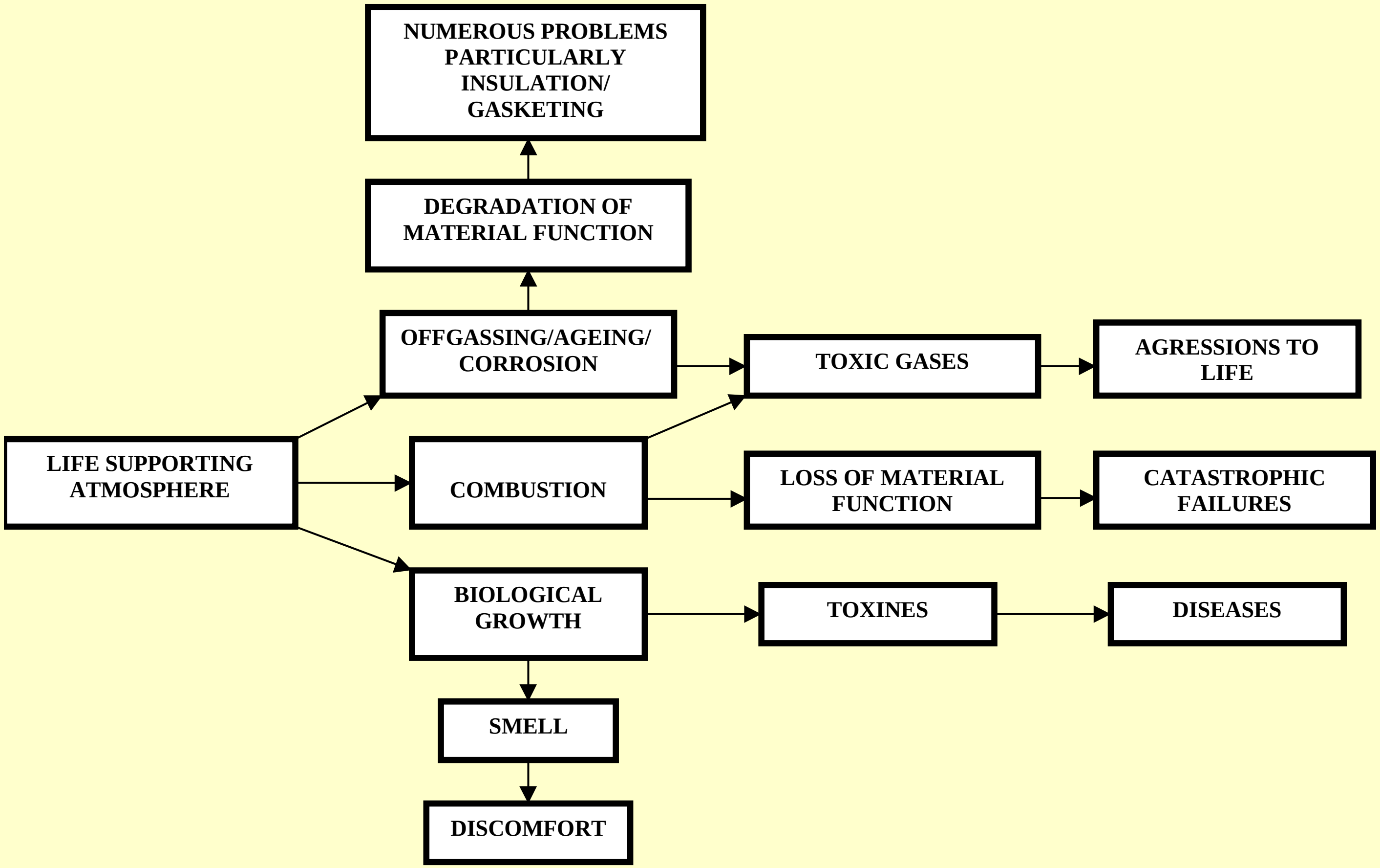
Space environment effects on materials (cont'd)

- Environment in habitable modules

  Although designed to support life in space, the presence of breathable air, water, organic materials and human activity can negatively affect the properties of materials. Damage of materials can occur in the form of corrosion, stress-corrosion, biological growth, combustion, friction and wear.



Internal environment



Internal environment: biological growth

• Bacteria and fungi feed on skin epithelia, lipids and other products of human activity. These products are introduced into the habitable atmosphere from human breath, sweat etc. and adhere to the internal surfaces.

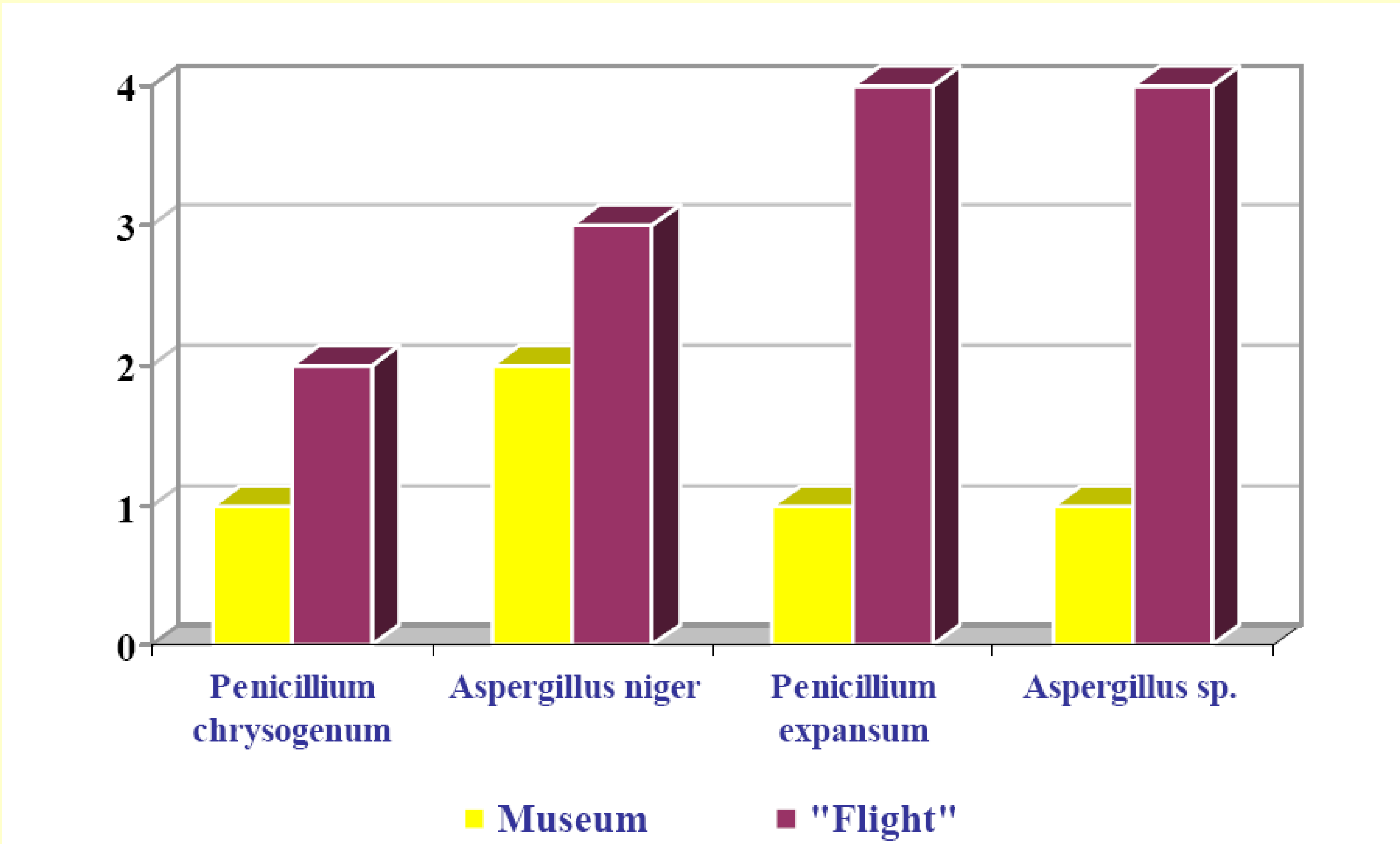
• Biological growth generate products of metabolism, such as organic acids which can corrode steel, glass and plastic.

• The photos show examples of damage to electronic equipment and an aluminium plate caused by fungi and bacteria on the MIR station.

• 250 species of microorganisms were found on MIR.

Internal environment: biological growth (cont'd)

Aggressiveness of fungal strains recovered from MIR



Source: N. Novikova

Internal environment: fire

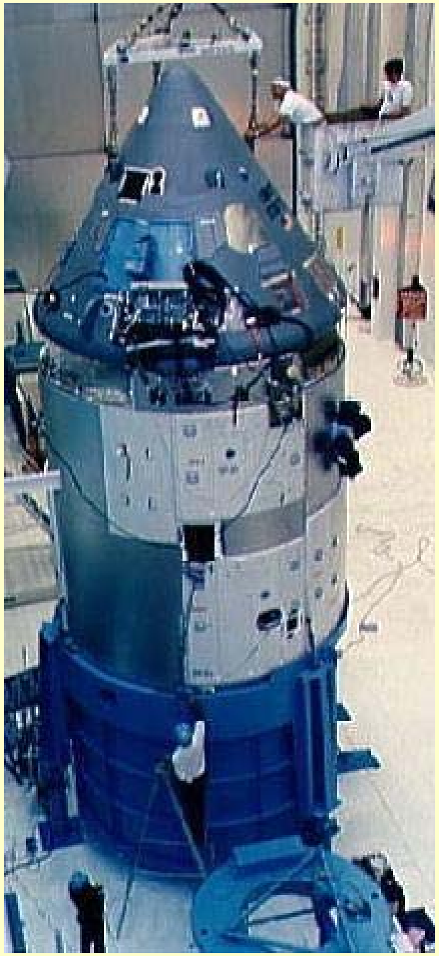
FIRE on MIR (23 February 1997). After a dinner cosmonaut Sasha Lazutkin activates a backup oxygen canister to accommodate the overlapping six-man crew. Soon after, the master alarm erupts. American astronaut Jerry Linenger's eyes widen at the sight of a 4-foot flame shooting across the Kvant 1 research module.

Warm air doesn't rise in a weightless environment, so fires can't spread with earthly speed. But this one has a built-in oxygen supply. The blowtorch-like flame renders the station's water-based extinguishers useless and blocks access to one of the two Soyuz vehicles.

THE RESPONSE Unable to suppress the fire directly, commander Valeri Korzun aims the extinguisher at the far wall to keep it from melting. The rest of the crew shuts down equipment and powers up the accessible Soyuz. Fourteen minutes later, the canister burns out. "Russian officials reported it was like a cigarette burning for a few seconds," Linenger says, "but it was a 14-minute, raging blowtorch. I've never seen smoke spread like it did on MIR."

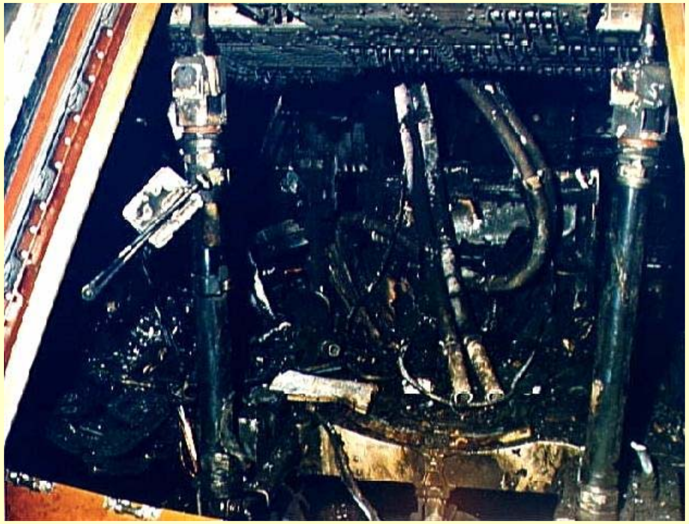
LESSONS LEARNED On the International Space Station, oxygen canisters include a containment shield and are subject to stricter quality control - an unidentified internal flaw caused the MIR fire. Cable cutters are now standard too, as jury-rigged power and data lines between modules prevented the crew from sealing hatches. (www.popsci.com).

Internal environment: fire (cont'd)



On 27 January 1967, tragedy struck the Apollo program when a flash fire occurred in command module 012 during a launch pad test of the Apollo/Saturn space vehicle being prepared for the first piloted flight, the AS-204 mission. Three astronauts died in this tragic accident.

The findings of an investigation on the accident led to major design and engineering modifications, and revisions to test planning, test discipline, manufacturing processes and procedures, and quality control. With these changes, the overall safety of the command and service module and the lunar module was increased substantially.



Source NASA

Effect of space environment on subsystems (1/2)

SPACECRAFT SUBSYSTEMS	SPACE ENVIRONMENTS: Neutral Thermosphere	Thermal Environment	Plasma	Meteoroids/Orbital Debris
Avionics		Thermal Design	Upsets due to EMI from Arcing, S/C Charging	EMI Due to Impacts
Electrical Power	Degradation of Solar Array Performance	Solar Array Designs, Power Allocations, Power System Performance	Shift in Floating Potential, Current Losses, Reattraction of Contaminants	Damage to Solar Cells
GN&C/Pointing	Overall GN&C/Pointing System Design		Torques due to Induced Potential	Collision Avoidance
Materials	Materials Selection, Material Degradation	Material Selection	Arcing, Sputtering, Contamination Effects on Surface Properties	Degradation of Surface Optical Properties
Optics	S/C Glow, Interference with Sensors	Influences Optical Design	Reattraction of Contaminants, Change in Surface Optical Properties	Degredation of Surface Optical Properties
Propulsion	Drag Makeup/Fuel Requirement		Shift in Floating Potential Due to Thruster Firings Making Contact with the Plasma	Collision Avoidance, Additional Shielding Increases Fuel Requirement, Rupture of Pressurized Tanks
Structures		Influences Placement of Thermally Sensitive Surfaces, Fatigue, Thermally Induced Vibrations	Mass Loss From Arcing and Sputtering, Structural Size Influences S/C Charging Effects	Structural Damage, Shielding Designs, Overall S/C Weight, Crew Survivability
Telemetry, Tracking, & Communications	Possible Tracking Errors, Possible Tracking Loss		EMI Due to Arcing	EMI Due to Impacts
Thermal Control	Reentry Loads/Heating, Surface Degradation due to Atomic Oxygen	Passive and Active Thermal Control System Design, Radiator Sizing, Freezing Points	Reattraction of Contaminants, Change in absorptance/ emittance properties	Change in Thermal/Optical Properties
Mission Operations	Reboost Timelines, S/C Lifetime Assessment	Influences Mission Planning/ Sequencing	Servicing (EVA) Timelines	Crew Survivability

Source: NASA Ref Publ. 1390

Effect of space environment on subsystems (2/2)

	SPACE ENVIRONMENTS				
SPACECRAFT SUBSYSTEMS	Solar Environment	Ionizing Radiation	Magnetic Field	Gravitational Field	Mesosphere
Avionics	Thermal Design	Degradation: SEU's, Bit Errors, Bit Switching	Induced Potential Effects		
Electrical Power	Solar Array Designs, Power Allocations	Decrease in Solar Cell Output	Induced Potential Effects		
GN&C/Pointing	Influences Density and Drag, Drives Neutrals, Induces Gravity Gradient Torques		Sizing of Magnetic Torquers	Stability & Control, Gravitational Torques	Effect on GN&C for Re-entry
Materials	Solar UV Exposure Needed for Material Selection	Degradation of Materials			Degradation of Materials Due to Atmospheric Interactions
Optics	Necessary Data for Optical Designs	Darkening of Windows and Fiber Optics			
Propulsion	Influences Density and Drag			Influences Fuel Consumption Rates	
Structures	Influences Placement of Thermal Sensitive Structures		Induces Currents in Large Structures	Propellant Budget	Tether Structural Design
Telemetry, Tracking, & Communications	Tracking Accuracy, Influences Density and Drag		Locating South Atlantic Anomaly	May Induce Tracking Errors	
Thermal Control	Influences Reentry Thermal Loads/Heating				
Mission Operations	Mission Timelines, Mission Planning	Crew Replacement Timelines			

Source: NASA Ref Publ. 1390

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Metallic materials used in space

- Structural non-ferrous alloys typically aluminium (eg. AA2xxx, AA6xxx, AA7xxx) and titanium alloys
- Steels, typically austenitic stainless steels, high carbon high chromium steels and Maraging steels
- Light metals such as magnesium alloys
- Nickel and nickel alloys, including Monel, Inconel, and other nickel and cobalt-base superalloys
- Refractory metals, principally niobium and molybdenum
- Copper and copper alloys, beryllium copper, bronze and brass
- Precious metals such as gold and silver
- Welding, brazing and soldering alloys

Examples of applications for metallic materials

Material type	Applications	Examples
Aluminium alloys	Primary and secondary structures, plating in electronics, thermal control and corrosion protection, aluminised layers on other materials	ATV primary structure (AA2219) CUPOLA forged monolith. dome (AA2219) VEGA skin and stiffeners (AA7075) COLUMBUS internal structure (AA7175)
Titanium alloys	Primary and secondary structures, fasteners, propulsion system components	ROSETTA oxidiser and fuel tanks (Ti-6Al-4V) VENUS EXPRESS prop. system tubing (Ti-3Al-2.5V)
Stainless steels	Primary structures, highly loaded components, pyrotechnic devices, bearings	MSL Core Facility vacuum chamber (AISI 316L) ATV connecting bolts (PH-13-8 Mo, AISI 286)
Nickel alloys	High-temperature, high-strength applications, fasteners, surface plating	COLUMBUS structural elements (Inconel 718)
Copper alloys, gold and sliver alloys	Electrical and electronic applications	All spacecraft (electronic assemblies, conductor leads, plating of terminals in EEE parts)

Non-metallic materials used in space

- Reinforced plastics typically CFRPs with epoxy and cyanates resins
- Thermoplastics (eg. polycarbonates, PEEK) for screens, fibre reinforced applications, MLIs, PCBs
- Rubbers and elastomers in vibration dumping systems, seals and membranes
- Ceramics and glasses in thermal and electrical insulations, coatings, fibres and composites (C-C and CMC).
- Lubricants in mechanisms of deployable solar arrays, slip rings, antennae, thermal louvres (MoS_2, PTFE)
- Potting compounds, sealants and foams in electrical connectors, structural joints, vibration dumping (epoxies, polyurethanes)
- Paints for corrosion protection and thermal control (ZnO low solar absorptance and high emittance, carbon black for high absorptance and high emittance)

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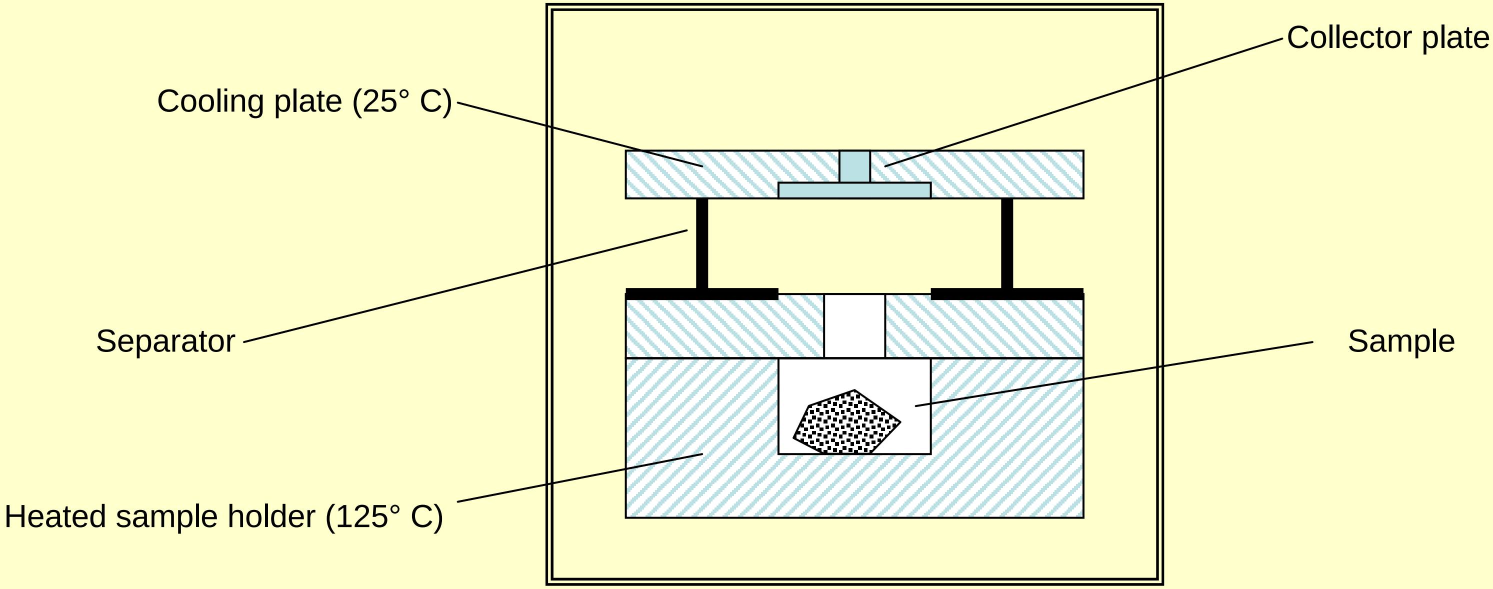
Testing and requirements of space materials

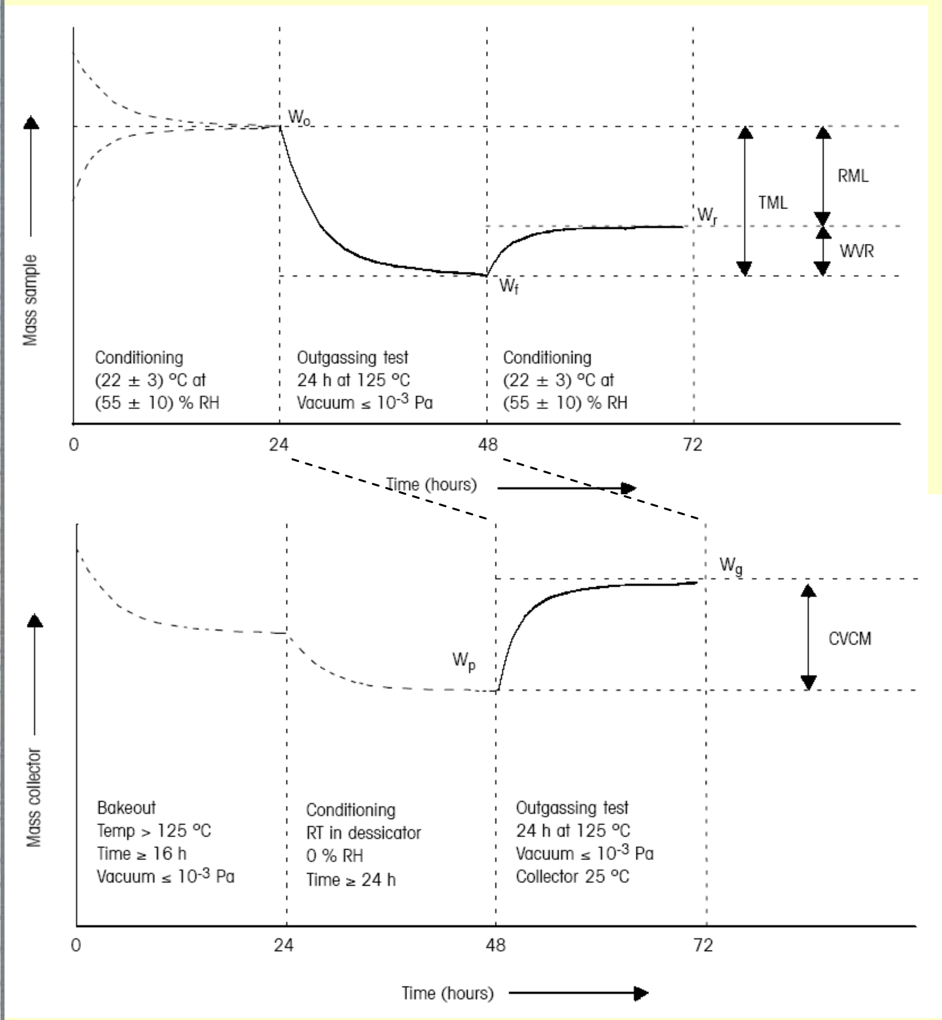
- Materials have to withstand the service environment, either external or internal to the spacecraft (habitable modules). Materials are required to possess a number of properties in order to be suitable for a specific mission.
- Materials properties, both functional and environmental, are evaluated by testing against specific requirements.
- The approval of materials is typically based on previous use (space proven materials) and on the outcome of an evaluation programme.
- For ESA projects, requirements are detailed in ECSS-series of standards (European Cooperation for Space Standardization). NASA standards are also used particularly in manned space programmes.

External environment: outgassing

- Outgassing or sublimation is the release of gaseous species from a material under vacuum conditions.
- Outgassing test (Micro VCM as per ECSS-Q-70-02): measurement of total quantities of outgassed and condensed material under standard conditions (pressure 10^{-6} mbar, duration 24 hrs, T sample 125°C, T collector 25°C)



External environment: outgassing (cont'd)



TML (Total Mass Loss)

CVCM (Collected Volatile Condensable Material)

RML (Recovered Mass Loss)

WVR (Water Vapour Regained)

- **Outgassing acceptance criteria** (ECSS-Q-70-02A):

  TML < 1.00% (if water is a problem)

  RML < 1.00%

  CVCM < 0.10%

- The use of pure mercury, cadmium and zinc is prohibited

External environment: thermal cycling

- A test to determine the ability of a material or part to withstand variations in ambient temperature under vacuum

- Standard test conditions are (ECSS-Q-70-04):

  100 cycles between -100 and +100°C

  Cooling/heating rate: 10°C /min

  Dwell time at extremes: 5 min

  Vacuum 10^{-5} mbar (minimum)

- The acceptance criteria are defined based on the mission requirements. Typically, there shall not be indication of cracking, overheating, or significant degradation of a relevant property.

- Test results are assessed by visual and SEM examination, thermo-optical properties, adhesion and electrical tests.

External environment: thermal cycling (cont'd)

Typical materials or elements that can be tested by thermal cycling are:

- Adhesives
- Adhesive bonded joints
- Coatings (paints, thermal and protective)
- Insulating materials
- Metallic bonded joints
- Plated or chemical conversion coated metallic surfaces
- Metallised plastic films
- Organic or non-organic bonding
- Potting compounds
- Pressure-sensitive tapes
- Printed circuit boards
- Reinforced structural laminates
- Sealants
- Soldered or welded joints.

External environment (cont'd)

- A variety of tests can be carried out on materials or parts to evaluate specific properties which are relevant to the expected mission conditions. This includes:

  - Thermo-optical properties

  - Solar Ultraviolet Radiation

  - Atomic oxygen (ATOX)

  - Electrical properties

- Evaluation of materials or parts is based on the effects following the test, typically in terms of mass loss, changes in thermo-optical properties and surface morphology, degradation of mechanical properties and physical damage.

- Acceptance criteria are based on mission requirements

Internal environment: offgassing

- The offgassing test is carried out to identify and quantify the volatile products offgassed from materials, parts or an assembly.

- Test conditions (ECSS-Q-70-29): Temp. 50°C, 20.9% oxygen with nitrogen or argon (balance), 1 Atm, test duration 72 hrs, mass (material) 5g/l test volume.

Concentration (C): the amount of a volatile offgassed product divided by the spacecraft internal free volume (eg. Shuttle Cabin 65 m^3; Spacelab 77 m^3; Soyuz 10.5 m^3; Mir 350 m^3; ISS 720 m^3)

SMAC: Spacecraft Maximum Allowable Concentration (SMAC) is the maximum concentration of a volatile offgassed product that is safe for the crew in a specified period of time

Toxicity Hazard Index (T): An indication of the potential resulting effects of a number of different volatile products present in the spacecraft atmosphere at one time.

Internal environment: offgassing (cont'd)

The Toxic Hazard Index (T) value is used to determine the maximum allowable offgassing.

$$T = C_1/SMAC_1 + C_2/SMAC_2 + \ldots + C_n/SMAC_n$$

Typical acceptance criteria:

- Prelim. material screening: CO < 25µg/g, Total organics < 100µg/g,
- The quantity of each individual offgassed product shall result in a predicted spacecraft concentration below the SMAC value,
- Toxic Hazard Index (T) shall not exceed 0.5

Test failures at component level may be caused by inadequately cured paints, conformal coatings, adhesives or the use of alcohol for cleaning.
Correction can be achieved by baking (e.g. 48 hours at 50°C)

Internal environment: odour

- The odour test is carried out to determine whether an odour is objectionable or revolting (odour scale 3 and 4)
- Requirements are detailed in NASA-STD-6001
- The odour of a material or assembled item is objectionable or revolting if an average of value 2.5 or higher on the odour scale is obtained
- Sample preparation is similar to that for the offgassing test
- Test panels are composted by 5 qualified panellists

ODOUR SCALE	
0	Undetectable
1	Barely detectable
2	Easily detectable
3	Objectionable
4	Revolting

Internal environment: flammability

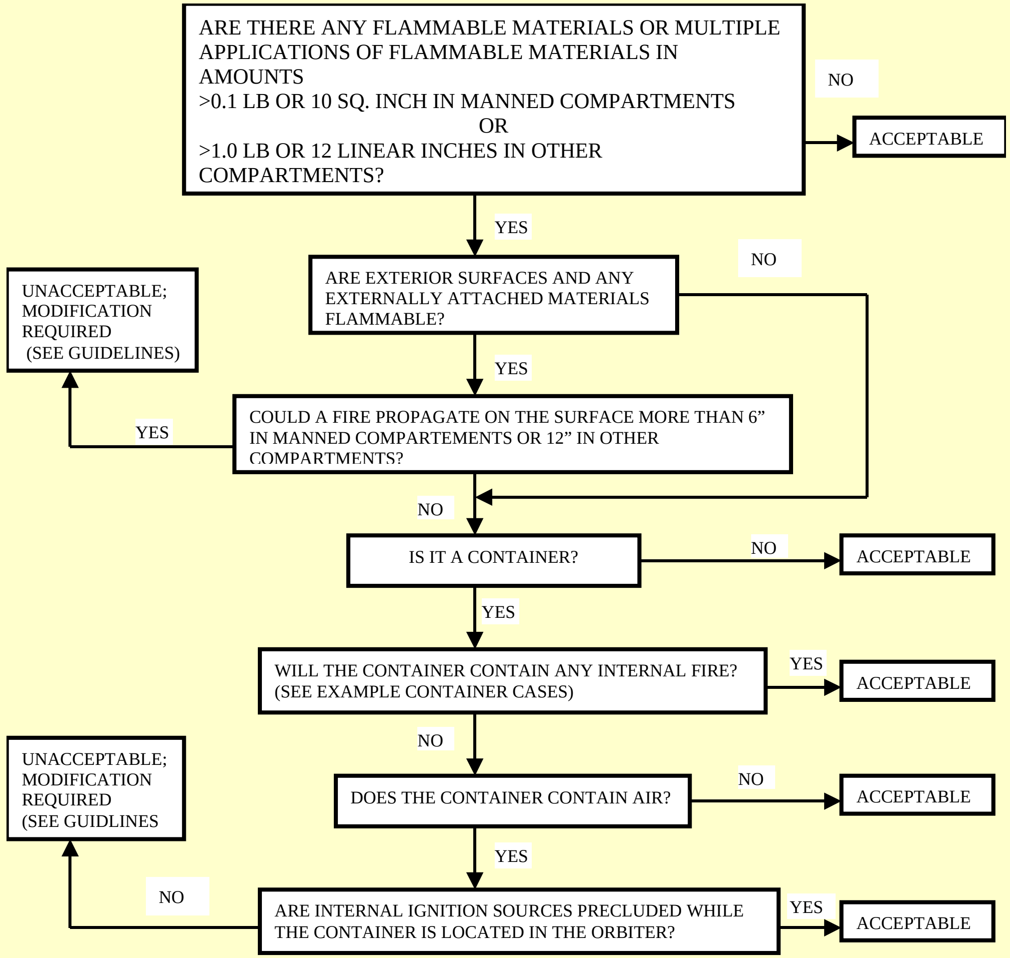
- Spacecraft fire control is based on minimizing potential ignition sources and eliminating materials that can propagate fire
- Ignition sources are always assumed to be present in habitable environments. The major factor in the tragic Apollo 204 fire was assumption that flammability could be controlled by eliminating ignition sources
- Materials must be non-flammable or non-propagating in the service environment (i.e. for a specific oxygen concentration).

  For example:

  - Self-extinguishing within 6 inches for internal volumes (24.5% 0_2)

  - Self-extinguishing within 12 inches for external environment (NSTS PB - 21.0% 0_2)

Internal environment: flammability (cont'd)



Internal environment: flammability (cont'd)

- Testing for flammability (ECSS-Q-70-21):
  - Upward Propagation test
  - Wire Flammability test

  The test environment: depending on the application (min. 20% O_2)

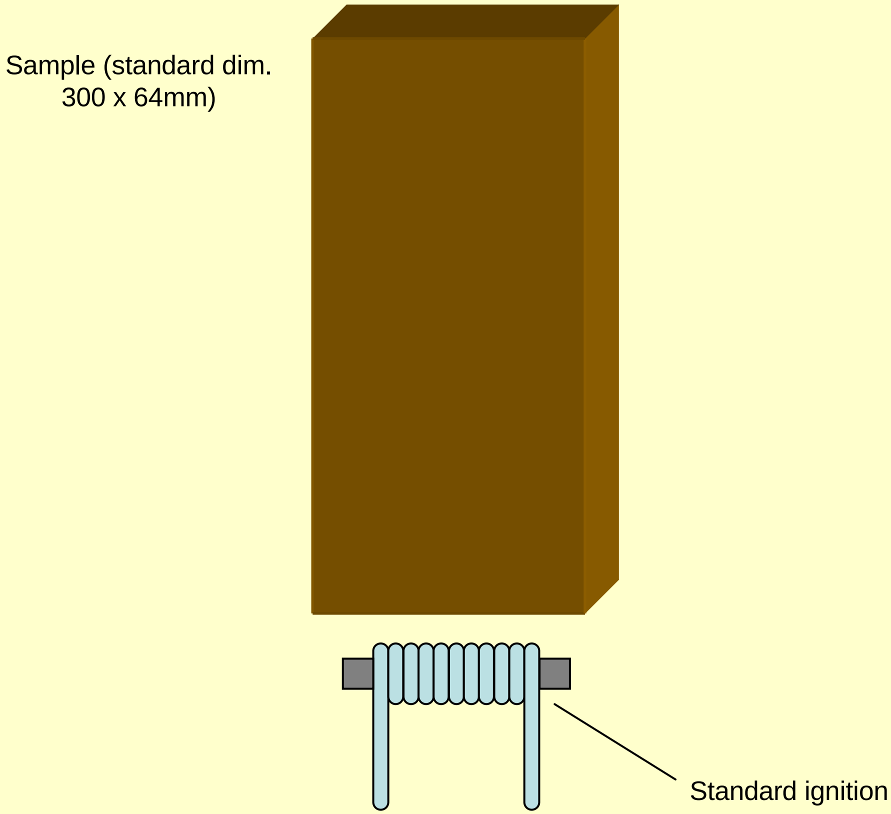
- The test is carried out to determine whether a material or wire, when exposed to a standard ignition source, will self-extinguish and not produce burning debris which can propagate fire.

- Acceptance criteria for the Upward Propagation test:
  - Self-extinction within 150mm
  - No transfer of burning debris
  - Self-extinction within a specified duration

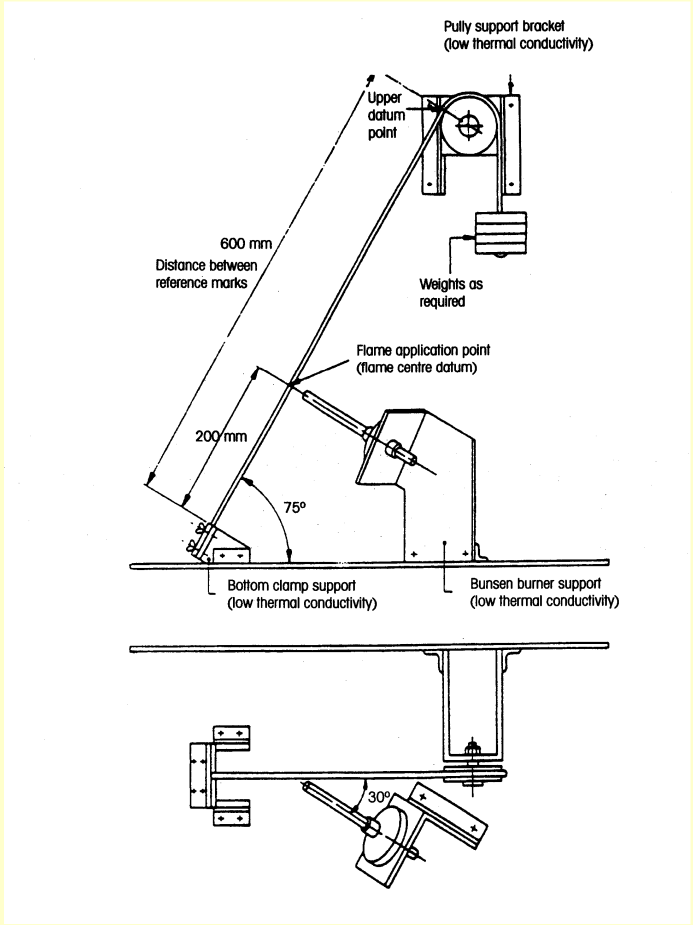
- Acceptance criteria for the Wire Flammability test:
  - Before ignition, while wire heating to the maximum op. temperature, no spontaneous combustion or damage to the insulation
  - During ignition and combustion no burning droplets or particles
  - Self-extinction within 10s and within 150mm

Internal environment: flammability (cont'd)

Upward Propagation Test set up

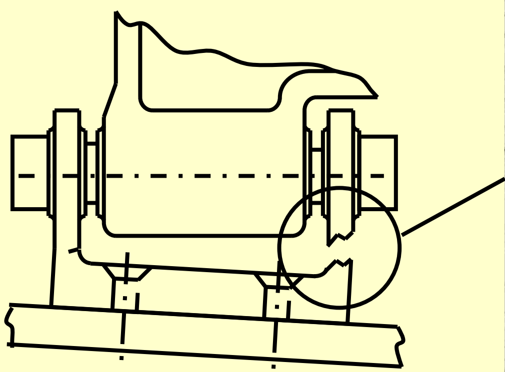


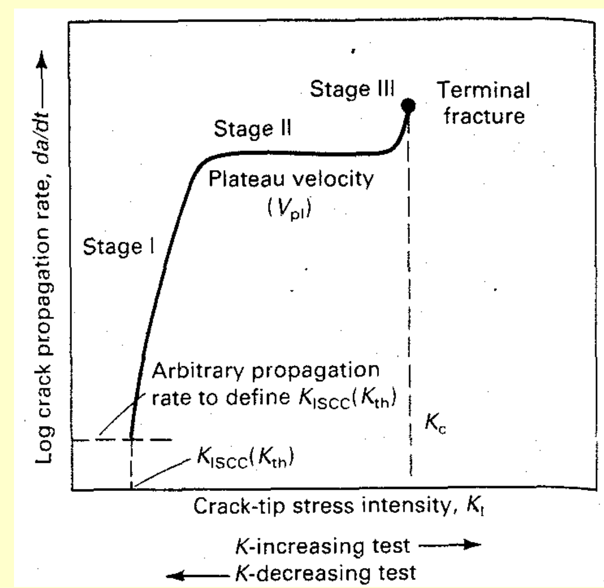
Wire Flammability Test set up



Internal (ext.) environment: stress-corrosion

- Stress Corrosion Cracking (SCC) is caused by combined action of sustained tensile stress and corrosion which results in failure of materials at stresses lower than expected. Materials have different susceptibility to SCC





Internal (ext.) environment: stress-corrosion (cont'd)

- SCC is one of the most important causes of structural failures at launch sites
- Poor resistance to SCC is one of the most common causes for rejecting a material during project reviews
- SCC failures can occur even when a structure is unloaded (e.g. during storage) in the presence of residual stress in a component
- SCC is particularly relevant for propulsion systems, where aggressive substances (propellant, oxidiser, cleaning fluids) can promote SCC failures

Environments that can cause SCC

Material	**Environment**
Alluminum alloys	NaCl-H2O2 solution NaCl solution Sea water Air, water vapors
Ordinary Steels	NaOH solutions NaOH-Na2SiO2 solutions Calcium, ammonium and sodium nitrate solutions Mixed acids HCN solutions Acidic H2S solutions Sea water
Stainless Steels	Acid cloride solutions NACl-H2O2 solutions Sea water H2S NaOH-H2S solutions Condensing steam from chloride waters
Titanium Alloys	Red fuming Nitric Acid Sea water N2O4 Methonol-HCL
Inconel	Caustic soda solutions

Internal (ext.) environment: stress-corrosion (cont'd)

Methods to prevent SCC failures in spacecraft hardware:

• Selection of SCC resistant materials

• Appropriate selection of manufacturing processes aimed to reduce residual stresses (incl. heat treatments)

• Selection of detailed design solutions aimed to reduce tensile stresses in the Short-Transverse (S-T) direction of the material.

Note: resistance to SCC in metals is least in the ST grain direction.

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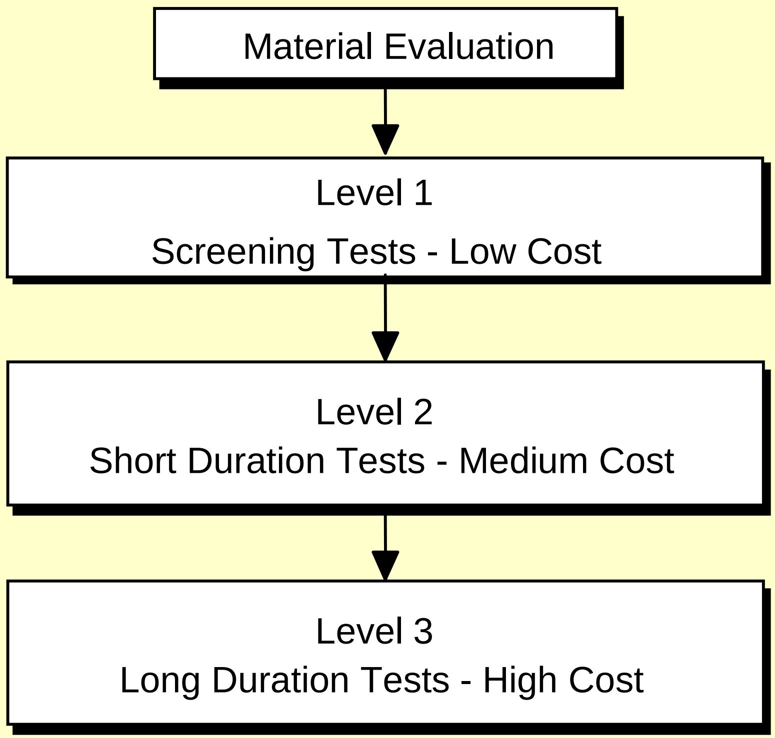
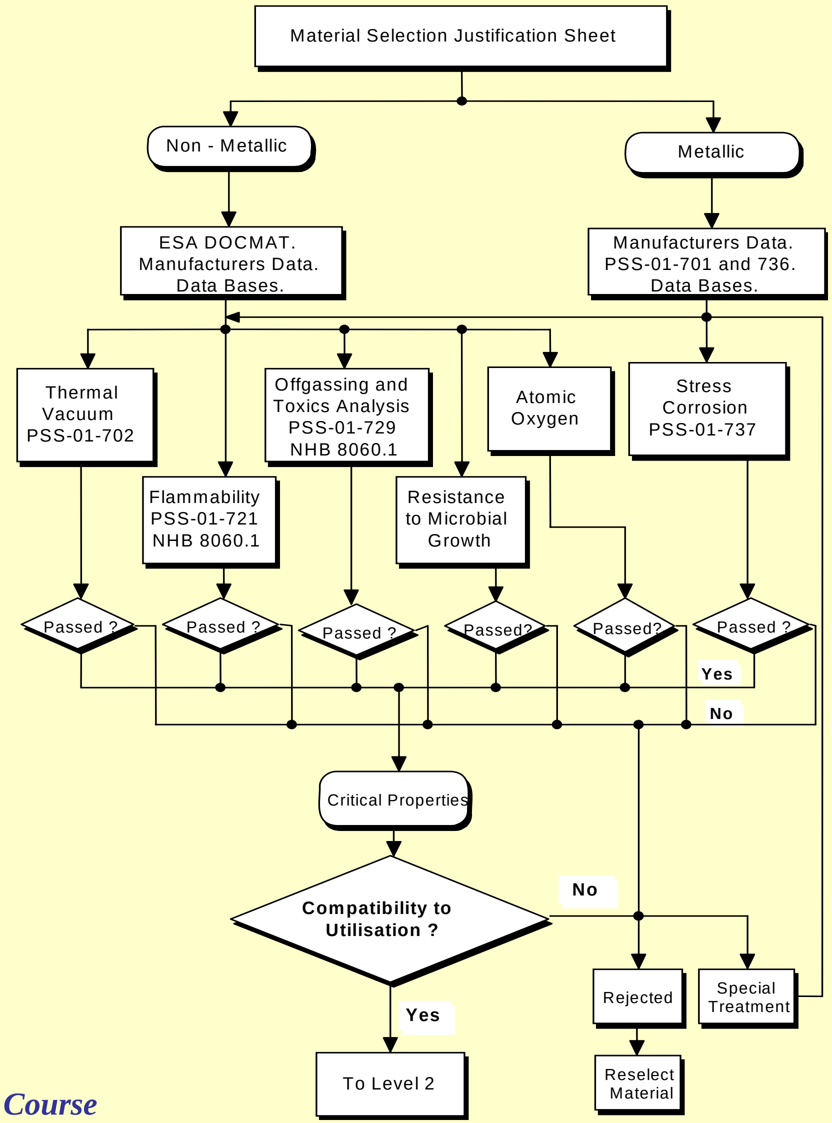
  - Internal environment (pressurised modules)
- *Materials used in space*
- *Requirements and testing of space materials*
- ***Evaluation of materials***
- *Processes for space*
  - Classification
  - Most used processes
  - Electronics and surface protection
- *Selection of materials, parts and processes*

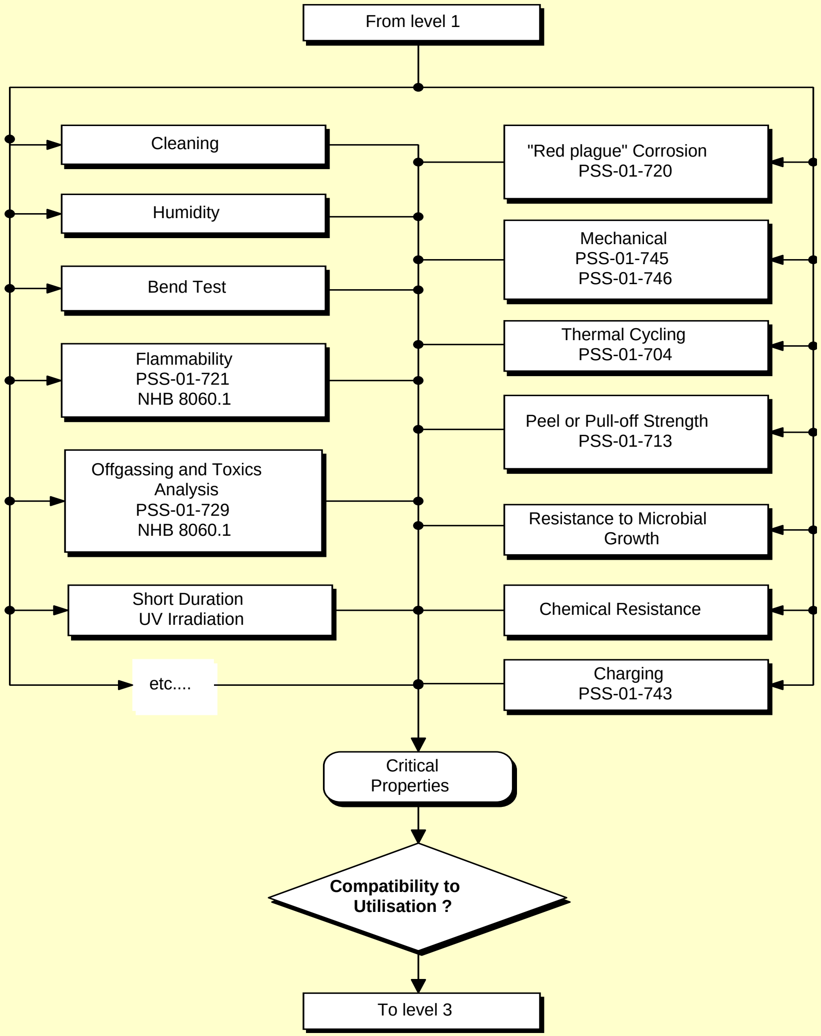
Evaluation of materials



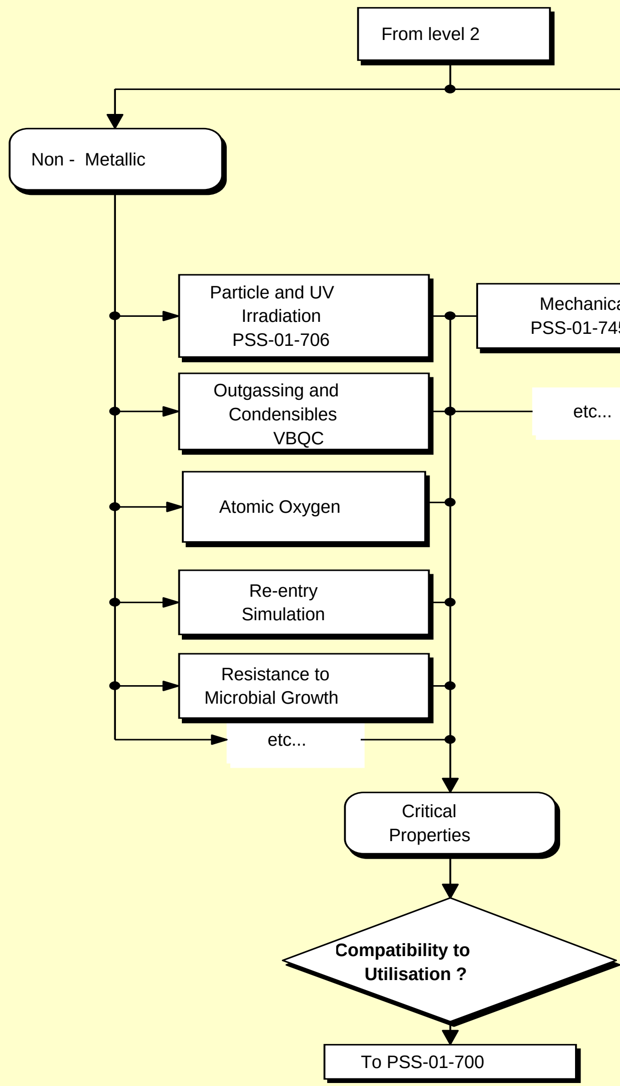
Evaluation of materials – Level 1



Evaluation of materials – Level 2



Evaluation of materials – Level 3



Procurement of materials

- Each procured material or part is covered by a procurement specification defining, as a minimum:

  - Standard definition of material (or part)

  - Chemical composition and form (or characteristics)

  - Specifications (with reference to international standards, eg. AA, AISI, ASM etc for metals)

  - Manufacturer, date of fabrication, and shelf life when relevant

  - Lot or batch number

  - Quality test results and test methods

  - Acceptance criteria (including, as applicable, lot acceptance testing, source inspection, receiving inspection)

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Processes for space

- Processes for space are covered either by International or National aerospace standards, or by ECSS or NASA specifications.
- Verification (qualification) of processes follows similar logic as for materials
- Evaluation semantics (ECSS-Q-70B 14 Dec 2004)

Element	Evaluation process
Materials	Validation*
Process	Verification*
Product/ Mechanical part	Qualified
Test facility	Certified/ Accredited

(*) Commonly, qualification is often used for both materials and processes

Processes for space: classification

Process	Definition	PSS-01-700	ECSS-Q-70
Critical process	- A process which in case of failure can adversely affect performance or destroy a major part or system function, or	yes	-
	- the quality of which cannot be assessed solely by examining the end product, or	yes	-
	- which have previously caused problems, or	yes	yes
	- for which the contractor has no experience	yes	yes
Special process	A process in which the outcome cannot be adequately verified without destroying the manufactured part (e.g., heat treatment, bonding, welding)	-	yes
Standard process	A process that is well documented, has a previous history of use, is well understood and for which standard inspection procedures exist	-	-

Processes for space: classification (cont'd)

- A special process requires:

  - Verification (qualification)

  - Strict control of process parameters

  - Non-destructive inspection (NDI)

  - Destructive testing (e.g., chemical analysis, tensile test) of representative samples

  - Periodic control of process equipment/materials

  - Training/certification of personnel

  - Records retention/ archiving

- A critical process requires special approval (RFA) and some or all the above

Processes for space (cont'd)

- Adhesive bonding
- Composite manufacturing
- Encapsulating and moulding
- Painting and coating (ECSS-Q-70-25 Aeroglaze Z306, ECSS-Q-70-34 Aeroglaze H332, ECSS-Q-70-35 Aeroglaze L300)
- Cleaning (for electronic assemblies ECSS-Q-70-08)
- Welding and brazing (National or Int. aerospace standards)
- Crimping and wire wrapping (ECSS-Q-70-26 and ECSS-Q-70-30, respectively)
- Soldering (ECSS-Q-70-08)
- Surface treatments (ECSS/PSS, National or Int. aerospace standards)
- Plating (for electronic assemblies ECSS-Q-70-08)
- Machining
- Metal forming
- Heat treatments
- Marking (for outgassing ECSS-Q-70-02)
- Non-destructive inspection (National or Int. aerospace standards)
- Miscellaneous processes (casting, mechanical joining, PCB fabrication, etc.)

Processes for space: electronics

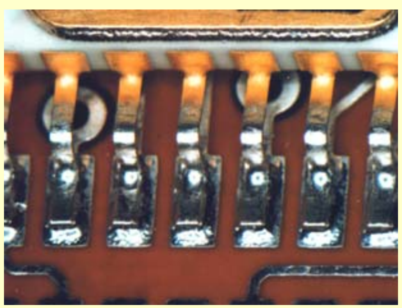
The control of the following processes is required for ensuring high reliability of electronics for space:

- PCB's manufacturing
  - Fabrication and control of rigid and flexible PCB's
  - Conformal coating
- Soldering processes
  - Manual soldering
  - Machine soldering
  - Surface mounting
- Crimping and wire wrapping
- Repair and modification of PCB assemblies
- Cleaning of PCB assemblies
- Testing and inspection for workmanship
- Operators and inspectors training and certification

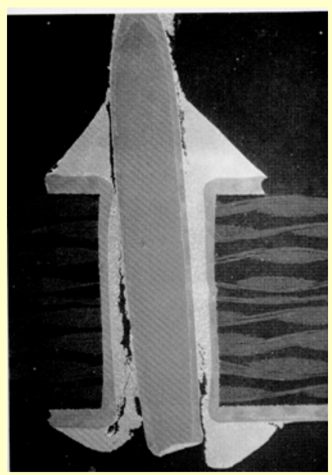
Processes for space: electronics (cont'd)

Workmanship requirements of soldered joints (not exhaustive):

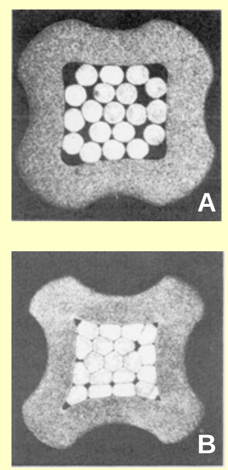
- Clean, smooth, bright undisturbed solder surface
- Sufficient solder fillet between conductor and termination areas
- Contour of conductor sufficiently visible
- Correct design for stress relief
- Good wetting indicated by small contact angles
- Correct amount and distribution of solder
- Absence of defects such as nicks, cracks, pits, discoloration, burns, high porosity



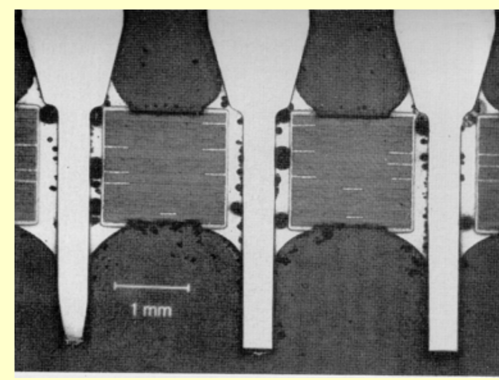
Good soldering



Failed joint (vibration tested)



A Under-crimping
B Acceptable



Poor soldering (high porosity)

Processes for space: lead-free solders

The required finishes for electronic part terminations, terminal pins and lugs, and the termination pads on PCBs are tin-lead alloys:

Solder	Melting range	Applications
Sn63 (63% Sn 37% Pb)	183C	Soldering PCBs where temp. limitations are critical
Sn62 (62% Sn 36 Pb 2% Ag)	175-189C	Soldering of components having Ag plated or paint (ie ceramic capacitors) finish.
Sn60 (60% Sn 40% Pb)	183-188C	Soldering wire/cable harness or terminals and coating of pre-tinning metals
Sn96 (96% Sn 4% Ag)	221C	Special use eg. soldering terminal posts

EU directives on "Waste Electrical and Electronic Equipment" and the Restriction of the use of Hazardous Substances in electrical and electronic equipment (RoHS) prohibit the use of Pb in solder alloys in commercial equipment. This limitation may cause an indirect effect on the aerospace industry.

Lead-free alloys can cause defects related to poor solderability, difficult inspection criteria, higher melting points which damage both parts and multilayer PCBs, they are difficult to rework, and have poor fatigue resistance.

Processes for space: no preferred materials list for electronics

Why are there no preferred materials lists for electronic components?

MATERIAL+PROCESS

↓

APPLICATION

↑

ENVIRONMENT

Materials must be considered together with related processes and with reference to the environment (manned/unmanned, LEO or GEO etc.)

Processes for space: surface protection of AA

Corrosion protection of aluminium alloys (AA) is achieved by applying one the following processes:

- Chemical conversion coating (CCC)

  Primer used in the aircraft industry (e.g. Alodine 1200, greener alternatives under evaluation). Temporary protection, base for painting.

- Anodisation

  Electrolytically formed anodic coatings: chromic (Type I) and sulphuric acid (Type II) coatings. Higher corrosion protection than alodining

- Plating

  High corrosion protection. Nickel plating is used in electronics (boxes, plates) for its high electrical conductivity. Hard and brittle.

Note: for steels, passivation, Ag and Ni plating are most used. Ag and Ni plating can induce hydrogen embrittlement (bake-out required!).

Processes for space: surface protection of AA

General requirements for the corrosion protection of aluminium alloy surfaces on the International Space Station (1/2)

3xxx, 4xxx, 5xxx and 6xxx Aluminium Alloys

General Corrosion Protection:
Chemical Conversion Coatings (CCC) can be always used with or without paint.

Electrical bonds

- **Permanent**
  - Class H and S bonds*: CCC are permitted providing that the resistance requirements are met
  - Class R bonds*: CCC are permitted providing that the resistance requirement is met and the bond is **hermetically sealed**
- **Removable**
  - Class H and S bonds*: CCC are permitted providing that the resistance requirements are met
  - Class R bonds*: Metallic (i.e. Nickel) plating is required.

(*) As per SSP 30245 "Space Station Electrical Bonding Requirements":

Class S bond: resistance less than 1.0 Ohm

Class H bond: resistance less than 0.1 Ohm

Class R bond: resistance less than 0.0025 Ohm

Processes for space: surface protection of AA

General requirements for the corrosion protection of aluminium alloy surfaces on the International Space Station (2/2)

2xxx and 7xxx Aluminium Alloys

General Corrosion Protection:

- **Chemical Conversion Coating (CCC) shall be used, or**
- **Anodising, or**
- **Metallic (i.e. Nickel) plating.**

Electrical bonds

Permanent

- Class H and S bonds*:
CCC are permitted providing that the resistance requirements are met
- Class R bonds*:
CCC are permitted providing that the resistance requirement is met and the bond is **hermetically sealed**.

Removable

- Class H and S bonds*:
CCC are permitted providing that the resistance requirements are met
- Class R bonds*:
Metallic (i.e. Nickel) plating is require

(*) As per SSP 30245 “Space Station Electrical Bonding Requirements”:

Class S bond: resistance less than 1.0 Ohm

Class H bond: resistance less than 0.1 Ohm

Class R bond: resistance less than 0.0025 Ohm

Processes for space: Cr-free CCCs

The most common type of chemical conversion coating (CCC) currently used for aluminium alloys contains hexavalent chromates (Cr(VI)). This includes Alodine 1200 and Iridite 1200.

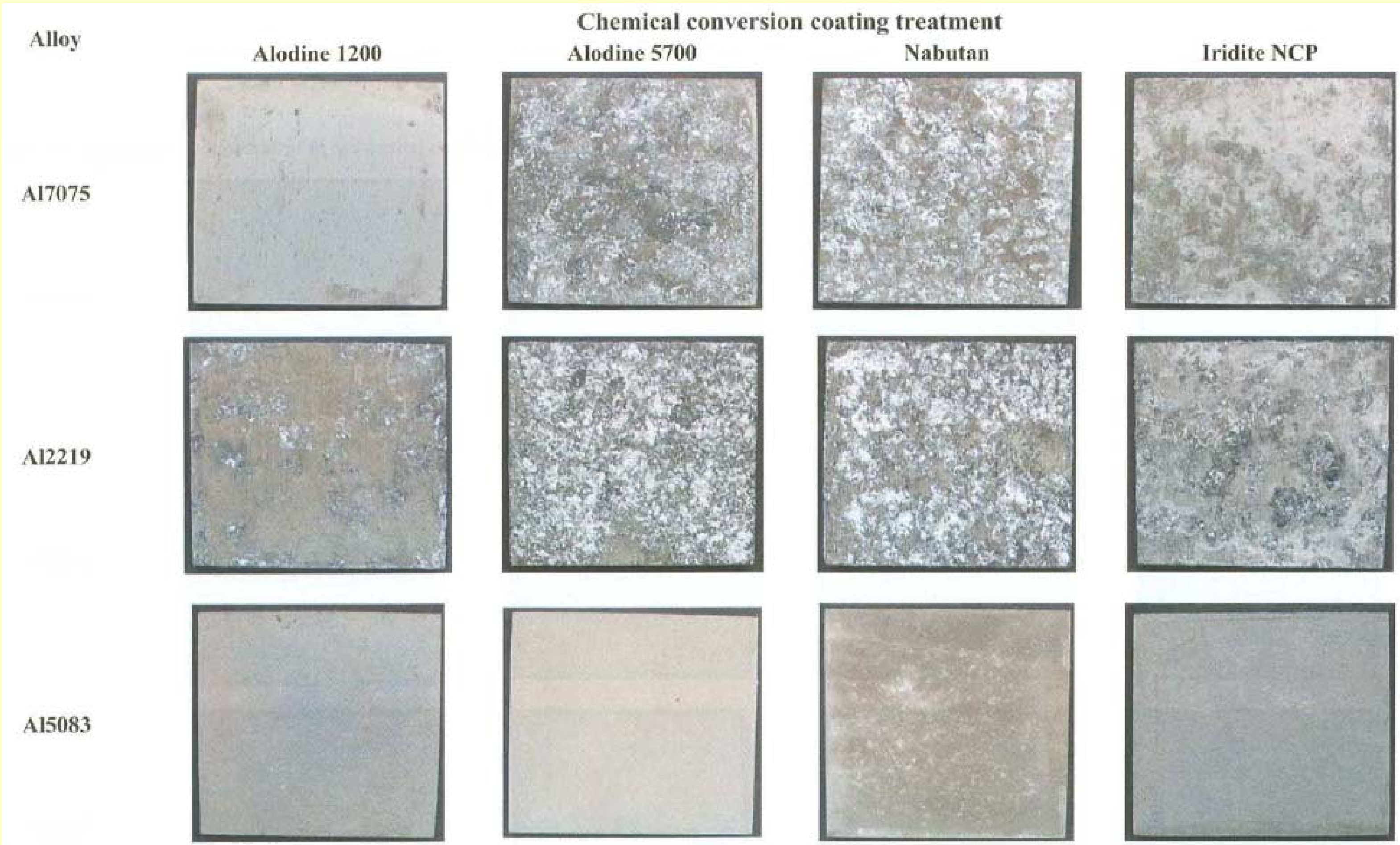
EU directives (RoHS) prohibited chemical products including Cr(VI) -based CCCs. Although the aerospace industry is currently exempted, preliminary assessments have been carried out on greener chromate-free CCC products.

In recent studies, samples of aluminium alloys have been surface treated with chromate-free CCCs, and subjected to tests such as salt spray corrosion test and thermal cycling, roughness and electrical resistance measurements

Test results indicate that chromate-free CCCs generally provide a much lower corrosion protection of aluminium alloys compared to the traditional Cr(IV) -based CCCs.

Processes for space: Cr-free CCCs

Samples of aluminium alloys after environmental testing consisting of thermal cycling (500 cycles -50C/+100C in air) and salt spray testing (ASTM-B-117)



Source: ESA STM-276

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Selection of materials, parts and processes

Materials, parts and processes (MPP) for space should be selected with the following criteria:

- MPP that have been successfully used in an identical application in other space programs, with respect to service conditions and lifetime

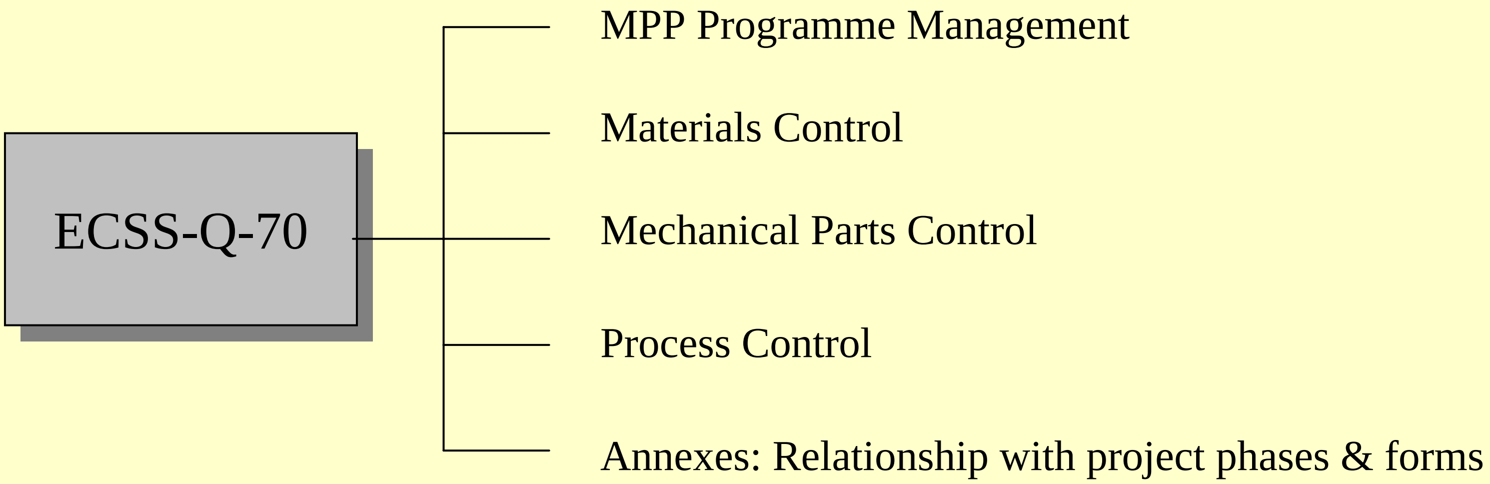
- MPP for which a satisfactory validation/verification/qualification has been obtained and documented, and is representative of the intended application with sufficient margins

- MPP that are included in ESA and NASA data base (eg. listed in ECSS-Q-70-71)

Note: "Space qualified" MPP do not exist. Each MPP is qualified within a defined set of conditions (qualification envelope). Expected service conditions shall be within the qualification envelope.

Selection of MPP: requirements

ECSS-Q-70B Materials, Mechanical parts and processes



Selection of MPP: requirements (cont'd)

ECSS-Q-70	Summary/remarks
1. Introduction	
2. Materials, Parts and Processes Program Mgmt	- Define organisation in PA Plan - MPP manager to supervise activities, ensure requirements implementation; reporting on validation and qualification; contact point for the customer. - MPP reviews performed to obtain from the customer the validation and qualification status - Establishment and consolidation of MPP lists. *Preliminary* at PDR, *as-designed* at CDR, *as-build* at QR - MPP to satisfy project technical constraints - Establish contamination and cleanliness control program. Requirements specifications and control plan (critical appl.)
3. Materials Control	- Technical criteria: available selection and testing specifications identified (e.g., ECSS-Q-70-2 for outgassing) - Selection priority guidelines - Declared Materials List content - Critical Materials: materials not meeting requirements or with unknown characteristics to be documented by a Request for Approval (RFA), including details of subsequent evaluation/validation phases as necessary - Each material to be covered by a procurement specification - Ensure validation status and traceability of materials - Limited life materials to be controlled and as necessary re-certified

Selection of MPP: requirements (cont'd)

ECSS-Q-70	Summary/remarks
4. Mechanical Parts Control.	- Technical criteria: generic statement about meeting requirements of the standard - Selection guidelines/ type reduction actions - Declared Mechanical Part List content - Critical mechanical parts to be documented by a Request for Approval (RFA), including details of subsequent evaluation/qualification phases as necessary - Each mechanical part to be covered by a procurement specification - Ensure qualification status and traceability of parts - Limited life parts to be controlled
5. Process Control	- Technical criteria: generic statement about materials and parts used during implementation of processes to satisfy the requirements of the standard - Selection priority guidelines - Declared Process List content - Critical Processes: to be documented by a Request for Approval (RFA), including details of subsequent evaluation/validation phases as necessary - Each to be covered by a process specification - Ensure validation status and traceability of processes - Process Implementation (process control) - Definition of special process
6. Annex A	- Relationship of MPP activities with project phases

Selection of MPP: requirements (cont'd)

Classification of materials (DML, DPL, DMPL)

List consolidation

1. Aluminium and aluminium alloys	11. Adhesive tapes
2. Copper and copper alloys	12. Paints and inks
3. Nickel and nickel alloys	13. Lubricants
4. Titanium and titanium alloys	14. Potting compounds, sealant, foams
5. Steels	15. Reinforced plastics
6. Stainless steels	16. Rubbers and elastomers
7. Filler metals: welding, brazing, soldering	17. Thermoplastics (tapes, MLI)
8. Miscellaneous metallic materials	18. Thermoset plastics
9. Optical materials	19. Wires and cables
10. Adhesives, coatings, varnishes	20. Misc. non metallic (ceramics…)

Selection of MPP: requirements (cont’d)

Classification of materials (DML, DPL, DMPL)

51. Spacing parts (washers, spacers)
52. Connecting parts (bolts, nuts, rivets, inserts, clips,…)
53. Bearing parts (ball-bearings, needle bearings,…)
54. Separating parts (pyrotechnics, springs, cutters,…)
55. Control parts (gears,…)
56. Fluid handling parts (diffusers, …)
57. Heating parts
58. Measuring instruments (gauges, thermocoules,…)
59. Optical passive equipment
60. Magnetic parts
61. Other parts

ESA standards on materials and processes

ECSS-Q-70B Materials, mechanical parts and processes
ECSS-Q-70-01A Contamination and cleanliness control
ECSS-Q-70-02A Thermal vacuum outgassing test for the screening of space materials
ECSS-Q-70-03A Black-anodizing of metals with inorganic dyes
ECSS-Q-70-04A Thermal cycling test for the screening of space materials and processes
ECSS-Q-70-05A Detection of organic contamination of surfaces by infrared spectroscopy
PSS-01-706 The Particle and Ultraviolet (UV) Radiation Testing of Space Materials
ECSS-Q-70-07A Verification and approval of automatic machine wave soldering
ECSS-Q-70-08A Manual soldering of high-reliability electrical connections
ECSS-Q-70-09A Measurement of thermo-optical properties of thermal control materials
ECSS-Q-70-10A Qualification of printed circuit boards
ECSS-Q-70-11A Procurement of printed circuit boards
ECSS-Q-70-13A Measurement of the peel and pull-off strength of coatings and finishes using pressure E-sensitive tapes
ECSS-Q-70-18A Preparation, assembly and mounting of RF coaxial cables
ECSS-Q-70-20A Determination of the susceptibility of silver plated copper wire and cable to “red plague” corrosion
ECSS-Q-70-21A Flammability testing for the screening of space materials
ECSS-Q-70-22A The control of limited shelf-life materials
ECSS-Q-70-25A The application of the black coating Aeroglaze Z306
ECSS-Q-70-26A Crimping of high-reliability electrical connections
ECSS-Q-70-28A The repair and modification of printed circuit board assemblies for space use
ECSS-Q-70-29A The determination of offgassing products from materials and assembled articles to be used in a manned space vehicle crew compartment
ECSS-Q-70-30A The wire wrapping of high-reliability electrical connections
ECSS-Q-70-33A The application of the thermal control coating PSG 120 FD
ECSS-Q-70-34A The application of the black electrically conductive coating Aeroglaze H322
ECSS-Q-70-35A The application of the black electrically conductive coating Aeroglaze L300
ECSS-Q-70-36A Material selection for controlling stress-corrosion cracking
ECSS-Q-70-37A Determination of the susceptibility of metals to stress-corrosion cracking
ECSS-Q-70-38A rev.1High-reliability soldering for surface-mount and mixed technology

ESA standards on M&P (cont'd)

ECSS-Q-70-45A Standard methods for mechanical testing of metallic materials **ECSS-Q-70-46A** General requirements for threaded fasteners	**PSS-01-748** Requirements for ESA-Approved Skills Training and Certification (Electronic Assembly Techniques) **ECSS-Q-70-71A** rev.1Data for selection of space materials and processes

- ECSS standards can be downloaded from http://www.ecss.nl/
- PA&S requirements (including the requirements for M&P) for ESA Microgravity programmes can be found on the Human Spaceflight Product Assurance and Safety Office (PASO) website http://paso.esa.int/
- ESA Materials and Processes http://esmat.esa.int/
- ESA Erasmus Experiment Archive http://eea.spaceflight.esa.int/

Stress-corrosion cracking

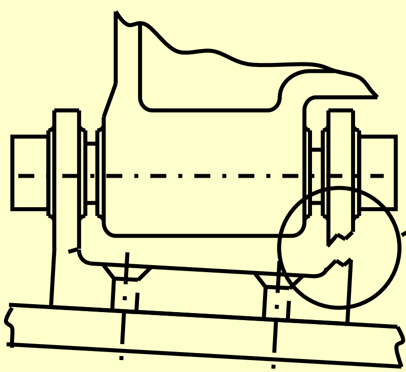
Dr G. Bussu, ESA Payload PA&S Office

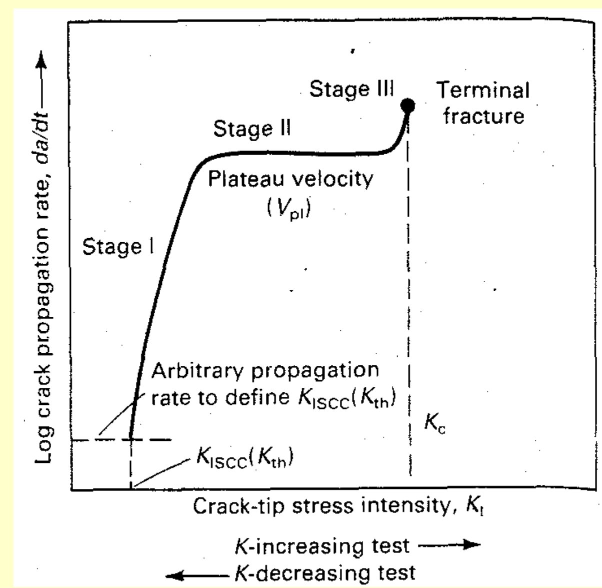
Stress-corrosion cracking

- ***What is stress-corrosion cracking (SCC)***
- ***Testing materials for SCC***
  - Smooth specimens testing
  - Materials classification and SCC tables
  - Fracture mechanics-based testing
- ***SCC testing for space propulsion systems***
  - SCC behaviour of Ti alloys
- ***The ESA experience with Rosetta***

What is stress-corrosion cracking

- Stress Corrosion Cracking (SCC) is caused by combined action of sustained tensile stress and corrosion which results in failure of materials at stresses lower than expected. Materials have different susceptibility to SCC



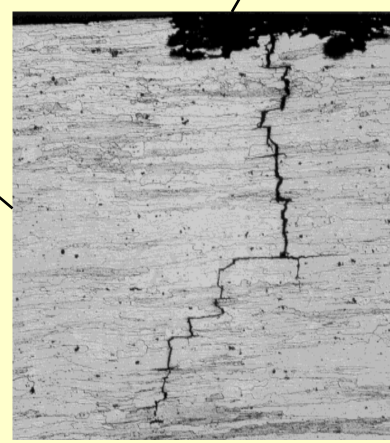


What is stress-corrosion cracking (cont'd)

- For stress-corrosion to occur the following three conditions must be fulfilled:

The presence of a corrosive environment

The material is susceptible to stress-corrosion



The presence of a sustained tensile stress (residual or applied)

- SCC is a complex failure phenomenon, and in many cases, its mechanisms have not been understood

Testing materials for SCC

Prevention of SCC failures and characterisation of materials

Smooth specimens testing

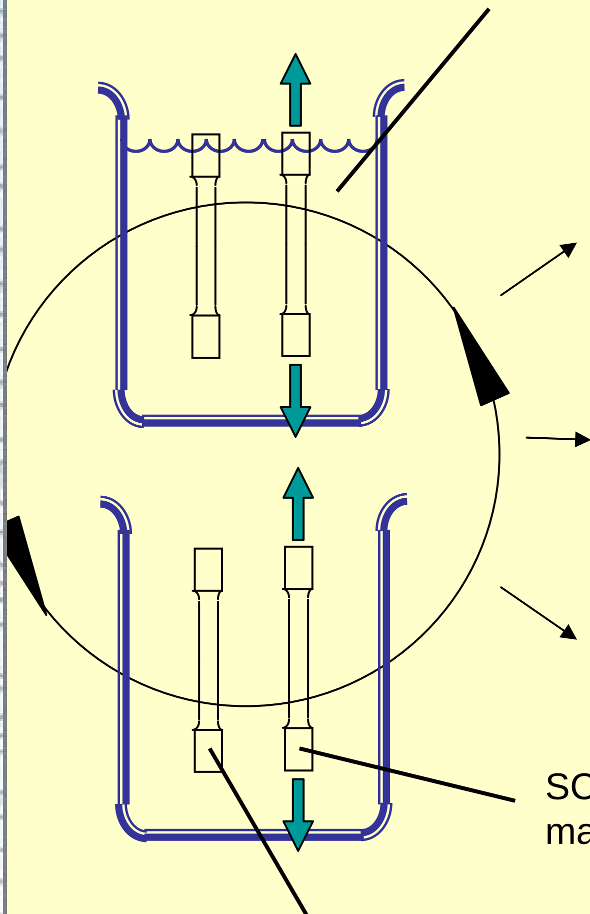
- Standardized in agreement with NASA (ECSS-Q-70-36 and 37)
- General purpose SCC testing and classification (three tables)
- Alternate immersion in salt water under constant load (75% of yield)
- Simple and not expensive
- Relevant to humid environment appl.
- Not based on fracture mechanics
- Database exists (ESA/NASA)

Fracture mechanics-based testing

- Not standardized
- Specific applications and environments
- Based on fracture mechanics (Kiscc)
- Expensive and requires a high level of expertise
- No database exists
- Dedicated test facility
- Test fluid contamination problems
- Health and safety issues

Testing materials for SCC: smooth specimens

Alternate immersion in 3.5% NaCl water solution for 30 days



- No failure
- No relevant reduction in tensile strength
- No metallographic evidence of SCC

→ **High resistance to SCC**

- No failure
- No relevant reduction in tensile strength
- But there is metallographic evidence of SCC

→ **Moderate resistance to SCC**

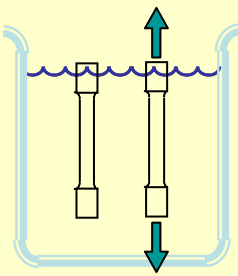
- Failures occur during testing
- There is a reduction in tensile strength
- There is evidence of SCC from metallography

→ **Low resistance to SCC**

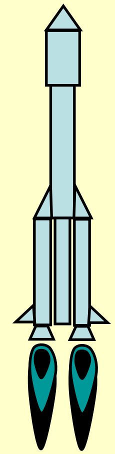
SCC specimens (S-T) under constant load (corresp. to 75% of the material yield strength)

Control specimens (exposed unloaded)

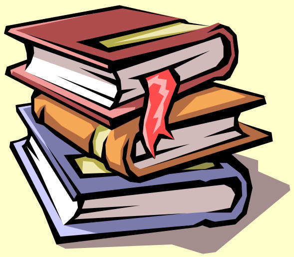
Testing materials for SCC: materials classification



TESTING
(multiple batch testing)



IN-SERVICE EXPERIENCE



LITERATURE DATA

↓

CLASSIFICATION

Testing materials for SCC: smooth specimens (cont'd)

Materials are selected from tables (ECSS-Q-70-36 or NASA equivalent) based on the level of susceptibility to SCC (smooth specimen testing):

Table I (highly resistant) materials should be selected for structural applications from this table,

Table II (moderately resistant) materials are allowed only if a suitable alloy cannot be found in Table I,

Table III (low resistant) materials should not be selected for structural applications,

Table II and III materials are accepted only if it can be demonstrated that for a specific application the probability of SCC is remote (case-by-case approach).

Testing materials for SCC: smooth specimens (cont'd)

Materials & tempers listed in Table I of ECSS-Q-70-36A (1/3)

(a) Steel	Condition
Carbon steel (1000 series)	Below 1 225 MPa (180 ksi) UTS
Low alloy steel (4130, 4340, etc.)	Below 1 225 MPa (180 ksi) UTS[1]
(E) D6AC, H-11	Below 1 450 MPa (210 ksi) UTS
Music wire (ASTM 228)	Cold drawn
HY-80 steel	Quenched and tempered
HY-130 steel	Quenched and tempered
HY-140 steel	Quenched and tempered
1095 spring steel	Quenched and tempered
300 series stainless steel (unsensitised)[2]	All
400 series Ferritec stainless steel (404, 430, 431, 444, etc.)	All
21-6-9 stainless steel	All
Carpenter 20 Cb stainless steel	All
Carpenter 20 Cb-3 stainless steel	All
A286 stainless steel	All
AM350 stainless steel	SCT 1000[4] and above
AM355 stainless steel	SCT 1000 and above
Almar 362 stainless steel	H1000[5] and above
Custom 450 stainless steel	H1000 and above
Custom 455 stainless steel	H1000 and above
15-5 PH stainless steel	H1000 and above
PH 14-8 Mo stainless steel	CH900 and SRH950 and above[6,7]
PH 15-7 Mo stainless steel	CH900
17-7 PH stainless steel	CH900
Nitronic 33[3]	All
(E) Maraging steel MARVAL X12	All

1. A small number of laboratory failures of specimens cut from plate more than 2 inches thick have been observed at 75 % yield, even within this ultimate strength range. The use of thick plate should therefore be avoided in a corrosive environment when sustained tensile stress in the short transverse direction is expected.
2. Including weldments of 304L, 316L, 321 and 347.
3. Including weldments.
4. SCT 1000 = sub-zero cooling and tempering at 538 °C (1 000 °F).
5. H1000 hardened above 538 °C (1 000°F).
6. CH900 cold worked and aged at 480 °C (900 °F).
7. SRH950 = solution treated and tempered at 510 °C (950 °F).

(E) ESA classification not in NASA MSFC-SPEC-522A.

(b) Nickel Alloy	Condition
Hastelloy C	All
Hastelloy X	All
Incoloy 800	All
Incoloy 901	All
Incoloy 903	All
Inconel 600[3]	Annealed
Inconel 625	Annealed
Inconel 718[3]	All
Inconel X-750	All
Monel K-500	All
Ni-Span-C 902	All
René 41	All
Unitemp 212	All
Waspaloy	All

3. Including weldments

Testing materials for SCC: smooth specimens (cont'd)

Materials & tempers listed in Table I of ECSS-Q-70-36A (2/3)

(c) Aluminium alloys:			
Wrought[1,2]		Cast	
Alloy	Condition	Alloy[3]	Condition
1000 series	All	355.0, C355.0	T6
2011	T8	356.0, A356.0	All
2024, rod bar	T8	357.0	All
2219	T6, T8	B358.0 (Tens-50)	All
(E) 2419	T8	359.0	All
(E) 2618	T6, T8	380.0, A380.0	As cast
3000 series	All	514.0 (214)	As cast[5]
5000 series	All[4,5]	518.0 (218)	As cast[5]
6000 series	All	535.0 (Almag 35)	As cast[5]
(E) 7020	T6[6]	A712.0, C712.0	As cast
7049	T73		
7149	T73		
7050	T73		
7075	T73		
7475	T73		

1. Mechanical stress relieved (TX5X or TX5XX) where possible.
2. Including weldments of the weldable alloys.
3. The former designation is shown in parenthesis when significantly different.
4. High magnesium content alloys 5456, 5083 and 5086 should be used only in controlled tempers (H111, H112, H116, H117, H323, H343) for resistance to stress-corrosion cracking and exfoliation.
5. Alloys with magnesium content greater than 3,0 % are not recommended for high-temperature application, 66 °C (150 °F) and above.
6. Excluding weldments.

(E) ESA classification - not in NASA MSFC-SPEC-522A.

(d) Copper Alloy	
CDA no. [1]	Condition (% cold rolled) [2]
110	37
170	AT, HT [3,4]
172	AT, HT [3,4]
194	37
195	90
230	40
422	37
443	10
510	37
521	37
619	40 (9 % B phase)
619	40 (95 % B phase)
688	40
706	50
725	50, annealed
280, 524, 606, 632, 655, 704, 710	0
715, (E) 917, (E) 937	0

1. Copper Development Association alloy number.
2. Maximum per cent cold rolled for which stress-corrosion-cracking data are available.
3. AT – annealed and precipitation hardened.
4. HT – work hardened and precipitation hardened.

(E) ESA classification not in NASA MSFC-SPEC-522A.

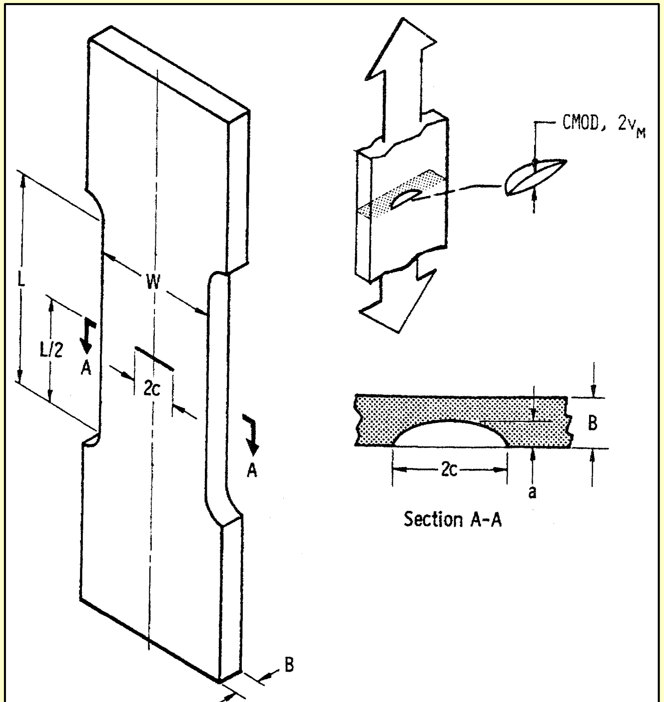
Testing materials for SCC: smooth specimens (cont'd)

Materials & tempers listed in Table I of ECSS-Q-70-36A (3/3)

(e) Miscellaneous Alloy (wrought)	Condition
Beryllium, S-200C	Annealed
HS 25 (L605)	All
HS 188	All
MP35N	All
Titanium, 3Al-2.5V	All
Titanium, 6Al-4V	All
Titanium, 13V-11Cr-3Al	All
(E) Titanium OMI 685, IMI 829	All
Magnesium, M1A	All
Magnesium, LA141	Stabilised
Magnesium, LAZ933	All

Testing materials for SCC: fracture mechanics testing

Fracture mechanics-based testing



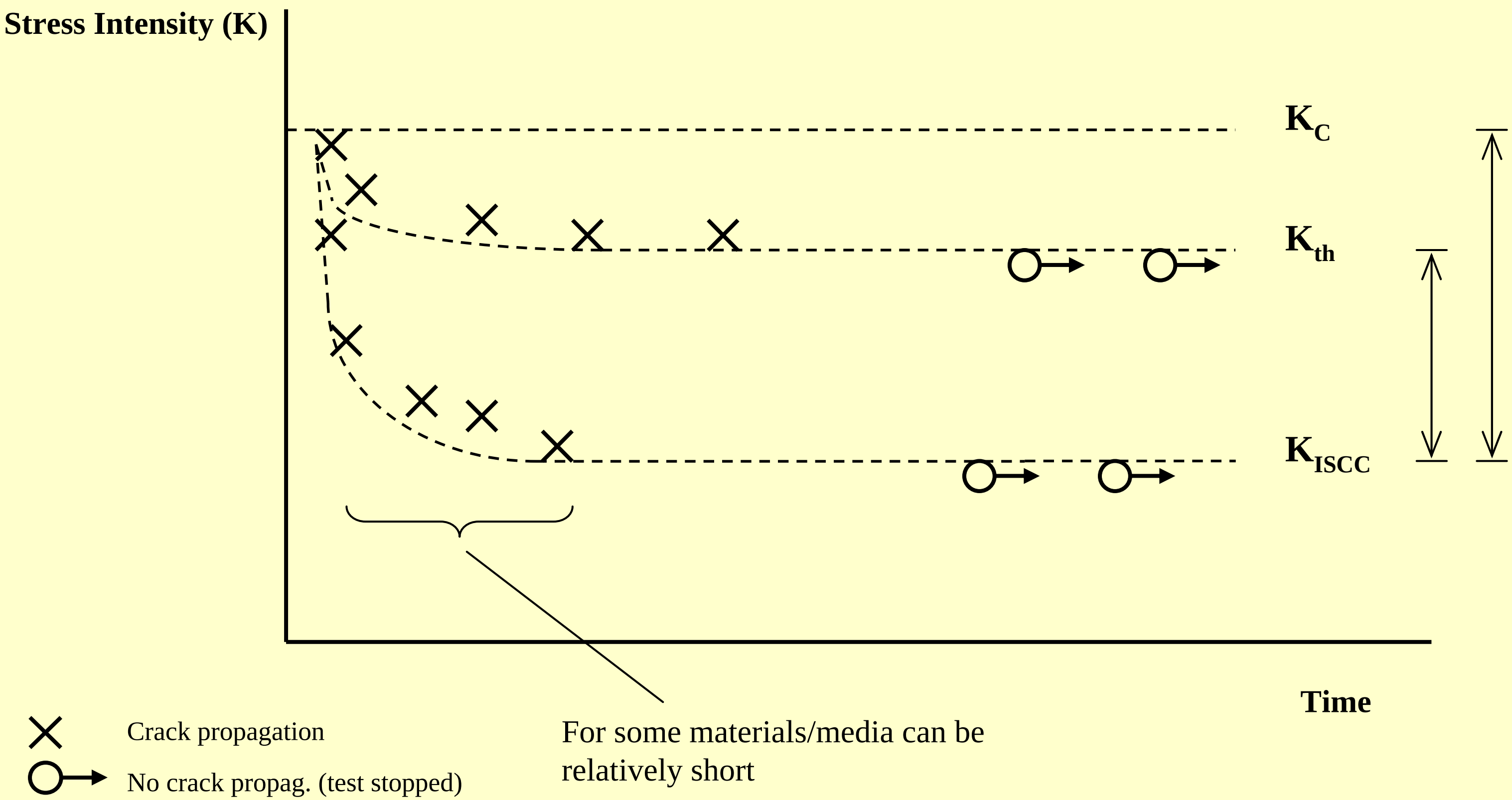
Typical Surface-Crack Specimen (Grip Details Omitted) and Nomenclature

- Fatigue pre-cracked specimens
- Initial crack represents a manufacturing defect present in a component
- Applied stress levels should include tensile residual stress of the real structure
- SEM examination of fracture surfaces to confirm that SCC occurred

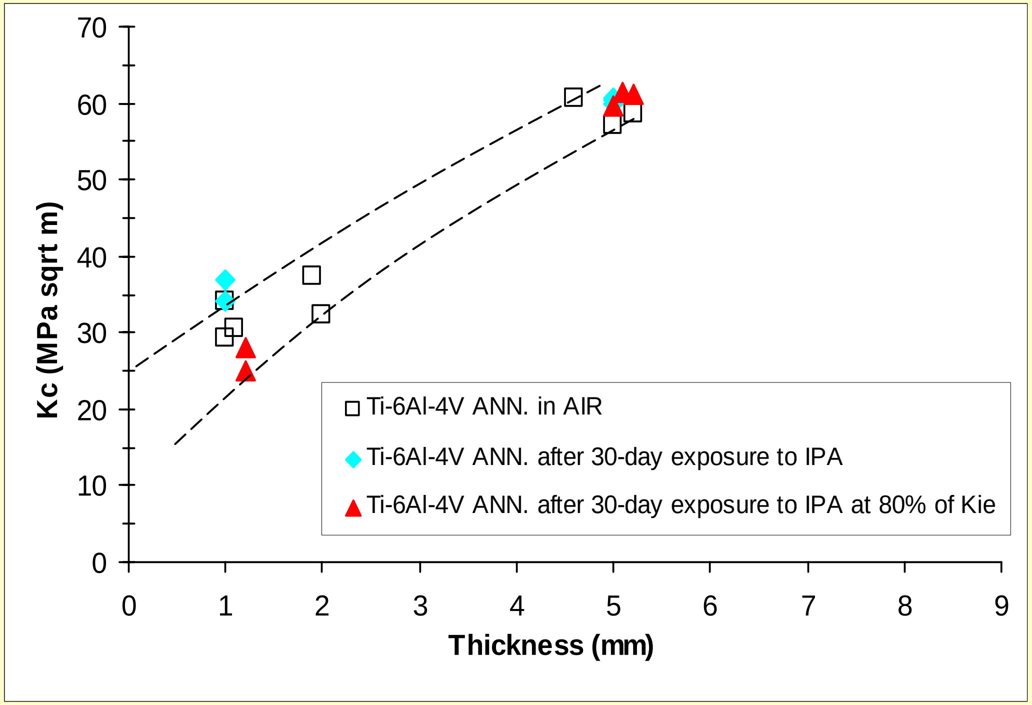
Testing materials for SCC: fracture mechanics testing

K_{ISCC} Stress-corrosion threshold stress intensity factor

K_{th} Crack propagation threshold under sustained loading in air



Testing materials for SCC: fracture mechanics testing (cont'd)



- Example of test results performed on a flat centre-cracked tensile (SCT) specimen of Ti-6Al-4V plate in Isopropyl alcohol (IPA)
- Specimens were fatigue pre-cracked, exposed to IPA and tested for toughness (K_C) to assess any degradation caused by the exposure to IPA.
- Test results are compared with those obtained in air

SCC testing for space propulsion systems

- Propellants and oxidisers are extremely reactive and aggressive substances and can promote SCC
- Residual stresses are introduced in propulsion components, particularly in tanks, by the welding process. The weld residual stress is only partially relieved by heat treatment
- Residual stress measurements carried out on a Ti-6Al-4V TIG welded tank indicated the presence of hoop stresses of the order of 100 MPa in the HAZ (post-weld heat treated). Residual stresses were lower in the parent metal
- The presence of residual stress and the exposure to aggressive substances makes SCC particularly relevant to spacecraft propulsion systems, particularly tanks

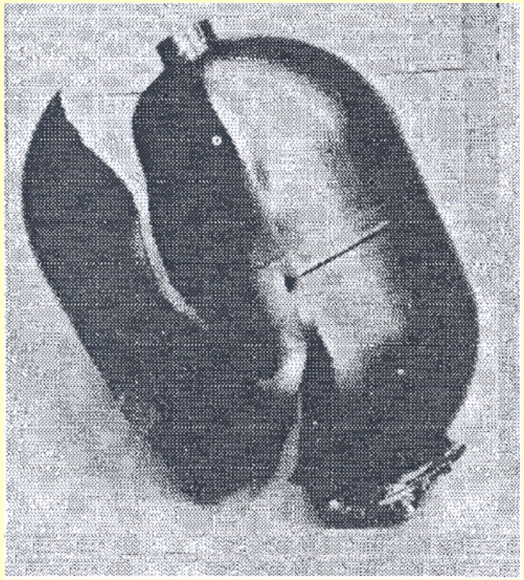
SCC testing for space propulsion systems (cont'd)

- The first documented case of SCC failure can be traced back to 1965 with the failure of a pressurised Ti-6Al-4V tank containing liquid N_2O_4 at Bell Aerospace (USA).
- In 1966 an investigation carried out by NASA gave the following results (tanks pressurised to wall stress of 620MPa):

Ti-6Al-4V tank	Red N_2O_4	30°C	Time to failure 8 days
Ti-6Al-4V tank	Red N_2O_4	40°C	Time to failure 3 days
Ti-6Al-4V tank with Teflon bladder	Red N_2O_4	40°C	Time to failure 23 days
Shot peened Ti-6Al-4V tank	Red N_2O_4	40°C	No failure after 30 days
Ti-6Al-4V tank	N_2O_4 1.0% NO	70°C	No failure after 30 days

SCC testing for space propulsion systems (cont’d)

- Ti-6Al-4V is susceptible to SCC if exposed to N_2O_4 with NO levels of less than 0.7%
- SCC of Ti-6Al-4V in pure N_2O_4 was observed for stress levels between 275 and 620 MPa
- K_{ISCC} /K_{IE} values between 0.8 and 0.3 were reported under various test conditions
- The addition of 1.5 - 2.0% water inhibits SCC, however it causes the formation of HNO_3
- There is a lack of published test data for Ti-6Al-4V welds



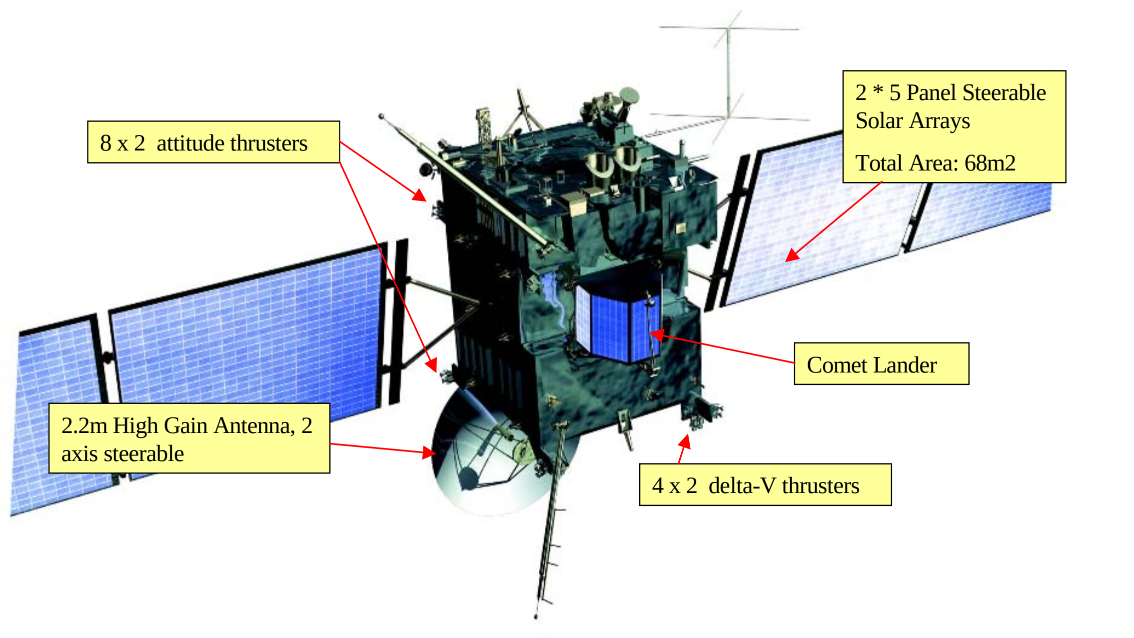
The ESA experience with Rosetta

- ROSETTA is an ESA scientific satellite for deep space exploration (comet observation). Due to launch in January 2003, its launch was put on hold after ARIANE 5 experienced a defective orbit injection in December 2002.

- During this stand-by period the satellite was stored with its Ti-6Al-4V alloy tanks filled with MON-1 (N_2O_4 with 0.7-1.0% NO). For safety reasons it was decided that the tanks should be unloaded, if the new launch date had been postponed beyond March 2004. However, on 2nd March 2004 ROSETTA was successfully launched on ARIANE 5.

- If the tanks had to be unloaded, inevitable chemical modifications of the propellant would have exposed the titanium alloy walls to the risk of SCC. This risk was associated with the possible formation of NO-lean N_2O_4 and HNO_3 caused by the contamination with water during N_2 flushing.

The ESA experience with Rosetta (cont'd)



ESA ROSETTA Satellite

Mission: after entering orbit around Comet 67P Churyumov-Gerasimenko in 2014, the spacecraft will release a small lander onto the icy nucleus of the comet, then spend the next two years orbiting the comet as it heads towards the Sun.

Main structure 2.8 x 2.1 x 2.0 metres

Diameter of solar arrays 32 metres

Launch mass total 3,000 kg (approx.)

Propellant 1,670 kg (approx.)

Science payload 165 kg

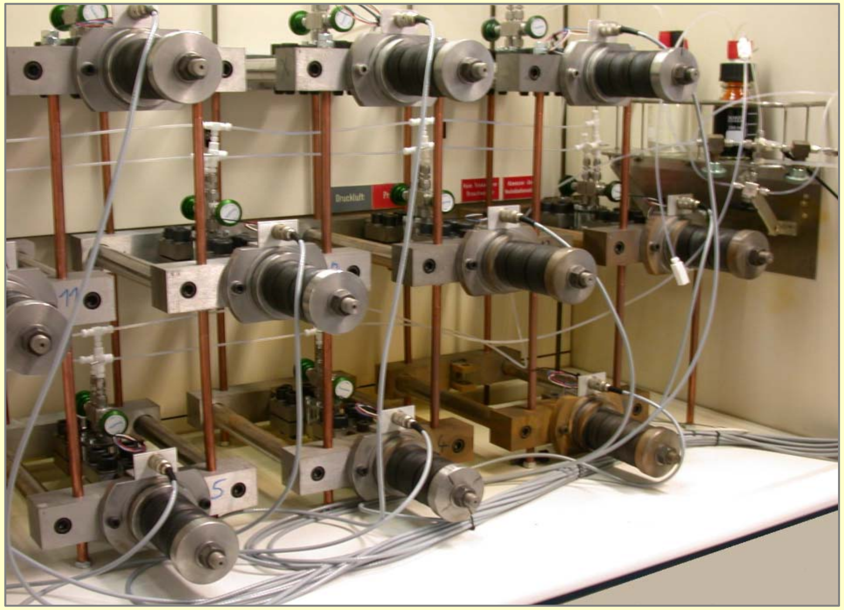
Lander 100 kg

SA output 850 W at 3.4 AU, 395 W at 5.25 AU

Propulsion subsystem 24 bipropellant (MMH, NTO MON-1) 10N thrusters

Operational mission 12 years

The ESA experience with Rosetta (cont'd)



ESA SCC test facility at DLR

- A test programme was carried out to assess the risk of SCC damage to the Rosetta tanks. A special SCC test facility was designed and built for the purpose. The ESA test facility allowed simulating the Rosetta internal tank environment by subjecting tank material samples to a representative chemical exposure and stress history.
- Test results showed that by using a specially developed tank offloading, cleaning and reloading procedure, no SCC damage would have occurred.
- The ESA test facility is used to test materials in a number of environments (eg. IPA, NTO, Hydrazine, MON-1, HNO_3)

The ESA experience with Rosetta (cont'd)

Example of SCC test results for Ti-6AL-4V 2.5 mm thick samples exposed to air, N_2O_4 with low NO content and 20% HNO_3 water solution