EPFL

Introduction to the Design of Space Mechanisms

Theme 4:

Materials

Part 2

Gilles Feusier

Theme 4 – Part 1 Summary

- Mechanical Properties:
  - Strength
    - Hooke's Law $\sigma = E \cdot \varepsilon$
    - Ultimate and Yield Strength
  - Fatigue strength
    - Stress-intensity factor K and its critical value K_c $K = f(\sigma, \sqrt{a}) \geq K_c$
    - Three regions of crack growth
    - Fatigue: cyclic stresses, tensile stresses, plastic deformation
    - Crack initiation (material, size of defect, geometry, environment, loads)
  - Wear
  - Hertz Pressure
  - Friction
  - Thermomechanical effects
    - Thermal expansion
    - Fatigue

Material Properties (continued)

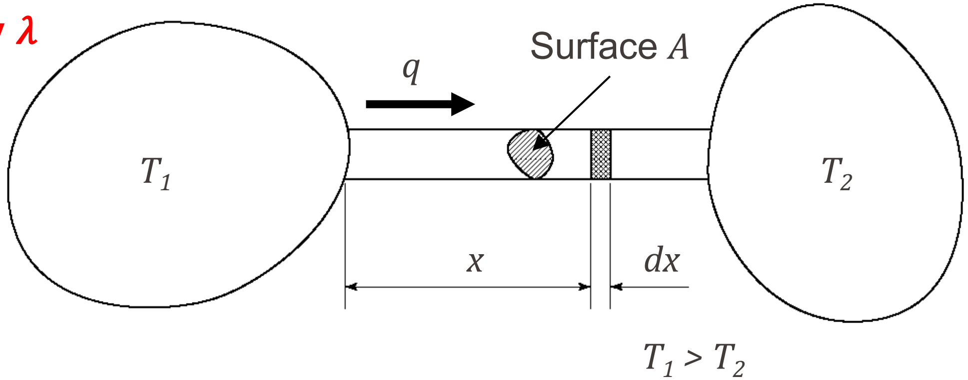
- Thermal: Heat transfer, Conductivity
- Electrical
- Magnetic
- Chemical (outgassing, aging, …)
- Optical
- Material selection

Thermal Properties

- Thermal Conductivity
  - Heat transfer, heat dissipation through **conduction**
    - **Thermal conductivity λ**

$$q = -\lambda \cdot \frac{dT}{dx} \cdot A$$

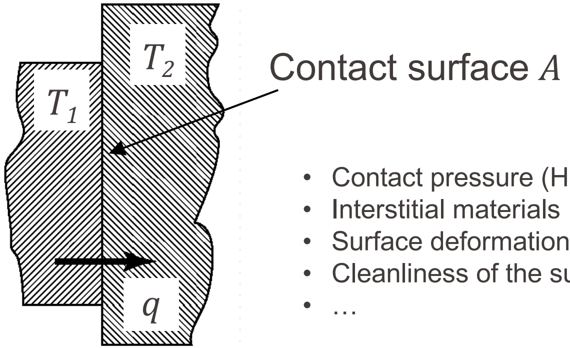
$$[\lambda] = \frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}}$$



  - Heat transferred through the **surface**
    - **Thermal contact conductance κ**

$$q = -\kappa \cdot A \cdot (T_1 - T_2)$$

$$[\kappa] = \frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}$$

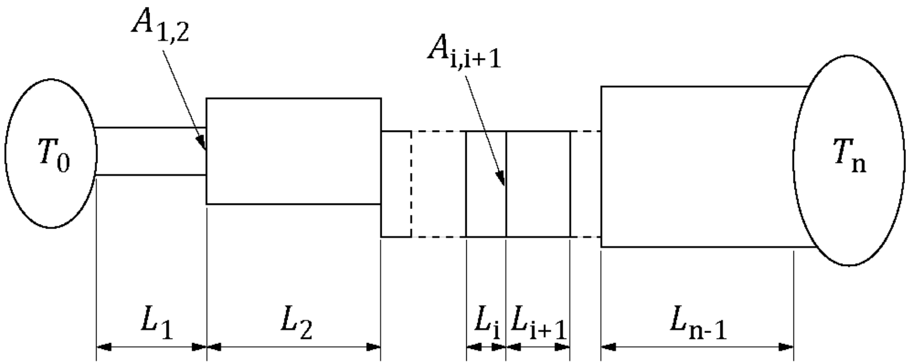


- Contact pressure (Hertz pressure …)
- Interstitial materials
- Surface deformations, roughness
- Cleanliness of the surface
- …

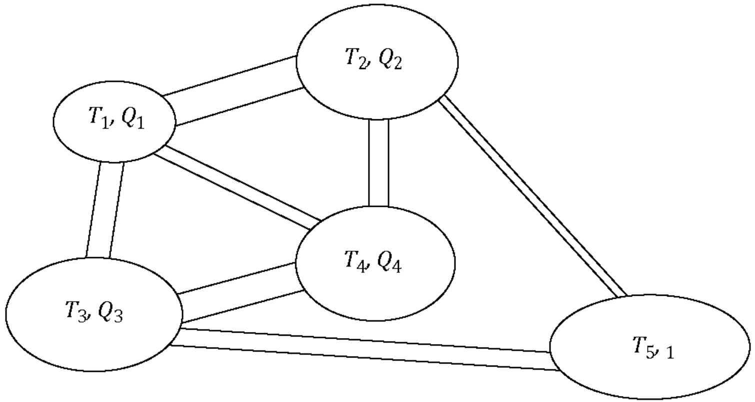
Thermal conductivity

- Assembly of parts
  - Thermal network
    - **Linear model**

$$\lambda_{comb} = \left\{ \sum_{i=1}^{n-1} \frac{1}{\lambda_i \cdot \frac{A_i}{L_i}} + \sum_{i=0}^{n-1} \frac{1}{\kappa_{i,i+1} \cdot A_{i,i+1}} \right\}^{-1}$$



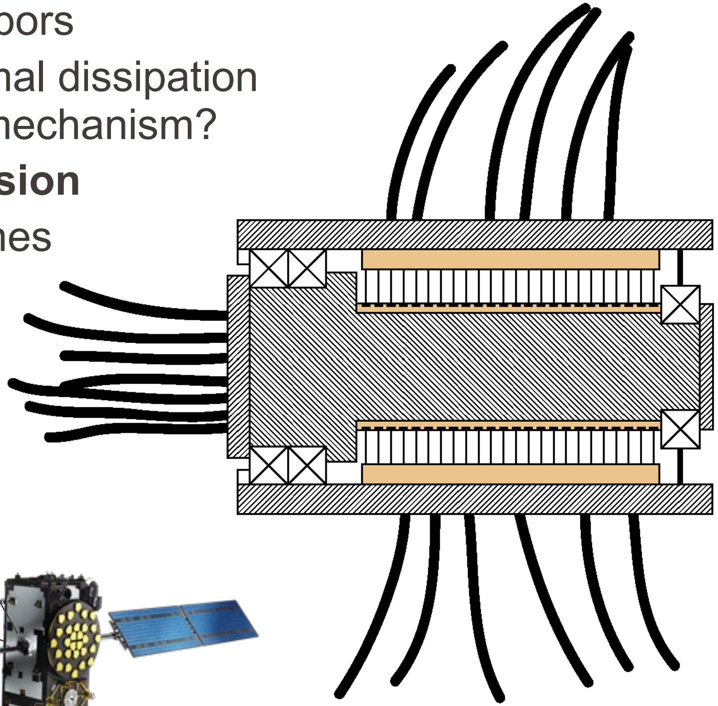
    - **Complex model**
      - Q_i are dissipative sources
      - Heat transfer equations are similar to the Kirchhoff's circuit laws in electricity
    - **Continuous model**
      - Finite Element (FE) model
  - Full model shall include radiation heat transfer (convection does not apply in vacuum)

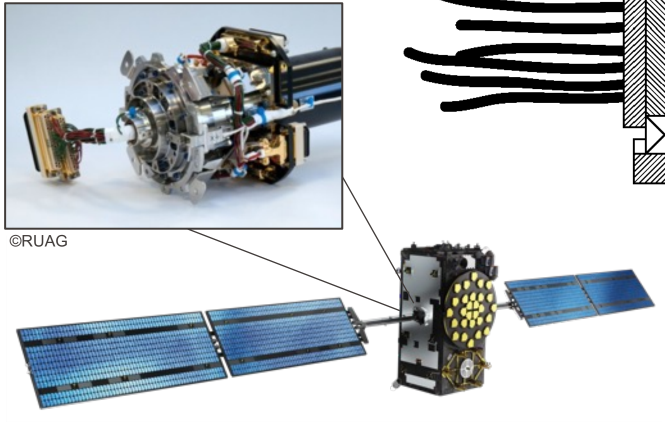


Exercise 4.3: Thermal conductivity

Thermal aspects for a mechanism

- A slipring assembly for a solar array drive mechanism
  - Turn to your neighbors
  - What are the thermal dissipation issues on such a mechanism?
  - **5 minutes discussion**
  - Share your outcomes





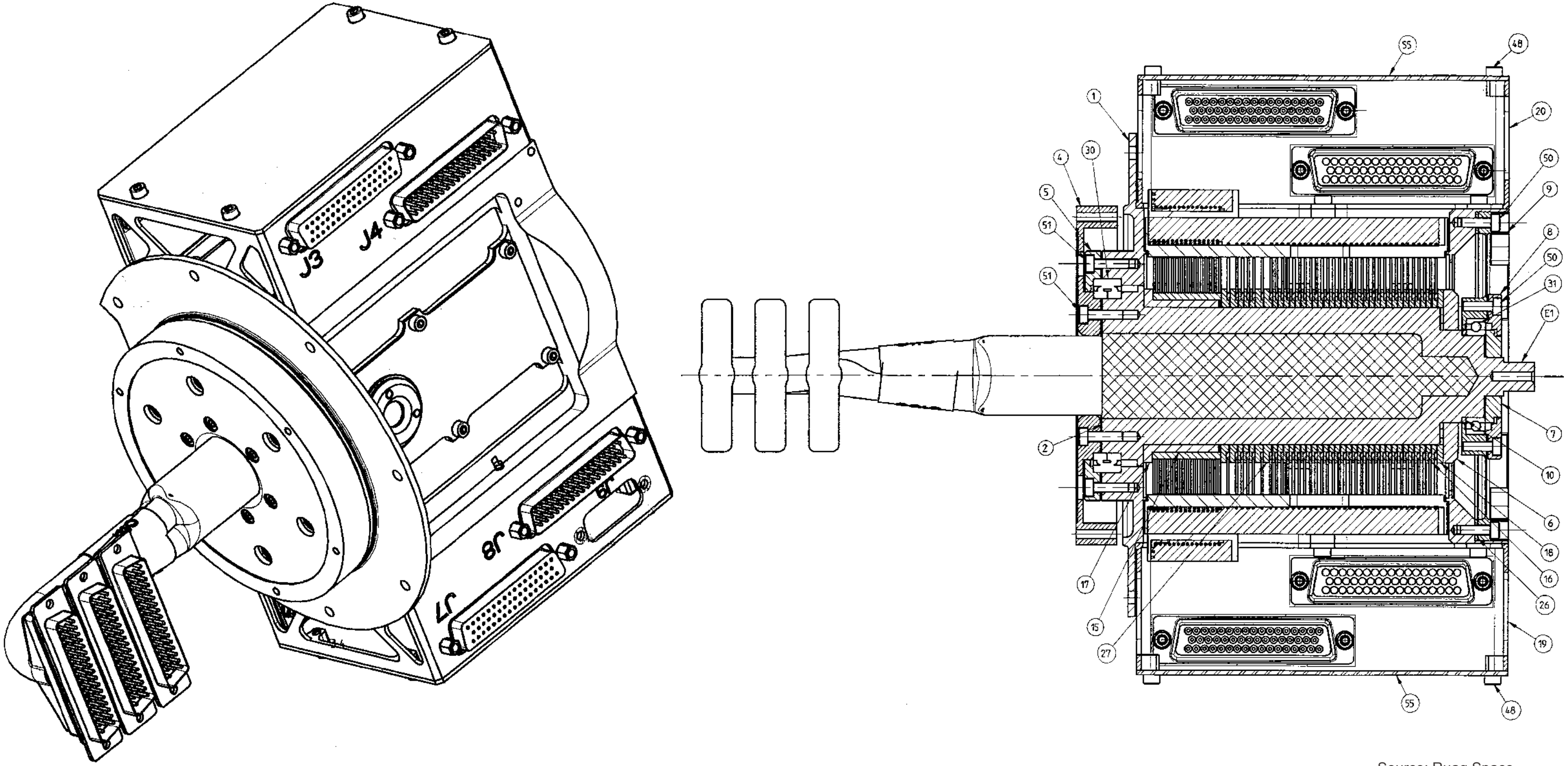
©RUAG

©GSA, ©European GNSS Agency

©Kübler

©MOOG

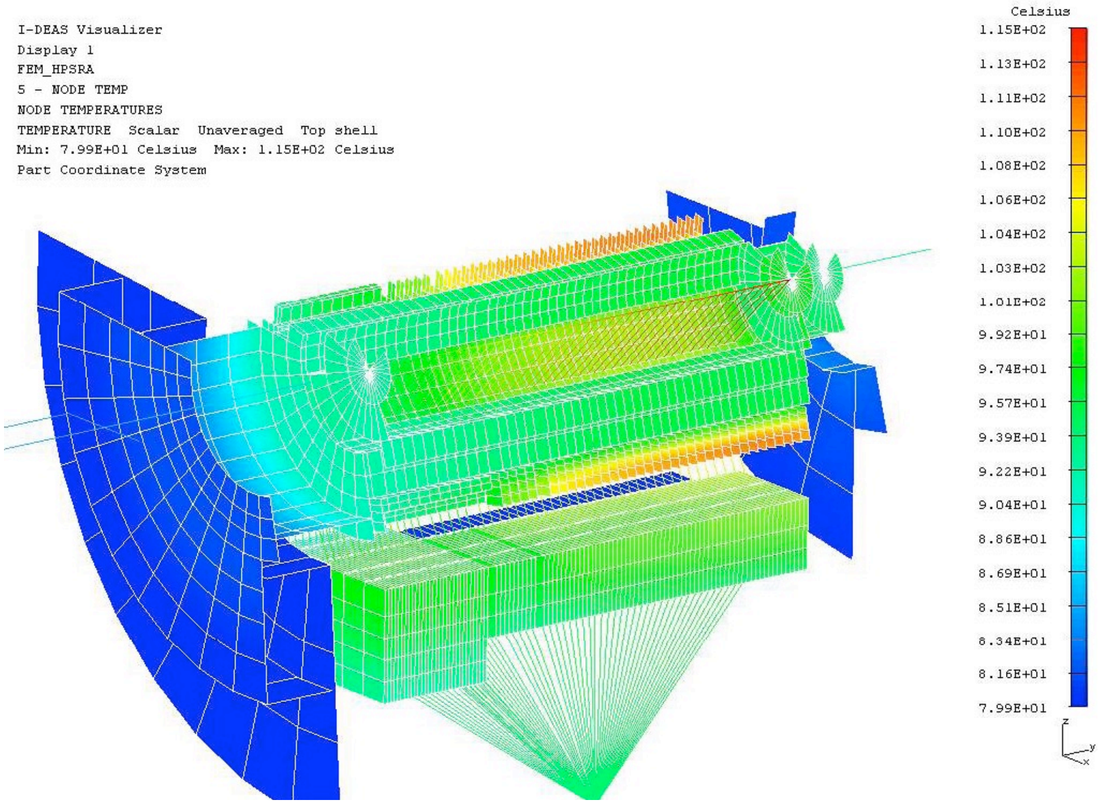
Thermal aspects for a mechanism



Source: Ruag Space

Thermal aspects for a mechanism

- Example of a Finite Element model



Electrical Properties

- Electrical resistivity ρ [Ω m]
  - Metals < Semi-conductors < insulators

Orders of magnitude at 20°C

Silver:	$1.59 \cdot 10^{-8}$	Ω·m
Copper:	$1.7 \cdot 10^{-8}$	Ω·m
Aluminum:	$2.65 \cdot 10^{-8}$	Ω·m
Tin:	$14.2 \cdot 10^{-8}$	Ω·m
Stainless steel:	$69 \cdot 10^{-8}$	Ω·m
Graphite:	$250 \cdot 10^{-8}$ to $3 \cdot 10^{-3}$	Ω·m (depends on orientation)
Epoxies:	10^{12} to 10^{14}	Ω·m
Ceramic:	10^{17}	Ω·m

  - Conductivity σ [S / m] $\sigma = \dfrac{1}{\rho}$ Note (SI units): [S] = Siemens = [1 / Ω]

- Temperature coefficient α [1/K]
  - Linear approximation: $\rho(T) = \rho_0 \cdot (1 + \alpha(T - T_0))$

Where ρ_0 is the electrical resistivity at temperature T_0

Electrical Properties

- Interfaces are key
  - Low resistance galvanic contacts shall be insured for all parts
    - Metallic parts shall never have a floating potential
      - ⇒ Risk of **electrostatic discharge**!
  - Corrosion and oxidation of the galvanic contact shall be avoided
    - Coating of the contact surface
      - Tri-chrome passivation for aluminum(*)
      - Nickel plating of the surfaces maybe required
      - …

(*) *originally chromate (Cr^{6+}) conversion coating for aluminum, hazardous, replaced by Cr^{3+} less hazardous. Future?*

Source: Steiger Galvanotechnique SA

Magnetic Properties

- **Ferromagnetism**
  - It's a key property for space mechanisms
    - ⇒ Shall not perturbate the magnetic fields measured by the on-board sensors
    - Many ferromagnetic parts in mechanisms
      - Motors, position sensors, components with permanent magnets, …
      - Magnetic leakages shall be as low as possible
  - Curie temperature (T_C)
    - Loss of permanent magnetic ferromagnetism above T_C
      - Operation of the mechanism can stop after a high temperature excursion
- **Para- diamagnetism**
  - Of secondary importance, except for very specific applications
    - Measurement of the terrestrial magnetic field
    - Specific detectors

Outgassing

- When material are exposed to vacuum: **outgassing**
  - Outgassing through evaporation of the material: **vapor pressure**.
    - **Hg, Zn, Cd, Mg** are **forbidden** or in very little quantity in alloys
    - For **organic materials** (glues, insulators, lubricants …): list of materials and tests.
  - Outgassing by **absorption**: volatile materials absorbed in the structure or in the porosities at atmospheric pressure
    - Movement of the atoms by diffusion
  - Outgassing by **adsorption**: volatile materials adsorbed at the surface (water, hydrocarbon, gas, atoms, ions, …)

- The desorption is activated by:
  - Increase of the temperature
  - Decrease of the pressure

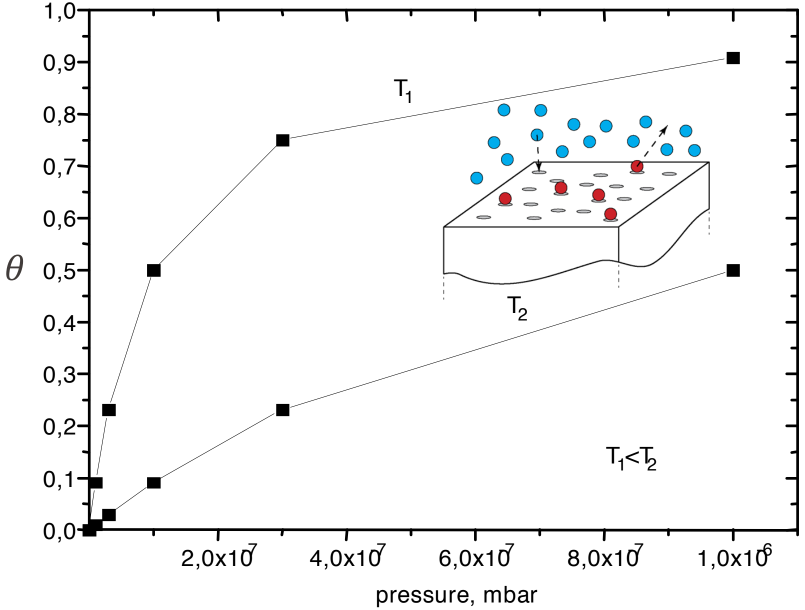
Outgassing

- **Outgassing by diffusion** Molecular flow: $Q = -D\dfrac{dc}{dx}$
  - Controlled by Fick's laws
    - Diffusion coefficient D
    - Concentration (gradient ${dc}/{dx}$) of the diffusing substances
    - Activation energy $(D = D_0 e^{\left(-\frac{E}{kT}\right)})$
    - Temperature
- **Outgassing of adsorbed substance**
  - The surface coverage θ is in equilibrium at given pressure P and temperature T:
    - **Langmuir** adsorption isotherm

$$\theta = \frac{V}{V_m} = k(T)\cdot\frac{P}{1 + k(T)\cdot P}$$

    - The decrease of the pressure reduce the surface coverage.

Source: J.L. de Segovia, Instituto de Física Aplicada, CETEF "L. Torres Quevedo", CSIC, Madrid, Spain [4.5] http://www.cientificosaficionados.com/libros/CERN/vacio9-CERN.pdf



$k(T)$: equilibrium constant (interaction between adsorbed material and material of the surface of the body)

Outgassing

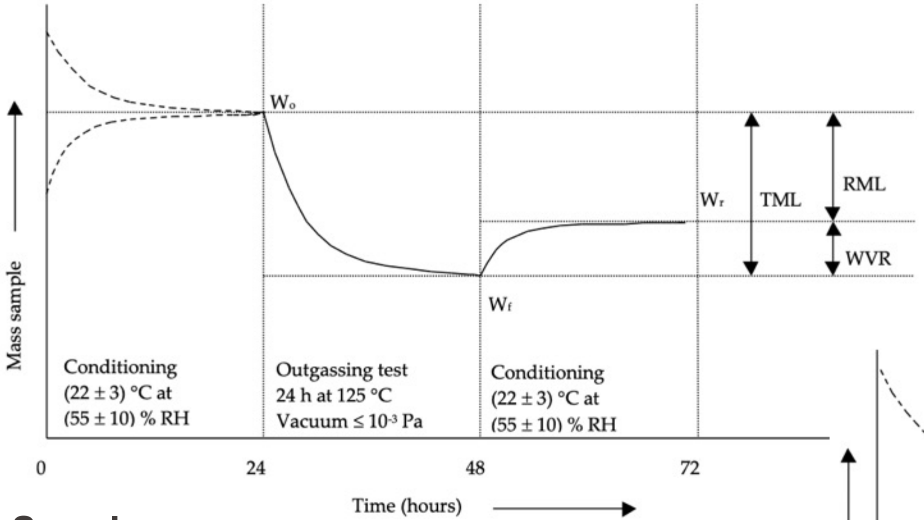
- Characteristics of the outgassing of materials
  - Several parameters are important for space applications (ECSS-Q-ST-70-02C [4.6])

- **TML**	**Total Mass Loss**	< 1%	(corrective actions may apply)
- **RML**	**Recovered Mass Loss**	< 1%	(corrective actions may apply)
- **CVCM**	**Collected Volatile Condensable Material**	< 0.1%	(limits can be more stringent, e.g. near optics)
- WVR	Water Vapor Regained (RML = TML - WVR)		

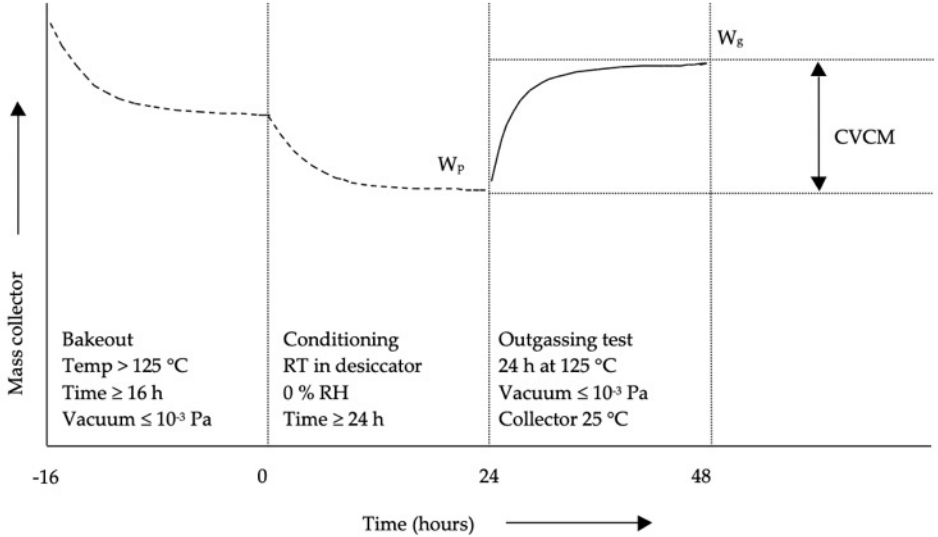
  - Other aspects of outgassing, may be important in particular in manned flights
    - Toxicity
    - Odor
  - Material Identification Card (MIC)
    - Strict procedure shall be applied
      ⇒ Test reports, certificate of conformity

Outgassing

Source: ECSS-Q-ST-70-02C Space Product Assurance - Thermal vacuum outgassing test for the screening of space materials [4.6]



Sample mass



Collector mass

Outgassing

- Space materials: not pure materials ⟹ participation of all outgassing mechanisms

- **Metals**: outgassing rate is lowering very rapidly
  - Mainly N_2, CO, CO_2, H_2, H_2O
  - Except for high vapor pressure metals (e.g. Hg, Zn, Cd, Mg)
  - Contaminants (bad cleaning, use of not adapted cutting oils, …)

- **Organic Materials (polymers)**: complex mechanisms
  - Modification of the properties (mechanical, thermal, …)
  - Decomposition of the material, elimination of additives (plasticizer, antioxidants …). Effects of vacuum, radiations, increase of temperature.

Outgassing

- **Water absorption** of materials is not always harmful with respect to contamination.

- Materials with TML > 1.0 % and RML < 1.0 % could be accepted if the following conditions are met (ECSS-Q-ST-70-02C):
  1. no equipment at a temperature below -100 °C is involved;
  2. water desorption is fast (e.g. in the case of polyimide films and polyurethane paints);
  3. no high voltage equipment is involved;
  4. dry gas purging controls the water reabsorption during ground life up to launch.

Chemical Properties

- Aging
  - Material deterioration as a function of time
    - Embrittlement
    - Delamination (composite materials, glue bonding, …)
    - Loss of mechanical properties
      - Decrease of the ultimate strength
      - Creep, deformation
      - Crack growth (e.g. stress corrosion cracking)
      - Loss of elasticity of polymers
    - Deterioration of insulators
      - Loss of insulation
      - Spark tracking
    - Etching and oxidation (e.g. by ATOX - O^+)
    - Diffusion of acceptors or donors in semiconductors
      - Loss of performances of electronic components

Chemical Properties

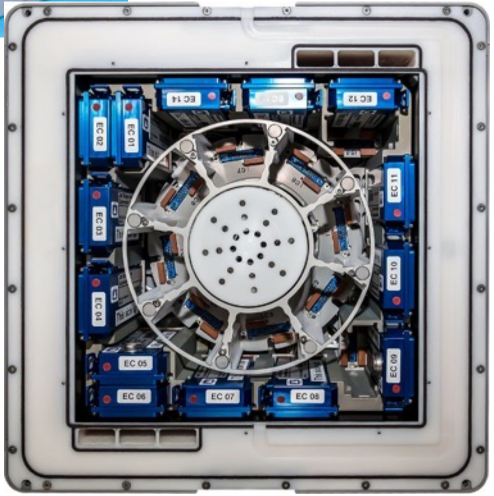
- Biocompatibility
  - Micro-g research applications
    - Mechanisms in contact with leaving cells
      - Bioreactors
      - Animal or phytologic cultivation cells
      - Materials in contact with the astronauts

Source: Mécanex SA, IMT, ETH Space Biology Group

Space Biology Reactor

Source: HSLU

KUBIK 2



Source: Kayser Italia S.r.l.

Chemical Properties

- Electrochemical potential
  - Contact of two conducting materials with the presence of an electrolyte

→ An electrical potential is generated between the two materials

  - If electrical courant can flow (ion and electron exchange), there will be corrosion
  - The corrosion will benefit from a high electrochemical potential difference

  - **Consequences**: material with close electrochemical potential shall be selected
  - Use of galvanic series relationship for selecting the materials in contact

Chemical Properties

- Large electrochemical potential between the materials in contact shall be avoided:
  - Harsh environment: < 0.15V
  - Normal environment: < 0.25V
  - Controlled environment (clean room): < 0.5V
- Ground handling, cleaning, storage conditions have a large impact on corrosion in space

➡ Processes shall be mastered

Source: http://corrosion-doctors.org/Definitions/galvanic-series.htm

Anodic Index

Metallurgy	Index (V)
Gold, solid and plated, Gold-platinum alloy	0.00
Rhodium plated on silver-plated copper	0.05
Silver, solid or plated; monel metal. High nickel-copper alloys	0.15
Nickel, solid or plated, titanium an s alloys, Monel	0.30
Copper, solid or plated; low brasses or bronzes; silver solder; German silvery high copper-nickel alloys; nickel-chromium alloys	0.35
Brass and bronzes	0.40
High brasses and bronzes	0.45
18% chromium type corrosion-resistant steels	0.50
Chromium plated; tin plated; 12% chromium type corrosion-resistant steels	0.60
Tin-plate; tin-lead solder	0.65
Lead, solid or plated; high lead alloys	0.70
Aluminum, wrought alloys of the 2000 Series	0.75
Iron, wrought, gray or malleable, plain carbon and low alloy steels	0.85
Aluminum, wrought alloys other than 2000 Series aluminum, cast alloys of the silicon type	0.90
Aluminum, cast alloys other than silicon type, cadmium, plated and chromate	0.95
Hot-dip-zinc plate; galvanized steel	1.20
Zinc, wrought; zinc-base die-casting alloys; zinc plated	1.25
Magnesium & magnesium-base alloys, cast or wrought	1.75
Beryllium	1.85

Chemical Properties

- Compatible couples for bimetallic contacts

According to

ECSS-Q-ST-70C Rev.2
Materials, mechanical parts and processes

Key:

0: Can be used without restriction.

1: Can be used in a non-controlled environment (e.g. assembly area and general non-clean room environment).

2: Can be used in a clean room environment.

3: Needs specific measures to avoid galvanic corrosion when these combinations are selected.

Pure metals and alloys in alphabetical order (including carbon)	Aluminium-Copper alloys	Al (pure), Al-Zinc alloys	Cadmium	Cast iron (austenic)	Chromium	Copper, Brasses	Cupro-Nickel, Al-bronzes, Si-bronzes	Gold, Platinum, Carbon, Rhodium	Gun-metal (CuZn10 alloy), P-bronzes, Sn-bronzes	Magnesium	Nickel, Monel, Inconel, Nickel/Molybdenum-alloys	Silver	Sn-Pb alloys (all), Tin, Lead	Stainless steel 18/8 (300 series)	Stainless steel 13Cr (400 series)	Steel (carbon, low alloy), Cast iron	Titanium and Ti-alloys	Zinc, Beryllium
Aluminium-Copper alloys	■	1	1	3	3	3	3	3	3	2	2	3	1	2	2	3	2	2
Al (pure) Al-Zinc alloys		■	1	3	3	3	3	3	3	2	3	3	2	3	3	3	3	2
Cadmium			■	2	2	2	2	2	2	1	2	2	0	1	1	2	2	2
Cast iron (austenic)				■	1	1	1	2	1	3	1	2	1	1	1	2	1	3
Chromium					■	1	0	0	1	3	1	0	2	0	0	2	0	3
Copper, Brasses						■	0	2	0	3	1	1	2	1	1	3	0	3
Cupro-Nickel Al-bronzes Si-bronzes							■	2	0	3	1	1	2	2	1	3	0	3
Gold Platinum, Carbon Rhodium								■	2	3	2	0	3	0	1	3	0	3
Gun-metal(CuZn10 alloy) P-bronzes Sn-bronzes									■	3	1	1	1	0	0	3	0	3
Magnesium										■	3	3	2	3	3	3	3	3
Nickel Monel Inconel Nickel/Molybdenum-alloys											■	2	2	1	0	2	1	3
Silver												■	3	0	0	3	0	3
Sn-Pb alloys (all) Tin, Lead													■	1	1	1	3	1
Stainless steel 18/8 (300 series)														■	1	3	0	3
Stainless steel 13Cr (400 series)															■	3	0	3
Steel (carbon, low alloy) Cast iron																■	0	3
Titanium and Ti-alloys																	■	3
Zinc Beryllium																		■

Optical Properties

- Emittance, Reflectance, Absorbance, Transmittance
  - Capacity of a material to radiate, reflect, absorb or transmit electromagnetic waves
    - High emittance surfaces for thermal control
      - White coating/paint
      - MLI (multi-layer insulation)
    - High transmittance materials (potentially for limited bandwidth)
      - Optical elements, lenses
      - Optical filters
      - Optical fibers
    - High absorbance materials
      - Black coating/paint for some sensors
      - Black coating/paint for thermal control

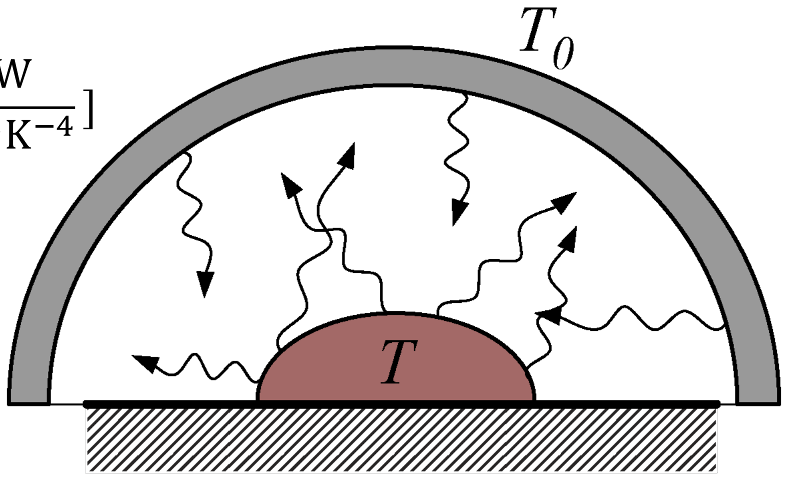
Optical Properties

- Thermal radiation
  - Total radiative energy flux per unit surface (w) is depending on:
    - The material property: **emittance ε**
    - The temperature T of the part and T_0 of the thermal well (e.g. deep space at 4K)
  - w is the hemispherical energy emitted on the whole spectrum

$$w = \sigma \cdot \varepsilon \cdot (T^4 - T_0^4) \quad [\frac{\mathrm{W}}{\mathrm{m}^2}]$$

where $\sigma = \dfrac{2\pi^5 k^4}{15 c^2 h^3} = 5.67 \cdot 10^{-8} \quad [\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}^{-4}}]$

Stefan-Boltzmann constant



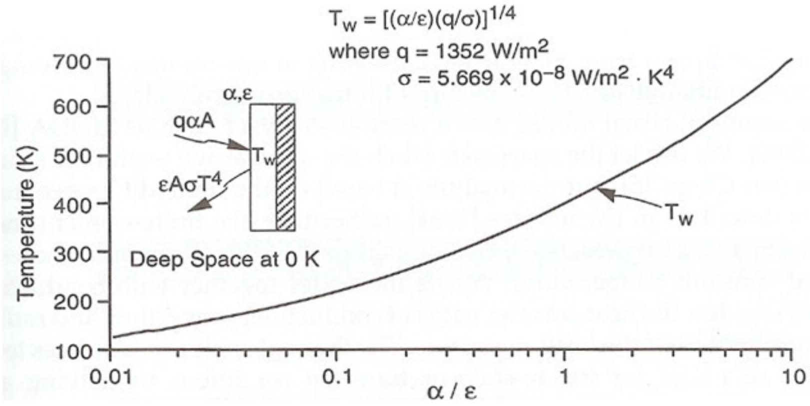
In general, the heat sink has a limited angular aperture (e.g. for the heat exchanges inside a mechanism).
It means that the calculation is much more complex using the integral of the solid angle of the **luminance** (monochromatic directional energy flux).
Finite Element calculation is required.

Optical Properties

- A solid exposed to a light source absorb energy
  - Property: **absorbance** α

$$w_{absorbed} = \alpha \cdot w_{incident}$$

  - For the thermal control of spacecraft, it is important to know the absorbance for the whole solar spectrum.
  - The emittance of the exposed parts of the spacecraft is relevant only for the infrared bandwidth (at temperatures ranging from 300K to 400K).
  - According to the ratio $\alpha/_{\varepsilon}$ an equilibrium temperature is established

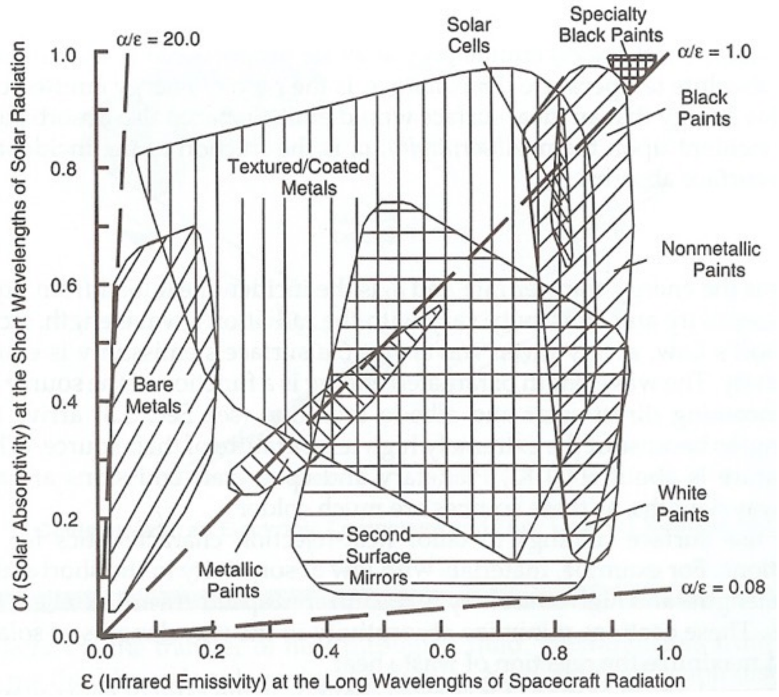


Source:
Th. P. Sarafin (ed.), Spacecraft, Structures and Mechanisms, Wiley J. Larson, Managing ed., 2003, p. 301

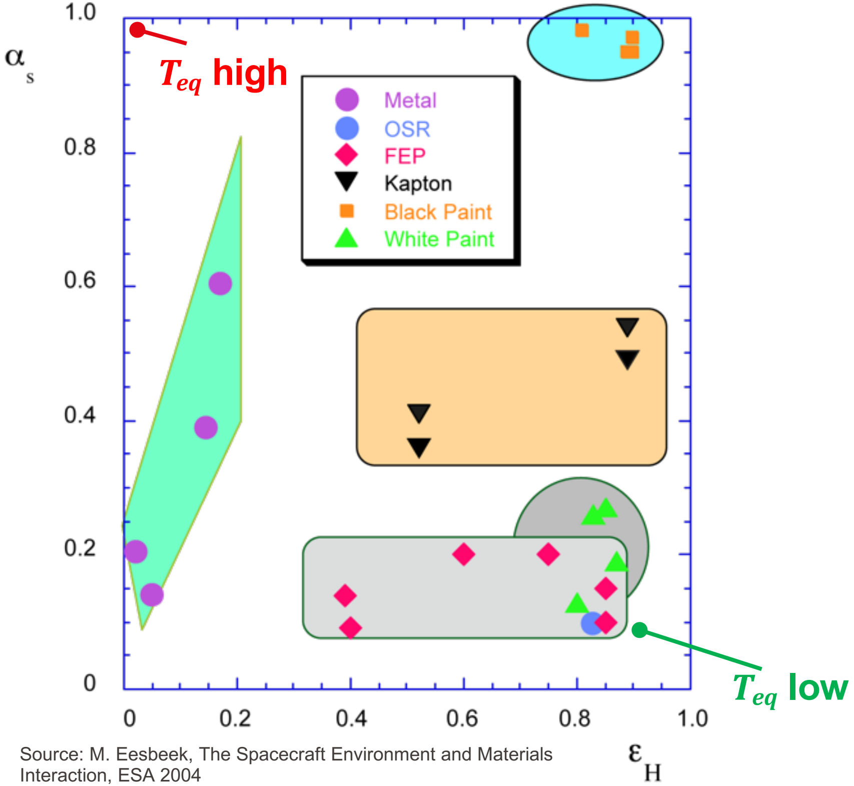
Optical Properties

Exercise 4.4: Thermal equilibrium

- Selection of the materials according to their efficiency for heat exchanges $(^{\alpha}/_{\varepsilon} \searrow \Rightarrow T_{eq} \searrow)$



Source: Th. P. Sarafin (ed.), Spacecraft, Structures and Mechanisms, Wiley J. Larson, Managing ed., 2003, p. 301



Source: M. Eesbeek, The Spacecraft Environment and Materials Interaction, ESA 2004

Optical Properties

- Aging of the coatings and paints

White paints

e.s.h: Equivalent Sun Hours

Coating	α_s initial	$\Delta\alpha_s$ after 1100 e.s.h.	$\Delta\alpha_s$ after 1100 e.s.h. + e^- + p^+
PSB	0.135	0.025	0.20
SG120FD	0.2	0.042	0.145
PSBN	0.16	0.010	0.11
SG121FD	0.154	0.011	0.078
PCBE	0.23	0.003	0.063
PCBZ	0.19	0.03	0.17
Z93P	0.136	0.025	0.094
S13GP6N	0.20	0.021	0.193

Source: M. Eesbeek, The Spacecraft Environment and Materials Interaction, ESA 2004

Material Selection: main criteria

- Functional requirements and constrains
- Material properties
- Available manufacturing processes
- Complexity of the manufacturing
- Configuration required by the function (design)
- Availably of substitute materials
- Corrosion and operational deterioration
- Thermal stability
- Specific properties
  - Low density
  - High stiffness / mass ratio
  - Low fusion temperature
  - Specific thermal expansion properties (including non–usual ones)
  - Electrical conductivity, superconductivity
  - Wear resistance
  - Biocompatibility
  - …
- Costs (material and process), availability

Material Selection

- Common materials used for space projects (non-exhaustive)
  - Metals (careful selection of temper as well!)
    - Aluminum alloys (7075, Al-Li, 6061 …)
    - Titanium alloys (Ti6Al4V …)
    - Iron alloys (stainless steel, low stress corrosion cracking)
    - Nickel alloys (Inconels …)
  - Organic compounds
    - Epoxy, Polyurethane …
    - Polyimides (Vespel, Kapton), PTFE (Teflon), PEEK (polyetheretherketone) …
  - Composite materials
    - Reinforced composites (glass, carbons …)
    - Carbon-carbon composites
    - Honeycomb panels
  - Ceramics (brittleness may limit their use)

Stress Corrosion Cracking (SCC)

- Combined action of:
  - sustained tensile stress
  - corrosion
- ➢ initiation and growth of cracks
- ➢ **premature failure of materials**
  @ lower stresses

➢ Proper material selection!

Source: ESA

Material Selection: Stress Corrosion Cracking

- ECSS-Q-ST-70-36C “Material selection for controlling stress-corrosion cracking”:
  - **Table 5-1**: preferred (no need for stress corrosion evaluation)
  - **Table 5-2**: shall only be considered for use when a suitable alloy cannot be found in Table 5-1
  - **Table 5-3**: only be considered for use in applications where the probability of stress-corrosion is remote.

Table 5-1: Alloys with high resistance to stress-corrosion cracking

(a) Steel	Condition
Carbon steel (1000 series)	Below 1 225 MPa (180 ksi) UTS
Low alloy steel (4130, 434	
(E) D6AC, H-11	
Music wire (ASTM 228)	
HY-80 steel	
HY-130 steel	
HY-140 steel	

Table 5-1: Alloys with high resistance to stress-corrosion cracking *(cont.)*

(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
...			
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		
...			

Table 5-2: Alloys with moderate resistance to stress-corrosion cracking (cont.)

(c) Aluminium alloys[1,2]			
Wrought		Cast	
Alloy	Condition	Alloy	Condition
2024 rod, bar, extrusion	T6, T62	319.0, A319.0	As cast
2024 plate, extrusions	T8	333.0, A333.0	As cast
2124 plate	T8		
2048 plate	T8		
4032	T6		
5083	All [3]		
5086	All [3]		
5456	All [3]		
7001	T75, T76		
(E) 7010	T736		
7049	T76		
7050	T736,T76		
7075	T76		
7175	T736,T76		

Table 5-3: Alloys with low resistance to stress-corrosion cracking *(cont.)*

(b) Aluminium Alloys[1,2]			
Wrought		Cast	
Alloy	Condition	Alloy	Condition
2011	T3, T4	295.0 (195)	T6
2014	All	B295.0 (B195)	T6
2017	All	520.0 (220)	T4
2024	T3, T4	707.0 (607, tern-alloy 7)	T6
...			
7075	T6		
7175	T6		
...			

Material Selection

- ECSS-Q-ST-70C Rev.2 “Materials, mechanical parts and processes”
- ECSS-Q-ST-70-71C Rev.1 “Materials, processes and their data selection”
  - ***But no specific material data*** (originally listed in superseded ECSS-Q-70-71A rev. 1 “Data for selection of space materials and processes”)
  - ESA/ESTEC personal has access internally to a material data base: European Space Materials Database (ESMDB)

- Some data available on internet (use carefully as a first screening, not necessarily validated)
  - https://outgassing.nasa.gov
  - https://www.spacematdb.com
  - https://matdb.jaxa.jp/main_e.html
  - https://matrex.cnes.fr *(login required, restricted access)*
  - …

Theme 4 Summary

- Strength
  - Hooke's Law
  - Ultimate and Yield Strength
- Fatigue strength
- Wear
- Hertz Pressure
- Friction
- Thermal
  - Thermomechanical effects
  - Heat transfer, Conductivity

Theme 4 Summary - continued

- Electrical
  - Equipotential of the parts
  - Galvanic corrosion
- Magnetic
  - Ferromagnetism, Curie temperature
- Chemical
  - Outgassing (TML, RML, CVCM, …)
  - Aging
  - Biocompatibility
  - Electrochemical potential
- Optical
  - Thermal radiations
  - Aging
- Material selection
  - Main criteria
  - Use of standards

Next week

- Theme 5 – Part 1: Structures
- Exercises 4.3, 4.4
- Second part of Mini Project (architecture) will start