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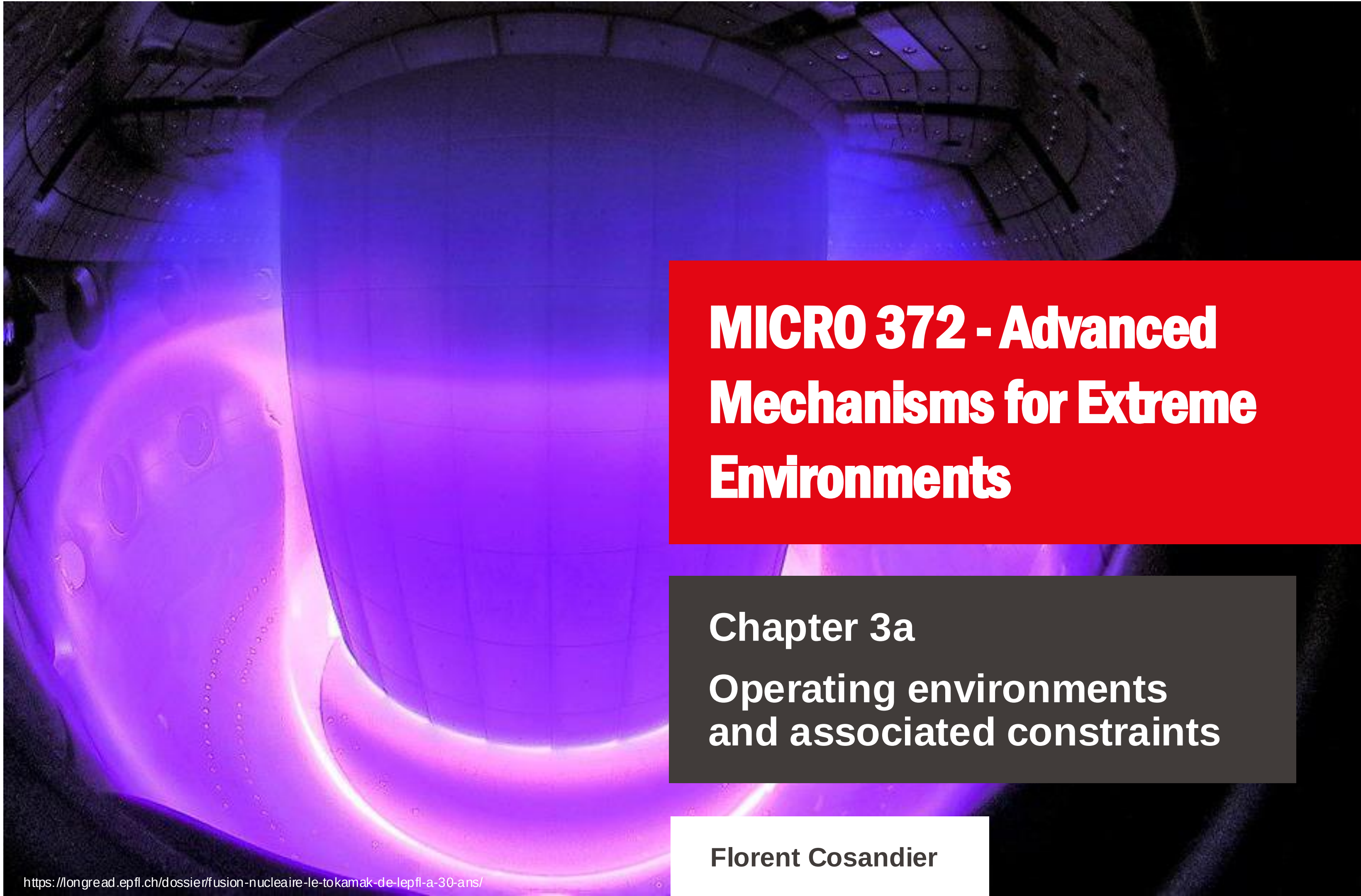


# MICRO 372 - Advanced Mechanisms for Extreme Environments

## Chapter 3a

## Operating environments and associated constraints

Florent Cosandier

https://longread.epfl.ch/dossier/fusion-nucleaire-le-tokamak-de-lepfl-a-30-ans/

École polytechnique fédérale de Lausanne

# Operating environments

- Vacuum environment
- Outgazing
- Cryogenic environment
- High temperature environment
- Radiative environment
- Dusty environment
- Sterile environment
- In vivo environment
- Micro-gravity environment
- Vibrations
- Micro-vibrations (within satellites)
- Magnetic environment

# Operating environments

For **each environment**, we will address some of **the following questions**:

- **What is** the environment and **how is it defined**?
- What are the **physical characteristics** of such an environment?
- **Where** can such an environment be found?
- **What mechanisms** and applications are likely to operate in such an environment?
- **What effects** can such an environment have on a mechanical system?
- What are the **basic measures and principles** to be observed **when designing a mechanical system** for such an environment?
- What are the **standards** and **norms** to be observed when designing a mechanism for such an environment?
- What are the right **references** and **documents** to use?

# Vacuum environments

*Vacuum in two evacuated hemispheres by Otto von Guericke in 1657 in Magdeburg*


THE REGENSBURG EXPERIMENT

# Vacuum environments - Definition

**What is VACUUM** and **how is it defined**?

- A vacuum environment is a physical condition characterized by a significant reduction or absence of matter, particularly gases. In a vacuum environment, the **pressure of gases is** substantially **lower than the atmospheric pressure** typically experienced **at sea level on Earth**. This condition can be defined by specifying the pressure level within the environment.

- Vacuum environments are often defined using pressure units such as pascals (Pa), torr, millibars (mbar), or inches of mercury (in Hg). Here are some common pressure levels used to describe vacuum environments:

| Pressure Range | Pressure, mbar | Molecules per cm$^3$ |
|---|---|---|
| Low Vacuum: | $10^3$ to 10 | $2.65 \times 10^{19}$ to $2.65 \times 10^{16}$ |
| Medium Vacuum: | 10 to $10^{-3}$ | $2.65 \times 10^{16}$ to $2.65 \times 10^{13}$ |
| High Vacuum: | $10^{-3}$ to $10^{-7}$ | $2.65 \times 10^{13}$ to $2.65 \times 10^{9}$ |
| Ultra-High Vacuum: | $10^{-7}$ to $10^{-12}$ | $2.65 \times 10^{9}$ to $2.65 \times 10^{4}$ |

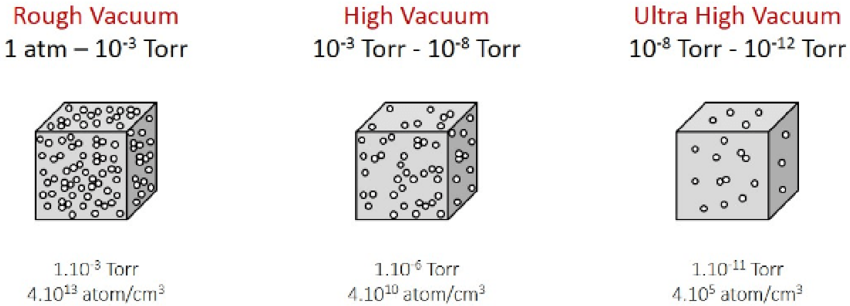
vacaero.com

# Vacuum environments – Scale comparison





- There are roughly **2.65 x $10^{19}$ or 26,500,000,000,000,000,000 molecules in a cubic centimeter of gas** at $10^3$ mbar, which is **atmospheric pressure** at sea level.
- Under lower and lower pressure, the molecules spread out further and further, until, at **ultra-high vacuum ($10^{-12}$ mbar)**, there are **only 2.65 x $10^4$ or 26,500 molecules per cubic centimeter**.
- At this density, there is only **one molecule roughly every 0.33 mm in space**. Since the **diameter of each gas molecule** is much less than this (**4 x $10^{-8}$ cm for air**, for example), there is a great deal of space between molecules.
- To put it into proportion, if gas **molecules** were **grains of sand**, at ultra-high vacuum they would be **1,650 meters apart.**
- At these **extremely low pressures**, the **collisions between molecules, which normally dictate the properties of gases**, **become very infrequent** and a **different theoretical model is required to explain their properties** (the so-called **Kinetic Theory of Gases**).




vaccoat.com

# Vacuum environments – Where?

## Where can vacuum environment be found?

Vacuum environments, which are characterized by low or negligible air pressure, can be found in various natural and artificial settings. Here are some places where vacuum environments can be encountered:

- **Outer space**
- **Spacecraft and satellites**
- **High-altitude (balloons)**
- **Laboratory vacuum chambers**
- **Vacuum insulation**
- **Vacuum pumps**
- **Vacuum tubes**
- **Particle accelerators**
- **Semiconductor manufacturing**
- **Vacuum sealed food packaging**
- **Underwater environments**

# Vacuum environments - Characteristics

What are the **physical characteristics** of vacuum environment?

- **Low pressure**
- **Absence of air**
- **No sound transmission**
- **Absence of atmosphere**
- **No buoyancy**
- **Radiative heat transfer**
- **No conduction nor convection of heat**
- **Extreme temperature variations**
- **No pressure waves**

# Vacuum environments – Effects on mechanisms

What **effects** can **vacuum environment** have **on a mechanical system?**

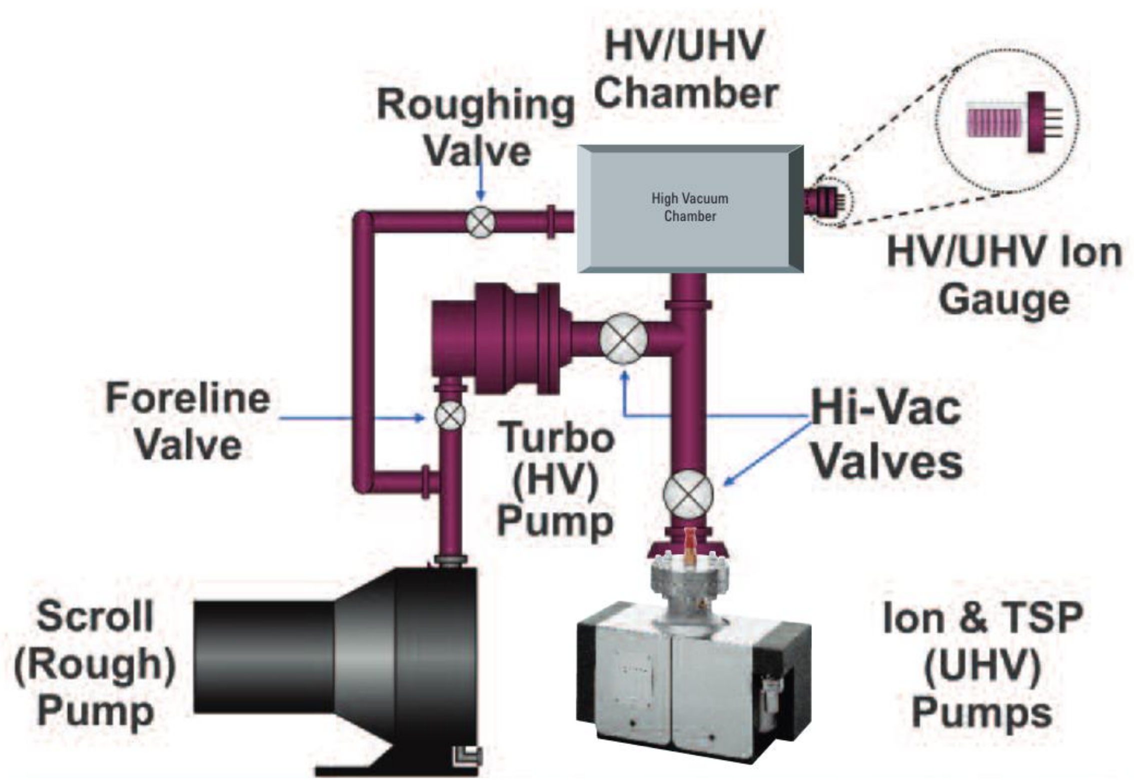
- **Lubrication issues**
- **Sealing challenges**
- **Material outgassing**
- **Thermal effects**
- **Pressure differential stresses**
- **Corrosion resistance**
- **Vibration and acoustic effects**
- **Electrostatic charging**
- **Vacuum-specific wear and tear (usure naturelle – e.g. erosion from ion sputtering)**

# Vacuum environments – Standards and reference documents



- **What are the standards, norms and reference documents to be observed when designing a mechanism for vacuum environment?**
  - **International Standards Organization (ISO) Standards**:
    - ISO 1127 (flange dimensions)
    - ISO 1609 (vacuum gauges)
    - ISO 3669 (vacuum terminology)
  - **American Vacuum Society (AVS)** Standards
  - **ASTM International** Standards: ASTM E595 (outgassing measurement)
  - **MIL-STD-1540**: Test Requirements for Space Vehicles
  - **European Cooperation for Space Standardization** (**ECSS**): ECSS-Q-ST-70-02C – Thermal vacuum outgassing test for the screening of space materials
  - National Aeronautics and Space Administration (**NASA**) Documents

# Vacuum environments – Basic HV/UHV system

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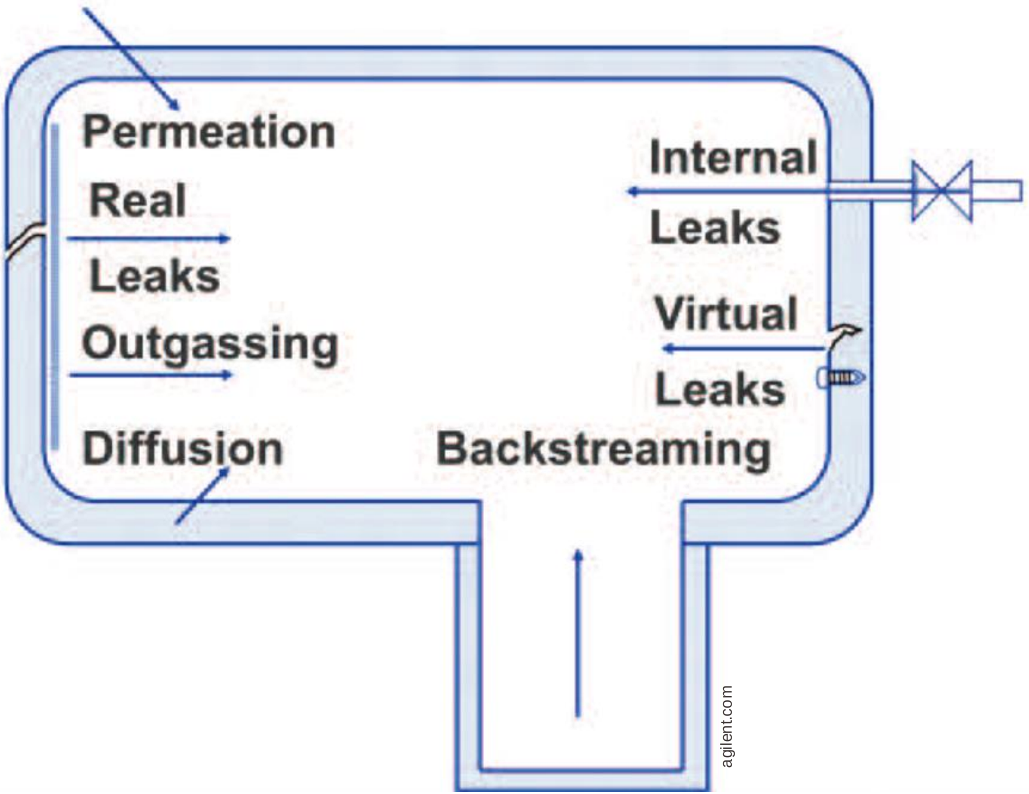
# Vacuum environments – Origins of gas load



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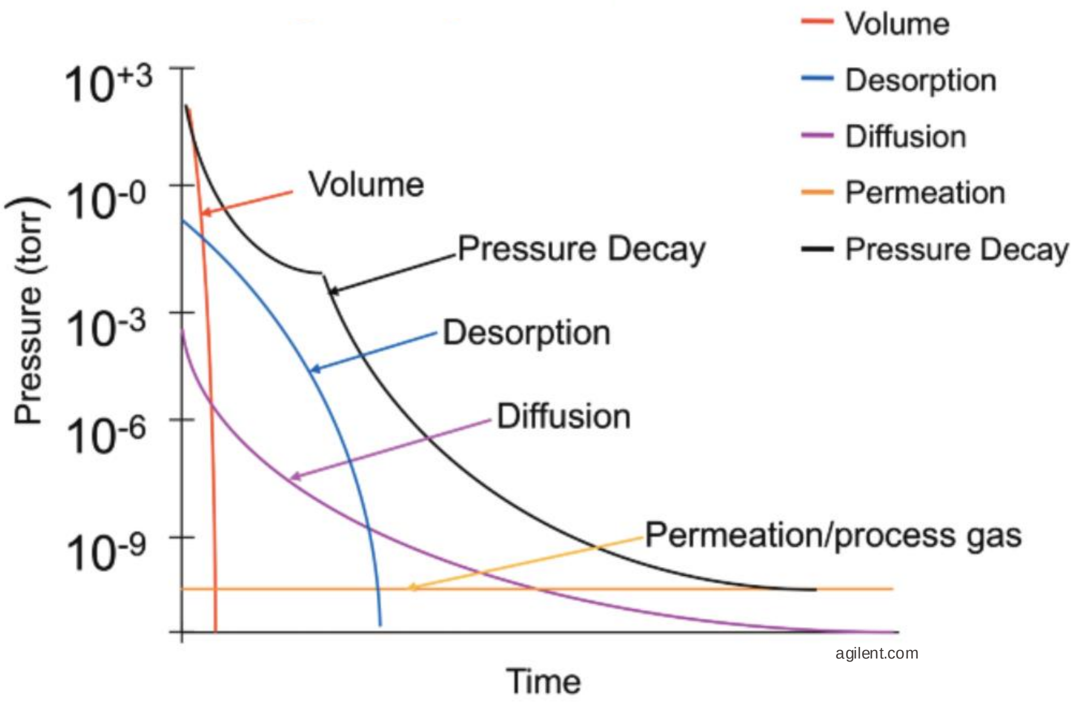
# Vacuum environments – Gas load limiting pumpdown





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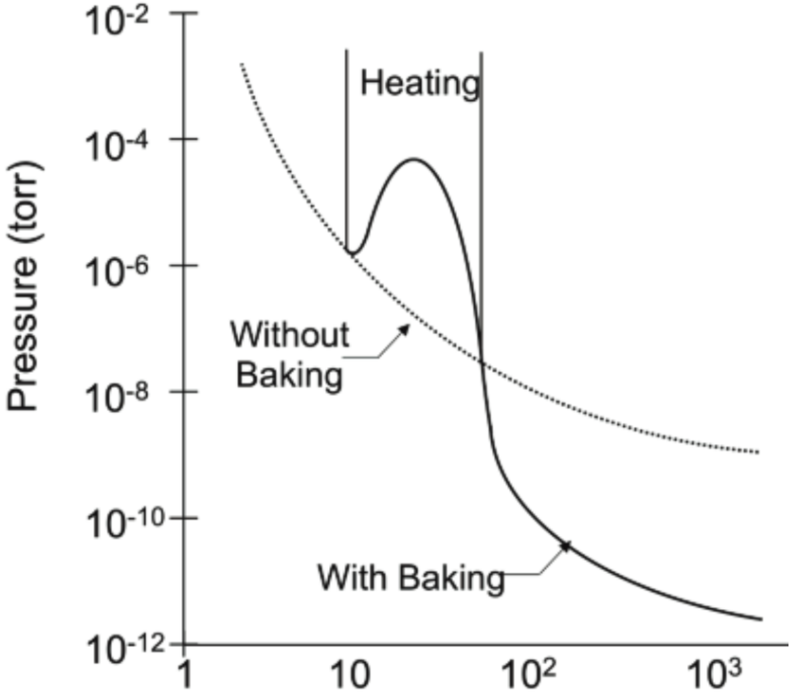
# Vacuum environments – Degassing by backing







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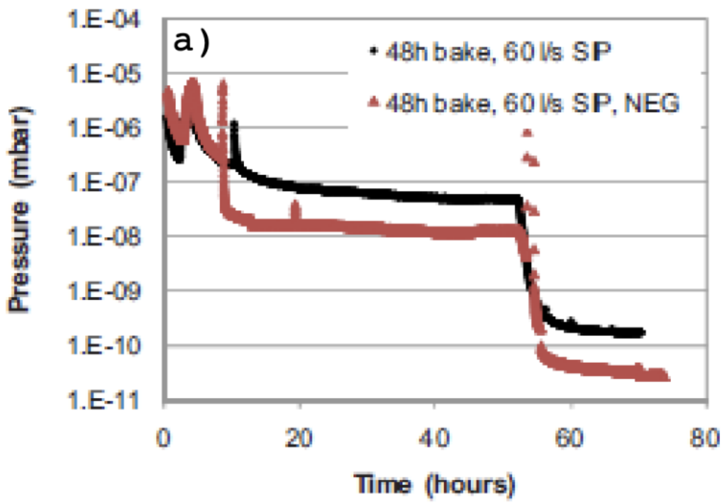


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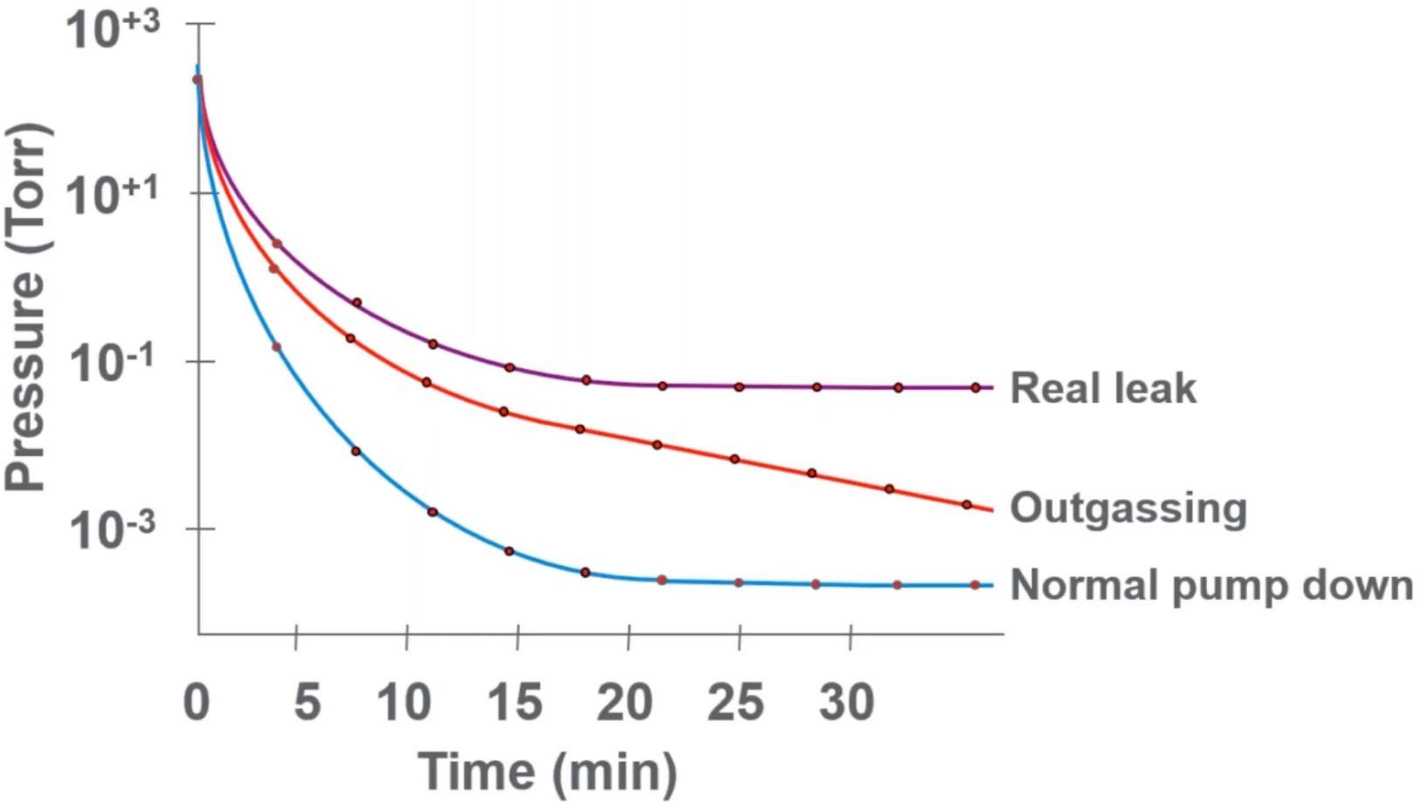
# Vacuum environments – Leak VS outgassing





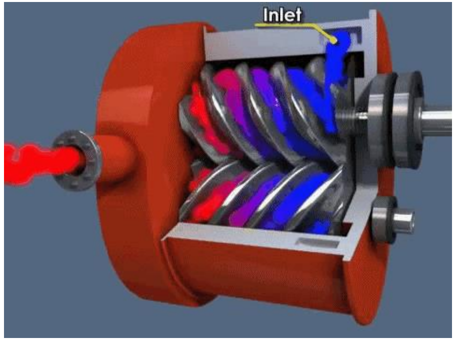
# Vacuum environments – Primary pump types

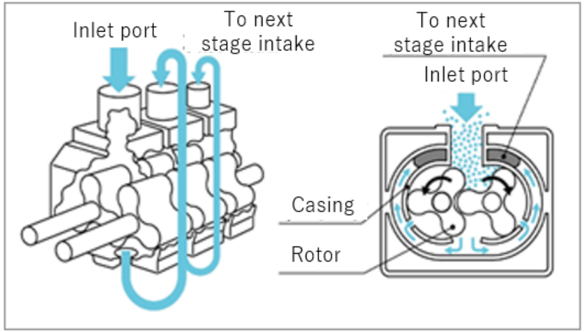


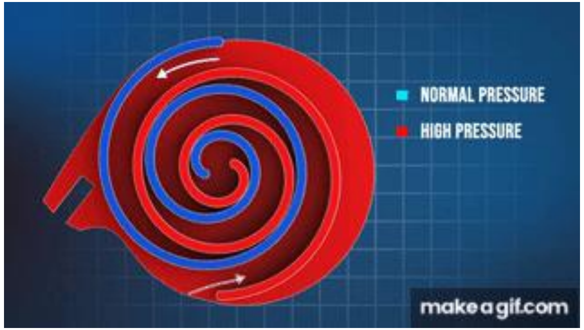


The main fore pumps (which preferably are oil-free and dry)

- Diaphragm pumps
- Scroll pumps
- Multi-stage roots pumps
- and Screw pumps



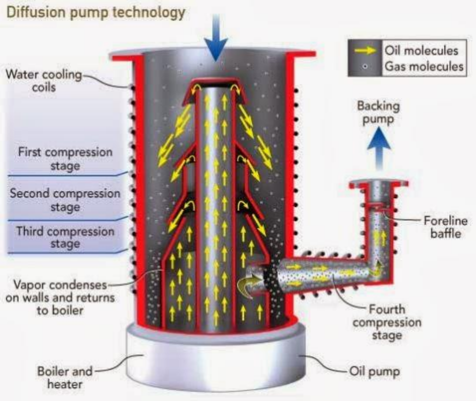



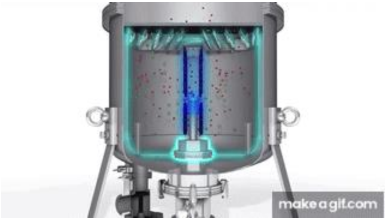



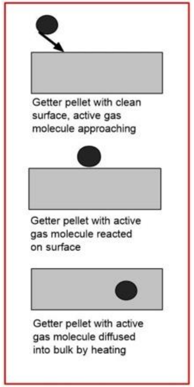
# Vacuum environments – Secondary pump types

The main pumps capable of delivering HV, UHV and XHV

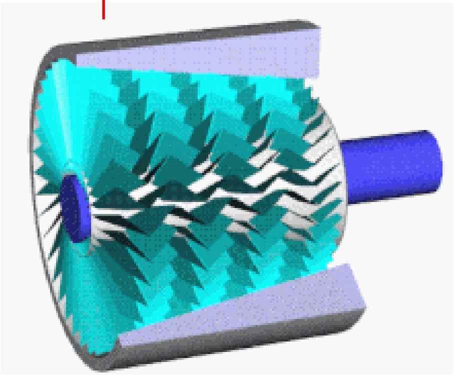
- Diffusion pumps
- Cryopumps
- Ion getter pumps (IGPs)
- Titanium sublimator pumps (TSPs)
- Non-evaporable getters (NEG) pumps
- and Turbomolecular pumps (TMPs)

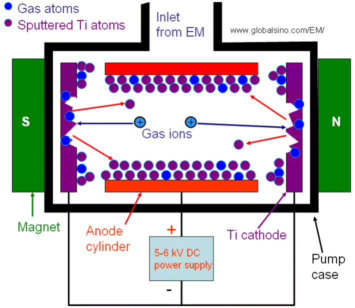


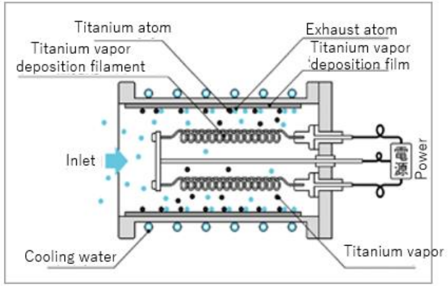




*Getter pellets can react with gas molecules, whichusually form a low vapor pressure ceramic compound.*





# Vacuum environments – Turbo molecular pump

# Vacuum environments – Vented screws





- Use of vented screws to avoid virtual leaks
  - Axial hole to avoid pockets at the end of the screw
  - Notch under the screw head to avoid pocket under the head

# Vacuum environments - Feedthrough

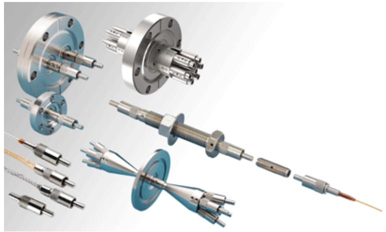
<u>**Definition**</u>: An assembly which has as its main purpose, the pass-through of substances or energy from outside of a hermetically-sealed vacuum chamber to the inside. A vacuum feedthrough must remain leak-free under high and ultra-high vacuum.

- Electrical Feedthrough

- Liquid & Gas Feedthroughs

- Motion & Manipulation Feedthroughs

- Fiber Optic Feedthroughs



- Viewport Feedthroughs

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# Vacuum environments – Friction in vacuum

- Coverage of surfaces is reduced with desorption
- No more adsorbed gases to form a film that prevents contact

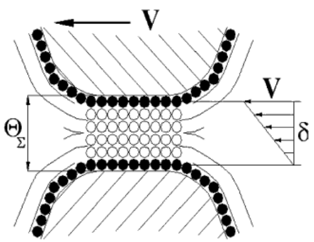

Fig. 3.3 Scheme of the viscous friction.

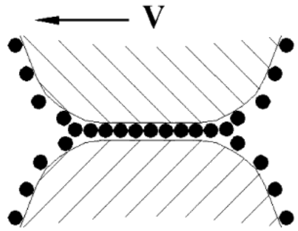

Fig. 3.11 Scheme of adhesive friction process.

| # | Friction materials | Friction coefficient in air | Friction coefficient in vacuum |
|---|---|---|---|
| 1 | Fe-Fe | 0.3 | 1.9 |
| 2 | Fe-Mg | 1.0 | 0.6 |
| 3 | Fe-Cd | 1.5 | 0.4 |
| 4 | Fe-Pb | 0.9 | 0.4 |
| 5 | Stainless steel- Stainless steel | 0.5 | 2.9 |
| 6 | Stainless steel-Cu | - | 0.3 |
| 7 | Stainless steel-Al | 0.4 | 0.3 |
| 8 | Stainless steel- kovar | - | 0.4 |
| 9 | Stainless steel- brass | 0.4 | 0.8 |

# Vacuum environments – Human in vacuum, what happen?

QUESTION: what do you feel in a vacuum chamber before pressurization and consciousness are lost? On December 14, 1966, **NASA spacesuit technician** and test subject **Jim LeBlanc** found out. Suited up in an early Moon suit prototype, he entered a triple-doored vacuum chamber. Then, his pressurization hose somehow became disconnected and LeBlanc became the only person to survive near-vacuum pressures when his suit dropped from 3.8 psi to 0.1 psi in 10 seconds. What happened next??

nasa.org

# Vacuum environments - References

- https://www.agilent.com/cs/library/training/Public/UHV_Seminar_Handbook.pdf
- *Mechanics and Physics of Precise Vacuum Mechanisms* by Deulin E. A., Mikhailov V. P., Panfilov Y. V., Nevshupa R. A., Springer, 2010
- *Vacuum Technology: Practice for Scientific Instruments*, Yoshimura N., Springer Science & Business Media, 2007
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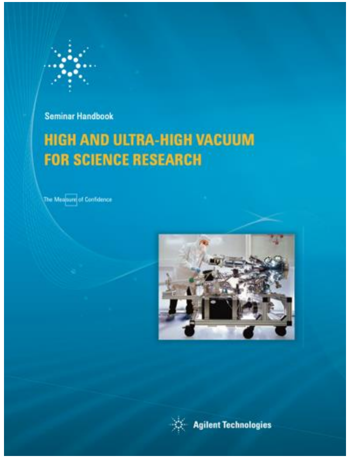
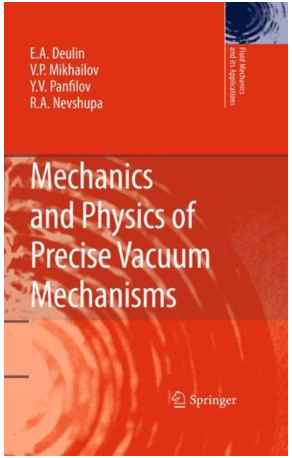
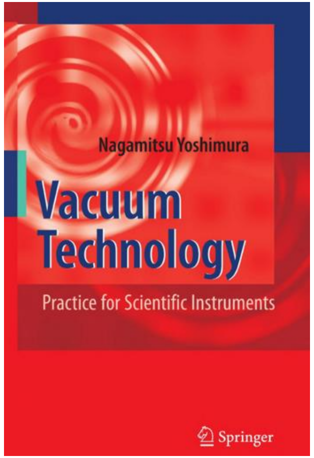
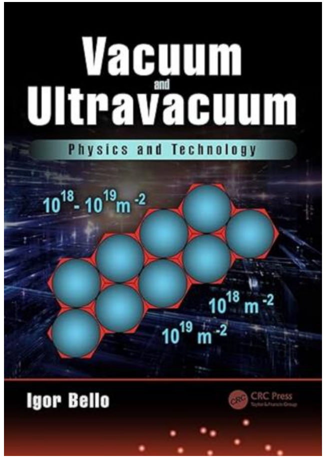


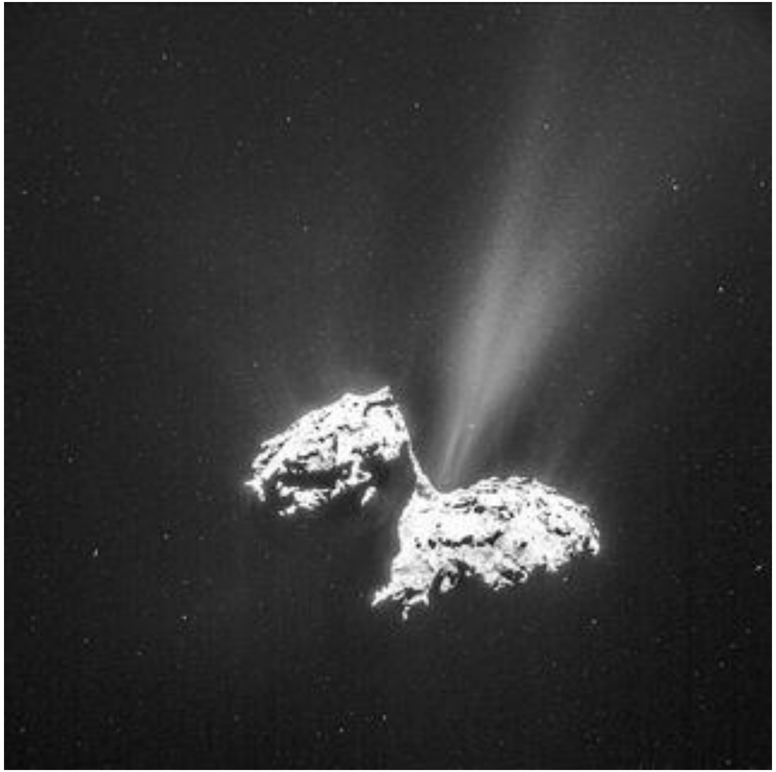



# Outgazing

*Outbursts on Comet 67P/Churyumov-Gerasimenko are captured in this image taken by the Rosetta spacecraft on Feb. 6, 2015*



space.com

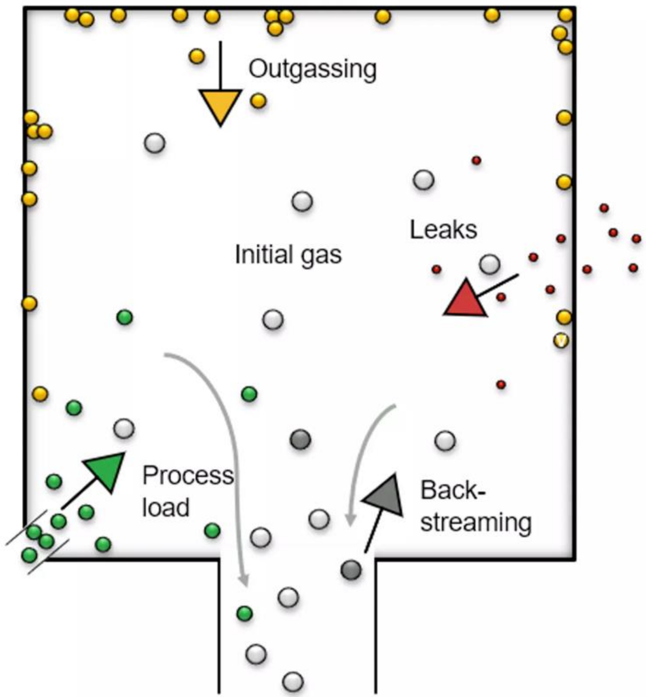
# Outgazing – Gas load contribution



- Contributions to the gas load of a system can come from:

  1. Initial or the 'bulk' gas in the system
  2. Process load
  3. Back-streaming
  4. Leaks
  5. Outgassing

- For a leak-tight system in High Vacuum (HV) with no process load, outgassing could contribute up to 100% of the gas load.

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# Outgazing - Contribution of different species





- The relative contribution of different species to the gas load varies with pressure.
- For many High Vacuum (HV) applications water vapour is the major concern in terms of outgassing.
- However, for achieving Ultra High Vacuum (UHV) in all metal systems, H2 outgassing is critical.
- The table below shares typical major gas loads at various pressures.

| Pressure (mbar) | Major Gas Load |
|---|---|
| Atmosphere | Air ($N_2$, $O_2$, $H_2O$, Ar, $CO_2$) |
| $10^{-3}$ | Water vapour (75-95%), $N_2$, $O_2$ |
| $10^{-6}$ | $H_2O$, CO, $CO_2$, $N_2$ |
| $10^{-9}$ | CO, $H_2$ $CO_2$, $H_2O$ |
| $10^{-10}$ | $H_2$, CO |
| $10^{-11}$ | $H_2$, CO |

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# Outgazing - Mechanisms contributing to outgassing

- There are **4 main mechanisms** which **contribute to outgassing** (shown in the diagram):

  **Vaporisation** of the actual surface material itself (in metals this is negligible at typical operating temperatures)

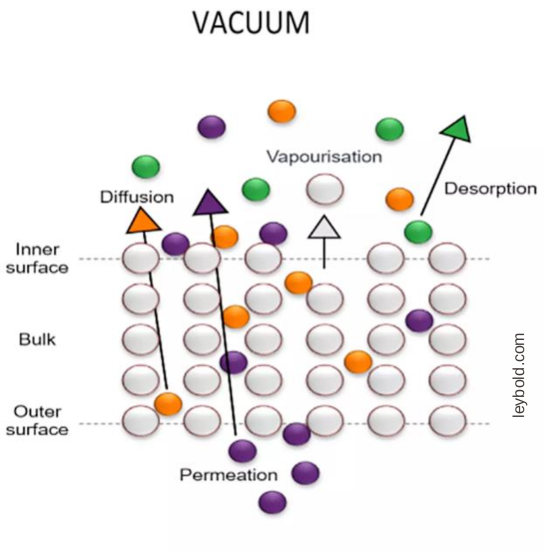
  **Desorption** — this is the reverse process of adsorption; the release of molecules bound at the surfaces of the chamber and internal fixtures

  **Diffusion** — this is the movement of molecules from the inner structure of the material to the surface

  **Permeation** — this is the movement of molecules from the external atmosphere through the bulk to the vacuum surface

- The extent to which **each of these affect outgassing** depends on the **composition of both the gas and the surface material** (and its history).

- **Outgassing rates** are a sum of these contributions.

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# Outgazing - Outgassing rate equation

A thorough treatment considering:

- gas removed from the system by pump
- gas desorbing from the surfaces
- gas re-adsorbed

leads to the differential equation: [1]

$$\frac{d^2 n_v}{dt^2} + \left(\frac{\bar{v}}{4V}(\alpha A_s + A_p) + \frac{1}{\tau}\right)\frac{dn_v}{dt} + \frac{\bar{\alpha}}{4V}\frac{A_p}{\tau} n_v = 0$$

But a reasonable approximation of is given by: [2]

$$\dot{Q} = \sum \frac{a_{1h} \cdot A}{\left(\frac{t}{1h}\right)^{\alpha}}$$

Outgassing flow rate ($\dot{Q}$)

Outgassing rate at 1 hour ($a_{1h}$)

Decay constant ($\alpha$)

- Keep in mind that the value of the decay constant gives an indication of the material and outgassing mechanism. For example:

| | |
|---|---|
| α ≈ 1.1-1.2 | ultra-clean metal surfaces |
| α ≈ 1 | metals, glasses and ceramics |
| α ≈ 0.4-0.8 | polymers |
| α ≈ 0.5-0.7 | highly porous surfaces |
| α ≈ 0.5 | diffusion-controlled outgassing from the bulk |

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# Outgazing - Typical outgassing values and conclusion

| Material | Average (mbar l s$^{-1}$cm$^{-2}$) |
|---|---|
| Aluminum | 3.0 X 10$^{-7}$ |
| Iron | 2.7 X 10$^{-7}$ |
| Brass | 1.5 x 10$^{-6}$ |
| Copper | 2.3 x 10$^{-8}$ |
| Gold | 1.1 x 10$^{-7}$ |
| Mild steel | 6.2 x 10$^{-7}$ |
| Stainless Steel | 1.9 x 10$^{-7}$ |
| Zinc | 2.6 x 10$^{-7}$ |
| Titanium | 1.0 x 10$^{-8}$ |
| Pyrex | 9.9 x 10$^{-9}$ |
| Neoprene | 4.0 x 10$^{-5}$ |
| Viton A | 1.1 x 10$^{-6}$ |
| PVC | 3.2 x 10$^{-6}$ |
| PTFE | 1.4 x 10$^{-6}$ |

Table 2: outgassing values, where t = 1 hour

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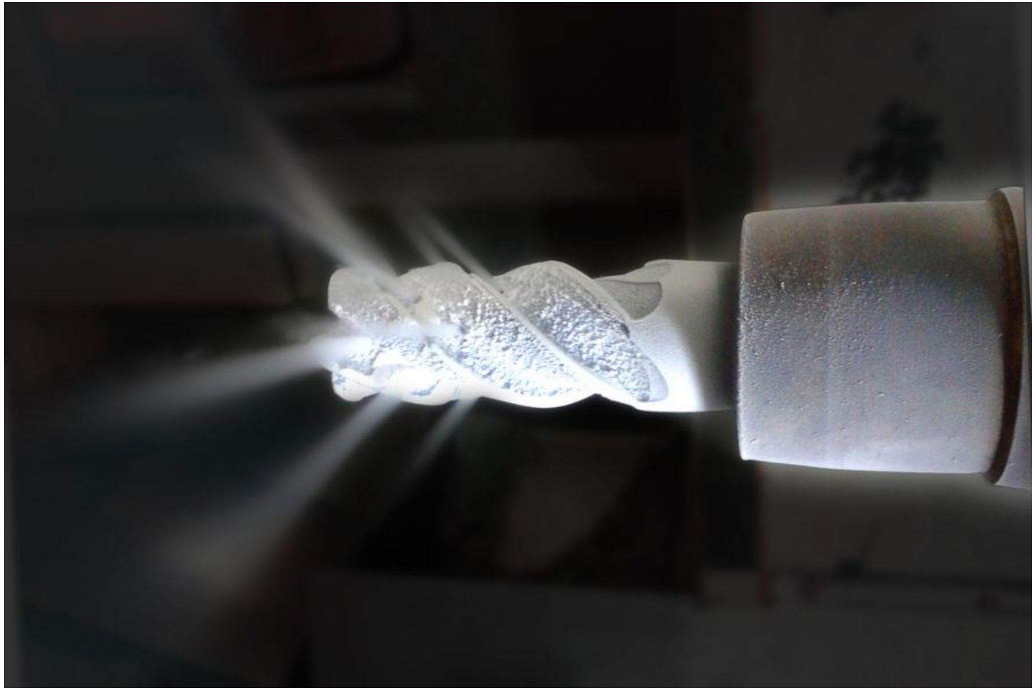
- Outgassing is often the largest contributor to a system's gas load (especially below Medium Vacuum) and limits the achievable ultimate pressure.
- It occurs via several processes including vaporisation, desorption, diffusion and permeation.
- The major contributions to outgassing depend on the vacuum level but in HV it stems mainly from water vapour, whilst hydrogen is most common when working with metals at UHV.
- There are many outgassing rates available in the literature, however there is significant variation in these. While variations in outgassing rates can primarily be attributed to the measurement method used and sample preparation; the development of a standard for rate measurement techniques would be valuable.

# Outgazing - References


- https://outgassing.nasa.gov/
- https://www.leybold.com/en/knowledge/blog/introduction-to-outgassing
- Dégazage des solides en ultravide : quelques notions de base pour les techniciens du CERN, Chiggiato P., CERN, 2012
- A Review of Outgassing and Methods for its Reduction. Grinham R., Chew A., In Applied Science and Convergence Technology, Vol 26, pp. 95-109, 2017

# Cryogenic environments

*Cryogenic machining: Mecachrome has replaced the cutting oil normally used for machining with liquid nitrogen, which vaporises when it comes into contact with the tool.*



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# Cryogenic environments - Introduction

- **What is cryogenics?**
  - The **branch of physics** dealing with the **production and effects** of **very low temperatures.**
- **Cryogenic environments definition:**
  - Cryogenic environments refer to extremely low-temperature conditions typically **below -150°C** (-238°F) or 123 K.
  - Such conditions are encountered in applications involving the use of cryogenic fluids and materials.

**Table 1.** Normal boiling points of common cryogenic fluids.

| Cryogen | (K) | (°C) | (°R) | (°F) |
|---|---|---|---|---|
| Methane | 111.7 | -161.5 | 201.1 | -258.6 |
| Oxygen | 90.2 | -183.0 | 162.4 | -297.3 |
| Nitrogen | 77.4 | -195.8 | 139.3 | -320.4 |
| Hydrogen | 20.3 | -252.9 | 36.5 | -423.2 |
| Helium | 4.2 | -269.0 | 7.6 | -452.1 |
| Absolute zero | 0 | -273.15 | 0 | -459.67 |

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# Cryogenic environments – Where?

**Where can one find a cryogenic environment?**

- **Laboratories and research facilities:**
  - Cryogenic laboratories
  - Particle physics and astronomy observatories
  - Materials science laboratories
- **Space exploration:**
  - Rocket propulsion systems
  - Space telescopes and instruments
- **Medical facilities:**
  - Cryopreservation facilities
  - Cryosurgery
- **Industrial applications:**
  - Cryogenic storage tanks
  - Food processing
  - Cryogenic grinding
  - Cooling superconducting magnets
- **Aerospace and defense:**
  - Aircraft testing facilities
  - Military applications
  - Superconducting power transmission
  - Fusion energy research
- **Cryogenic transportation:**
  - Specialized tanker trucks and containers transport cryogenic liquids, such as liquid nitrogen and liquid helium

# Cryogenic environments - History

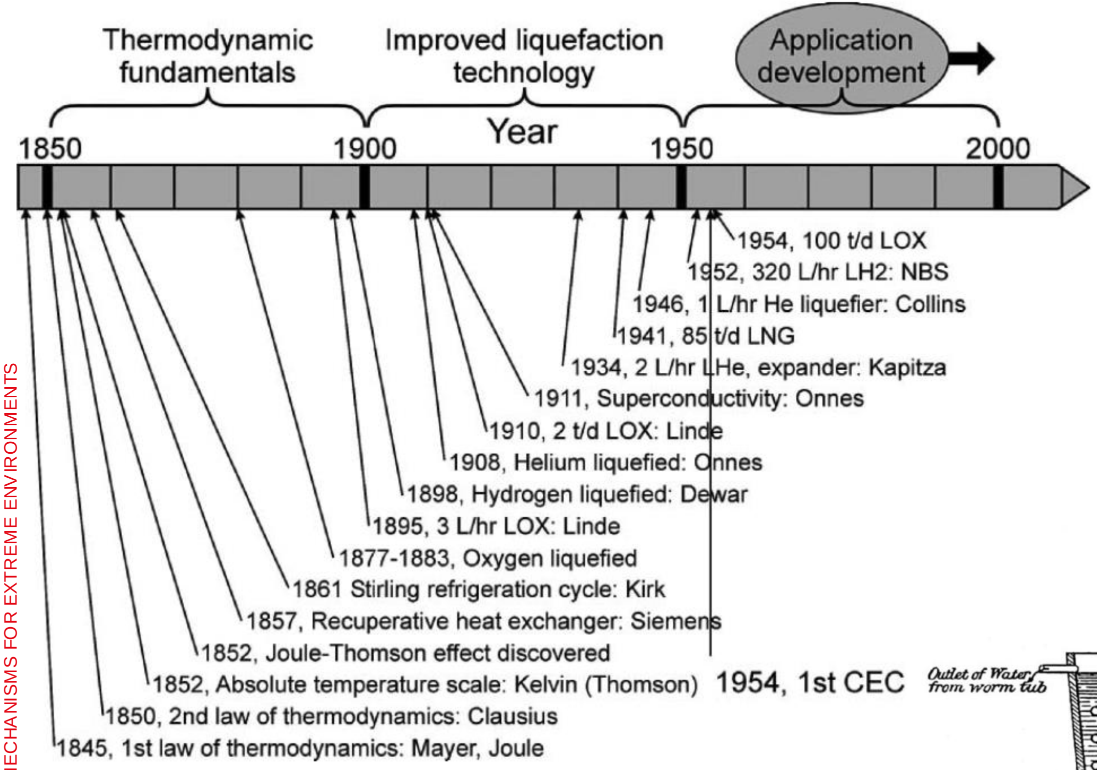
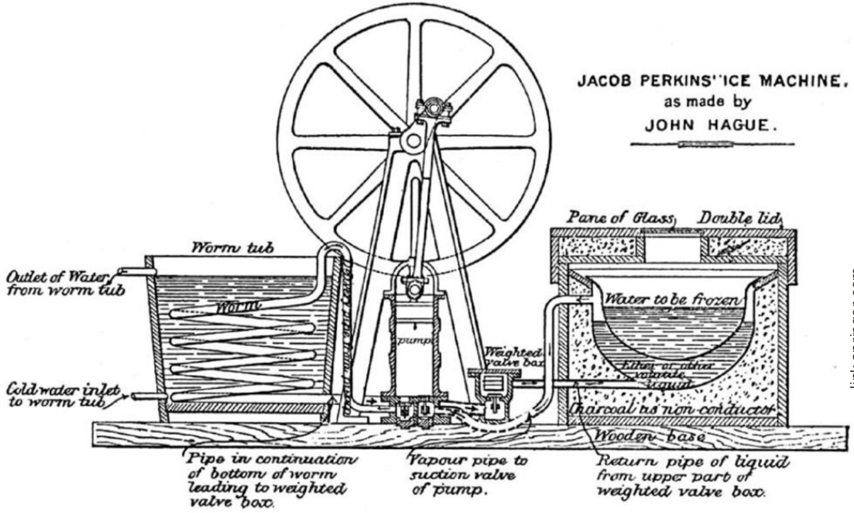



FIGURE 1.3. Cryogenic developments from 1850 to 1950.

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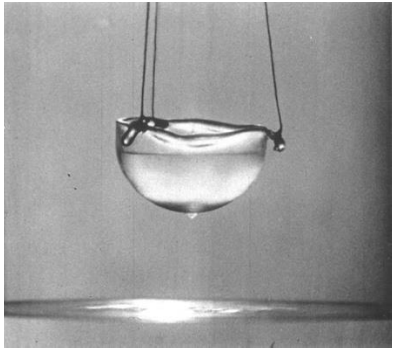
# Cryogenic environments - Properties

**What are the physical characteristics of cryogenic environments?**

- Low temperature
- Thermal contraction
- Superconductivity
- Superfluidity
- Cryogenic fluids and gases
- Brittleness
- High thermal insulation
- Reduced gas pressure
- Thermal expansion mismatch
- Cryogenic effects on materials
- Reduced chemical reactivity
- Condensation and frost



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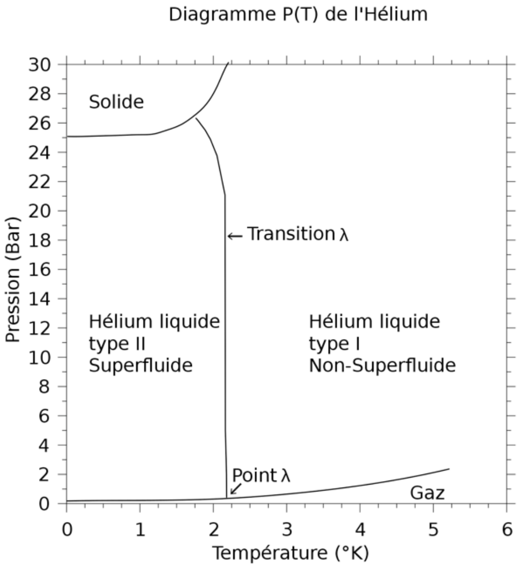


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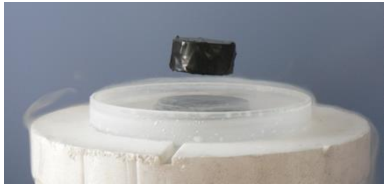
# Cryogenic environments - Applications

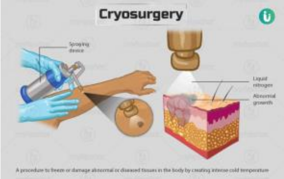
Cryogenic environments are used in various scientific, industrial, and medical applications. Some common examples include:

- Superconductivity



- Space Exploration

- Medical Applications




- Cryopreservation

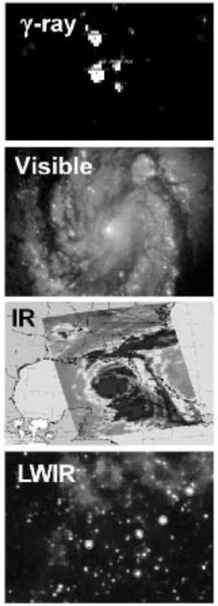
- Particle Physics

- Materials Research

# Cryogenic environments – Detectors operating temperatures

TABLE 11.1. Types and wavelengths of electromagnetic radiation, the blackbody temperature that emits such radiation, and applicable detector types and their required operating temperature

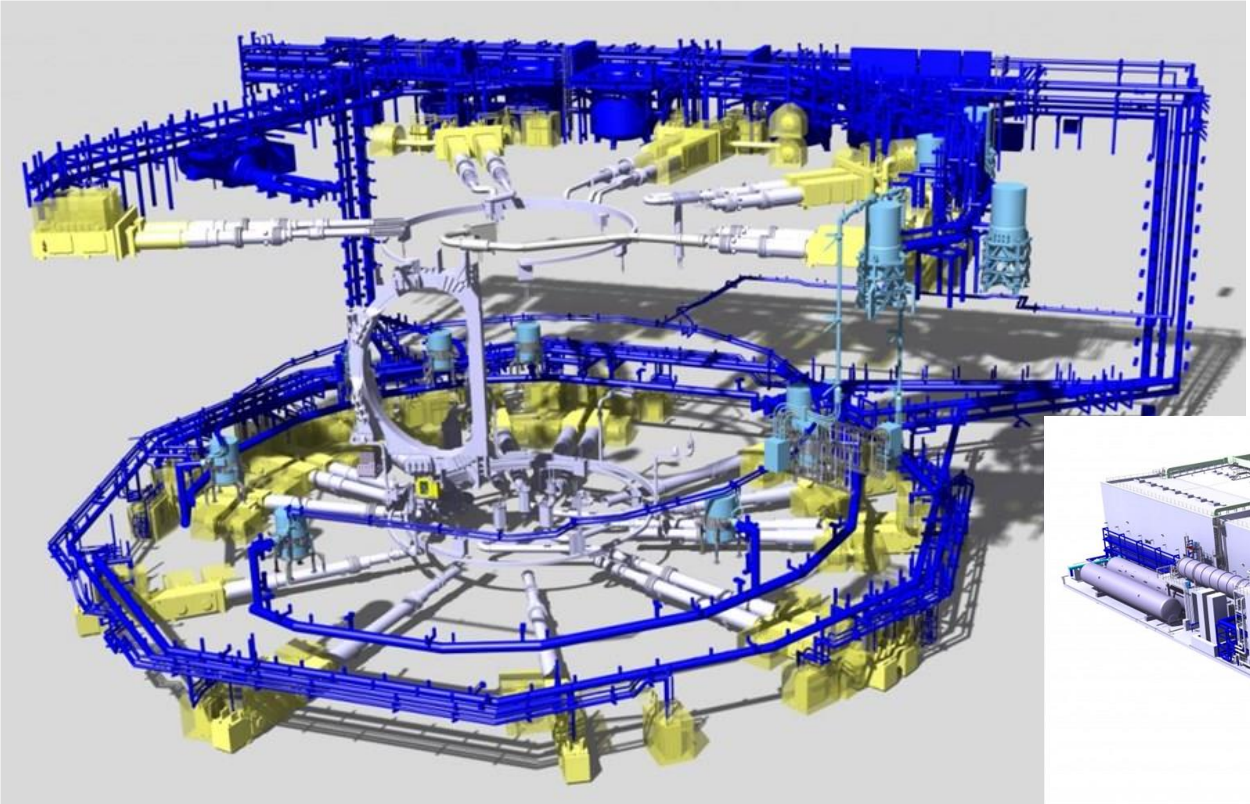
| Radiation Type | Wavelength (microns) | Blackbody Temp. (K) | Detector Technology | Detector Temp. (K) |
|---|---|---|---|---|
| γ-rays | $10^{-5}$ | $3 \times 10^{8}$ K | Ge Diodes | 80 K |
| γ-rays | $10^{-4}$ | $3 \times 10^{7}$ K | Ge Diodes | 80 K |
| x-rays | $10^{-3}$ | $3 \times 10^{6}$ K | micro calorimeters | 0.05 K |
| x-rays | $10^{-2}$ | $3 \times 10^{5}$ K | | 0.05 K |
| UV | 0.1 | 30,000 K | CCD/CMOS | 200-300 K |
| visible | 1 | 3000 K | CCD/CMOS | 200-300 K |
| IR | 2 | 1500 K | HgCdTe | 80-130 K |
| IR | 5 | 600 K | HgCdTe | 80-120 K |
| LWIR | 10 | 300 K | HgCdTe | 35-80 K |
| LWIR | 15 | 200 K | HgCdTe | 35-60 K |
| LWIR | 20 | 150 K | Si:As | 7-10 K |
| LWIR | 50 | 60 K | Ge:Ga | 2 K |
| LWIR/μwaves | 100 | 30 K | Ge:Ga | 1.5 K |
| microwaves | 200 | 15 K | Bolometers | 0.1 K |
| microwaves | 500 | 6 K | Bolometers | 0.1 K |




*SPITZER Superfluid Helium Cryostat*

Cryogenic Engineering - Fifty Years of Progress, Klaus D. Timmerhaus, Richard P. Reed, Springer, 2007

# Cryogenic environments – Case study : ITER



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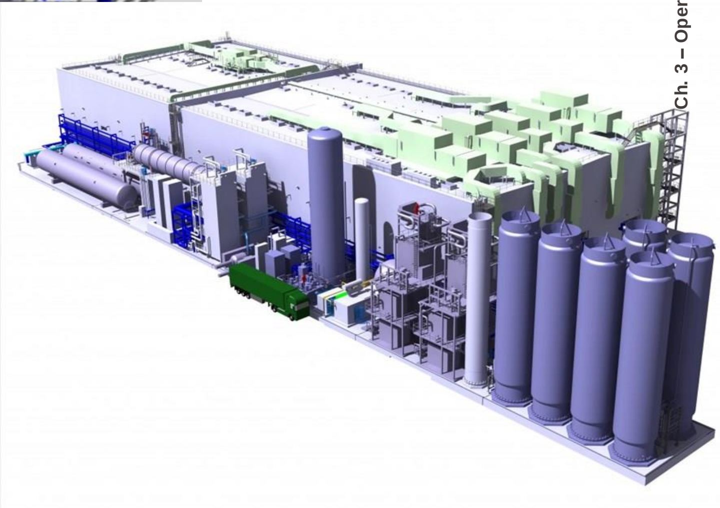
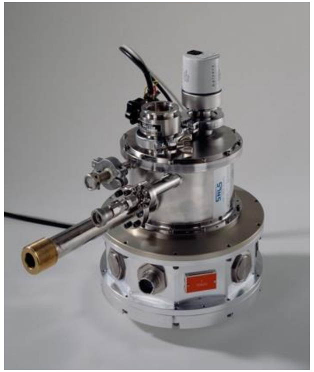


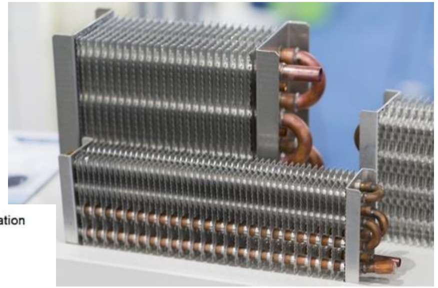
With a cooling capacity of 75 kW at 4.5 K and 1300 kW at 80 K (nitrogen), ITER's cold production system will be the most powerful in the world, integrated into a single installation. After the Large Hadron Collider at CERN, it will be the largest cryogenic system ever built.

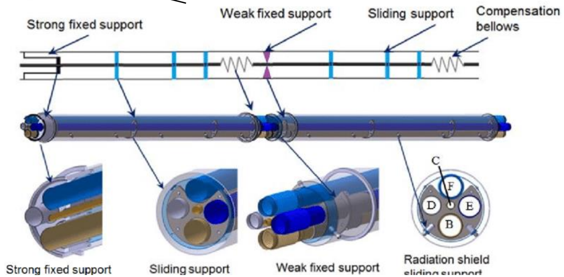
# Cryogenic environments - equipment

What are the elements that may compose a cryogenic system?

- Cryogenic fluids
- Cryogenic containers or Dewars
- Cryostats
- Cryogenic pumps
- Heat exchangers
- Pressure relief valves
- Insulation materials
- Cryogenic transfer lines
- Cryogenic refrigeration systems
- Control systems
- Safety systems
- Vacuum systems
- Instrumentation
- Superconducting magnets





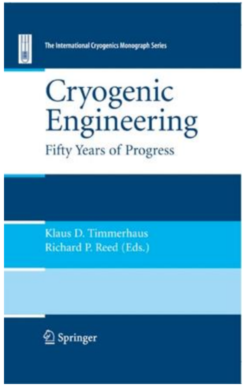


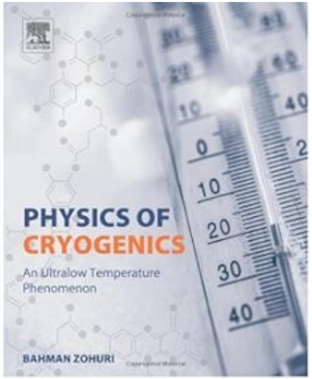
# Cryogenic environments – Effects on mechanisms

- **Thermal contraction:** as components and materials cool down, they contract or shrink in size.
- **Material properties:** some materials may become more brittle and prone to fracture, while others may exhibit altered elasticity and reduced ductility.
- **Sealing and gasket performance:** become less flexible and less effective.
- **Lubrication and friction:** lubricants and oils may become less viscous and less effective.
- **Materials compatibility:** some plastics and elastomers can become brittle and lose their flexibility, while metals may experience changes in their electrical conductivity and thermal expansion characteristics.
- **Condensation and frost formation:** may require additional insulation or moisture control measures.
- **Cryogenic fluid handling:** fluids can become more viscous and have different flow characteristics.
- **Stress and deformation:** due to differences in coefficients of thermal expansion.
- **Fatigue and material degradation:** cryogenic cycling, where the system experiences repeated cooling and warming, can induce fatigue and material degradation over time.
- **Instrument calibration:** instruments and sensors used in the system may require recalibration or adjustments to account for changes in their performance at cryogenic temperatures.

# Cryogenic environments – Standards and reference documents

- **What are the standards, norms and reference documents to be observed when designing a mechanism for cryogenic environment?**
  - **International Standards Organization (ISO) Standards:**
    - ISO 21029-1:2018 - Cryogenic vessels - Static vacuum insulated vessels - Part 1: Design, fabrication, inspection, and testing
    - ISO 21028-2:2018 - Cryogenic vessels - Transportable vacuum insulated vessels - Part 2: Design, fabrication, inspection, and testing
  - **Cryogenic Engineering - Fifty Years of Progress, K. D. Timmerhaus, R. P. Reed, Springer, 2007**
  - **Physics of Cryogenics - An Ultralow Temperature Phenomenon, Bahman Zohuri, Elsevier, 2017**



# High temperature environment





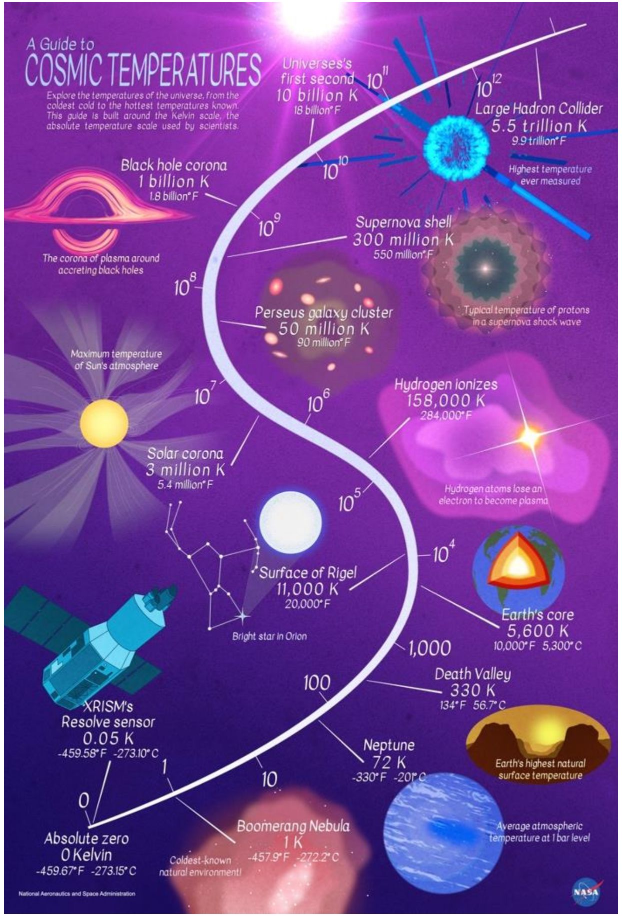
*Parker Solar Probe and Solar Orbiter are observing our Sun like never before*

skyatnightmagazine.com

# High temperature env. - Introduction

## Comparisons of temperatures in various scales

| | Temperature | |
|---|---|---|
| | Kelvin | Celsius |
| Absolute zero (precisely by definition) | 0 K | −273.15 °C |
| Blackbody temperature of the black hole at the centre of our galaxy, Sagittarius A | 15 fK | −273.149999999999985 °C |
| Lowest temperature achieved | 100 pK | −273.149999999900 °C |
| Coldest Bose–Einstein condensate | 450 pK | −273.14999999955 °C |
| One millikelvin (Precisely by definition) | 0.001 K | −273.149 °C |
| Cosmic microwave background (2013 measurement) | 2.7260 K | −270.424 °C |
| Water triple point (Precisely by definition) | 273.16 K | 0.01 °C |
| Water boiling point | 373.1339 K | 99.9839 °C |
| Iron melting point | 1811 K | 1538 °C |
| Incandescent lamp | 2500 K | ≈2200 °C |
| Sun's visible surface | 5778 K | 5505 °C |
| Lightning bolt channel | 28 kK | 28000 °C |
| Sun's core | 16 MK | 16 million °C |
| Thermonuclear weapon (peak temperature) | 350 MK | 350 million °C |
| Sandia National Labs'Z machine | 2 GK | 2 billion °C |
| Core of a high-mass star on its last day | 3 GK | 3 billion °C |
| Merging binary neutron star system | 350 GK | 350 billion °C |
| Relativistic Heavy Ion Collider | 1 TK | 1 trillion °C |
| CERN's proton vs nucleus collisions | 5.5 TK | 5.5 trillion °C |




ADVANCED MECHANISMS FOR EXTREME ENVIRONMENTS

Ch. 3 – Operating environments and associated constraints

en.wikipedia.org

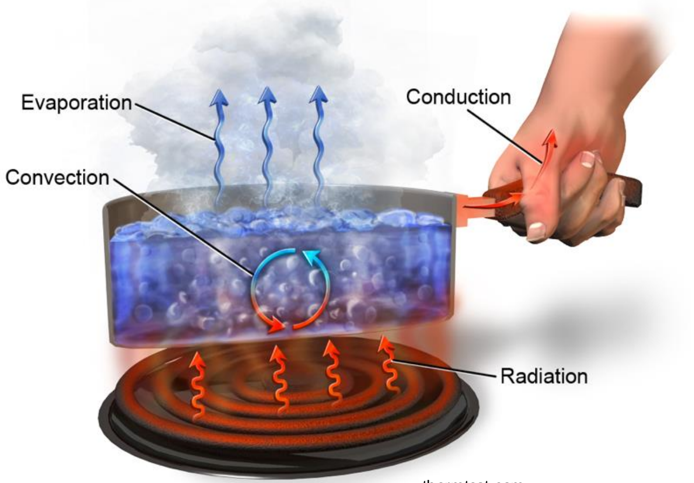
# High temperature env. – Heat transfer

- **Conduction**: Heat transfer in a solid or a stationary fluid (gas or liquid) due to the random motion of its constituent atoms, molecules and /or electrons.
- **Convection**: Heat transfer due to the combined influence of bulk (advection) and random motion for fluid flow over a surface.
- **Radiation**: Energy that is emitted by matter due to changes in the electron configurations of its atoms or molecules and is transported as electromagnetic waves (or photons).

## Remarks

- **Conduction** and **convection require** the presence of **temperature variations** in a **material medium**.
- Although **radiation** originates from matter, its transport **does not require a material medium** and occurs most efficiently in a vacuum.

**Mechanisms of Heat Transfer**




thermtest.com

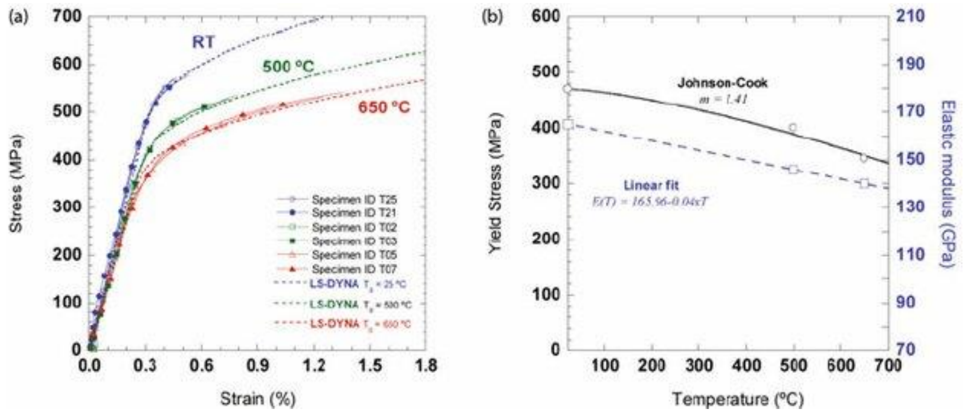
# High temperature env. – Applications examples



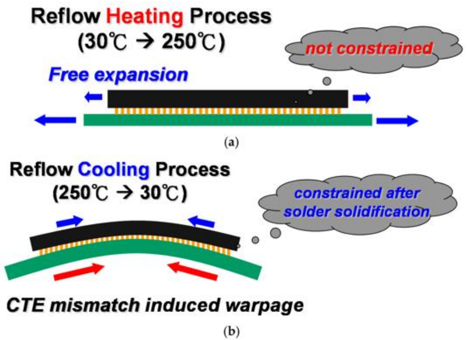
- **Metallurgy**: production of metals and alloys.
- **Welding**: joining metals through melting.
- **Glassmaking**: melting silica for glass production.
- **Ceramics**: firing ceramics and pottery.
- **Heat treatment**: changing material properties.
- **Semiconductor manufacturing**: fabricating computer chips.
- **Aerospace**: high-temperature engines and space travel.
- **Power generation**: generating electricity with high-temperature processes.
- **Chemical reactions**: reactions requiring high temperatures.
- **Food processing**: cooking and baking in industrial ovens.
- **Medical sterilization**: sterilizing equipment with high-temperature steam.
- **Space exploration**: extreme temperatures in space.
- **Material testing**: testing materials under extreme conditions.
- **Incineration**: burning waste at high temperatures.
- **Thermal energy storage**: storing energy using high temperatures.

# High temperature env. – Effects on mechanisms

- Material degradation
- Material softening
- Thermal expansion (mismatch)
- Thermal stress
- Fatigue failure
- Warpage
- Deformation and misalignment
- Reduced lubrication effectiveness
- Loss of lubrication viscosity
- Seal and gasket failure
- Electrical component degradation
- Instrument calibration shift
- Safety hazards
- Material selection challenges




Erice, B et al., *Effect of the temperature, strain rate and microstructure on flow and fracture characteristics of Ti-45Al-2Nb-2Mn+0.8vol.% TiB2 XD alloy*, The European Physical Journal Special Topics. 206. 3-14. 2012




mdpi.com

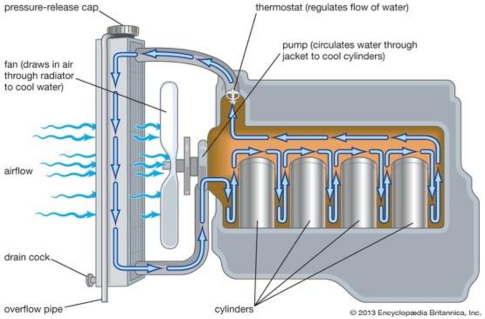
# High temperature env. – Risk mitigation strategies

**What are the basic measures and principles to be observed when designing a mechanical system for a high temperature environment?**

- Heat shielding

ig.space

- Cooling system

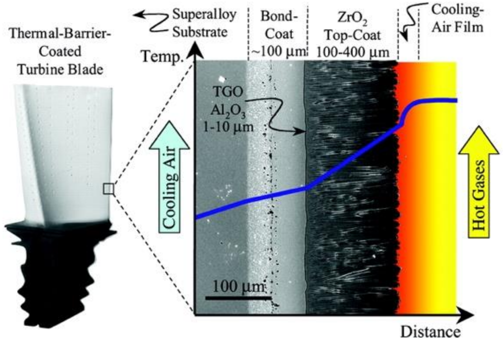



britannica.com

- Thermal straps

nasa.gov

- Thermal coatings



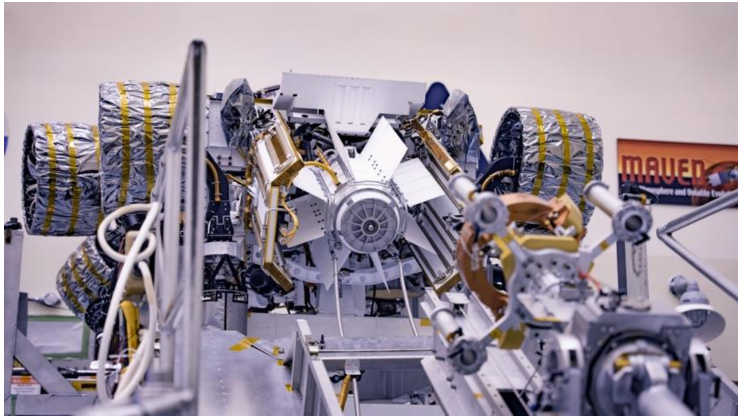

N. P. Padture et al., *Thermal Barrier Coatings for Gas-Turbine Engine Applications*, in Science, 2002

# High temperature env. – Case study: Mars rover thermal management system

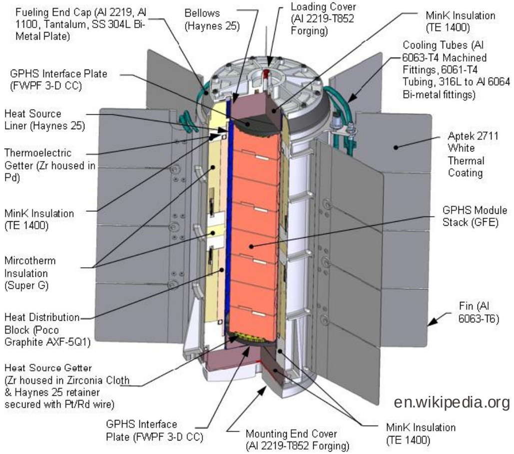




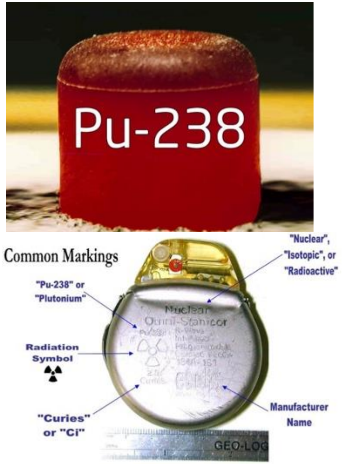
- Multi-Mission Radioisotope Thermoelectric Generator for NASA'S Mars 2020 Perseverance rover
- Type of **nuclear battery** that uses an array of **thermocouples** to **convert the heat** released by the decay of a suitable radioactive material **into electricity** by the Seebeck effect
- Used to warm a spacecraft/rover in the frigid depths of space, or in sub-zero temperatures on a planet, moon or asteroid, to keep vital systems, mechanical operations, and instruments functioning
- Also, **nuclear-powered cardiac pacemakers** were manufactured by many companies (bottom right)



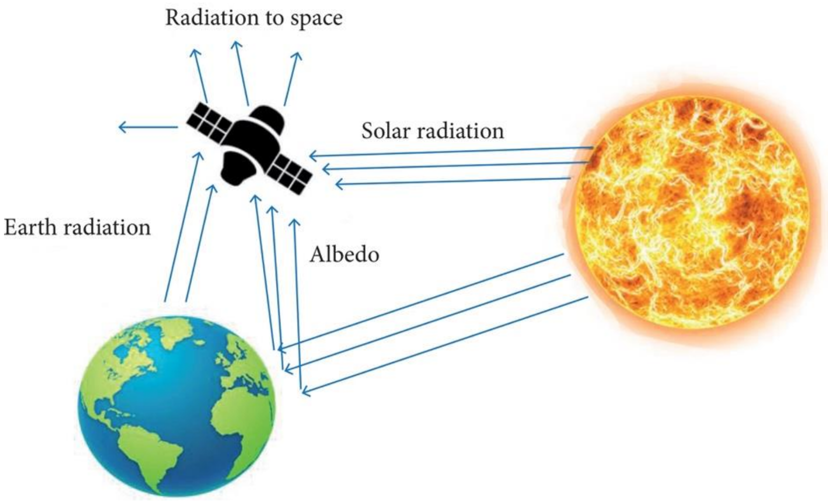

rps.nasa.gov




en.wikipedia.org

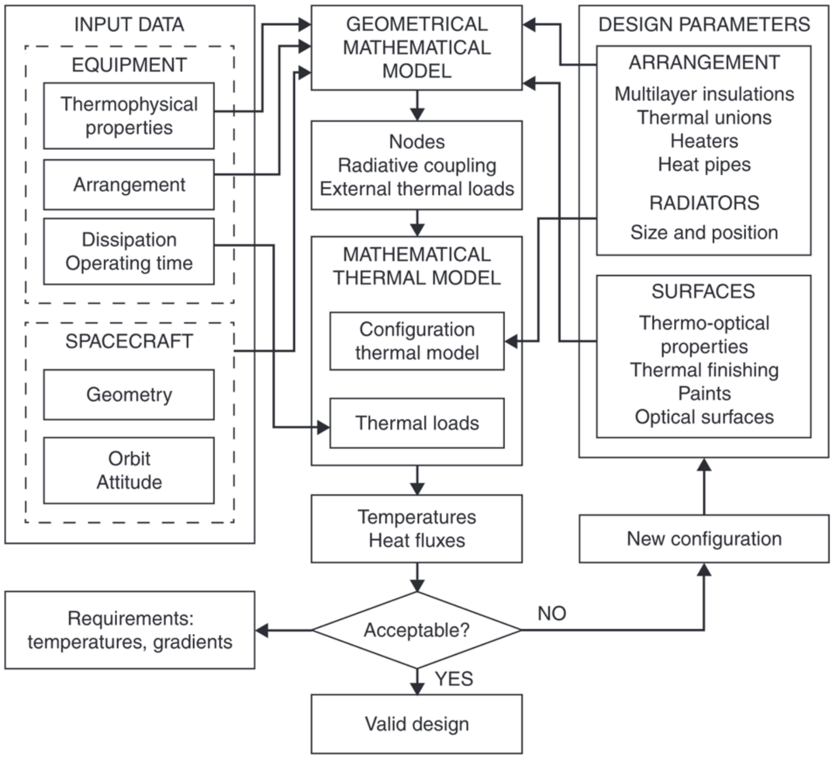


# High temperature env. – Case study: spacecraft thermal management




scielo.br

**Figure 18.1** Thermal control subsystem design process flowchart

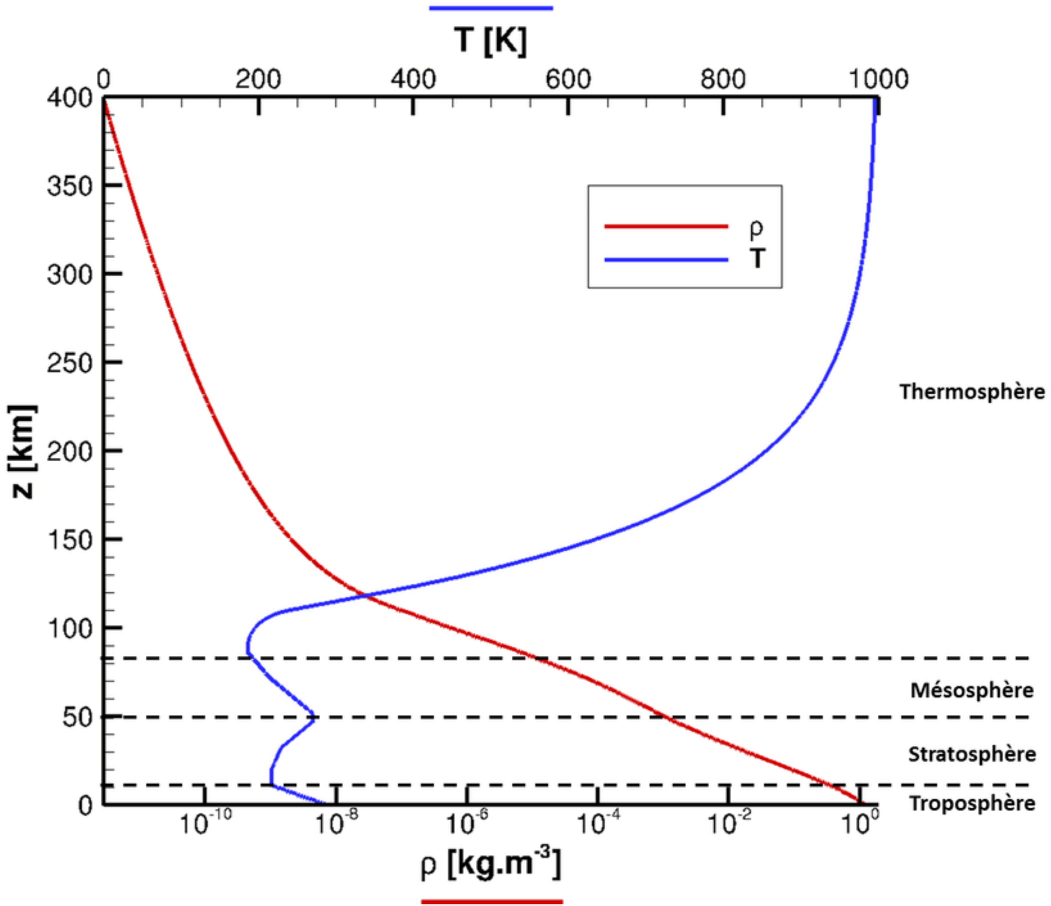



Meseguer J. et al., *Spacecraft Thermal Control*, Woodhead Publishing, 2012

# High temperature env. – Case study: spacecraft thermal management

video link

# High temperature env. – Thermal altitude profile of the atm



# High temperature env. – References

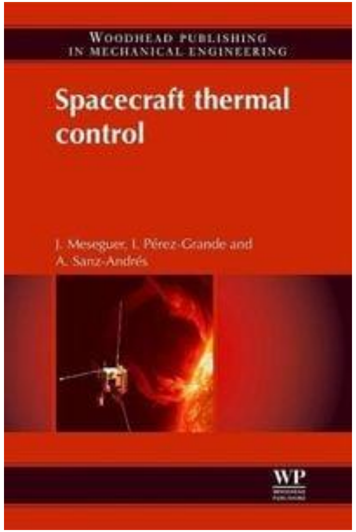




NASA Passive Thermal Control Engineering Guidebook

https://www.nasa.gov/wp-content/uploads/2021/10/7.soa_thermal_2021_0.pdf?ref=uclsciencemagazine.com

Meseguer J. et al., Spacecraft Thermal Control, Woodhead Publishing, 2012



# Radiative environments

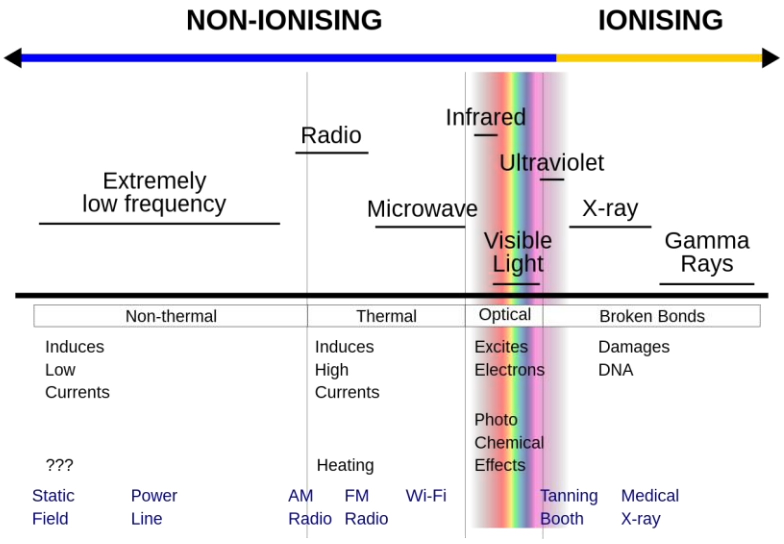


*Photograph of an H-bomb explosion from the "Canopus" nuclear test on 24 August 1968 on the Fangataufa atoll in French Polynesia*

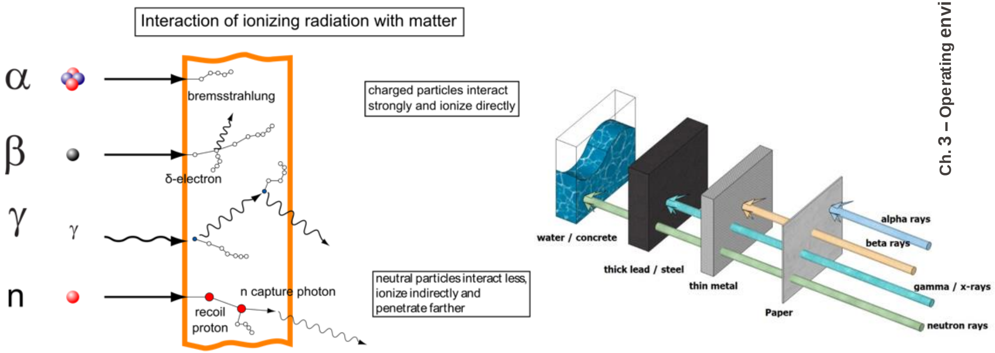
www.un.org

# Radiative env. – Definition and types of radiation

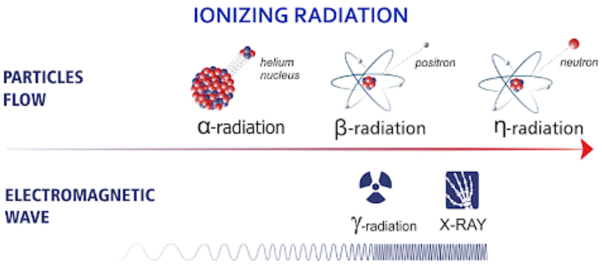
- It encompasses **subatomic particles and** a range of electromagnetic radiation, which includes both **ionizing radiation (such as X-rays and gamma rays)** and **non-ionizing radiation (such as ultraviolet, visible, infrared, microwave, and radiofrequency radiation).**
- Ionizing nuclear radiation consists of subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules by detaching electrons from them.
- The radiative environment is characterized by factors such as **radiation intensity**, **energy distribution**, and **frequency**.




en.wikipedia.org




mdpi.com

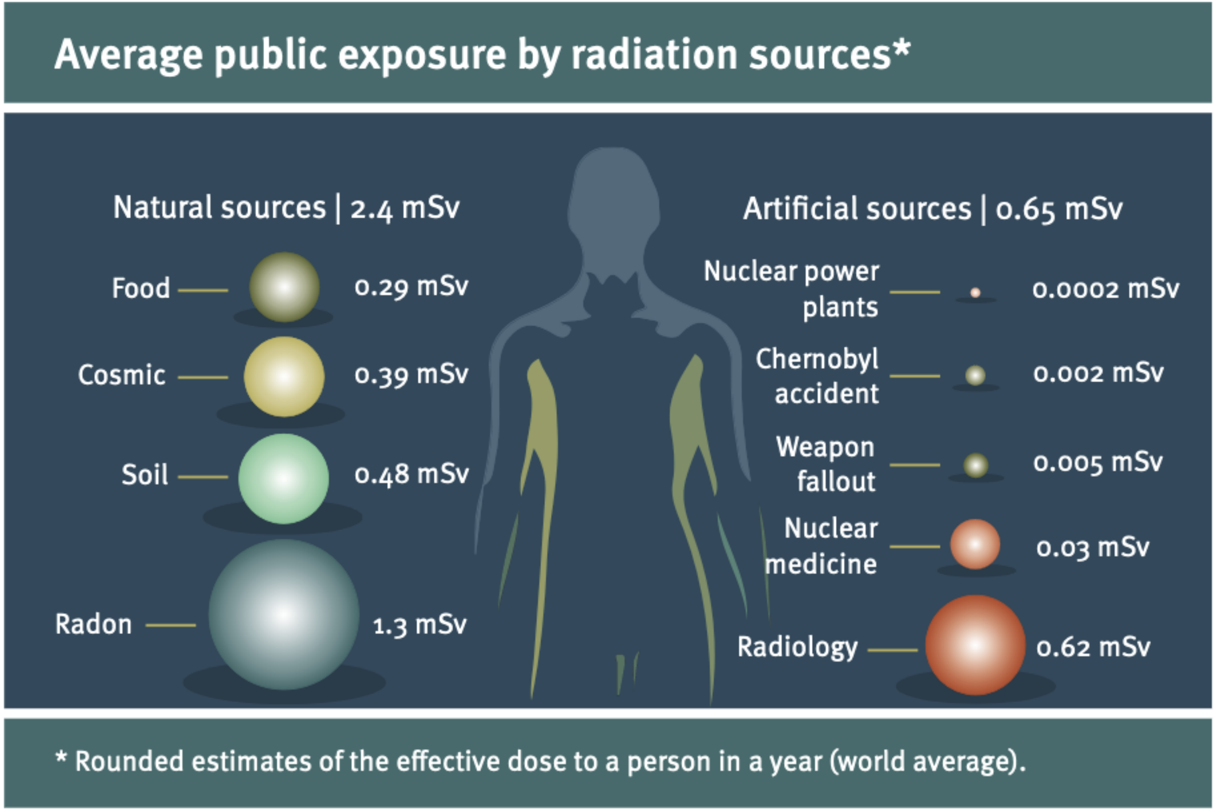


# Radiative env. – Sources of radiations





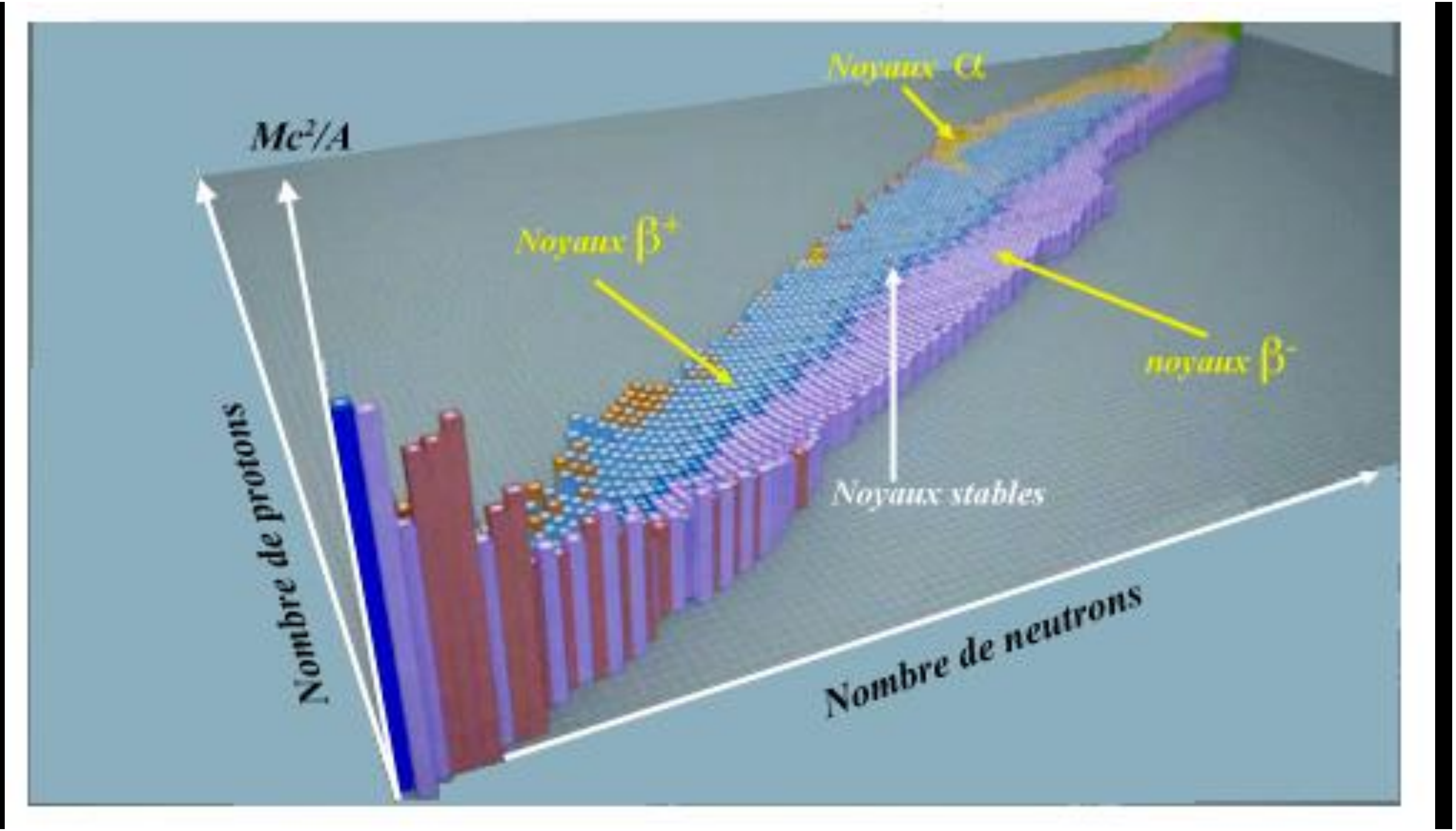





unscear.org

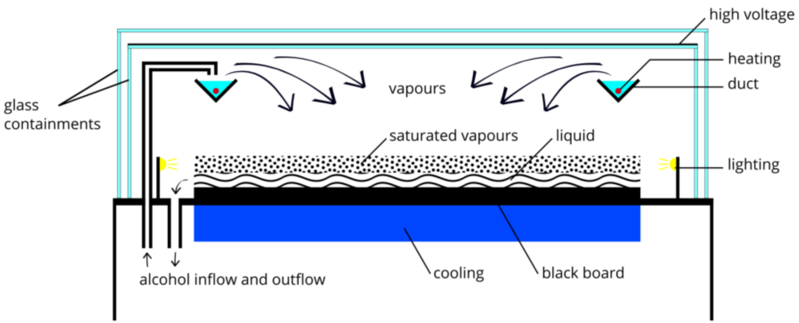
# Radiative env. – Valley of stability

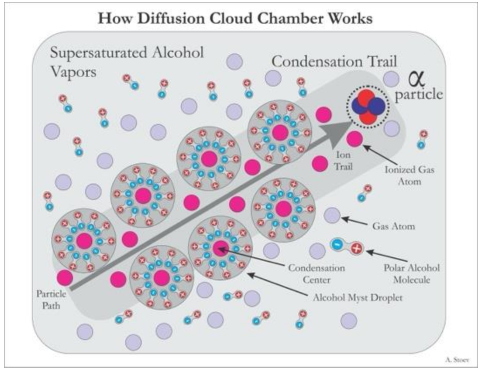


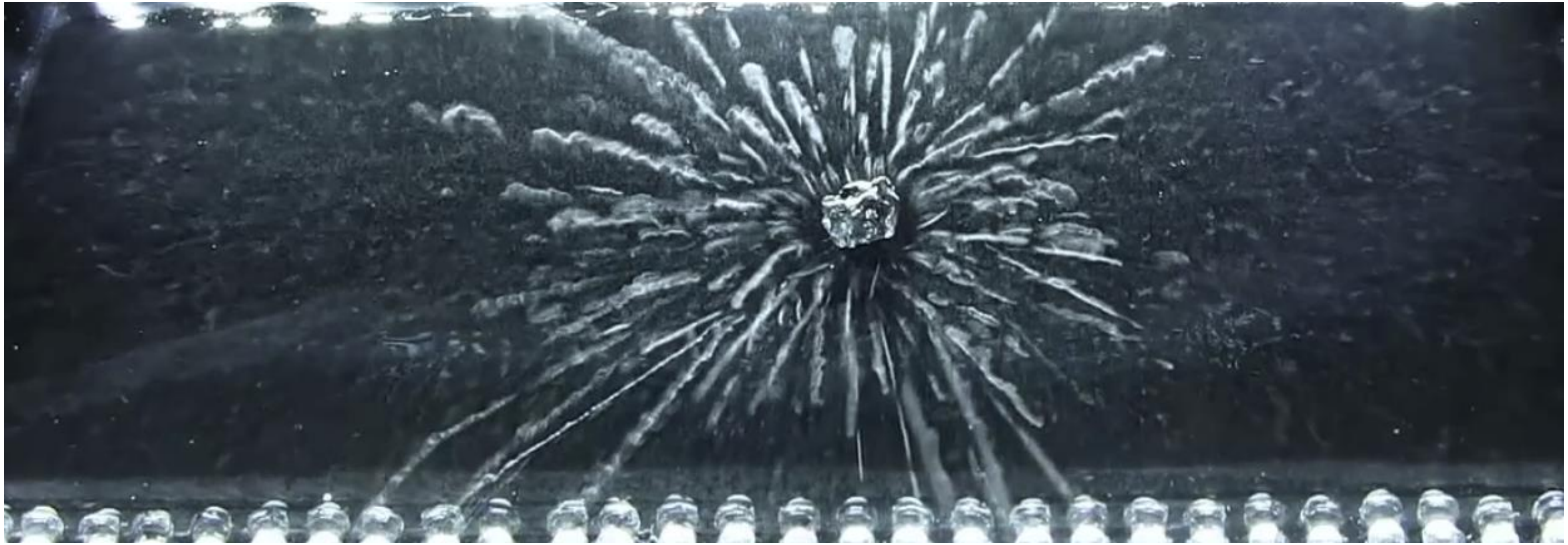



video link

# Radiative env. – Cloud chamber

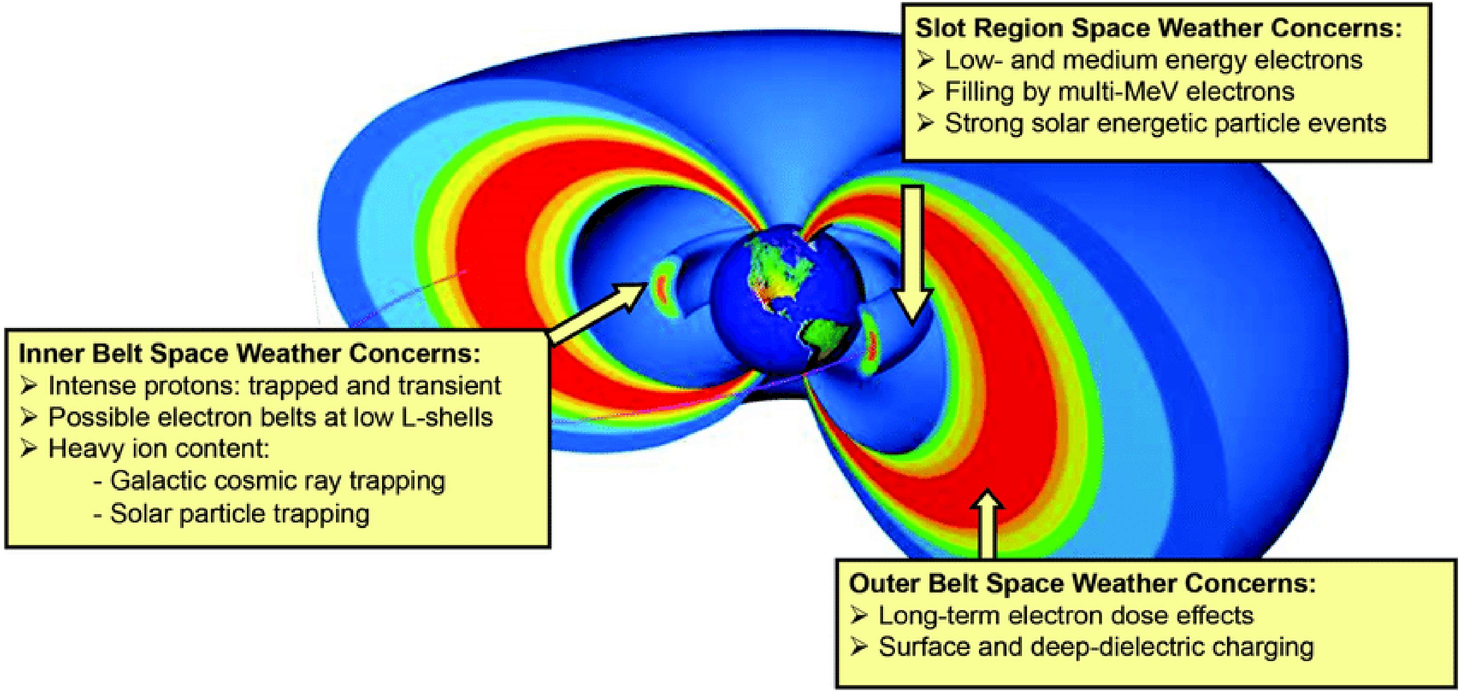



EPFL

# Radiative env. – Van Allen belts





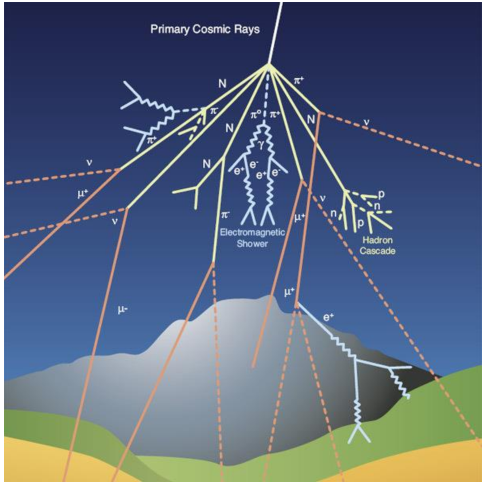


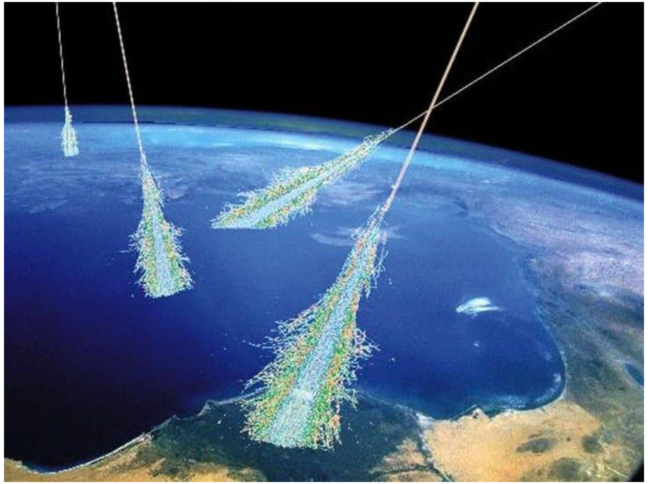

researchgate.net

# Radiative env. – Cosmic ray

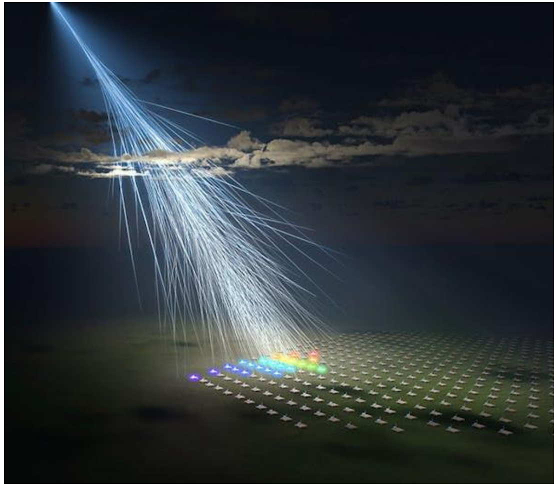



- The Earth's surface constantly receives about **one hundred muons** (charged particles similar to electrons but with higher mass) **per square meter per second.**
- These **muons are secondary particles** generated in the atmosphere by interactions caused by protons or heavy nuclei from distant sources.
- Upon reaching Earth, **only muons and neutrinos persist**, as other produced particles vanish or transform.
- Higher-energy cosmic rays result in more secondary particles, creating **showers rich in billions of particles** that spread **over several square kilometres** on Earth's surface.



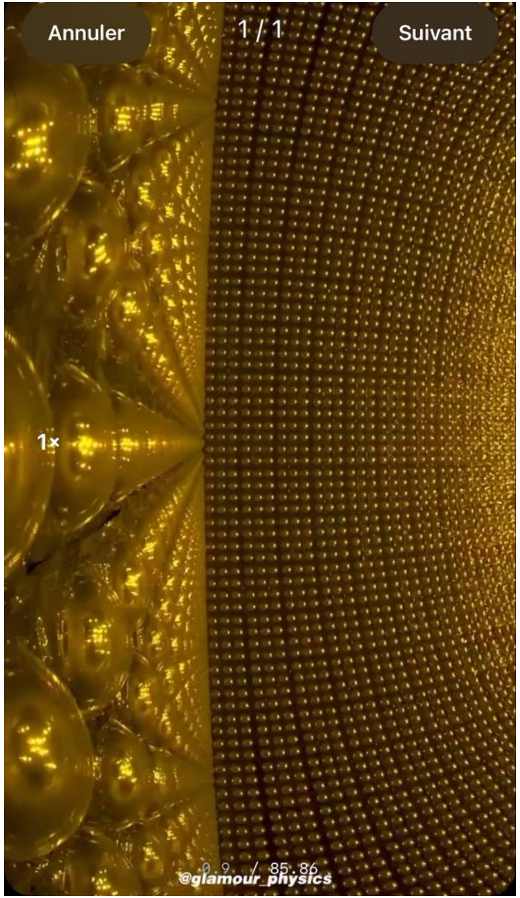
cern.org



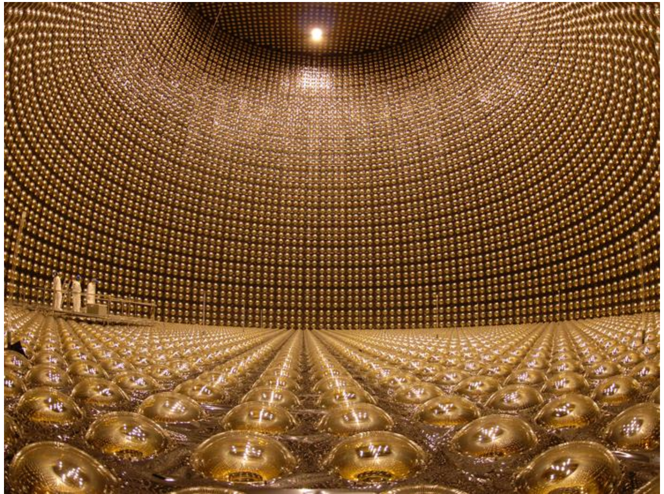
theconversation.com

# Radiative env. – Neutrinos's detectors



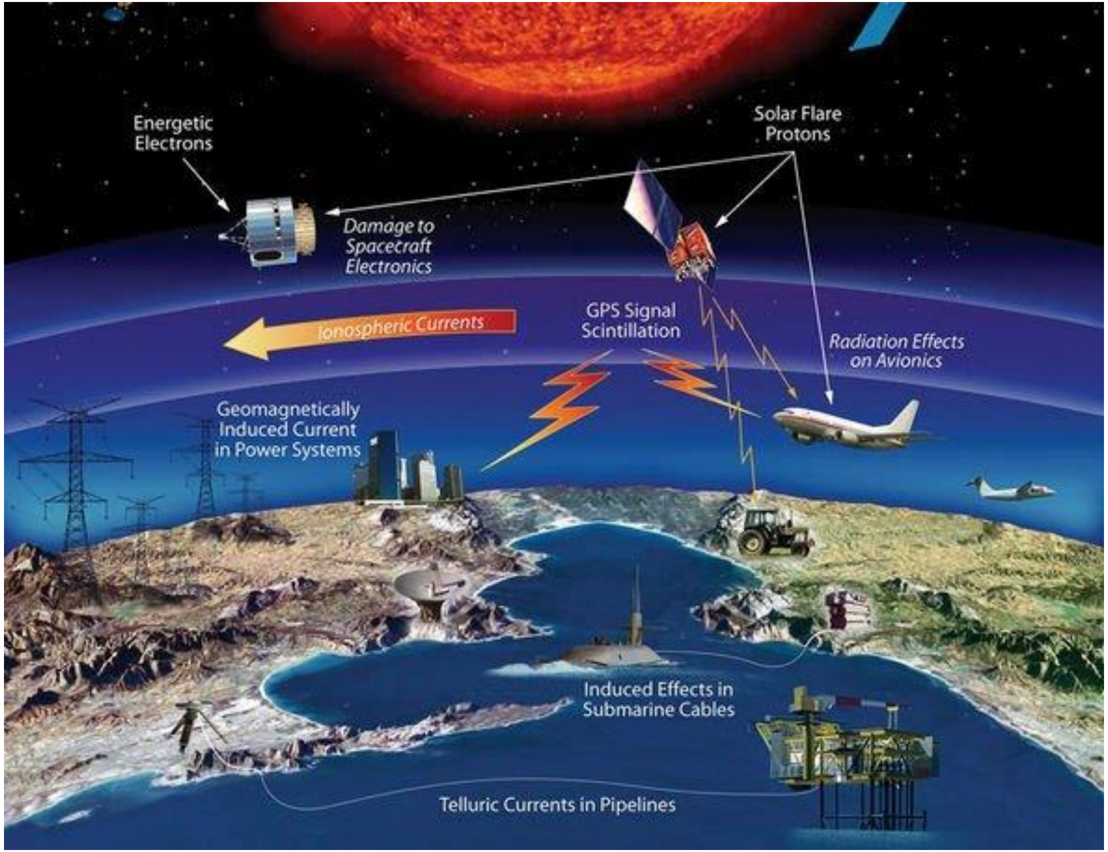

- **Super-Kamiokande is a neutrino detector** built under Mount Ikeno in Japan, near the town of Hida. It is located at **a depth of 1000 metres**.
- It consists of a cylindrical stainless steel tank that is 41.4 m tall and 39.3 m in diameter holding **50,220 metric tons** of ultrapure water.
- Mounted on the superstructure are **11,146 photomultiplier** tubes 50 cm in diameter that face the inner detector and 1,885 20 cm photomultiplier tubes that face the outer detector



businessinsider.com

# Radiative env. – Solar winds

Effects of space weather on Earth and technology




nasa.gov

# Radiative env. - Effects on materials

**A radiative environment can have several effects on a mechanical system, depending on the type, intensity, and duration of radiation exposure. These effects can vary from minimal or negligible to potentially significant, particularly in radiative environments with high levels of ionizing radiation. Some of the effects that radiation can have on a mechanical system are:**

- **Material degradation :** as structural changes, embrittlement, or reduced mechanical properties, can lead to the weakening or failure of mechanical components and component aging and compromise the structural integrity
- **Corrosion:** of metals and degrade the integrity of mechanical systems
- **Lubrication breakdown:** results in reduced lubricity, increased friction, and accelerated wear of moving parts
- **Mechanical wear:** dust and particles may become activated by ionizing radiation
- **Vibration and imbalance:** radiation-induced material changes or damage can lead to imbalances in rotating machinery
- **Temperature effects:** high-energy radiation can generate heat in materials and mechanical components
- **Electromagnetic interference (EMI):** caused by non-ionizing radiation, such as radiofrequency (RF) and microwave radiation
- **Electrical and electronic components:** can induce electrical charges and disrupt electronic circuits, leading to radiation-induced faults in microprocessors or memory modules can lead to system failures or shutdowns.

# Radiative env. – Material degradation

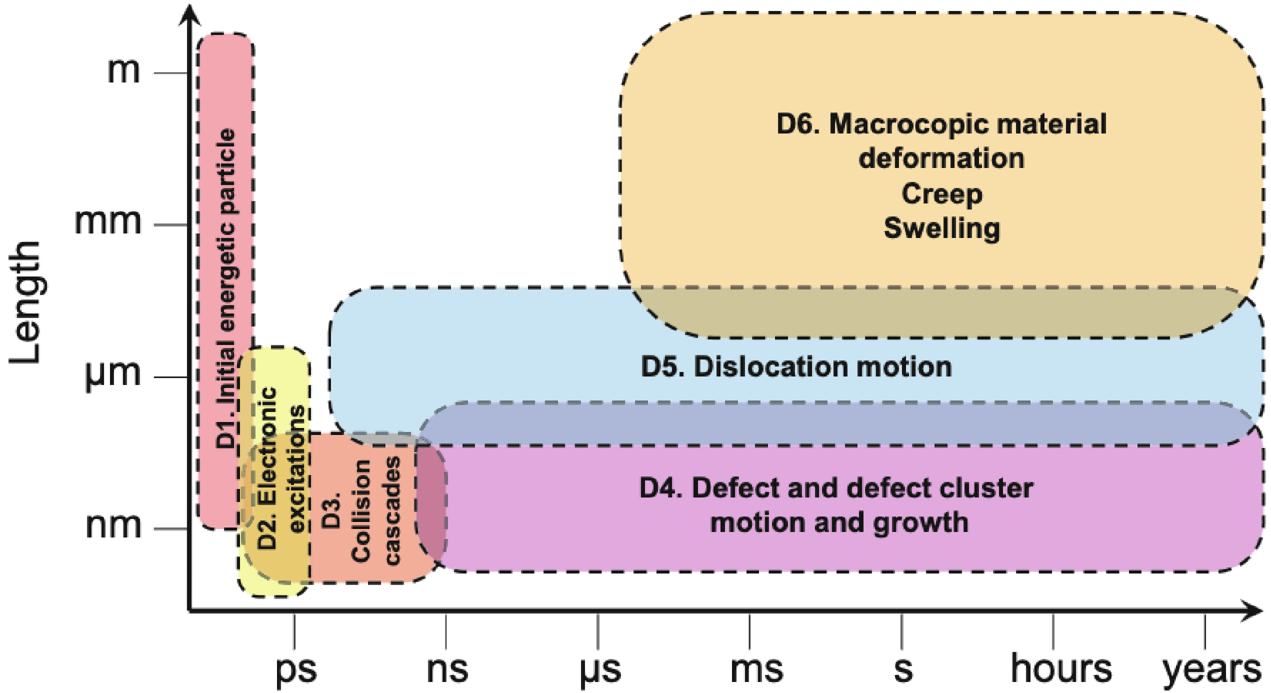
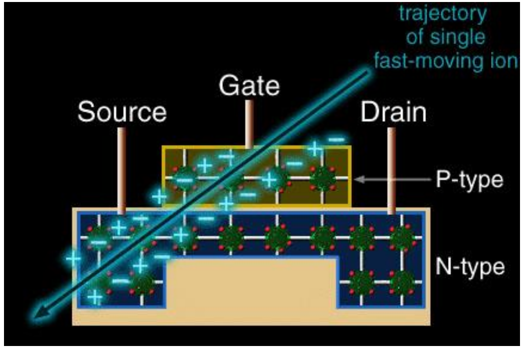


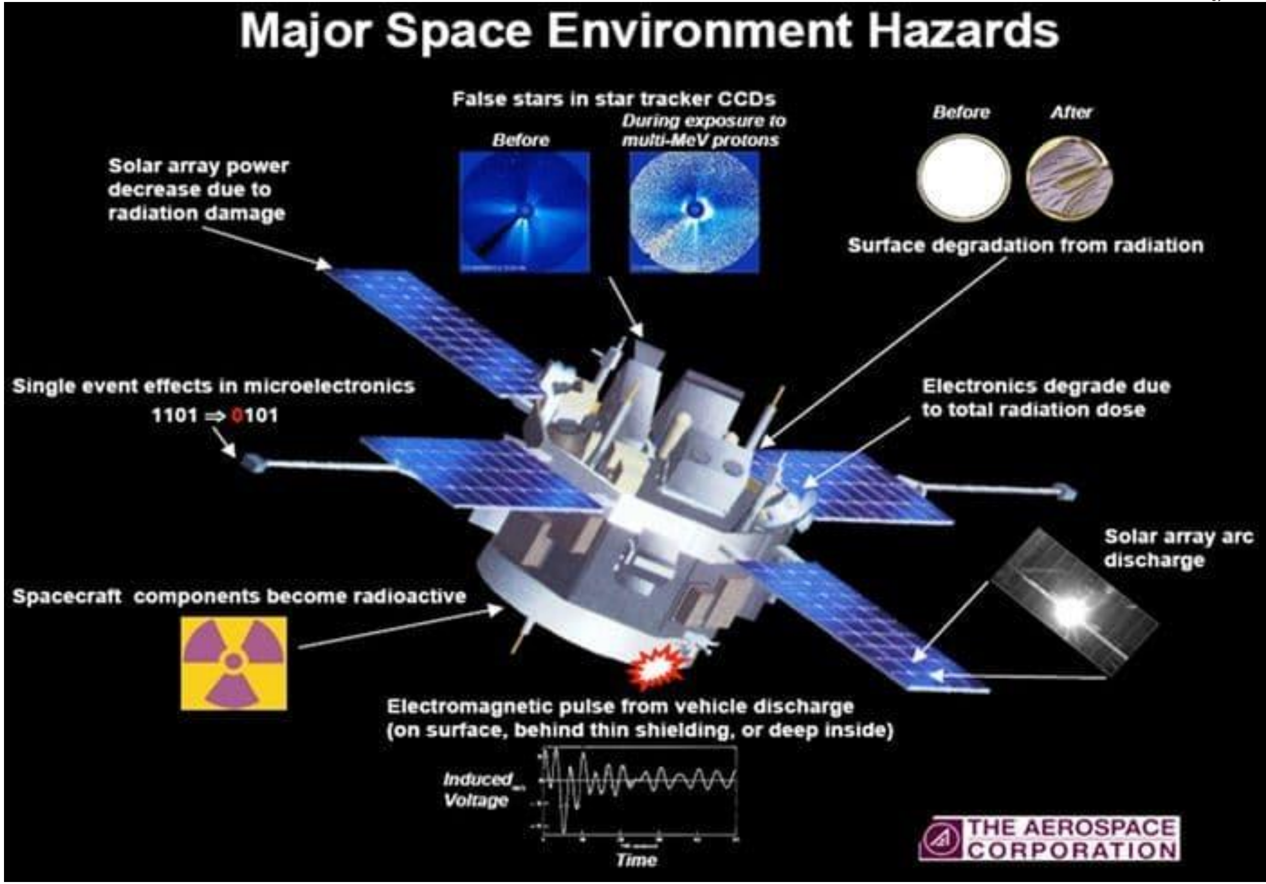

**Fig. 2** Multiple levels of physics involved in radiation effects. The codes D1–D6 are used as cross-references in the main text. The box limits in space and time are very rough and should not be taken as any kind of sharp limits

K. Nordlund and M. P. Short, *Modeling of Radiation Damage in Materials: Best Practices and Future Directions*, Springer Nature Switzerland AG 2019

# Radiative env. – Damages caused by radiations




windows2universe.org




passive-components.eu

# Radiative env. – Mitigation measures and design principles





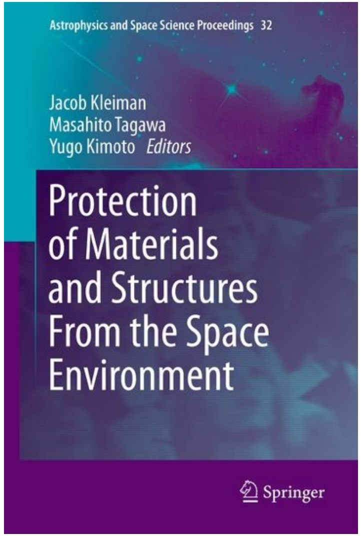


**What are the measures and principles to be observed when designing a mechanical system working in a radiative environment?**

- **Radiation hardening:** use radiation-tolerant electronics and materials like ceramics.
- **Redundancy:** implement redundancy in critical components and systems.
- **Shielding:** may involve using thick layers of metal or other radiation-absorbing materials.
- **Thermal management:** properly manage the system's thermal environment to ensure that temperature extremes caused by radiation exposure do not damage components or affect performance.
- **Minimize complexity:** keep the design as simple as possible. Fewer components and interconnections can reduce the likelihood of radiation-induced failures and simplify troubleshooting.
- **Radiation modeling:** use radiation modeling and simulations to predict how radiation will affect the system. This can help in designing appropriate shielding and redundancy.
- **Testing in simulated environments:** test the system in a simulated radiative environment to assess its performance and identify any issues that may arise during actual operation.

# Radiative env. – Standards and references


- **NASA Standards**: NASA-STD-5001, NASA-STD-8739, and NASA-STD-8739.4.
- **ESA Standards**: ECSS-E-ST-33 and ECSS-Q-ST-70.
- **Protection of Materials and Structures From the Space Environment**, J. Kleiman, M. Tagawa, Y. Kimoto, Springer Berlin, 2012



# Dusty environments

*The Moon*

Ball of Rock" - Rich Addis

# Dusty environments – Dust particles


cleanroomtechnology.com

# Dusty environments – Characteristics of Dust

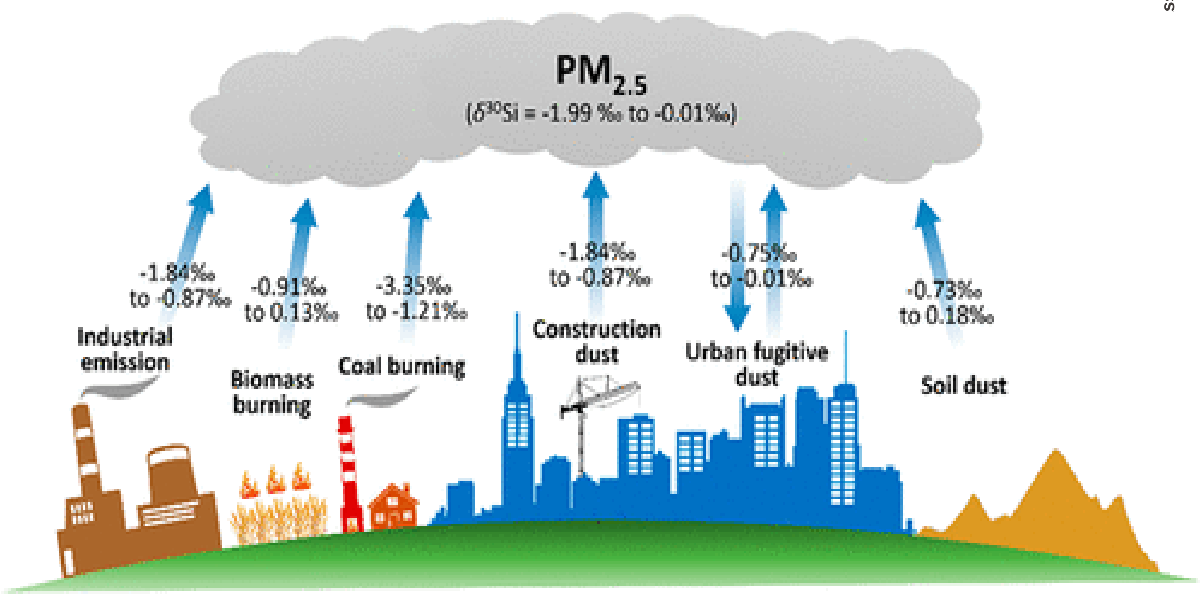




- **Larger particles - larger then 100 µm**
  - Terminal velocities > 0.5 m/s
  - Fall out quickly
  - Includes, room dust, coarse sand, gravel, and sea spray, snow
- **Medium-size particles - in the range 1 to 100 µm**
  - Sedimentation velocities greater than 0.2 m/s
  - Settles out slowly
  - Includes fine ice crystals, pollen, hair, large bacteria, windblown dust, fly ash, coal dust, fine sand, and small dust
- **Small particles - less than 1 µm**
  - Falls slowly, take days to years to settle out of a quiet atmosphere. In a turbulent atmosphere they may never settle out
  - Can be washed out by water or rain
  - Includes viruses, small bacteria, metallurgical fumes, oil smoke, tobacco smoke

# Dusty environments – Dust sources

- Soil erosion
- Industrial process
- Construction activities
- Agricultural operations
- Natural events
- Volcanic eruptions

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# Dusty environments - Cleanrooms





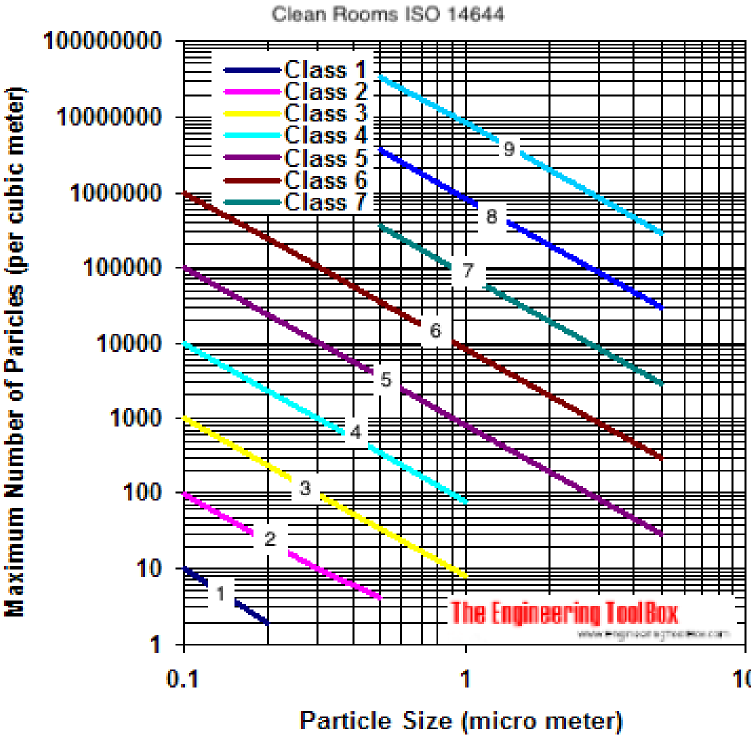
- Clean rooms maintained virtually free of contaminants, such as dust or bacteria, are used in laboratory work and in the production of precision parts for electronics or aerospace equipment.

- In the clean room standard ISO 14644-1 "Classification of Air Cleanliness" - the classes are based on the equation

$$Cn = 10^{N} (0.1/D)^{2.08}$$

Where:

- Cn = maximum permitted number of particles per cubic meter equal to or greater than the specified particle size, rounded to whole number
- N = ISO class number - must be a multiple of 0.1 and be 9 or less
- D = particle size in micrometers

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# Dusty environments – Effects on mechanisms

**What effects can a dusty environment have on a mechanical system?**

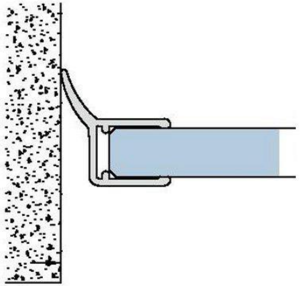
- **Abrasion and wear** → Dust particles can lead to wear and erosion of moving parts, such as bearings, seals, gears, and conveyor belts. Over time, this can result in increased friction, reduced efficiency, and mechanical failure.
- **Contamination of lubricants** → Dust can infiltrate lubrication systems, contaminating oils and greases.
- **Clogging and blockages** → Dust accumulation can clog filters, screens, and air intake systems, reducing the efficiency of equipment and impeding airflow.
- **Reduced cooling effectiveness** → Dust can accumulate on cooling fins, radiators, and heat exchangers, reducing their ability to dissipate heat effectively. This can lead to overheating
- **Corrosion** → Dust may contain corrosive substances or moisture, leading to accelerated corrosion of metal components
- **Vibration and imbalance** → Dust accumulation on rotating components can cause imbalance and vibration
- **Reduced system lifespan**

# Dusty environments – Mitigation strategies

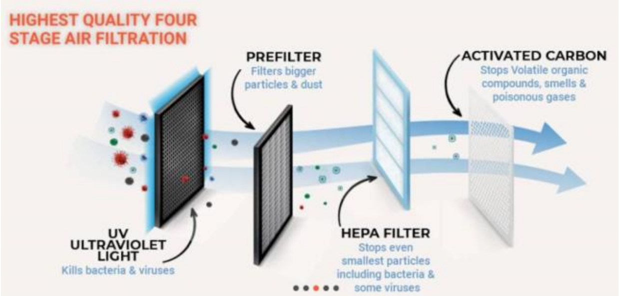
What are the **basic measures and principles** to be observed **when designing a mechanical system for a dusty environment**?

- **Sealed enclosures (A)**
- **Effective filtration (B)**
- **Positive pressure (C)**
- **Dust control measures (D)**
- **Lubrication considerations**
- **Design for accessibility**
- **Vibration control**

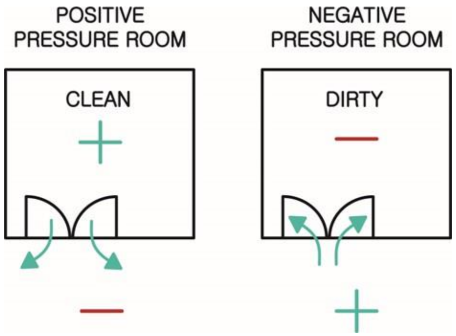
A



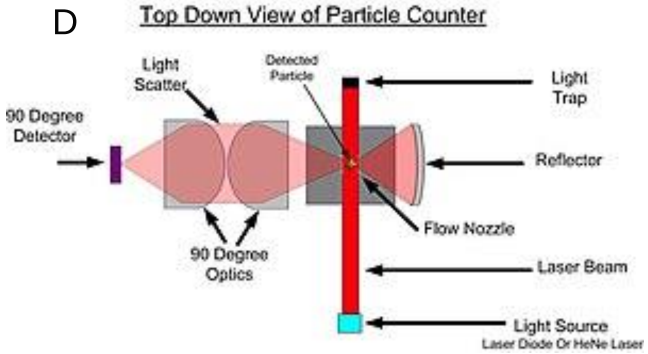
B




C

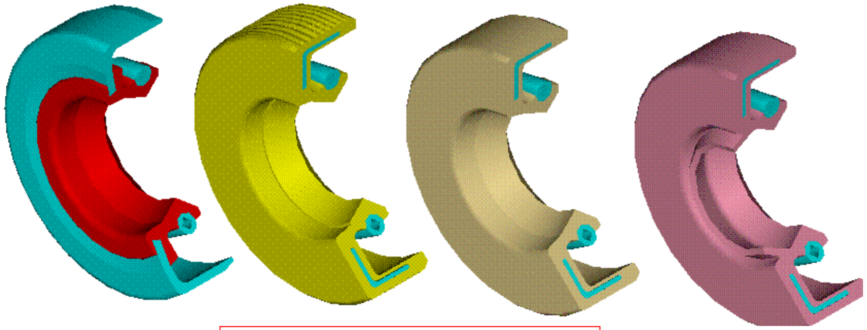



D

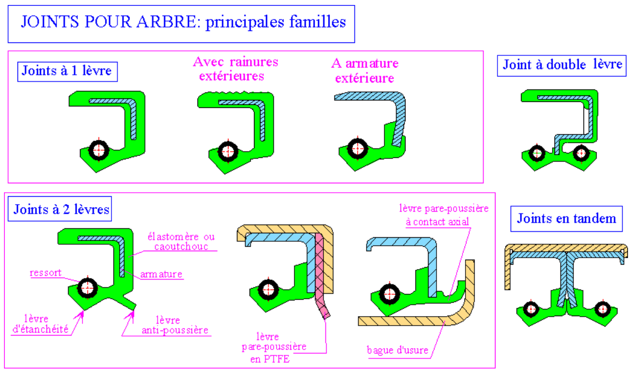


# Dusty environments - Lip seals

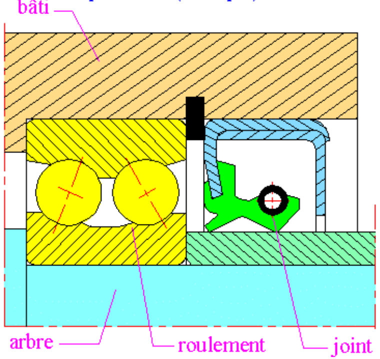




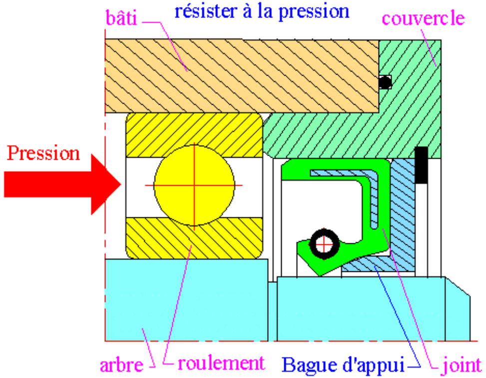
EXEMPLES DE MONTAGE



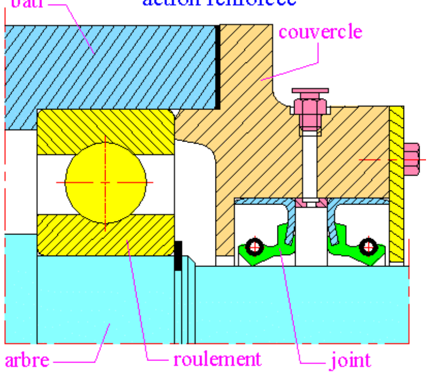

Rétention du lubrifiant et exclusion des polluants (exemple)




Exemple avec bague d'appui pour résister à la pression




Exclusion des polluants et rétention d'huile "action renforcée"

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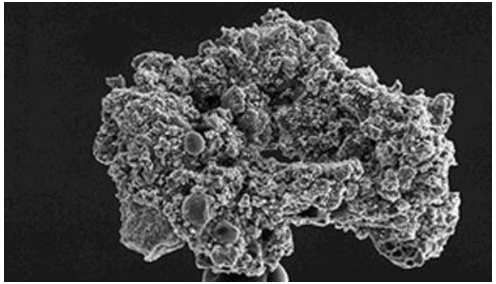
# Dusty environments – Lunar regolith

- **Lunar dust** turned out to be a bit of a **nightmare for the Apollo astronauts**. For one thing, it clung to everything. The astronauts got dust all over their suits, which **degraded the material** over time. The **particles even mucked up a lot of the equipment the astronauts were using, including cameras, radiators, buttons**, and more. And the dust blown out during the descent to the lunar surface made it difficult for the astronauts to see where they were going. "I think probably one of the most aggravating, restricting facets of lunar surface exploration is the dust and its **adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be**," Apollo 17 astronaut Gene Cernan said during a debrief after the mission in 1973.

theverge.com



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