



BSI Standards Publication

Space engineering — High voltage engineering and design handbook

National foreword

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**Space engineering - High voltage engineering and design
handbook**

Ingénierie spatiale - Manuel d'ingénierie et de
conception haute tension

Raumfahrttechnik - Handbuch für
Hochspannungstechnik und Design

This Technical Report was approved by CEN on 14 June 2021. It has been drawn up by the Technical Committee CEN/CLC/JTC 5.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.



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European Foreword

This document (CEN/CLC/TR 17603-20-05:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 "Space", the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-20.

This Technical report (TR 17603-20-05:2021) originates from ECSS-E-HB-20-05A.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

Introduction

The subject of high voltage engineering and design has been part of the spacecraft design process since the early times of spaceflight.

This was due to need for high voltage power conditioners being a key element of communication links. The relate expertise was built up in Europe in the decade of the 1980 with the support of the development of modern Electronic Power Conditioners (EPC's), to operate Travelling Wave Tube Amplifiers for telecommunication satellites and for high power radar applications.

In 1989 ESA launched its first high power radar for earth observation onboard the ERS-1 (European Remote Sensing Satellite), achieving a technology for 15 kV – 17 kV in space.

Today typically between some ten and over hundred EPC's with operating voltages of 5 kV - 8 kV are placed on many of the telecommunications satellites.

Several space borne radars with travelling wave tubes and klystrons are in orbit using voltage up to 20 kV. Various detectors for various kind of space environment with voltage between a few hundred volts and up to 30 kV are used in many missions, high power lasers up to 150 kV were studied, and even some experiments onboard the International Space Station using fancy high voltage sources.

The latest trend is the increasing use of electric propulsion for satellites dealing with supply voltage in the range between a few hundred volts and above 10 kV. High voltage related anomalies have been observed only a few times, some in the early years of building up experience, some also later, especially when new developments were done with new teams inexperienced in the field.

A need was identified for a standard already in the early years of the space flight, the US air force and NASA presented a series design and test handbook in the 1970's and 1980's. In Europe, ESA started discussing a draft standard with industry: the PSS-02-303 draft 2 from 1992 "Requirements for High Voltage Transformer and Components used in Electronic Power Conditioners for ESA Space Systems" this became a quasi standard reference in many space projects, even if it was never formally released. The growing diversity of high voltage application gave finally the urgency to make a new approach for standardization. The discussion started in 2007 with ECSS who led to the conclusion, that a standard would not satisfy the immediate needs for projects, as it would be too wide to cover the diverse applications and also would not be suitable to transfer the "know-how" of high voltage engineering and design. Therefore it was decided to produce a handbook to give a broad scope of knowledge and recommendations for design and test of high voltage equipment and components.

This document aims to satisfy these needs and provides a detailed view of high voltage knowledge aspects as well as giving a guideline to identify suitable design rules.

Proper design of high voltage effects of these processes is part of the system engineering process as defined in ECSS-E-ST-20, where only a small subset of high voltage requirements is given.

For new projects involving high voltage equipment and design it is useful to provide this handbook as a reference to generate suitable requirements specific to the targeted high voltage application.

Chapter 7 of this document gives some "best practice" statements.

Only a smart answer can be given to the definition of the range of voltages which should be considered as high voltages: The ECSS-E-ST-20C states for the definition of a high voltage "AC or DC voltage at which partial discharges, corona, arcing or high electrical fields can occur". For space environment this can occur ". This in fact can already appear at 60 V – 80 V if a low pressure environment in an inert gas provides a critical pressure for "Paschen Breakdown". Under air (N₂/O₂ mixtures) this can occur for voltage of above 300 V.

1

Scope

This Handbook establishes guidelines to ensure a reliable design, manufacturing and testing of high voltage electronic equipment and covers:

- Design
- Manufacturing
- Verification/Testing

of equipment generating, carrying or consuming high voltage, like: high voltage power conditioner, high voltage distribution (cables and connectors).

This Handbook is dedicated to all parties involved at all levels in the realization of space segment hardware and its interface with high voltage for which ECSS-E-ST-20C is applicable.

This handbook sets out to:

- summarize most relevant aspects and data of high voltage insulation
- provide design guidelines for high voltage insulation
- provide design guidelines for high voltage electronic equipment
- give an overview of appropriate high voltage test methods
- establish a set of recommendations for generation design and verification rules and methods
- provide best practices

Applicability is mainly focused on power conditioning equipment but may be also applicable for all other high voltage electric and electronic power equipment used on space missions, except items of experimental nature.

References

EN Reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS System – Glossary of terms
EN 16603-10-02	ECSS-E-ST-10-02	Space engineering - Verification
EN 16603-10-03	ECSS-E-ST-10-03	Space engineering - Testing
EN 16603-10-04	ECSS-E-ST-10-04	Space engineering - Space environment
EN 16603-20	ECSS-E-ST-20	Space engineering - Electrical and electronic
EN 16603-20-01	ECSS-E-ST-20-01	Space engineering - Multipactor design and test
EN 16603-20-06	ECSS-E-ST-20-06	Space engineering - Spacecraft charging
EN 16603-32	ECSS-E-ST-32	Space engineering - Structural general requirements
EN 16602-30-11	ECSS-Q-ST-30-11	Space product assurance - Derating – EEE components
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-	AIAA 2008-4632 (2008)	A model for the active control of low frequency oscillations in Hall thrusters, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 21 - 23 July 2008, Hartford, CT
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-	ASTM D-2214 (2002)	Standard Test Method for Estimating the Thermal Conductivity of Leather with the Cenco-Fitch Apparatus
-	ASTM-D-2240 (2010)	Standard Test Method for Rubber Property: Durometer Hardness
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-	T.W. Dakin (1960)	Electrical Insulation Deterioration, Electrotechnology, Vol. 3, pp. 129-13.

EN Reference	Reference in text	Title
-	ESA contract 18697/04/NL/MV (July 2005)	Quick maintenance for high voltage equipment with the new not toxic boron nitride powder (BN100) superior thermal conductive and lightweight filler

Terms, definitions and abbreviated terms

3.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply, in particular for the following terms:

acceptance	life profile	repair
applicable document	lifetime	residual risk
approval	maintainability	review
critical item	maintenance	risk
derating	material	safety
design	mission	single point failure
development	model	space debris
efficiency	nonconformance	space system
environment	payload	spacecraft
failure	performance	specification
flammability	procedure	standard
function	process	subsystem
hazard	product	supplier
hazardous event	product assurance	support system
inhibit	project	system
inspection	quality	tailoring
integration	quality assurance	toxic
interface	quality control	traceability
launcher	redundancy	validation
life cycle	reliability	verification

3.2 Terms specific to the present document

3.2.1 conducted emission (CE)

desired or undesired electromagnetic energy that is propagated along a conductor

3.2.2 critical pressure

pressure at which corona or partial discharge can occur in an equipment

3.2.3 dielectric

pertaining to a medium in which an electric field can be maintained

NOTE Depending on their resistivity, dielectric materials can be described as insulating, antistatic, moderately conductive or conductive. The following gives a classic example of classification according to the resistivity:

- more than $10^9 \Omega \text{ m}$: insulating
- between $10^7 \Omega \text{ m}$ and $10^9 \Omega \text{ m}$: antistatic
- between $10^3 \Omega \text{ m}$ and $10^6 \Omega \text{ m}$: static dissipative
- between $10^{-2} \Omega \text{ m}$ and $10^2 \Omega \text{ m}$: moderately conductive
- less than $10^{-2} \Omega \text{ m}$: conductive

3.2.4 dose

energy absorbed locally per unit mass as a result of radiation exposure side of an object in the same direction as the plasma velocity vector

3.2.5 double insulation

barrier between conductors or elements of an electronic circuit such that after any credible single failure, conductors or elements of an electronic circuit are still insulated from each other

3.2.6 electrical bonding

process of connecting conductive parts to each other so that a low impedance path is established for grounding and shielding purposes

3.2.7 electrical breakdown field strengths

electrical field strengths where a breakdown of an electrical insulation occurs

NOTE Electrical breakdown field strengths is expressed in V/m, resp. more practically in kV/cm or kV/mm.

3.2.8 electronic power conditioner (EPC)

high voltage power conversion equipment dedicated to supply travelling wave tubes (TWT's).

3.2.9 electrical breakdown

loss of insulation properties of a dielectric material – temporary or permanent

3.2.10 electrostatic discharge

rapid, spontaneous transfer of electrical charge induced by a high electrostatic field

3.2.11 electrical breakdown voltage

electrical voltage where a breakdown of an electrical insulation occurs, units are in V, resp. more practically in kV (kilo Volts)

3.2.12 electrical insulation

dielectric material providing capability to withstand an electrical voltage

3.2.13 electromagnetic compatibility (EMC)

ability of equipment or a system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

3.2.14 electromagnetic interference (EMI)

undesired electrical phenomenon that is created by, or adversely affects any device whose normal functioning is predicated upon the utilization of electrical phenomena

NOTE It is characterized by the manifestation of degradation of the performance of an equipment, transmission channel, or system caused by an electromagnetic disturbance.

3.2.15 emission

electromagnetic energy propagated by radiation or conduction

3.2.16 grounding

process of establishing intentional electrical conductive paths between an electrical circuit reference or a conductive part an equipment chassis or space vehicle structure

NOTE grounding is typically performed for safety, functionality, signal integrity, EMI control or charge bleeding purpose.

3.2.17 high voltage

AC or DC voltage at which partial discharges, corona, arcing or high electrical fields can occur

3.2.18 insulator

insulating dielectric

3.2.19 internal charging

electrical charge deposition on internal materials shielded at least by the spacecraft skin due to penetration of charged particles from the ambient medium

NOTE Materials can be conductors or dielectrics.

3.2.20 internal dielectric charging

internal charging of dielectric materials

3.2.21 ion engine

electric propulsion thruster which operates by expelling ions at high velocities

3.2.22 latching current limiter (LCL)

latching current-limiting function used for power distribution, switching and protection

3.2.23 outgassing

mass of molecular species evolving from a material per unit time and unit surface area

3.2.24 plasma

partly or wholly ionized gas whose particles exhibit collective behaviour through its electromagnetic field

3.2.25 radiofrequency (RF)

frequency band used for electromagnetic waves transmission

3.2.26 radiated emission (RE)

radiation and induction field components in space

3.2.27 radiation

transfer of energy by means of a particle (including photons)

NOTE In the context of this document, electromagnetic radiation below the UV band is excluded. This excludes visible, thermal, microwave and radio-wave radiation.

3.2.28 solar cell assembly (SCA)

solar cell together with interconnector, cover glass and if used, also a by-pass diode

3.2.29 surface charging

electrical charge deposition on the surface of an external or internal material

3.2.30 susceptibility

malfunction, degradation of performance, or deviation from specified indications, beyond the tolerances indicated in the individual equipment or subsystem specification in response to other than intended stimuli

3.2.31 susceptibility threshold

interference level at a test point which just causes malfunction in the equipment, subsystem, or system

3.2.32 thruster

device for altering the attitude or orbit of a spacecraft in space through reaction

NOTE e.g. chemical rocket, cold-gas emitter or ion engine.

3.2.33 travelling wave tube amplifier (TWTA)

specific term for high frequency power amplifiers based on travelling wave tubes (TWT's) in combination with an electronic power conditioner (EPC)

3.2.34 vacuum

environment with a pressure of 10 Pa or below

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
AC	alternating current
BOL	beginning-of-life
CDR	critical design review
DC	direct current
EGSE	electrical ground support equipment
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EOL	end-of-life
EP	electric propulsion
EP	epoxy resin
EPC	electronic power conditioner power
ESA	European Space Agency
ETFE	ethylene-tetrafluoroethylene copolymer
FEPP	field emission electric propulsion
FEP	fluoroethylene-propylene
GEO	geostationary orbit
HV	high voltage
ICD	interface control document
LCL	latching current limiter
LEO	low Earth orbit
MEO	medium (altitude) Earth orbit
MLI	multi-layer insulation
PCB	printed circuit board
PD	partial discharges
PDR	preliminary design review
PI	polyimide
PUR	poly-urethane
PTFE	poly-tetrafluoroethylene
RF	radio frequency
r.m.s.	root-mean-square
SI	silicon (rubber)
SPT	stationary plasma thruster
TM/TC	telemetry/telecommand

Abbreviation	Meaning
TRB	test review board
TRR	test readiness review
TWT	travelling wave tube
TWTA	travelling wave tube amplifier
UV	ultraviolet

High voltage design considerations

4.1 Environment

4.1.1 Impact of environment

High voltage design of electronic systems is driven by the properties of the electrical insulation. The specific environment of a spacecraft can influence the high voltage insulation with immediate or with long-term impact. The impact of the environment depends on the type of electrical insulation. A coarse classification of the potential impacts depending on the environment is given in Table 4-1. Detailed explanations and “special cases” are described in the subsequent sections.

Table 4-1: Course Classification of the potential impact to electrical insulations by environmental type

Environmental Factor	Gaseous Insulation	Liquid Insulation	Solid Insulation	Vacuum Insulation
Pressure	significant, immediate	depending on design, immediate	depending on design	significant, immediate
Temperature	minor, immediate	significant, immediate and long-term	significant, immediate and long-term	moderate
Radiation	moderate, immediate and long-term	moderate, long-term	moderate, long-term	moderate, immediate and long-term
Particles (debris)	not relevant ^{a, b}	not relevant ^{a, b}	not relevant ^a	significant, immediate and long-term
Plasma	not relevant ^a	not relevant ^a	depending on design	significant, immediate and long-term
Mechanical	not relevant ^c	minor	significant	not relevant ^c
a. assuming plasma and particles are kept outside a contained liquid or gaseous environment b. classification can change to “significant” in case leakage caused by severe space debris impact is considered. c. surrounding structure and its possible damage by mechanical stress to be considered separately.				

4.1.2 Pressure

Most of the spacecrafts operate in a space environment which provides a low gas pressure according to the classification a high quality vacuum (residual pressure below 10^{-4} Pa). Under this condition the

electric strengths of the volume of residual gas is more than one order of magnitude higher than under typical atmospheric pressure (nominal Earth sea level pressure: $1 \text{ atm} = 1,013 \cdot 10^5 \text{ Pa}$). On its way from ground to space a spacecraft naturally experiences the pressure transition from ambient to vacuum. Typically this pressure change takes only a few minutes, but the “local” pressure next to the outer surface and inside the spacecraft can possibly stay longer at higher pressure. Through the entire life, the local pressure of the spacecraft remains higher than the pressure at a distance from the spacecraft. This is caused by slow venting of trapped gas volumes and due to continuous outgassing of various materials.

The pressure range between 10^{-2} Pa and 10^{+2} Pa , is very critical where the “Paschen Minimum” is approached and results in very low electric strengths (see section 4.2.2. for more details). A breakdown can appear at voltages below 350 V for air (N_2/O_2 mixtures) and even below 80 V for some noble gases and mixtures with low ionization energy.

Depending on the type of space mission and on the type of electrical insulation the impact of the environmental pressure is different; the implications of typical electrical insulations are discussed below:

a. Gaseous insulation in pressurized containment

In order to ensure a stable gas atmosphere a high voltages assembly can be placed in containment filled with a gas. The pressure stays constant even if the spacecraft is exposed to the space environment. The electric strength is determined mainly by the gas (mixture) and the established pressure. The electric strength stays constant over time, as long as the pressure stays constant. Pressure can decay by nominal leakage rate or by abnormal leakage of the container. Nominal leakage is important to be considered in the design for a given minimum lifetime. The breakdown voltage $\hat{U}_d$ of gas insulated high voltage set-up depends on the gas pressure p with the following relation:

$$\hat{U}_d \sim p^\alpha \text{ with } \alpha = 0,7 \dots 0,8 \quad [4-1]$$

This relation is valid for the technically useful pressure range ($10^5 \text{ Pa} - 10^6 \text{ Pa}$).

b. Liquid insulation in pressurized containment

Insulating liquids in containment can be affected by the pressure mainly under the following conditions:

- dissolved gases form bubbles under decreasing pressure
- the liquid itself starts to evaporate, forming gas bubbles

In both cases the electric strengths can be reduced significantly and a breakdown may occur immediate. As liquid insulations are rarely used in space application, the pressure dependency needs to be analysed for the specific case.

c. Solid insulation

In principle a pure, homogeneous solid insulation is not sensitive to environmental pressure, but in practice specific design cases need to be considered:

1. All conductors carrying high voltages are fully embedded into solid insulating material, there are no gas-filled gap and void and there is no significant electrical field present outside of the solid enclosure (typically achieved by gapless metallic enclosure or metallization of the outer surfaces).

Consequence: typically no pressure dependence

2. All conductors carrying high voltages are fully embedded into solid insulating material; however, significant electrical fields are present outside of the solid enclosure.

Examples:

- Potted modules without metallic shielding towards the outside
- Insulated stranded wires (gap between conductor and insulation)
- Voids and delimitations caused by non-perfect manufacturing process or by thermo-mechanical stress

Consequence: pressure dependency is given by:

- corona discharge occurring at pressures close to Paschen Minimum (immediate partial or full loss of insulation function) (see section 5.1.7)
- surface charging at high vacuum (low pressure) causing long-term stress on the solid insulation (ageing) (see section 4.2.5)
- partial discharges at various pressures causing long-term stress on the solid insulation (ageing) (see section 4.3.3)

d. Vacuum insulation in hermetically sealed containment

In principle a high quality vacuum can be maintained in a hermetically sealed vessel, even in long-term applications if only low outgassing materials are used inside. Naturally, there is no dependency on external pressure, as long as no significant leakage or outgassing occurs.

e. Gaseous / Vacuum insulation – non-sealed “open” construction

Electrical insulation is given by the natural environment, which can be the ambient air during ground operation, any pressure (between earth ambient pressure and space vacuum) during launch and in-orbit transitions, any vacuum pressure in the vicinity of space vacuum including raised pressure due to outgassing or leaking gas volumes. There is a strong dependence on the pressure given by the gas breakdown and vacuum physics. Extremely low electric strengths can appear, when reaching the Paschen Minimum.

Special attention needs to be paid to interplanetary missions with landers and probes entering the atmosphere of other planets. The gas composition and the pressure are typically different from the Earth atmosphere. Methane, hydrogen or carbon dioxide mixtures have different electric strengths than air (see section 5.1.7).

Attention should be paid, that vacuum insulated equipment in non-sealed “open” design has passed a sufficient outgassing time in the (space) vacuum environment, that outgassing and off-gassing processes have been decayed sufficiently.

4.1.3 Temperature

The temperature is affecting electrical insulation directly and indirectly depending on the type of insulation:

a. Gaseous insulation in pressurized containment

The breakdown voltage $\hat{U}_d$ of gas insulated high voltage set-up depends on the *absolute* gas temperature T with the following relation:

$$\hat{U}_d \sim (1/T)^\alpha \text{ with } \alpha = 0,7 \dots 0,8 \quad [4-2]$$

This relation is valid for the technically useful pressure range (10^5 Pa - 10^6 Pa).

Conclusion: the dielectric strength reduces with temperature increase, however, practical temperature variations are minor relative to the *absolute* temperature T , the influence is moderate, except for “application” at cryo-temperatures or at high temperatures (ovens, missions close to the sun etc.).

Indirect impacts can occur due to chemical decompositions at higher temperatures or due to condensation at low temperatures.

b. Liquid insulation in pressurized containment

The impact of temperature on insulating liquids can be direct or indirect. The direct impact is typically a decrease of breakdown strength with increasing temperature. There is no proven general law available as this effect is often dominated by additional factors, like impurities, fibres and water content. An indirect impact of the temperature can be caused by phase changes (freezing, evaporation), chemical decomposition at high temperatures, dissolving of gases. The formation of a gas bubble results in an immediate significant loss of dielectric strength.

c. Solid insulation

The impact of temperature on insulating solids can be direct or indirect. The direct impact is typically a decrease of breakdown strength with increasing temperature due to increased conductivity and higher electron energy. Especially in combination with AC voltage, a point can be reached, where a thermal run-away occurs, caused by a feedback between increased dissipation caused by increase of temperature. This kind of thermal breakdown appears in short term.

A long term (indirect) impact of temperature on solid insulation is the accelerated ageing. In principle, higher temperatures degrades dielectric strength over time due to chemical or electrochemical decompositions of the matter, however, the severity of this effect depends on the material. There are insulation materials like ceramics, which are less affected, whereas the organic insulation materials (i.e. the polymers) can be significantly affected.

A further (severe) factor of degradation of dielectric strength of solids is the cause by thermo-mechanical stress, especially thermal cycling causes permanent stress by material displacements. This effect is additionally enhanced in interface area of materials with different thermo-mechanical properties – i.e. at the connection between different insulating materials or between conductors and insulating materials. The thermo-mechanical stress finally results in formation of cracks or delamination enhancing electrical breakdown (see section 4.3).

d. Vacuum insulation

The practical situation is complex as there are different temperatures depending effects influencing the breakdown strength of vacuum insulation. In a pure vacuum gap between metallic conductors the current flow from emission sites on the metallic electrodes increase with temperature. In combinations with isolators, between the metallic conductors, there has been observed a significant decrease of breakdown strengths with increased temperatures. However, there are positive effects, when a vacuum insulated assembly is “baked out” before operated under high voltage. This cleaning effect is dominated by desorption of gas layers and humidity layers from surfaces (see section 4.2.5) and outgassing. It has been noticed, that as long as desorption and outgassing processes are present and high voltage is applied, a temperature increase can trigger insulation failures.

4.1.4 Energetic Particle Radiation

Energetic charged particles with energies in the MeV range and above are encountered throughout the Earth magnetosphere, in interplanetary space, and in the magnetospheres of other planets. Definitions and levels are given in ECSS-E-ST-10-04. Their impact on high voltage insulation is typically not relevant; however, some specific cases need to be highlighted.

- Gases are typically pre-ionized by radiation. This pre-ionization typically does not noticeably lower the electrical breakdown strength for AC and DC voltages, but reduces the scattering in the development time of the breakdown and thus is mainly relevant for pulsed voltages in the range of microseconds.
- Long-term exposure to radiation results in modification of the physical properties of some gaseous, liquid and solid material with the effect on lowering dielectric strength as a total does

effect. Especially, some polymeric solid insulation materials can be affected by such degradation. In this context, special attention should be paid to high voltage cables and installations on the outer surface of a spacecraft, where the accumulated radiation dose over time is higher than inside of the spacecraft.

- Trapping of charges can occur on surfaces of insulating materials as well as inside bulk materials. Such effects are characterized in ECSS-E-ST-20-06. Accumulated trapped charges in solids can displace and enhance the electrical field and promote electrical breakdown. Therefore materials with lower specific volume resistivity are advantageous in order to allow trapped charges to disappear. As an accumulative effect, the relevance of trapped charges is typically more significant for long duration mission or in harsh radiation environment.

4.1.5 Space Debris and Micrometeoroids

Spacecrafts are exposed to a certain flux of natural micrometeoroids and man-made space debris as described and defined in ECSS-E-ST-10-04. Collisions with these particles usually take place with very high speed. As of course the high velocity impact of heavy specimens is destructive to spacecraft and this not specifically related to high voltage, the impact of small specimen can potentially have some interaction with larger high voltages systems like:

- short circuiting of electrical elements, for example puncture of cable insulation
- triggering arcing and surface discharges on large electrical structures. i.e. solar generators or open non-encapsulated high voltage assemblies (plasma probes and sensors, electric propulsion units).

As the impact of (smaller) specimens create evaporated material and secondary particles potentially including plasma, there is the possibility of a direct arc ignition in a free gap between high voltage conductors and across isolators. Neutral particles can become charged and polarized in the electrical field, moving and forming bridges and strings between conductors as illustrated in Figure 4-1.

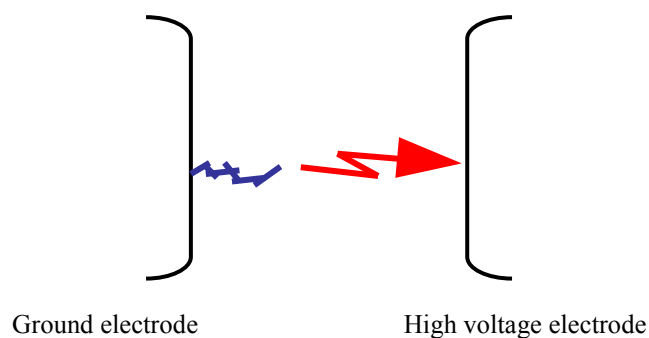


Figure 4-1: Arc Caused by Particle Bridge

4.1.6 Plasma

Spacecrafts are exposed to various plasma environments as described and defined in ECSS-E-ST-10-04. For high voltage designs there are principally two effects to be considered:

- Because of their higher mobility, electrons preferentially accumulate on exposed spacecraft surfaces, causing them to charge negatively. In plasmas, charging can reach hundreds or thousands of volts.

- For high potential (high voltage) surfaces, in dense plasmas, ions and electrons are drawn to negative and positive regions respectively, allowing a current to flow through the plasma. This acts as a current drain on high voltage systems. Even subsystems with relatively “low” high voltages, as such as solar generators can be affected.

Further details on spacecraft-plasma interactions can be found in the ECSS-E-ST-20-06 (Spacecraft Charging) standard.

As a consequence, plasmas can result in a leakage current or an immediate breakdown with uncovered high voltage conductors. Furthermore, in combination with high voltages, surfaces of insulating materials (exposed to plasma) can charge up and increase the electrical field stress on insulations.

4.1.7 Mechanical

For completeness, although not specific for high voltage design, but typical for any equipment on spacecraft, there are typical mechanical environmental conditions:

- Vibration loads
- Shock loads

These loads are caused mainly by the launcher (vibration) or by satellite deployment mechanisms (shock). More details can be found in ECSS-E-ST-32 (Structural general requirements).

As a possible consequence: solid electrical insulations and enclosures can crack, liquid can form gas bubbles under certain conditions, and contained gaseous insulations can be subject to leaks.

4.2 Electrical insulation

4.2.1 Categories of insulation

Electrical insulation is a mandatory key technology in “terrestrial” power applications, as high voltage power generation and transmission as well as in electronic applications. From these applications the electrical insulation has been categorized into:

- Gaseous insulation
- Liquid insulation
- Solid insulation
- Vacuum insulation

In addition, there are in use “mixes” across these categories, like composites of gaseous-solid, gaseous-liquid, and solid-vacuum.

For space applications, the classical categorization is fully valid with some specific considerations as discussed in more detail in the following sections. Since the electrical breakdown is the life limiting factor for all classes of insulation, the basic breakdown mechanisms are discussed for each category.

4.2.2 Gaseous insulation

The most common gaseous insulation on earth is air as it is the natural environment for any equipment on ground – as long as it is not fully encapsulated and exposed to a different environment (other gases, liquid, solid, vacuum). In general the properties of gaseous insulation can be classified as follows:

- Insulation strengths: low compared to liquid, solid or vacuum insulation
- Low degradation over lifetime
- Low sensitivity to temperature and humidity
- Breakdown strength is precisely predictable and repeatable under consideration of parameters for geometry, distance, temperature and humidity
- Radiation can lead to pre-ionization, which typically does not lower the breakdown strength, but narrows the scattering of breakdown voltage values.

Typical properties for various gases are given in the Table 4-2. Note that these properties are defined for normal ambient pressure and temperature.

For impact of

- temperature - see section 4.1.3 (equation [4-2]):
breakdown strengths reduces slightly with temperature.
- pressure variation close to ambient and higher - see 4.1.2 (equation [4-1]):
breakdown strength increases with higher pressure.
- low pressure range – see section 4.3.4 (Paschen curve):
there is always very low minimum breakdown strength at low pressure, the “Paschen Minimum”.
- geometry:
Electrical breakdown field strength increases slightly with decreasing gap distance. This effect is moderate for the distance range below 1 mm; above 1 mm distance it is less significant. Geometries with non-homogeneous electrical field (see section 5.1.3) typically have higher breakdown limits; however, they show partial discharges (corona) at lower voltages – compared to geometries with homogeneous field distribution.

With the objective to achieve a good electrical insulation for technical applications, typically ambient air or nitrogen (N_2) is used in encapsulated pressurized vessels. Higher insulation strength can be achieved by using Sulfurhexafluoride (SF_6). More information on practical insulation design is given in section 5.2.2.

Other gases like CO_2 , H_2 or as the inert gases (He, Ne, Ar, Kr, Xe) can be used due to other technical reasons or because they are naturally present.

In view of space exploration missions to other planets, it should be highlighted that the specific local atmosphere are composed of:

- Venus, Mars: primarily carbon dioxide
- Jupiter, Saturn, Uranus, Neptune: hydrogen-helium atmospheres
- Titan (moon of Saturn) and Triton (moon of Neptune): mainly nitrogen
- Other bodies within the Solar System with extremely thin atmospheres not in equilibrium: Moon (sodium gas), Mercury (sodium gas), Europa (oxygen), Io (sulphur), Escalades (water vapour).

Of course the specific different pressure levels have impact as well. For further details see section 4.1 (impact of environment), section 4.3.2 (for breakdown mechanisms) and section 5.2.4 (for practical insulation design).

Table 4-2: Properties of gaseous insulations

(see Notes 1, 2)

Gas	Density g/dm ³	Thermal conductivity W/m K	Evaporation temperature °C	Electrical breakdown field strength (see Note 3) kV/mm
Air	1,21	25,6·10 ⁻³	-	3,2
N ₂	1,17	25,5·10 ⁻³	-195,8	3,3
O ₂	1,33	26·10 ⁻³	-183,0	2,9
CO ₂	1,84	16·10 ⁻³	-78,5	2,9
H ₂	0,08	179·10 ⁻³	-252,8	1,9
He	0,17	149·10 ⁻³	-269,0	1,0
Ne	0,84	48,3·10 ⁻³	-246,0	0,29
Ar	1,66	17,5·10 ⁻³	-185,9	0,65
Kr	3,48	9,4·10 ⁻³	-152,9	0...8
Xe	5,50	5,5·10 ⁻³	-170,1	-
SF ₆	6,15	18,8·10 ⁻³	-63,8	8,9
<p>Note 1: Important: all values for the properties in this table are for general information only. For use in specific applications refer to individual data sheets and/or dedicated test data.</p> <p>Note 2: all properties referred to a temperature of 20 °C / pressure 1 atm = 1013 mbar = 1013 hPa</p> <p>Note 3: electrical breakdown field strengths for a homogeneous field with a gap distance of 1 cm under short-term stress</p>				

The electrical breakdown mechanism is explained in section 4.3.2. In principle the breakdown strengths of gases is independent of long-term effects – there is no ageing and degradation, except if the gas composition changes over time.

For uniform electrical fields (plane-to-plane configuration) the electrical breakdown voltage can be easily deduced from the electrical breakdown field strengths by the equation [4-1].

For insulating gaps with unsymmetrical, strong non-uniform electrical fields there exists a significant polarity effect. For geometries with the same gap distances the following behaviour can be considered:

- Uniform electrical fields lead to the highest breakdown voltages
- Non uniform electrical fields lead to a lower breakdown voltage compared to uniform fields
- Positive voltages applied to the electrode with the higher electrical field strength, in non-uniform fields, leads to a lower breakdown voltage than negative voltages applied to the electrode with the higher electrical field strengths
- Pre-discharges (corona) appear at the negative electrode in non-uniform fields if the electrical breakdown field strength (i.e. as given Table 4-2) is exceeded, the corona can stay stable until the voltage is raised to the level of breakdown voltage of the specific configuration.

4.2.3 Liquid insulation

Insulation strengths of liquid insulations are higher compared to gaseous insulation and in the order of magnitude equivalent to a solid or a vacuum insulation. Very high insulation strengths can be achieved, if the liquid is combined with foils and barriers of insulating solid (oil-paper, oil-cellulose, oil-polymer foil).

For technical applications with the objective to achieve a good electrical insulation, typically the preferred liquid insulations are mineral oil, silicon oil or castor oil for ground application; however, there is little experience in space.

Typical properties for various liquids are given in Table 4-3. Further details see section 4.1 (impact of environment), section 4.3.2 (breakdown mechanisms) and section 5.2.4 (practical insulation design).

Table 4-3: Properties of liquid insulations

(see Note 1)

Liquid	Density g/cm ³	Thermal conductivity W/m K	Dielectric Constant ϵ_r	Electrical breakdown field strength (see Note 2) kV/mm
Mineral oil	0,89	0,14	2,2	25
Silicon oil	0,97	0,16	2,8	10-30
Castor oil	0,96	0,18	4,5...5,7	17-25
Fluor Carbon e.g. FC770	1,79	0,065	1,9	>19
Note 1: Important: all values for the properties in this table are for general information only. For use in specific applications refer to individual data sheets and/or dedicated test data.				
Note 2: Electrical breakdown field strengths for a homogeneous field under short-term stress – long-term breakdown strength can be significantly lower.				

In principle the breakdown strengths of insulating liquids incurs the risk of long-term effects – degradation can be expected by chemical decomposition caused by chemical processes, radiation or electrical discharges (partial discharges). For mineral oil oxidation degradation is a specific problem, which can be further worsened by the presence of copper surfaces. Another degradation mechanism is related to water content.

Pre-discharges (corona) can appear at sharp-edged electrodes (non-uniform electrical fields) if the electrical breakdown field strengths is locally exceeded.

Gas content forming bubbles can weaken the insulation significantly; however, the bubble needs to exceed a critical size. Environmental pressure can play a role, especially in case of solved gases in the liquid or when pressure falls below the vapour pressure of the liquid.

Under the high electrical fields fibres of insulating material can be polarised and moved forming bridges between electrodes. These formation fibre bridges can severely reduce the breakdown strengths.

4.2.4 Solid insulation

Solid insulation is provided by broad choices of different materials, broadly classified into:

- Inorganic materials: ceramic, glass
- Organic materials: polymers, natural materials (cellulose, paper, mica).

With the broad variety of available solid insulation materials, there is consequently a wide spectrum of material properties. Very generally for solid insulation materials it can be stated:

- Insulation strengths exhibits a wide range depending on the material is typically higher than for gaseous insulations, and for the “good” a solid insulator comparable to liquid insulation.
- Degradation over lifetime is expected and can be significantly enhanced, if partial discharges are present.
- Breakdown strength has a wide scatter and depending on geometry, manufacturing process, environmental parameters and pre-stress.
- Short-term strength (seconds, minutes) is typically much higher than long term strengths (hours, days).
- Sensitive to temperature, especially thermo-mechanical stress and humidity (for organic materials). High temperature accelerates ageing and typically increases the conductivity of the insulation.
- Some materials (e.g. some polymers) degrade with radiation, however, the majority of materials are very stable (w.r.t. typical space radiation environments).
- Pressure does not affect the internal electrical strengths of the solid materials, however, if gas filled gaps or void are present, pressure-related effects should be considered.
- Geometries featuring sharp-edged embedded electrodes and conductors embark the risk of partial discharges and thus significant reduction of lifetime.
- Sensitive to internal contamination: particle pollution can lead to increase the electrical field and so trig a local accelerated degradation of the material due to manufacturing process

Typical properties for various solid materials are presented in Table 4-4, Table 4-5 and Table 4-6. Further details see section 4.1 (impact of environment), section 4.3.2 (breakdown mechanisms) and section 5.2.4 (practical insulation design).

Table 4-4: Properties of EP, PUR and SI

(see Note 1 & 2)

		Epoxy (not filled)	Epoxy (60 % quartz)	PUR	Silicon
Breakdown Strength E_d	kV/mm	15	15	15	20
Specific Resistance σ	Ω cm	10^{14}	10^{14}	10^{13}	10^{15}
Rel. Permittivity ϵ_r	-	3	4	4	3
Diel. Loss Factor (1 MHz) - $\tan \delta$	-	10^{-2}	10^{-2}	$2 \cdot 10^{-2}$	$5 \cdot 10^{-3}$
Tracking Resistivity	-	+	o	++	++
Specific Gravity γ	g/cm ³	1.2	1.8	1.2	1.2
Elastic Modulus	kN/mm ²	4	12	0.5	
Bending Strength	N/mm ²	140	135	135	
Tensile Strength	N/mm ²	80	90	*	*
Compressive Strength	N/mm ²	*	*	3	
Thermal Conductivity	W/K m	0.2	0.8	0.24	
Thermal Expansion	$10^{-6}/K$	65	35	200	
Max. Operat. Temp.	°C	125	130	80	170
Specific Heat c	J/ kg K	*	*	*	*
Arc Resistivity		o	o	-	-
Outgassing Rate		+	o	+	+
Symbols: ++ very good, + good, o average, – poor, -- very poor					

Note 1: Important: all values for the properties in this table are for general information only. For use in specific applications refer to individual data sheets and/or dedicated test data.

Note 2: Electrical breakdown field strength for a homogeneous field under short-term stress – long-term breakdown strength can be significantly lower.

Table 4-5: Properties of various polymers

(see Note 1 & 2)

		PTFE (Teflon)	PMMA (Acryl)	PC (Lexan)	Polyimide (Kapton)	Polyimide (Vespel)
Breakdown Strength E_d	kV/mm	25	30	35	25	*
Specific Resistance σ	Ω cm	10^{17}	10^{15}	10^{15}	10^{16}	10^{17}
Rel. Permittivity ϵ_r	-	2.1	3.7	3.0	3.5	3.4
Diel. Loss Factor (1 MHz) - $\tan \delta$	-	10^{-4}	$3 \cdot 10^{-2}$	$7 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
Tracking Resistivity	-	o	o	o	+	+
Specific Gravity γ	g/cm ³	2.15	1.13	1.20	1.42	1.43
Elastic Modulus	kN/mm ²	0.5	3.3	2.2	*	*
Bending Strength	N/mm ²	15	90..130	90	*	120
Tensile Strength	N/mm ²	20	64..75	*	180	91
Compressive Strength	N/mm ²	*	*	*	*	*
Thermal Conductivity	W/K m	0.25	0.19	0.2	*	*
Thermal Expansion	$10^{-6}/K$	120	90	65	*	*
Max. Operating Temp.	°C	250	85	115	260	*
Arc Resistivity	-	o	o	o	o	o
Outgassing Rate		o	_*	_*	+	+
Symbols: ++ very good, + good, o average, – poor, -- very poor						

Note 1: Important: all values for the properties in this table are for general information only. For use in specific applications refer to individual data sheets and/or dedicated test data.

Note 2: Electrical breakdown field strength for a homogeneous field under short-term stress – long-term breakdown strength can be significantly lower.

Table 4-6: Properties of porcelain and alumina

(see Note 1 & 2)

		Porcelain	Alumina
Breakdown Strength E_d	kV/mm	20..40	30..40
Specific Resistance σ	Ω cm	10^{12}	10^{14}
Rel. Permittivity ϵ_r	-	6	9
Diel. Loss Factor (1 MHz) - $\tan \delta$	-	$5 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
Tracking Resistivity	-	++	++
Specific Density γ	g/cm ³	2.5..2.6	*
Elastic Modulus	kN/mm ²	50..100	*
Bending Strength	N/mm ²	100..140	300
Tensile Strength	N/mm ²	40..60	*
Compressive Strength	N/mm ²	400..700	3000
Thermal Conductivity	W/K m	1.5..2.5	20..40
Thermal Expansion	$10^{-6}/K$	4..6	7
Specific Heat c	J/ kg K	800	800
Arc Resistivity		++	++
Outgassing Rate		++	++
Symbols: ++ very good, + good, o average, – poor, -- very poor			

Note 1: Important: all values for the properties in this table are for general information only. For use in specific applications refer to individual data sheets and/or dedicated test data.

Note 2: Electrical breakdown field strength for a homogeneous field under short-term stress – long-term breakdown strength can be significantly lower.

4.2.5 Vacuum insulation

Vacuum is principally an excellent electrical insulator. The absence of a conductive, semi-conductive or ionisable medium within the gap between electrodes results in quite good dielectric properties. Under optimum conditions the insulation capability can be in the order of an electrical breakdown field strengths of 60 - 80 kV/mm for a free vacuum gap.

In practice, the breakdown strength is lower as the surface of the electrodes and its "status" determines the breakdown mechanism. Concluding, the following influences need to be considered:

- electrode temperature, geometry, material
- conditioning
- voltage waveform
- residual gas pressure
- gas layers and contaminations on the electrode surface

A significant worsening of the breakdown strength can be associated to the presence of solid insulator in the vacuum gap, as it is typically the case, when spacers and feedthroughs are needed. Depending on the solid material, the shape of the insulator and the conditioning, the electrical breakdown field strength can be reduced by more than an order of magnitude (compared to the “free” gap).

Further details see section 4.1 (impact of environment), section 4.3.2 (breakdown mechanisms) and section 5.2.5 (practical insulation design).

4.2.6 Composites

Composites of insulating materials are used to combine the different properties of materials, typically to achieve improvements of some physical properties. The “classical” composites of electrical insulation materials are the following:

- liquid-solid
This combination is typically used to increase the electrical strength w.r.t. a pure liquid system: the liquid is combined with layers of a foil or an immersed structure. Oil combined with cellulose (paper) or with sheets of polymers (polyethylene, polycarbonate, polypropylene) ensures good barriers to avoid fibre bridges. The breakdown strength for short and long-term effects increases by a factor of 2 to 5.
- solid-gas
The combination of polymer foils with gas under pressure is used in a few applications to achieve high breakdown strengths. To be effective, this measure requires significant high pressure.
- solid-solid
Composites of different solid material are used to improve mechanical, thermal and thermo-mechanical properties, typical relevant examples are printed circuit boards (glass fibre embedded in epoxy resin), inorganic powders (glass, ceramic) as fillers in polymeric resins.
- solid-vacuum
Polymeric foils in combination with vacuum are used for cryogenic high voltage cables (i.e. in superconductive equipments).
An organic or inorganic powder (boron nitride) in combination with vacuum is proposed as an approach for high power space applications. (Reference: see results of ESA Contract 18697/04 and European Patent Application EP0993238). The powder is mechanically compressed in a containment embedding the high voltage assemblies.

4.3 Life limiting factors

4.3.1 Perspective

From the perspective of an electrical insulation the end of life is reached with the loss or degradation of the electrical insulation. This loss of electrical insulation can be seen as the threshold, where according to the applied voltage a certain current is exceeded. In most of the cases, this loss of insulation results in a drastic change of state, from high ohmic to a low ohmic state. In practice, the following are distinguished:

- (full) electrical breakdown
the insulation turns into a low ohmic state, typically short-circuiting the power source. The breakdown mechanisms are described in section 4.3.2.

- Paschen breakdown is one of the electrical breakdown mechanisms. As this mechanism is a potentially very relevant case, it is discussed in a special section (4.3.4).
- Partial breakdown -> named as “partial discharge” or “corona” leading to repetitive current spikes, these currents are typically low and not representing a full short circuit of the power source. The related mechanisms are described in section 4.3.3.
- Pre-breakdown currents can occur as a stable effect under certain conditions especially in vacuum insulations. They can represent a significant leakage current in combination with low power source. The related mechanisms are described in section 4.3.2.5. Similar effects, but with less significance can occur in gaseous or liquid insulation. In solid insulation a leakage current increase appears close to a full breakdown.

In the long-term the “loss of insulation” effects are linked to thermal or thermo-mechanical ageing, often accompanied by chemical ageing and (specially in space) by radiation induced degradation. Some considerations are presented in section 4.3.2.

4.3.2 Electrical breakdown

4.3.2.1 Breakdown parameters

The electrical breakdown is characterized by the following key parameters:

- electrical breakdown voltage
- electrical breakdown field strength
- breakdown time
- gap lengths

The relation between the electrical breakdown voltage U_d and the electrical breakdown field strengths E_d for homogeneous fields can be calculated by the following formula under consideration the gap lengths d

$$U_d = E_d \cdot d \quad [4-3]$$

As the electrical breakdown is a short-term effect (occurring in a few μs or even faster) always the peak values of U and E are considered w.r.t. AC and impulse voltage.

The electrical breakdown can be the result of a short excessive stress for duration of fractions of seconds, seconds or minutes, or a result of a long-term ageing effect after hours, days or years.

4.3.2.2 Breakdown mechanisms of gaseous insulation

The basic breakdown mechanism is caused by collision of charge carriers in the gas volume and interactions with the electrode surfaces (Townsend mechanism). In principle, the electrical field accelerates free electrons inside gas-filled gap. These accelerated electrons are colliding with gas atoms as shown in Figure 4-4. If the kinetic energy of the electrons is high enough, they ionize gas atoms, releasing further electrons. An avalanche of electrons can grow towards the anode, while the ions moving in opposite direction collide with the cathode releasing new electron. A well ionized, high conductive breakdown channel can develop in a time frame of a few microseconds. For higher gap distances the formation of a plasma channel can be promoted by photon emission (Streamer mechanism). Bridging of long gaps in the meter range is determined by the Streamer-Leader process, typically not relevant for limited sized space equipment.

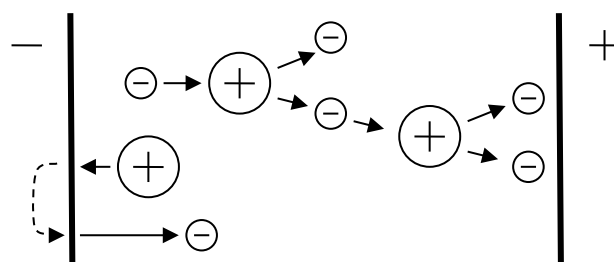
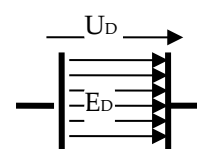
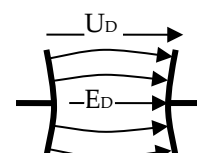
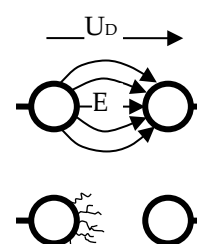
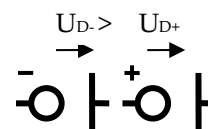


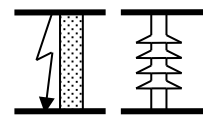
Figure 4-2: Discharge (breakdown) development in a gas volume between two electrodes by electron avalanche process

The following specific effects are taken into consideration:

- Homogeneous electrical field (assuming an ideal plane-to-plane electrode configuration) the breakdown voltage can be determined according to equation [4-3] from the gap distance and the breakdown field strengths as a characteristic value. This statement is valid for gap distances of a few mm or cm at close-to ambient pressure or higher.
- Slightly inhomogeneous electrical field (assuming curvature with larger radius) the breakdown voltage can be determined with the assumption made for the homogeneous field as stated above.
- Strongly inhomogeneous electrical field (assuming curvature with smaller radius) lead to high fields close to the curvature and lower field strengths in the remaining gap space. When the voltage is increased to a certain threshold – exceeding locally the breakdown field strengths at the curvature – local limited discharge occurs – without having a full breakdown. These limited discharges are called “external partial discharge” or “corona”. This corona leads to permanent current pulses – effective as a leakage current. With further increase of the voltage the corona increases (visible glow) and the related leakage current increases, too. When a critical voltage is reached, the corona is able to extend into the zone of lower field strength and this finally bridges the gap, which results into a full breakdown.
- For unsymmetrical inhomogeneous fields, there is a polarity effect caused by space charge formation, leading to the following consequences: if the electrode with the stronger curvature is at a negative potential, the corona starts at a lower voltage, but the breakdown voltage is higher – in comparison to the case with the electrode of the stronger curvature is positive (no corona or corona at voltage close to breakdown).
- The material of the electrode can affect the breakdown voltage due to the effect of different interactions with colliding free charge carriers.
- The surface of the electrode can affect (slightly reduce) the breakdown voltage due to the effect of surface roughness (local field enhancements).



- A solid insulator placed between two electrodes can reduce the breakdown strengths as surface layers (water, contamination) can change distribution of the electrical field significantly. By increasing the “creepage path” lengths of an insulator, this effect can be partially or fully compensated.



- Furthermore, the “triple-junction area” in the corner between two insulation media and the metal electrode can affect the breakdown strength (see section 5.1.9).



- The gaseous insulation is typically “self-healing”: after removing and reapplying the power source the insulation recovers to its initial strengths.
- The characteristic of a gaseous insulation breakdown is very well reproducible.

4.3.2.3 Breakdown mechanisms of liquid insulation

There is a common understanding, that very different basic breakdown mechanisms are driving the electric strengths of liquid insulation depending on the time of exposure to voltage and on environmental parameters:

- A pure collision mechanism in the liquid phase– comparable to the collision breakdown in gaseous insulation (see Figure 4-4.)– can only be assumed under extremely high field strengths, which are in practice never reached, as other effects are dominating the breakdown process (further explained below). So relevance of this effect is given only in very pure liquids (or liquefied gases) under short-term pulse stress (below μs).
- A “hidden gas breakdown” is assumed to occur at much lower electrical field strengths than the collision breakdown in the liquid phase. Gas bubbles can be formed easily by local overheating due to high field strengths in combination with electron collisions and conductivity. It has been noticed, that there is a typical dependency of the breakdown strengths in liquids on the pressure, which is in line with the explanation with the hidden gas breakdown (lower pressure results in lower strength). This breakdown mechanism is effective in a short-term regime between a few μs and seconds. A good degassing of a liquid and a sufficient pressurization is useful to ensure a high quality of the liquid insulation.
- A breakdown related to particles and fibres contributes to a considerable reduction of the electrical strengths in the time domain of seconds and minutes. It has been clearly confirmed, that particles present in the liquid are moved under in the force of the electrical field. Especially particles and fibres of isolating material can charge and react under field force to form fibre bridges or bouncing with high velocities between electrodes. As the natures of such contaminations are difficult to control, this effect is a main driver for breakdown in the mid-term regime between a few seconds and minutes. A method to reduce this effect is to introduce barriers in the high electrically stressed volume of a liquid insulation to prevent building up “fibre bridges” and to restrict particle motion as it is practically done in power industries by oil/paper, oil/wood, oil/cellulose or oil/polymer-foil combination. A filtering and cleaning of an insulating liquid is proposed in additions to ensure a high quality of the liquid insulation.
- As a long-term effect, the degradation of the electrical strengths of a liquid can be related to chemical processes (oxidation, decomposition) and absorption of other substances. Often absorption of water / humidity plays an important role. Typical countermeasures are a good hermetical encapsulation, sometime the use of chemical absorbers / cleaning and a proper selection of materials embedded in the liquid (for example: avoiding uncovered copper materials in oil).

The Figure 4-3 gives an orientation of the effect of the different mechanism on electrical strengths depending on the time domain.

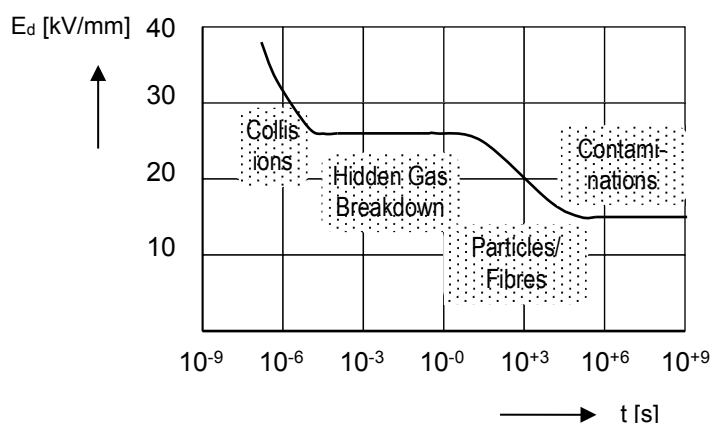


Figure 4-3: Electrical strengths of a liquid insulation (here: transformer oil in 2,5 mm gap) in relation to voltage exposure time and assumed breakdown mechanism

Most of the field related and surface related effects as explained for gaseous insulation (see section 4.3.2.2) are applicable for liquid insulation, too:

- Breakdown is driven by the local field strengths for inhomogeneous fields
- Polarity effect for inhomogeneous fields
- Dependency on electrode material and surface
- Electrical strengths reduction with surface of solid insulator (in not properly oriented and shaped)
- Sensitivity to triple-junction effects.

4.3.2.4 Breakdown mechanisms of solid insulation

Basically, three different breakdown mechanisms are determining the electrical strengths of a solid insulation. The duration of voltage application, the type of voltage stress (AC, DC), defects in the insulation and the shape of the electrodes are playing an important role on which of the processes is dominating:

- The “intrinsic breakdown” is a fast process (nanoseconds) occurring at high electrical field strengths. With electrical field strengths above a specific threshold the conductivity of a solid insulating material increases rapidly. Possible reasons are field emission of electrons and collisions. The field emission enables electrons to detach from the atomic structure due to high field forces. In short term local energy densities occur, the isolator is locally destroyed and a breakdown channel is formed. The local field emission is very effective at sites, where the local atomic grid is already weakened. This can be at local displacements caused by mechanical bending or stretching of the material, as well at structural changes (e.g. crystal grains, material change, contaminations, and cracks).
- The “thermal breakdown” is characterized by a general heating of the insulation. The heating effect is given by the intrinsic specific conductivity of the insulator, for AC stress enhanced by dielectric polarization losses. As the specific conductivity increases with increasing temperatures a “thermal run-away” effect can occur, if the critical threshold of the electrical field strengths is exceeded. The effect can be promoted in areas, where the insulation material is deviating (higher)

electric properties – at discontinuities or at more thermally isolated areas in a volume of material. The heating can take place over seconds, minutes or hours; however, the run-away effect itself finally leads to a full breakdown within seconds or even faster.

- The “partial discharge breakdown” results in a continuous local erosion of the isolation and leads to breakdown after many hours or even many years. So it is a definite long-term mechanism. The root causes are either irregularities like gas bubbles, delamination, cracks in the insulator or local zones of high electrical field strengths, i.e. at sharp edged electrodes, metal particle inclusion. Typical examples of irregularities causing partial discharge breakdown configuration are shown in section 4.3.3. These partial discharges are repetitive and erode the material starting from the initial irregularities. The resulting erosion channel can not grow linearly; in fact it develops typical tree-like structures. When the erosion “tree” bridges a significant part of the insulating gap, a sudden full breakdown occurs.

It is emphasised, that the electrical breakdown of solids is typically not reversible. With the full breakdown the isolator is punctured, often a carbonized (more or less conductive) channel is formed. The remaining electric strengths are a fraction of the original strengths. If the discharge energy is high enough, isolation can be cracked and fragmented.

As a consequence of the described breakdown mechanisms the following conclusions can be drawn for solid insulation:

- Any non-homogeneity or discontinuity within the solid insulation material – either macroscopic or microscopic – can promote a breakdown.
- High temperatures are not favourable.
- Materials with lower intrinsic conductivity and a low electric loss factor are advantageous in terms of thermal breakdown.
- Due to the complexity of the breakdown mechanisms, a precise prediction of breakdown strengths is impossible and measured breakdown strengths can vary from sample to sample very significant due to non-controllability of the many microscopic and macroscopic driving parameters. Due to this the prediction curve can be better found by test and statistical approach.

4.3.2.5 Breakdown mechanisms of vacuum insulation

In a “good” vacuum of below 10^{-2} Pa ($= 10^{-4}$ mbar) the free-path lengths of electrons is so high, that collisions with ions are very rare. Thus a collision based avalanche mechanism can not (primarily) cause an electrical breakdown. Therefore, the intrinsic electrical strength of vacuum is typically much higher (greater) compared to solid, liquid and gaseous insulation. However, under certain conditions charge carriers (electrons, ions) as well a gaseous matter and micro particles can be released from surfaces of electrodes and insulators. In the vacuum gap between two electrodes these released charge carriers, gases or micro-particles can easily move and “commute” between surfaces causing pre-breakdown and breakdown events.

In the following find a brief overview of these basic mechanisms and their relevance to space power design. Figure 4-4 shows the complex relations between several space vacuum related processes which can finally lead to catastrophic failures of a high voltage system. As a result four types of defect can occur:

- power loss by current flow
- solid breakdown (irreversible)
- surface flashover
- volume breakdown

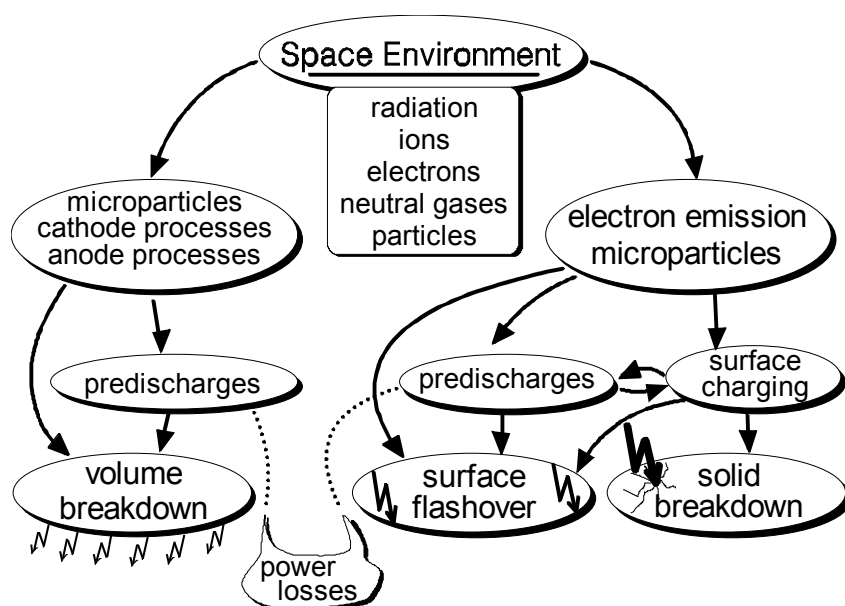


Figure 4-4: Vacuum breakdown phenomena

Predischarge currents, if they do not lead to a breakdown, can be a significant load for high impedance devices.

Solid breakdown caused by vacuum-related phenomena occurs when surface charging processes enhance the electrical field strength inside a solid dielectric or if permanent surface discharges erode the material until it fails.

Volume breakdown and surface flashover are caused by permanent or temporary overstress of the insulation. Usually an arc is built up, which is extinguished after the discharge current falls below a characteristic threshold value.

a. Volume Breakdown

The volume breakdown is characterized by a conductive path which is built up through the volume of a vacuum region. Surface phenomena at the cathode or anode and anode/cathode interactions play an important role in initiating the discharge. Basic theories of vacuum breakdown are mostly based on one of the following "classical" hypotheses:

- According to the Cathode hypothesis, field emission currents from irregularities at the cathode result in local heating, vaporization or dramatic micro-explosions, so that a gap bridging plasma is generated.
- The anodic theories assume that accelerated electrons emitted from the cathode surface lead to anodic reaction which finally result in a total breakdown of the gap.
- Referring to the Clump hypothesis, electrical field forces detach microparticles from the electrode surface, which are accelerated and trigger the breakdown by impacts with the opposite electrode.
- Some other theories assume complex physical interactions in semi conductive layers on the surfaces of the electrodes.

Nevertheless all the phenomena depend significantly on the electrode material, microscopic surface irregularities, composition of surface layers, pre-stressing, temperature, and voltage shape. Often, but not necessarily, the breakdown is preceded by a steady pre-breakdown current or self-limiting microdischarges.

In space power systems a pure vacuum "volume" breakdown is very rare, because non-bridged gaps have a much better voltage hold-off capability than complex constructions with solid-dielectric surfaces, which are vulnerable to "sliding" discharges. An exception is outgassing dominated volumes. There the breakdown mechanism can transition from the vacuum breakdown to the gaseous breakdown, which leads to drastically reduced breakdown voltages.

b. Surface Flashover

The surface flashover occurs as a vacuum discharge along the surface of a solid dielectric, which is used for construction, i.e. at spacers and feedthroughs, or for encapsulation of components and systems. Generation and propagation of the discharge are closely involved with surface phenomena. No single theory is capable of explaining the flashover mechanism, but a selection of basic hypotheses:

- The cathode-initiated flashover is initiated by electrons emitted from the cathode and triggering an avalanche process along the insulators surface.
- The anode-initiated flashover assumes surface damage, caused by impacts propagating with high velocity from the anode to the cathode.
- Radiation-induced flashover can be triggered by ultraviolet illumination at very low electrical fields, if a critical integrated energy threshold is exceeded.

Some effects influencing the flashover behaviour are the:

- Cathode triple junction zones, which are responsible for primary electron emission at inevitable microscopic irregularities (see section 5.1.9).
- Secondary electron emission, which is triggered by energetic particle impact and can contribute to charge carrier multiplication resulting in local, field enhancing surface charging.
- Gas desorption, which increases drastically, when areas are locally heated by impact or conductive processes, and can result in a limited gas discharge.

All of these phenomena are extremely sensitive to the material properties, geometry, composition of surface layers, surface roughness and impurities, pre-stress, temperature, and operating conditions of the system.

The flashover voltages of an insulator-bridged gap are up to one order of magnitude lower than those of a comparable non-bridged gap; i.e. stainless-steel electrode with a homogeneous gap of 10 mm length can withstand AC voltages exceeding 200 kV, an insulator made of PMMA (polymer: "Acryl") breaks down at 35 kV. Typically AC stress results in the lowest hold-off capabilities, usually almost two times lower than DC or impulse flashover voltages.

4.3.3 Partial discharges

Partial discharges are discharges which do not lead to an immediate breakdown. They can appear in solid insulations, as well as in liquids and in gas. The typical effect is that a local breakdown occurs in limited area in a larger volume of insulation. The reasons for this local breakdown can be locally enhanced high field strengths or a local weakness of the insulation, as well as both reasons in combination. Typical examples of irregularities causing partial discharges breakdown are shown in Figure 4-5.

It is clearly emphasised, that partial discharges in liquid and solid insulation are a significant accelerating factor for breakdown and for ageing. Therefore the presence of any configuration and irregularities causing partial discharge should be avoided as far as possible.

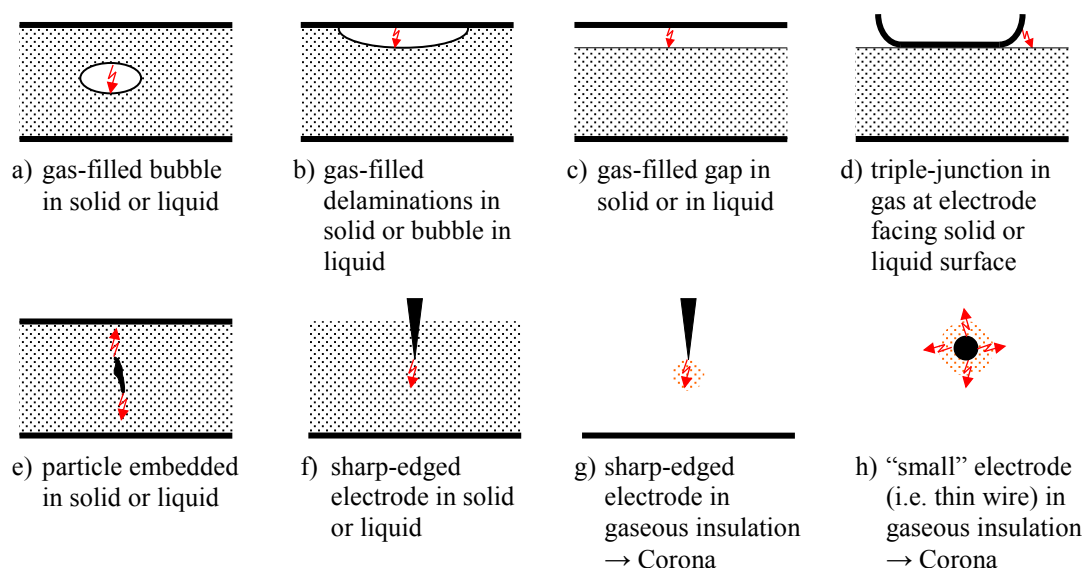


Figure 4-5: Typical partial discharge configurations

The configuration of a gas-filled void or a gap embedded or attached to a solid or liquid insulation (see Figure 4-5 a - d) is vulnerable to partial discharge by two main reasons:

- the gaseous insulation has typically the lower strengths, so if voltage and field strengths are increased, first the gaseous part breakdowns, while for solid or liquid parts initially withstand the breakdown.
- the gaseous insulation has typically a dielectric constant around $\epsilon \approx 1$ whereas the solids and liquids have an higher dielectric constant (many of them $\epsilon = 2$ to 6), similarly the electric conductivity of solids and liquid is higher than the conductivity of gas: as a consequence the distribution of the electrical field is penalizing the weaker gaseous insulation with a higher field strengths.

For space applications it is to highlight, that during and after launch the external pressure decreases and in accordance or with delay the pressure in a gas bubble is decreasing too. As a consequence partial discharge can occur after launch, which would not be there at ambient pressure.

The configurations of a sharp edged electrode or a particle embedded in a solid or liquid insulation (see Figure 4-5 e, f) causes partial discharge due to the high local electrical field strengths. A local discharge can occur. This local discharge is not able to breakdown the whole insulated gap – at least initially. Usually, continuous erosion due to partial discharges results in a full breakdown in long-term.

Typical “corona” configurations are shown in Figure 4-5 g and h, featured by a strong non-homogeneous field at sharp edged electrodes (needles, thin wires, corners). Similarly to Figure 4-5 e, f here the root cause of a partial discharge is a higher local field strengths due to a non-uniform electrical field. Normally, corona discharge is stable and does not degrade the gaseous insulation – in contrary as it is the case for partial discharges in solid or in liquid insulation.

It is noted, that

- for partial discharges occurring in a non-uniform electrical field in a gaseous insulation typically the expression “corona” is used.
- for partial discharge in liquids and solids the expression “inner partial discharges” is used to distinguish from “outer partial discharge” equal to “corona”.

- in the aerospace disciplines often the expression “corona” is used for effects related to the “Paschen breakdown” in low pressure (see section 4.3.4), however, this is misleading, as the Paschen breakdown is a full breakdown and not a partial discharge phenomenon.
- predischage resp. pre-breakdown phenomena in vacuum insulation as outlined in section 4.3.2.5 are not belonging to the category of partial discharges as they are based on different mechanisms.

A partial discharge is typical repetitive event. They repeat continuous varying intensity. In the common theory of partial discharge breakdown, the local irregularity can be described in an electrical circuit model as shown in Figure 4-6.

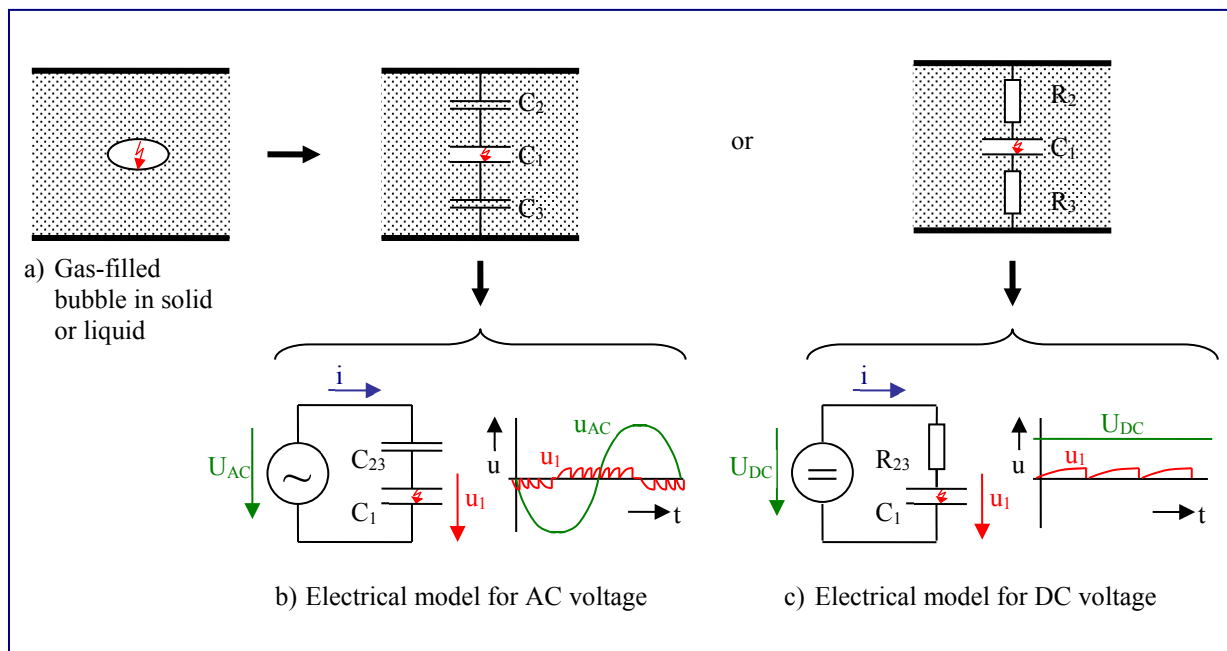


Figure 4-6: Electrical model of partial discharges for a gas-bubble in a solid

For an applied AC voltage the gas-filled bubble and the surrounding solid insulation material can be described by a series switching of capacitors – see Figure 4-6 b. The elements C_2 and C_3 are associated to the embedding solid insulation and can be merged into a replacement element C_{23} . Assuming that the voltage u_1 at the void capacitance C_1 is reaching a critical voltage to trigger a local breakdown, the element C_1 is immediately discharged. The recovery of the voltage u_1 is concurrent with the recharging of the void element C_1 . However, the recharging current i can be only transferred through C_{23} . As this current through a capacitor is determined by the differential equation as $i \approx C_{23} \frac{du_{AC}}{dt}$, the current depends on the steepness of the slope of the source voltage u_{AC} . Therefore with a sinus-waveform of u_{AC} the fastest repetition rate of partial discharges occurs at the zero transition of the applied voltage u_{AC} , whereas at the crest of the curve there are less or no pulses.

NOTE The correlation of the pulse occurring more frequent at zero-transition of the applied voltage is typical for internal partial discharge. It is clearly to be distinguished from corona discharges in a pure gaseous insulation.

- Corona typically appears close to the crest of the applied AC voltage.
- The capacitance value of a bulk insulation typically is in the range of 10..100 pF for fixations (spacers, insulators) and can be higher for cables (typically 10..100 pF per m) and much higher for capacitors (pF to μ F range).

For an applied DC voltage the gas-filled bubble can be described as capacitor C_1 . This capacitor element is switched in series with the surrounding solid insulation material represented by the resistor elements R_2 and R_3 - see Figure 4-6 c. The resistor elements can be merged into a replacement element R_{23} . Assuming that the voltage u_1 at the void capacitance C_1 is reaching a critical voltage to trigger a local breakdown, the element C_1 is immediately discharged. The recovery of the voltage u_1 is concurrent with the reaching of the void element C_1 . The recharging current i can only be transferred through R_{23} . As this current through a resistor is proportional to the applied voltage it stays stable with the DC voltage, however, as solid insulating material have a high insulation resistance, the recharging current is low and therefore partial discharges at DC appear rarely at a low repetition rate, sometime few pulses per hour or day.

At AC pulse can occur in each zero-transition, when the critical inception threshold is reached.

4.3.4 Paschen breakdown

The Paschen breakdown is an effect relevant for the breakdown of gaseous insulation. It is fully in line with the theory of avalanche breakdown as described in section 4.3.2.2 and in Figure 4-2. As a consequence of the avalanche breakdown there is always an optimum, where molecule distance (given by gas pressure) and electrical field strength (given by total gap distance) are providing optimum conditions for ionisation. For these "optimum" conditions the result is a very low breakdown voltage. This physical relation is expressed by the "Paschen Law" and the corresponding "Paschen Curve", which gives the breakdown voltage as a function of the product of pressure and the gap spacing as shown in Figure 4-7.

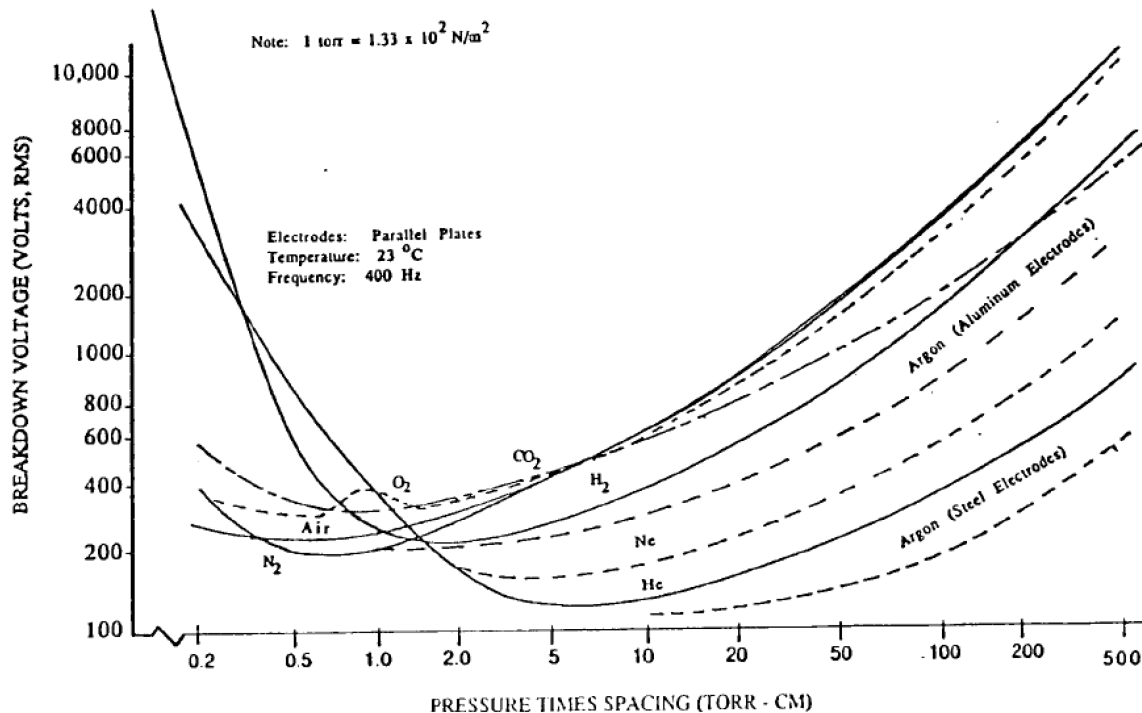


Figure 4-7: Breakdown voltage of gases vs. the product of pressure times gap spacing

Pressure Conversion: 1000 mbar = 1 bar = 1 atm = 10^5 Pa = 760 mm Hg = 760 Torr

Ref: Dunbar, W.G., High Voltage Design Guide: Aircraft, AFWAL-TR-82-2057, January 1983, pp. 33.

The Paschen Curve and its minimum depend on:

- Gas and Gas Mixture
- Voltage type: AC, DC or pulse

NOTE For most voltage types the peak voltage is the most determining value, except for pulsed voltage in the us-range and below.

- Electrode Material
- Electrode Shape

As the consequence the following aspects should be considered for space applications:

- The pressure conditions of the Paschen Minimum are always met, if a spacecraft transits from ambient pressure to space vacuum.
- The situation cannot be improved by increasing the gap distance (then the optimum breakdown conditions are met at a different pressure).
- Critical Paschen pressure condition can stay over long periods of time if the depressurization of a spacecraft is slow (improper venting in cavities, outgassing) or increase of leakage of pressurized systems.
- For typical gaps in the mm or cm range, the critical pressure is found in the range between 10^{-2} mbar and 10^1 mbar (1 Pa to 1000 Pa).
- Typical values for the pressure distances leading to the Paschen minimum are given in Table 4-7 with reference to technically relevant gap distances.

- Special conditions can apply for planetary probes entering atmospheres of other planets and bodies: the conditions for the relevant atmospheric gas mixtures are evaluated individually.

Table 4-7: Paschen Minimum for various gases

Gas	Breakdown Voltage <i>U_{d-min}</i> V	Paschen Minimum Pressure times Spacing		Pressure for Minimum vs. Gap Spacing			
		(pd) _{min} hPa μm	(pd) _{min} hPa mm	@ 1 mm hPa	@ 1 cm hPa	@ 10 cm hPa	@ 1 m hPa
SF ₆	507	3,5	0,0035	3,5	0,35	3,5 10 ⁻⁰²	3,5 10 ⁻⁰³
O ₂	450	9,3	0,0093	9,3	0,93	9,3 10 ⁻⁰²	9,3 10 ⁻⁰³
CO ₂	420	6,8	0,0068	6,8	0,68	6,8 10 ⁻⁰²	6,8 10 ⁻⁰³
Air	330	7,3	0,0073	7,3	0,73	7,3 10 ⁻⁰²	7,3 10 ⁻⁰³
N ₂	240	8,6	0,0086	8,6	0,861	8,6 10 ⁻⁰²	8,6 10 ⁻⁰³
H ₂	230	14	0,014	14	1,4	0,14	1,4 10 ⁻⁰²
Ne	130	53,2	0,0532	53	5,3	0,53	5,3 10 ⁻⁰²
Ar	94						
He	155	53,2	0,0532	53	5,3	0,53	5,3 10 ⁻⁰²

Pressure Conversion: 1000 mbar = 1 bar = 1 atm = 10⁵ Pa = 10³ hPa = 760 mm Hg = 760 Torr

Operation of high voltage close to Paschen breakdown conditions should be typically avoided. Suitable measures are proposed in section 5.1, 5.2.2 and 5.2.5.

4.3.5 Ageing

4.3.5.1 Ageing of gaseous, liquid and vacuum insulation

Gaseous and vacuum insulation are not subject to ageing effects. However, there are some “indirect effects” to be considered. Liquid insulation is vulnerable to ageing. The specific aspects of the different insulation types are briefly explained in the following:

For gaseous insulation:

- The pressure conditions can change over time, i.e. leakage of a pressurized containment can result over time into a decay to a critical low pressure.
- The chemical composition can change over time, by leakage of tanks etc. or by electrochemical processes.

As an example: SF₆ gas can be subject of decomposition in the presence of humidity and corona. Nevertheless an effect on gas volume breakdown strength is unlikely, unless a very significant amount of the gas volume has been changed. However, an indirect effect can occur as the chemical decomposition can create corrosive by-products (e.g. SF₆ reactions with humid air can result in aggressive by-products affecting surfaces of solid insulators).

For liquid insulation:

- The chemical composition can change over time, responsible processes can be:
 - Oxidation (example: mineral oil, acceleration of oxidation in presence of copper)
 - Partial discharge (destructing molecules or causing polymerisation)