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EUROPEAN COOPERATION FOR SPACE STANDARDIZATION

Space engineering

High voltage engineering and design handbook

ECSS Secretariat
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Requirements & Standards Division
Noordwijk, The Netherlands

Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

The material in this Handbook is defined in terms of description and recommendation how to organize and perform the work of design, manufacture, integrate and test high voltage equipment, modules and components for use in space applications. It complements ECSS-E-ST-20C and covers power conditioning elements as well as their interfaces to the power consumers.

This handbook has been prepared by the ECSS-E-HB-20-05A Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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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 (N_2/O_2 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.

2 References

ECSS-S-ST-00-01C	ECSS System – Glossary of terms
ECSS-E-ST-10-03C	Space engineering - Testing
ECSS-E-ST-10-02C	Space engineering - Verification
ECSS-E-ST-10-04C	Space engineering - Space environment
ECSS-E-ST-20C	Space engineering - Electrical and electronic
ECSS-E-20-01A	Space engineering - Multipaction design and test
ECSS-E-ST-20-06C	Space engineering - Spacecraft charging
ECSS-E-ST-32C	Space engineering - Structural general requirements
ECSS-Q-ST-30-11C	Space product assurance - Derating – EEE components
ECSS-Q-ST-70-10C	Space product assurance - Qualification of printed circuit boards
ECSS-Q-ST-70-11C	Space product assurance - Procurement of printed circuit boards
ECSS-Q-70-71A	Space product assurance - Data for selection of space materials and processes
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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
ASTM-D-638 (2010)	Standard Test Method for Tensile Properties: of Plastics
ASTM-D-695 (2010)	Standard Test Method for Compressive: Properties of Rigid Plastics
ASTM-D-794 (1993)	Practice for Determining Permanent Effect of Heat on Plastics
ASTM-E831 (2006)	Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis
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3 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-00-01C apply, in particular for the following terms:

acceptance

applicable document

approval

critical item

derating

design

development

efficiency

environment

failure

flammability

function

hazard

hazardous event

inhibit

inspection

integration

interface

launcher

life cycle

life profile

lifetime

maintainability

maintenance

material

mission

model

nonconformance

payload

performance

procedure

process

product

product assurance

project

quality

quality assurance

quality control

redundancy

reliability

repair

residual risk

review

risk

safety

single point failure

space debris

space system

spacecraft

specification

standard

subsystem

supplier

support system

system

tailoring

toxic

traceability

validation

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 Ω m: insulating
- between 10^7 Ω m and 10^9 Ω m: antistatic
- between 10^3 Ω m and 10^6 Ω m: static dissipative
- between 10^{-2} Ω m and 10^2 Ω m: moderately conductive
- less than 10^{-2} Ω 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
FEEP	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

Abbreviation	Meaning
TM/TC	telemetry/telecommand
TRB	test review board
TRR	test readiness review
TWT	travelling wave tube
TWTA	travelling wave tube amplifier
UV	ultraviolet

4 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 atm = $1{,}013 \cdot 10^5$ 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:

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

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

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

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-10-04C. 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-20-06C. 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-10-04C. 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 possibly 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.

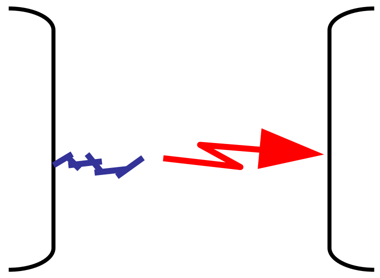


Figure 4-1: Arc Caused by Particle Bridge

4.1.6 Plasma

Spacecrafts are exposed to various plasma environments as described and defined in ECSS-E-ST-10-04C. 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-20-06C (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-32C (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/dm³	Thermal conductivity W/m K	Evaporation temperature °C	Electrical breakdown field strength (see Note 3) kV/mm
Air	1,21	$25{,}6 \cdot 10^{-3}$	-	3,2
N_2	1,17	$25{,}5 \cdot 10^{-3}$	-195,8	3,3
O_2	1,33	$26 \cdot 10^{-3}$	-183,0	2,9
CO_2	1,84	$16 \cdot 10^{-3}$	-78,5	2,9
H_2	0,08	$179 \cdot 10^{-3}$	-252,8	1,9
He	0,17	$149 \cdot 10^{-3}$	-269,0	1,0
Ne	0,84	$48{,}3 \cdot 10^{-3}$	-246,0	0,29
Ar	1,66	$17{,}5 \cdot 10^{-3}$	-185,9	0,65
Kr	3,48	$9{,}4 \cdot 10^{-3}$	-152,9	0...8
Xe	5,50	$5{,}5 \cdot 10^{-3}$	-170,1	-
SF_6	6,15	$18{,}8 \cdot 10^{-3}$	-63,8	8,9

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: all properties referred to a temperature of 20 °C / pressure 1 atm = 1013 mbar = 1013 hPa

Note 3: electrical breakdown field strengths for a homogeneous field with a gap distance of 1 cm under short-term stress

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 deducted 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, micanite).

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 δ	-	10^{-2}	10^{-2}	$2 \cdot 10^{-2}$	$5 \cdot 10^{-3}$
Tracking Resistivity	-	+	o	++	++
Specific Gravity γ	g/cm³	1.2	1.8	1.2	1.2
Elastic Modulus	kN/mm²	4	12	0.5	
Bending Strength	N/mm²	140	135	135	
Tensile Strength	N/mm²	80	90	*	*
Compressive Strength	N/mm²	*	*	3	
Thermal Conductivity	W/K m	0.2	0.8	0.24	
Thermal Expansion	10^{-6}/K	65	35	200	
Max. Operat. Temp.	ºC	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 δ	-	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/cm³	2.15	1.13	1.20	1.42	1.43
Elastic Modulus	kN/mm²	0.5	3.3	2.2	*	*
Bending Strength	N/mm²	15	90..130	90	*	120
Tensile Strength	N/mm²	20	64..75	*	180	91
Compressive Strength	N/mm²	*	*	*	*	*
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 δ	-	5.10^{-3}	2.10^{-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 it "status" determines the breakdown mechanism. Concluding, the following influences need to 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 it 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

$$U_d = E_d \cdot d \qquad [4\text{-}3]$$

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.

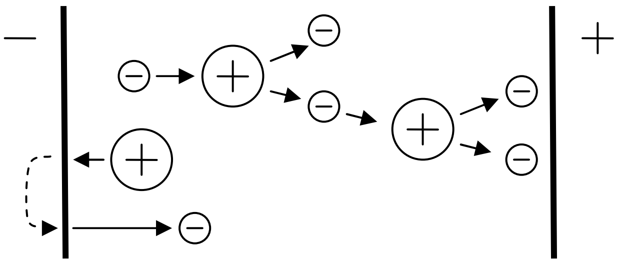
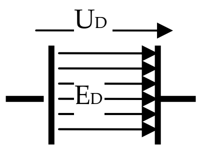


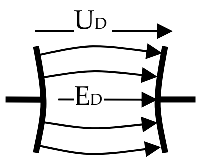
Figure 4-2: Discharge (breakdown) development in a gas volume between two electrodes by electron avalanche process

The following specific effects are taken into consideration:

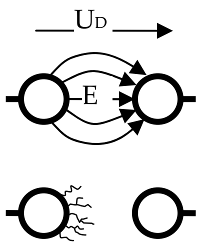
- Homogeneous electrical field (assuming an ideal plane-to-plane electrode configuration) the breakdown voltage can be determined according to equation [4-3] from the gap distance and the breakdown field strengths as a characteristic value. This statement is valid for gap distances of a few mm or cm at close-to ambient pressure or higher.



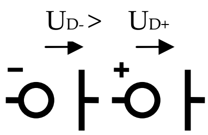
- Slightly inhomogeneous electrical field (assuming curvature with larger radius) the breakdown voltage can be determined with the assumption made for the homogeneous field as stated above.



- 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.

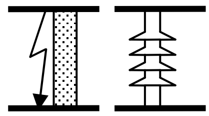


- For unsymmetrical inhomogeneous fields, there is a polarity effect caused by space charge formation, leading to the following consequences: if the electrode with the stronger curvature is at a negative potential, the corona starts at a lower voltage, but the breakdown voltage is higher – in comparison to the case with the electrode of the stronger curvature is positive (no corona or corona at voltage close to breakdown).

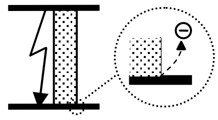


- The material of the electrode can affect the breakdown voltage due to the effect of different interactions with colliding free charge carriers.
- The surface of the electrode can affect (slightly reduce) the breakdown voltage due to the effect of surface roughness (local field enhancements).

- 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.

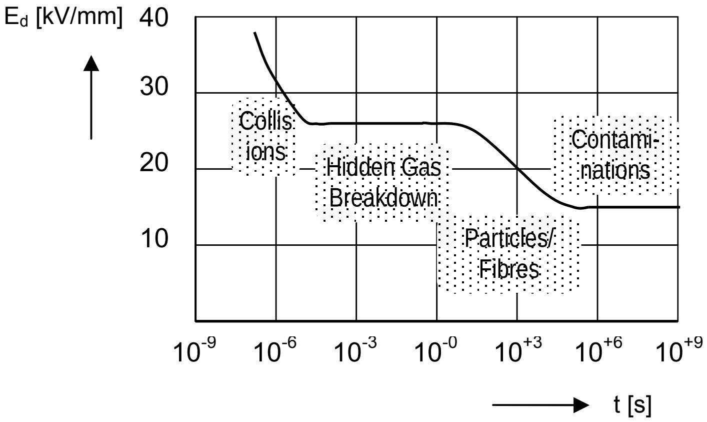


Figure 4-3: Electrical strengths of a liquid insulation (here: transformer oil in 2,5 mm gap) in relation to voltage exposure time and assumed breakdown mechanism

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 electrons 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

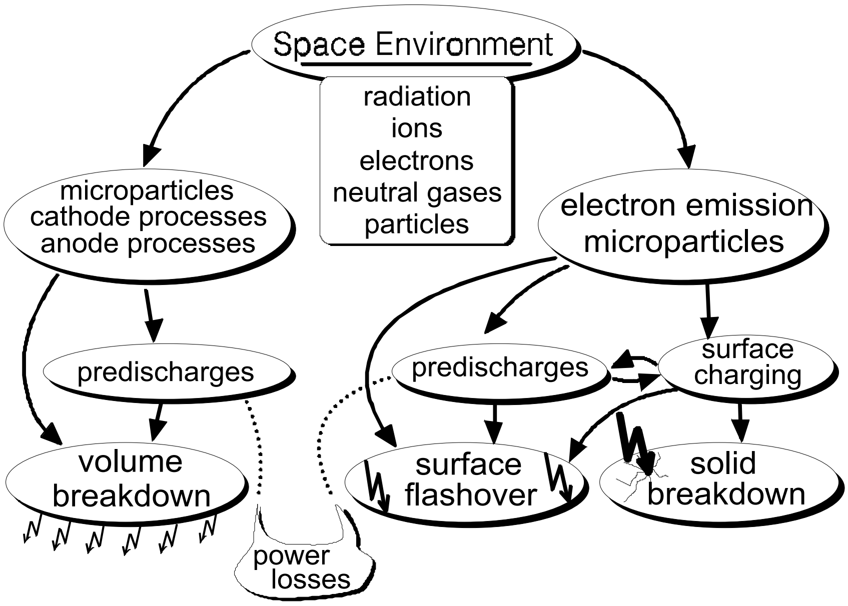


Figure 4-4: Vacuum breakdown phenomena

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.

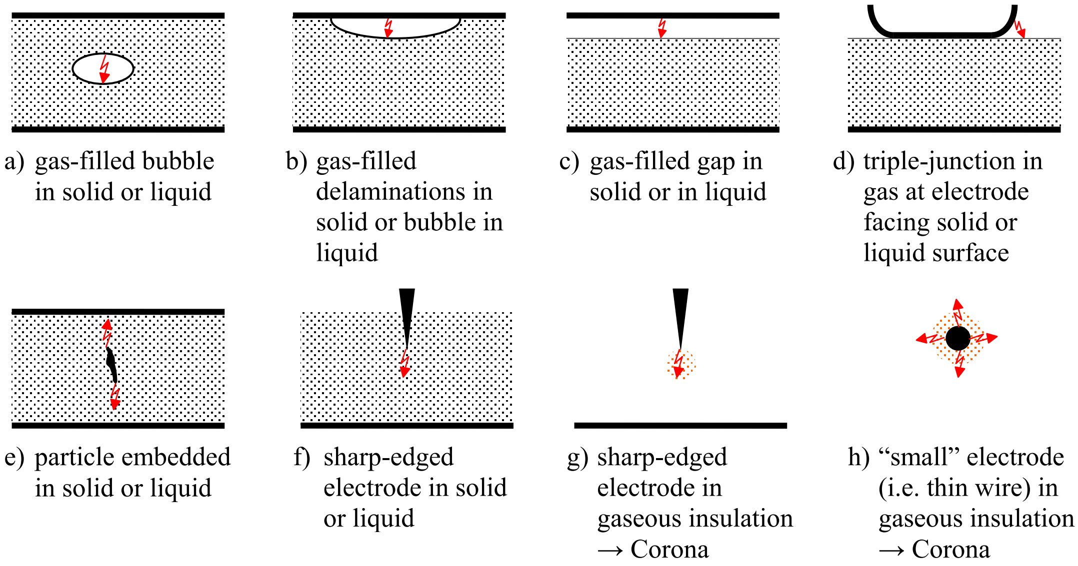


Figure 4-5: Typical partial discharge configurations

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 breaksdown, while for solid or liquid parts initially withstand the breakdown.
- the gaseous insulation has typically a dielectric constant around ε≈1 whereas the solids and liquids have an higher dielectric constant (many of them ε=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.
- predischarge 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.

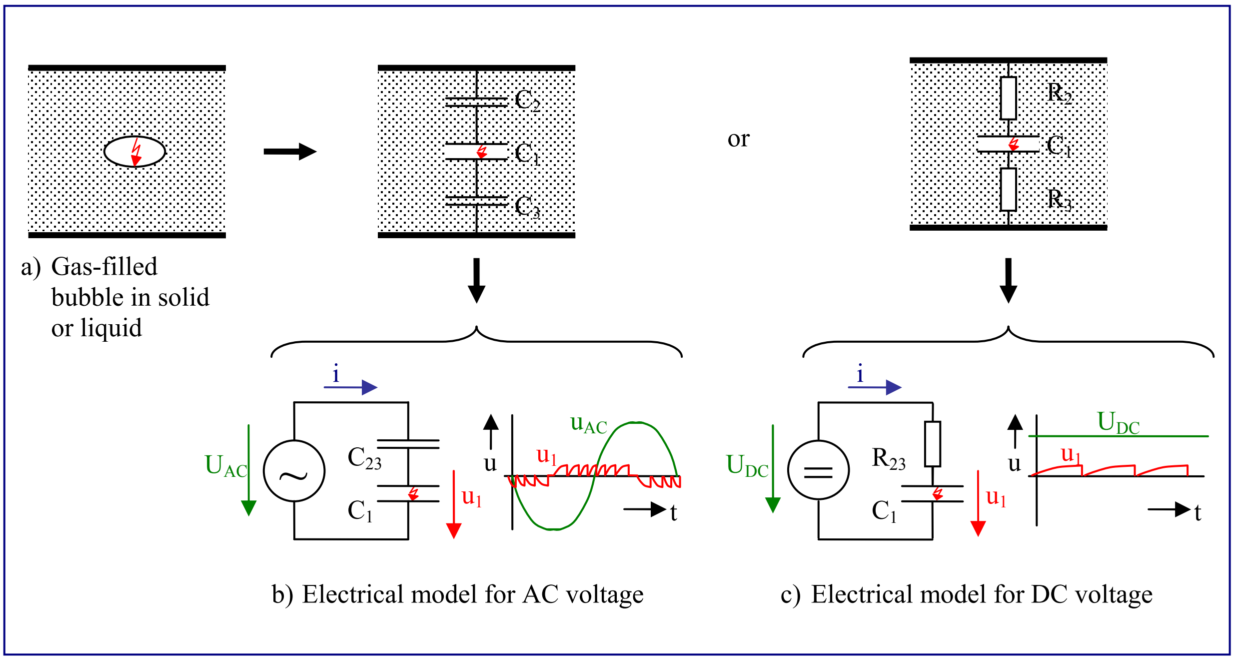


Figure 4-6: Electrical model of partial discharges for a gas-bubble in a solid

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 $i \approx C_{23} \, du_{AC}/dt$, 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 µF 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.

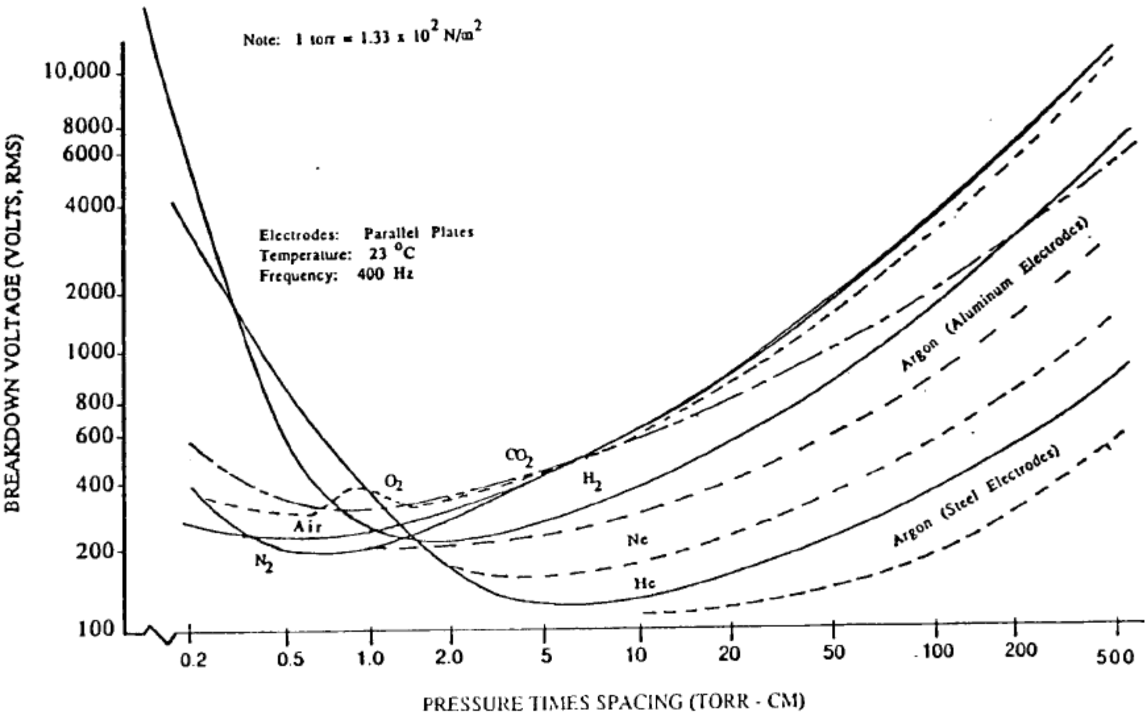


Figure 4-7: Breakdown voltage of gases vs. the product of pressure times gap spacing

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 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* *Ud-min* V	*Paschen Minimum Pressure times Spacing* *(pd)min* hPa µm	*(pd)min* hPa mm	*Pressure for Minimum vs. Gap Spacing* *@ 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 = 10^5 Pa = 10^3 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: SF_6 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. SF_6 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)

    — Radiation (destructing molecules, however, only relevant for extreme high radiation doses).

- Increase of water content (especially, if exposed to natural atmosphere)
- For encapsulated systems in space environment: the pressure conditions can change over time, i.e. leakage of a pressurized containment can result over time into decay to lower pressure. If the vapour pressure of the liquid or of solved gases (contaminants) is reached, gas bubble can be formed and trigger a breakdown.

  As liquid insulations are rarely used in space application, the above mentioned ageing effects are not further explained here. In case of use of such insulation, it is proposed to make advantage of available information from power industries and related research.

For vacuum insulation:

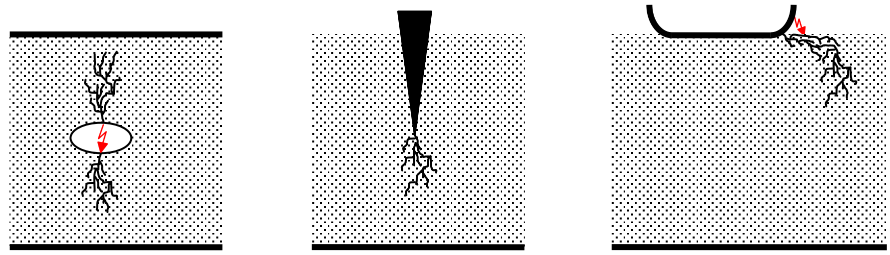
- The pressure conditions can change over time, i.e. leakage of a pressurized tank nearby can result over time into a raise to critical high pressure.
- Similarly, outgassing from surfaces can cause problems related to local "micro-atmosphere" – however, in most cases the outgassing effect decays with long exposure in a vacuum, which leads typically to an improvement of electrical strengths, not a worsening.

4.3.5.2 Ageing of solid insulation

4.3.5.2.1 Ageing mechanisms

Solid insulations are widely used in space applications and they are subject to various relevant ageing effects. As the various effects resulting to a breakdown in long-term are complex and interacting in a complex matter, there is actually no "universal" approach to explain ageing of solids and to predict lifetime precisely. The most relevant aspects are explained in the following:

- First of all, the final breakdown mechanism is assumed to be electrical and can happen (finally) in a short-term. The (final) breakdown mechanism is most likely one of the following: the pure "intrinsic" electric breakdown, thermal breakdown or partial discharge breakdown as already addressed in section 4.3.2.4. However, on the way to the breakdown on a long time-scale of hours, days or years, there is a significant influence of degradation by mechanical, thermal, thermo-mechanical, chemical, electro-chemical, radiation-induced, electrically induced processes as well as by the already addressed partial discharge driven mechanism.
- Partial discharges form erosive channels in the insulation. The starting point of the partial discharge is a weakness in the insulation, often, but not always in an area with higher field strengths. The erosion channel propagates over time. The channel path is not necessarily leading straight in the direction of the highest macroscopic electrical field and can subdivide into many branches forming tree-like structures (see Figure 4-8). The electrical breakdown occurs, when the insulation is weakened by the growing tree – i.e. when branches have been protruded that a significant part of the insulating gap is bridged. Treeing is often observed in polymeric insulation.



a) Gas-filled bubble with treeing in both directions

b) Sharp needle with treeing

c) Surface electrode with "sideward" treeing

Figure 4-8: Electrical treeing caused by partial discharges

- Erosion by partial discharge can start at zones with irregularities shown in the examples of Figure 4-5). Often irregularities are not visible and are related to defects in the molecular structure of the solid, anisotropic zones, zones of charge injections, border of grain etc.
- Thermo-mechanical stress is an important factor of ageing, as it can result in micro-cracking and delamination, enabling partial discharges and electrical breakdown.
- Thermal stress at high temperature accelerates chemical ageing effects; low temperatures can make the insulating material brittle and creating cracks.
- Mechanical stress (i.e. permanent pressure or tension in the material, or load cycles) can cause delamination and cracks.
- Chemical ageing is going along with modifications of the molecular structure, consequently the material properties change, typically with a loss of electrical and mechanical strengths.
- Water and humidity is an important factor for ageing, especially for polymeric materials. It can enter by diffusion in many materials. Moreover, the polar molecule of water is subject to movement by electric forces. The chemical structure of the material can be modified by hydrolysis. The electric insulation properties are modified due to presence of water/humidity is typically negative.
- Radiation can induce two effects: one is a local destruction of the molecular and atomic bindings of the material, the other one is the generation of charges. Especially in materials with high resistivity, the generated charges can increase the local electrical field strengths. Local destruction of molecules can make the polymeric materials more brittle, making the insulation more vulnerable w.r.t cracking.

4.3.5.2.2 Modelling of Ageing

The complexity of ageing mechanisms for electrical insulations is high. As a consequence, there are no models available with a general validity. Currently available models are either based on empirical data or a physical-mathematical approach. They are only usable for a limited range of materials, applications, and parameters. In the following, some approaches of lifetime modelling and estimations, are considered:

- Thermal ageing model
- Thermo-mechanical ageing model
- Electrical ageing
- Combined thermal and electrical ageing

It is clearly emphasized, that none of the presented methods to estimate lifetime can be used solely and without validation for the specific material and for the specific type of application/stress.

4.3.5.2.3 Thermal ageing model by Arrhenius

An ageing model based on temperature effects (only) is referring to the "classical" Arrhenius equation:

$$t = A \exp\left[\frac{W_a}{kT}\right] \qquad [4\text{-}4]$$

where:

- t lifetime
- A adjustable constant
- W_a activation energy
- k Boltzmann Constant
- T temperature

Note: that this equation considers temperature as the only ageing parameter. Electrical ageing mechanisms are not covered. The adjustable constant A can be determined experimentally. A very detailed statistical approach is described in the standard IEC 60216-1.

References are made to:

T.W. Dakin, "Electrical Insulation Deterioration Treated as Chemical Rate Phenomenon", AIEE Transactions, Vol. 67, pp. 113-122, 1948.

T.W. Dakin, "Electrical Insulation Deterioration", Electrotechnology, Vol. 3, pp. 129-13-, 1960.

IEC 60216-1 "Properties of thermal endurance, Part 1: Ageing procedures and evaluation test results" – International Standard.

4.3.5.2.4 Thermo-mechanical ageing model by Halpin

For solid materials thermo-mechanical ageing is an important factor, especially under the assumption, that formation of cracks and delamination is the root cause of a subsequent electrical failure. Based on experience with failures in complex printed circuit boards, fatigue related failures due to thermal cycling are resulting in a typical stress-lifetime plot as a straight line in a semi-logarithmic plot. An example is shown in Figure 4-9.

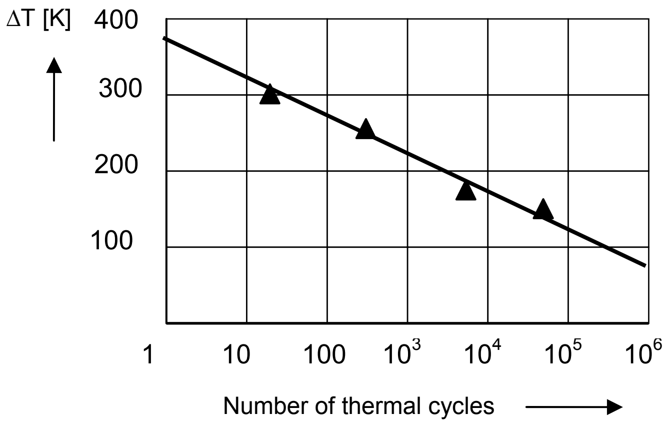


Figure 4-9: Example: Fatigue (thermo-mechanical stress-related) failures in assemblies expressed as stress (ΔT – temperature cycle amplitude) over number of thermal cycles

Under the assumption, that the Halpin model is valid, the stress-lifetime curve can be derived from a set of statistically relevant measurements at minimum 3 temperatures. Prediction of lifetime can be extrapolated from the straight line in the diagram.

Following this model a proof test at large amplitude of thermal cycling performed on a short time scale can allow to predict operational life as shown in Figure 4-10 including sufficient margin (expressed by the dotted line).

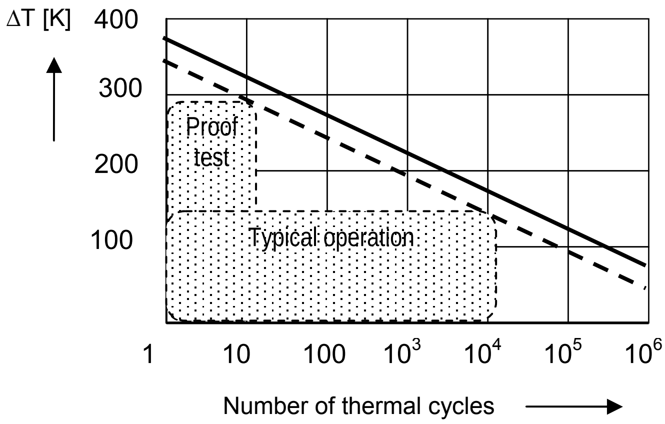


Figure 4-10: Example: Fatigue (thermo-mechanical stress-related) failures in assemblies expressed as stress (ΔT – temperature cycle amplitude) over number of thermal cycles

Note: this approach does not consider the effect of absolute temperature and of the absolute time of stress exposure.

The Halpin reference law is a straight line in the graphic number of cycles (logarithmic) versus thermal gradient. Under the assumption that a first reference point can be determined by experiment for a failure after N_1 cycles with a temperature gradient of ΔT_1 the applied Halpin law can be written as

$$N_1 = 10^{\left[\log(N_0) + \frac{\Delta T_0 - \Delta T_1}{36}\right]} \qquad [4\text{-}5]$$

where:

- N_0 Number of cycles till appearance of failure for reference point
- ΔT_0 Temperature gradient applied for determination of reference point in K
- N_1 Number of cycles till appearance of failure for expected point
- ΔT_1 Temperature gradient applied for determination of expected point in K

References are made to:

J. C. Halpin, "AVIP Air Force thrust for reliability", Institute of Environmental Sciences, Annual Technical Meeting, 31st, Las Vegas, NV, April 30-May 2, 1985, Proceedings (A86-23001 09-38). Mount Prospect, IL, Institute of Environmental Sciences, 1985, p. 206-218.

4.3.5.2.5 Electrical ageing based on inverse power law

The inverse power law considers the electrical field strengths as a driver for the lifetime as expressed in the following equation:

$$t = C\,E^{-n} \qquad [4\text{-}6]$$

where:

t lifetime,

C adjustable constant

E electrical field strengths

n constant

The constants *C* and *n* are investigated experimentally and are only valid for the material, the type of application and the ageing mechanism, which has been the subject of the experiment. If the ageing mechanism or relevant parameters change over time, a new curve is determined. Practically, the lifetime data are collected in a "log E over log t plot" or as "E over log t plot". The Data points should indicate a straight line.

4.3.5.2.6 Combined thermal and electrical ageing

A model for combined thermal and electrical ageing was presented by J.P. Crine (see references below). The mathematical expression determines the lifetime by an exponential factor expressing pure temperature dependence and a hyperbolic factor representing the influence of the electrical field:

$$t \cong \frac{h}{2kT}\exp\left[\frac{\Delta G_0}{kT}\right]\operatorname{csch}\left[\frac{e\lambda E}{kT}\right] \qquad [4\text{-}7]$$

where:

t lifetime

h Planck constant

k Boltzmann constant

T temperature

G_0 activation energy

e elementary electron charge

λ free path / submicrocavity size

E electrical field strengths

The constants G_0 and the parameter λ depend on the material and on the configuration. G_0 is determined by the material's activation enthalpy and the entropy of free space charges, so it fairly equivalent to the activation energy as stated in the Arrhenius equation (see eq. [4-4]). The parameter λ depends on the electrical field and defines the size of so-called submicrocavities, assuming the high electrical field strength is displacing the molecular structure in such a way that the free-path length of electrons allows collision based ionization effects. It can be difficult to determine the "unknown" parameters (G_0 and λ) of the equation [4-7] on a theoretical basis only.

A useful practical approach is to determine the relevant section of the stress-lifetime curve (*E* over log *t*) experimentally (see Figure 4-11). In accordance with the model, the resulting graph can be analysed separating two sections: the left section strongly depends on the electrical field strengths determining the ageing and the right section, nearly flat (independent on E-field). If the interception point can be clearly identified, it is possible to define a safe operating field strength limit.

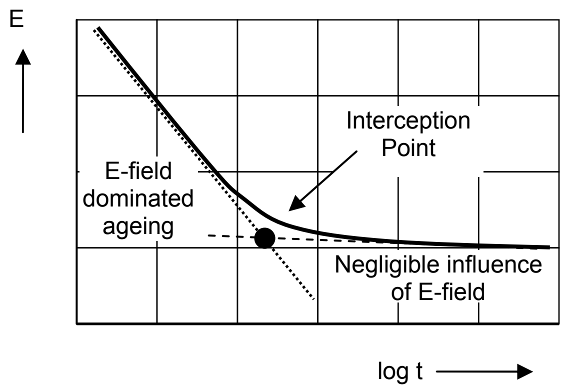


Figure 4-11: Electrical field strengths over time curve according to the Crine model

NOTE that this equation considers temperature and electrical field strength as the ageing parameter. Defects due to manufacturing processes or changes of environmental conditions are not directly reflected.

References are made to:

J.L. Parpal, J.-P. Crine, C. Dang, "Electrical Ageing of Extruded Dielectric Cables", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 4, No. 22, pp. 197-209, 1997.

J.-P. Crine, "Ageing and Polarization Phenomena in PE under High Electrical fields", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 9, No. 5, pp. 697-701, 2002.

Cygan P and Loghari J R 1990 Models for insulation aging under electrical and thermal multistress IEEE Trans.Elect.Insul. 25 923-34.

4.4 Typical applications

4.4.1 DC-DC High voltage power conditioners

High voltage conversion in space applications are in majority DC-to-DC voltage converters. For this type of power conversion there is typically an intermediate AC circuitry necessary, which means the DC-input voltage from the spacecraft power bus is converted into a high frequency AC voltage, before it is stepped up to high voltage level. The waveform of the intermediate voltage is either sine, square wave or something in-between. The frequency is typically in the range of 15-250 kHz. The basic principle of the power flow is shown in Figure 4-12. This AC voltage is typically fed into a transformer and then multiplied, either by the transformer itself or in combination with a multiplier circuit. Sometimes a post regulation at the output side is used as well, however, often the output voltage regulation is done at the low voltage section: either by a DC/DC pre-regulator (Buck, Boost, etc.) or by a regulated DC-to-AC converter.

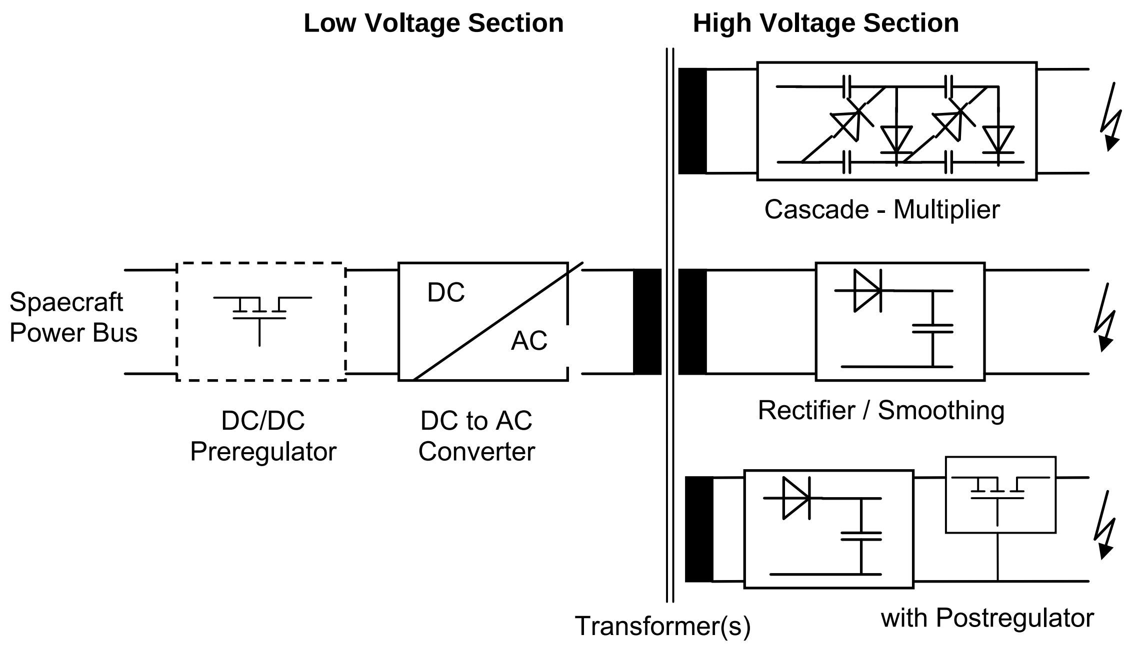


Figure 4-12: DC/DC power conversion chains for high voltage of an EPC

For the core part of the high voltage generation there are basically two different principles of conversion into high voltage:

- Transformer (with subsequent rectifier/filter for DC) – see Figure 4-13 a)
- Capacitor-Diode Networks ("Cockroft-Walton Multiplier", "Greinacher Cascade") as a single cascade: see Figure 4-13 b) or as a double cascade: see Figure 4-13 c)

The cascade multiplier is very mass efficient for a low power application (typically of a few Watts output power); the number of multiplier stages varies between 2 and 20. Higher numbers of stages are critical with respect to loop stability. Furthermore the ripple of the output voltage and the output impedance increase significantly.

Voltage step-up via a transformer is an efficient solution for conversion with power levels above a few Watts. For high DC output voltages a number of transformer windings can be individually rectified and switched in series.

It is important to limit the AC stress inside of the high voltage insulation as far as possible; therefore it is preferred to reduce the AC output voltage per windings in favour of adding the output voltage of a higher number of rectified smaller high voltage stages. The reduction of AC voltage reduces the risk of life time limiting partial discharges. Often the voltage per stage is between 600V and 1200V; however, the selection of the appropriate topology and voltage is typically the outcome of a trade-off of many different parameters and aspects.

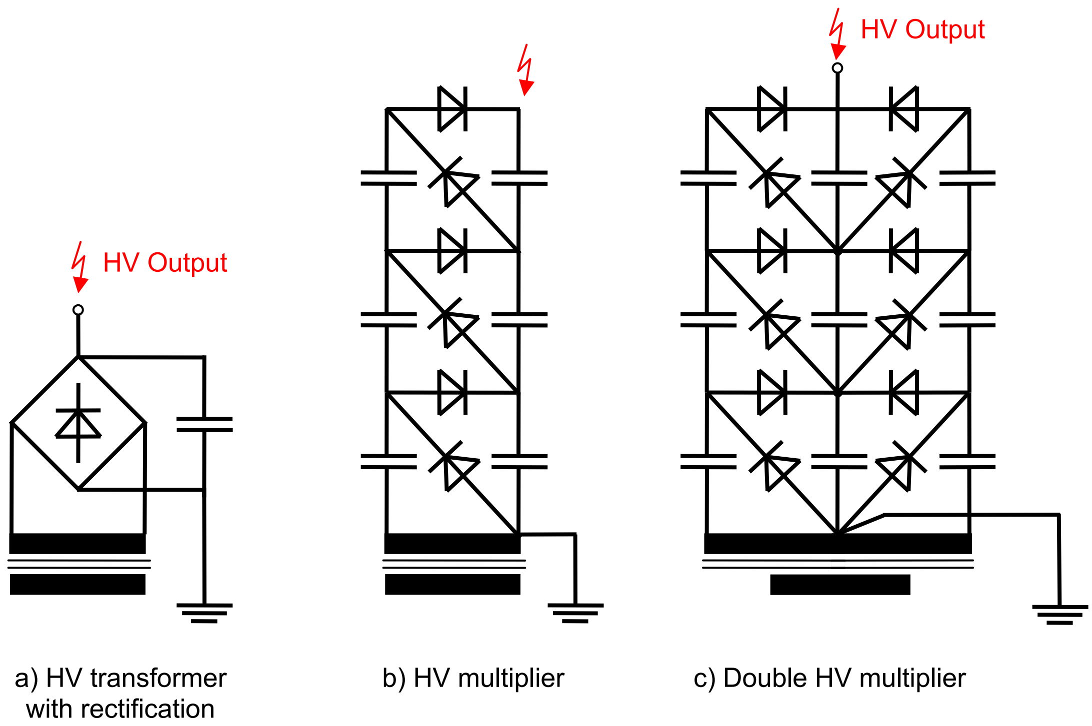


Figure 4-13: Topologies of electronic power conditioners

Only in a few applications transformerless circuits are used, but for the typical high power levels of communication EPC the use of high voltage transformers is inevitable.

4.4.2 Electronic power conditioners for TWTA

4.4.2.1 Electrical power conditioner for TWTA overview

Travelling Wave Tube Amplifiers (TWTA's) are commonly used for communication links of satellites and therefore have a very broad range of applications for communication satellites. In addition, TWTA's are used for any other communication links for satellites, probes, and other space vehicle, for example for ground-to-spacecraft up and downlinks or for inter-spacecraft communications links. Especially telecommunication satellites are equipped with a large number of TWT's (some 10 up to in the order of 100). The TWTA is formed by the Electronic Power Conditioner (EPC) and the Travelling Wave Tube (TWT). The TWT is an electron device (see section 4.4.2) and used to offer RF power of 40 W to 170 W for typical space applications in the Ka/Band and Ku-Band frequency range, for high power S-Band up to 500 W RF power are targeted. The efficiency of a TWT is up to the 70 % range and therefore the EPC has to delivery adequate DC power. Especially to due the high number of such devices on telecommunication satellites, their dimensions, mass, and efficiency (and cost) are major contributors to the satellites' budgets and therefore require special attention.

Generally, the EPC provides a number of very stable high voltage outputs required by the TWT. It generates these outputs from a more or less stable main bus voltage. Typically output voltages needed are the following:

- Helix Voltage
- Cathode Voltage
- Collector Voltages (typically 3 to 5 collectors)
- Heater Voltage (Low voltage floating on cathode potential)

In order to avoid negative impact on the RF performance, the TWT requires these voltages to be very stable vs. temperature, load, and life of the unit, as well as practically free of ripples. The EPC generates these high voltages out of a bus voltage of typically unregulated 28 V or regulated 50 V, 70 V or 100 V. The helix voltage is up to approximately 8500 V (for current Ka-Band tubes) and should be stable within 1 V for any output power level respectively within some 10 V vs. temperature and 15 years of life in orbit. The voltage ripple should be less than 0,5 V.

Furthermore, the EPC also needs to provide further functions: it has to accept and process Telecommands (typically pulse commands) and it has to generate analogue and digital telemetry signals. It has to generate secondary power supply voltages to supply a linearizer and/or channel amplifiers. An internal logic needs to ensure that the switch on of the TWT is safe and without stress for the TWT, and it has to have protection circuits to protect the TWT and the EPC against incorrect operation or high voltage arcing.

4.4.2.2 EPC design

Figure 4-14 shows the functional block diagram of an EPC. The main bus voltage (Vmb) is fed through an input filter into a preregulator which converts the input voltage into a constant output voltage (Vb). This preregulator is one of the key components of the EPC controlling commonly several main output parameters of the EPC and respectively as well of the TWT.

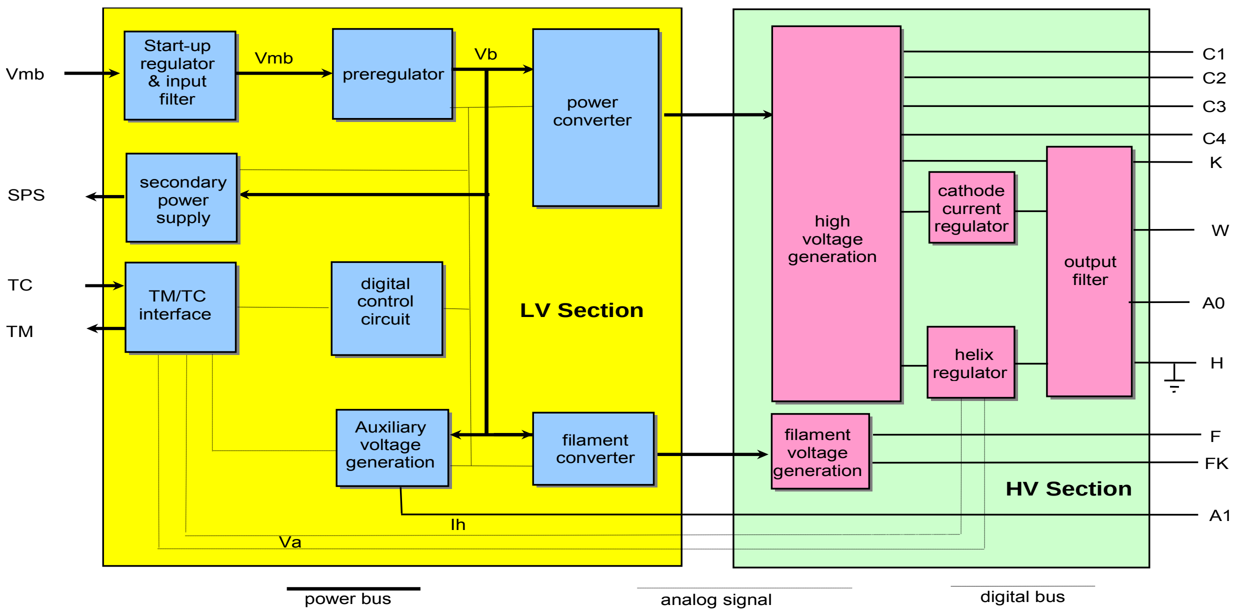


Figure 4-14: Functional block diagram of an EPC

The TWT interface consists of the collector voltage C_1,C_2,C_3,C_4 and eventually C_5, the cathode voltage K, the Wehnelt W and the anode voltage A0, the filament heater voltage F to F_K, the anode voltage A and the helix voltage H.

This regulator has to ensure high efficiency, low conducted susceptibility, good regulator loop stability and proper pulsed load behaviour. Suitable solutions are typically switch-mode power supplies of buck or boost type.

The DC-to-AC power converter is fed from the constant voltage V_b and generates a square wave or sine-wave output voltage by using a push-pull converter to generate the required voltage waveform including a definite gap time. The main features of the power converter are high efficiency, suppression of high voltage transformer ringing, inhibition of short-circuit currents in the switching transistors, and soft recovery for the high voltage diodes. An auxiliary preregulator generates a second constant output voltage (V_{b2}) which is used to generate the supply voltages for the internal electronics. The output of the auxiliary preregulator power is connected to the compensation unit and to the filament converter. The filament converter is then generating the necessary AC supply voltage for the TWT filament heating. The filament heater low voltage is floating on the high voltage potential of the cathode. A soft start is implemented for the filament converter to avoid surge currents when the tube filament is cold and has then a lower resistance.

An important part of the power chain is the high voltage generation. The method used to generate high voltage and to apply it to the TWT is an important influencing factor on TWT behaviour. With a suitable output filter design the tube can be switched ON by applying all high voltages simultaneously without an excessive spike on the helix current in the TWT.

An optimum output characteristic can be achieved by a serial high voltage concept. The output voltage of the power converter is transformed by one high voltage transformer and rectified by stacked doubler stages for collector, helix and anode voltages. The stability of the collector voltages is only determined by the pre-regulator output voltage Vb. In addition, the helix and anode voltage are regulated by the helix regulator and the cathode current regulator to ensure a constant RF behaviour of the TWT.

The in-orbit tunability is given by adjusting the cathode current via telecommand to the required operating point of the TWT. All internal processes of the EPC are typically managed by a digital control circuit. This functional block is integrated in an Application Specific Integrated Circuit (ASIC) or a Field Programmable Gate Array (FPGA).

On the low voltage side the EPC provides a number of additional low voltages SPS for supply of external units. For example: linearizer amplifier for the rf input signal of the TWT.

The strong need for cost and mass saving has led to the development of Dual EPC’s operating two TWT’s in parallel, for this purpose two identical high voltage output sections are couple through one high voltage transformer to one low voltage section. As both outputs now are following simultaneous the output voltage of the only pre-regulator, different set point of the high voltage fed to the both TWT’s can be only individually compensated by the cathode current regulators and the helix regulators on the high voltage side. Both have wider range for Dual EPC than those used in a single EPC.

4.4.2.3 EPC high voltage generation

This functional block comprising the high voltage generation consists of the main high voltage transformer, the rectifiers and voltage rectification stages as shown in Figure 4-15. The supply voltages for the TWT are generated by one high voltage transformer with various voltage rectifier circuits.

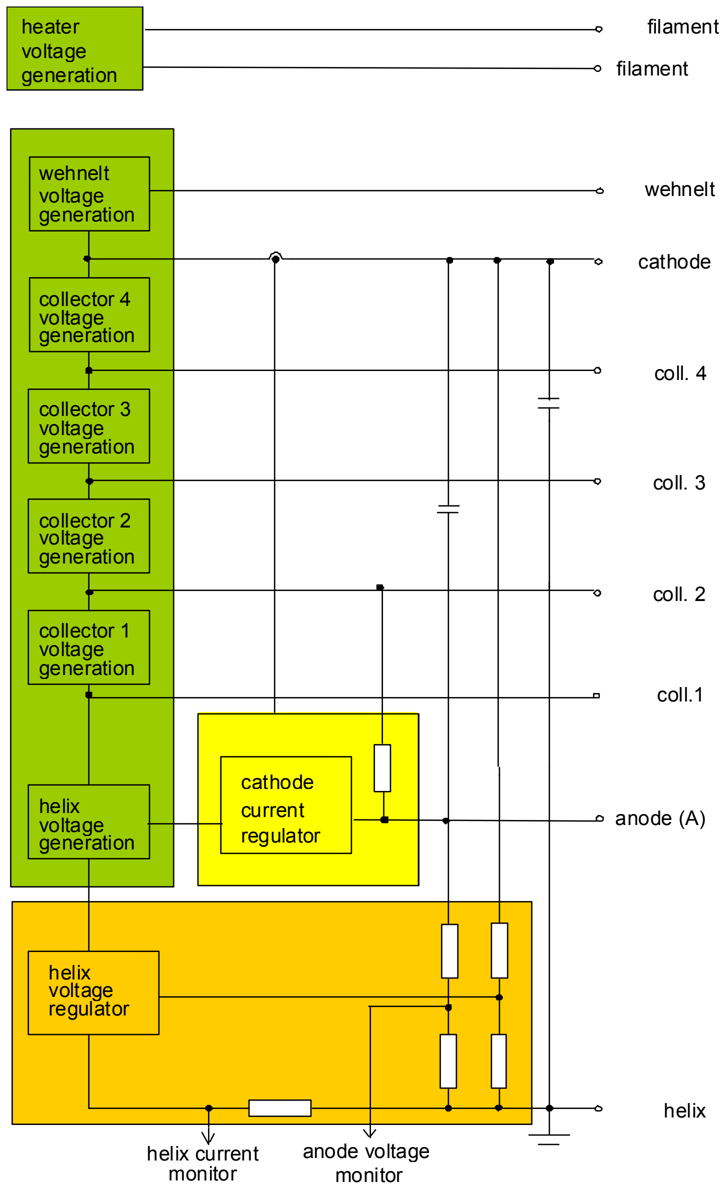


Figure 4-15: Example for a high voltage generation of an EPC

The collector voltages are generated by a number stacked rectifier circuits and routed to the output without any further filtering. However, current limiting resistors are inserted into the output lines to protect the EPC against external short circuits. The helix voltage is generated by the remaining doubler rectifier circuits which are stacked on the collector generation.

The anode 0 voltage is generated by connecting the input of the cathode current regulator to a suitable voltage of the serial high voltage generation. Some tubes require an anode 1 voltage; this is generated by the auxiliary voltage converter and a bridge rectifier circuit. The anode 1 Voltage is connected to the helix on the low voltage part.

The main high voltage transformer is the "heart of the EPC" and is challenge in manufacturing. Its design requires an optimization of the size of the unit. During manufacturing typically a transformer is precisely matched to a specific (already characterized) TWT or to a group of TWT. The matching is done by selecting suitable number of turns of the different transformer windings in accordance with the needs of a specific tube or a tube lot.

It is highlighted, that each manufactured TWT is unique in it characteristics, this requires dedicated manufacturing of a matched EPC, or some flexibility of set point for the output voltages or a combination of both. Modern EPC include tuning flexibility of a certain range to match to more than one specific tube, to compensate in-orbit drift of the output parameters and to adjust to different rf set points.

The high voltages required by the TWT are generated from the relatively low primary bus voltage. In the example shown in Figure 4-15 the voltage is stepped up by the HV transformer which mainly consists of a U-shaped tape wound core and the two epoxy potted HV coils (see Figure 4-16). The double-wound (bifilar) primary winding potted from the inside onto the slotted aluminium capsule forms the inner wrap of the HV coils. The aluminium capsule acts as a heat dissipater for heat generated within the windings and as a shield between the primary and secondary windings. The secondary windings are wound onto a bobbin which receives an insulation layer before being pushed over the aluminium capsule.

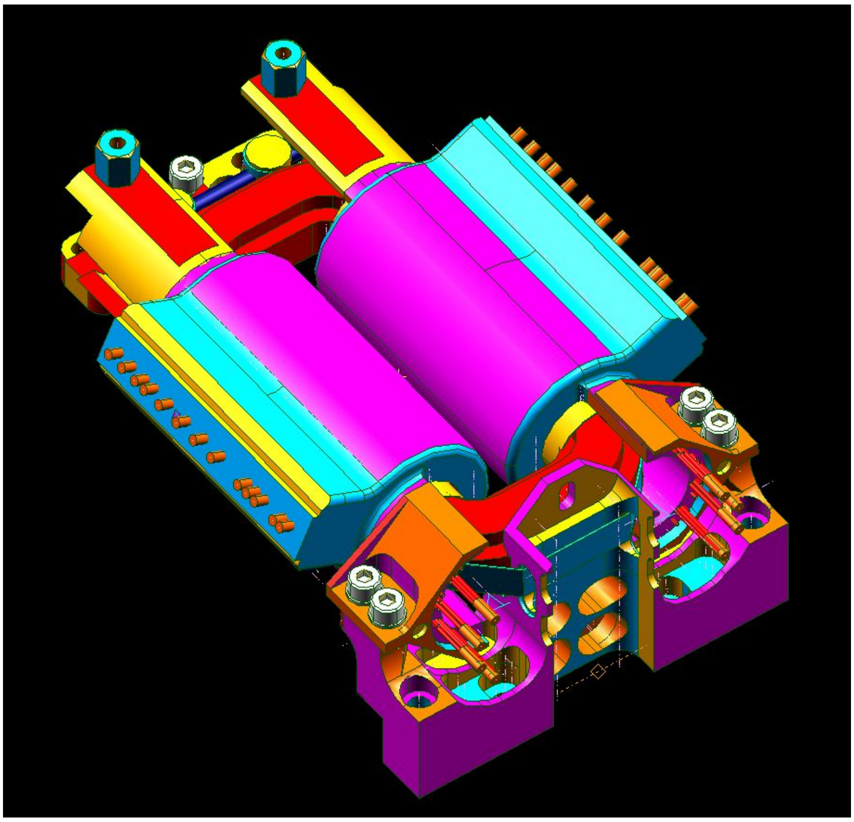


Figure 4-16: Example of a high voltage transformer for an EPC

Usually, the magnetic core is mechanically decoupled from the rest of the transformer, since ferromagnetic materials are sensitive to mechanical stress and therefore it is not recommended to fully encapsulate them into a potting material.

The high voltage windings are distributed into different sections, depending on the number output voltages required and depending on the intended electrical properties (inductances, field distribution, and coupling).

The primary windings are typically mounted on a separate bobbin, often installed in the centre hole of the high voltage bobbin, sometimes separated by a metallic shield.

Depending on the transformer output current, the wire size of the windings is selected at an acceptable minimum, often in a range of 0,1 mm diameter or less.

Most of the existing designs for EPC´s of communication satellite transponders are dimensioned for 6 - 8 kV operating voltage (DC).

With a given voltage from a spacecraft power bus and specified voltage of the TWT load the ratio of windings is globally given. The use of multiplier stages at the output and of boost converters at the input can change this ratio, but there are limitations (i.e. efficiency) in use of these measures.

The number of turns of the windings is mainly determined by the core material and core cross section (saturation, losses).

After optimization of the above parameters the "corner elements" of the transformer are defined:

- cross section of the magnetic core hole
- primary windings (turns, wire size)
- secondary windings (sections, turns, wire size)
- inner diameter(s) of the bobbin(s)

4.4.2.4 High Voltage Isolation Design of a Transformer

The insulating distances of the secondary windings are determined by the allowed electrical field strength. Due to conservative recommendation the maximum field strengths should be limited to 6 kV/mm for DC-fields and to 2 kV/mm for AC-fields, although for many insulation materials the real breakdown strengths are significantly higher.

In fact this means that for 8 kV DC operation voltage a minimum insulation distance of 1,3 mm is needed, for 15 kV a distance of 2,5 mm is needed – for homogeneous fields(!).

In practice, the electrical field in transformer windings is not homogeneous – moreover at corners of windings, thin wires, etc. the electrical field is enhanced. A field enhancement of 5 is allowed, but still under the condition, that max. field strength values are not exceeded. Therefore, the insulation thickness should be further increased.

It is highlighted, that an increase of the insulation distance should be done on both sides of the winding – for radial configurations the diameter increases by a factor of 4 (rule of thumb). In axial directions the insulation increase depends on the configuration of the section, but in worst cases, the high voltage levels can increase by a factor 2 (rule of thumb).

A further mass penalty arises with the increasing diameter of the bobbins and its high voltage insulation: the magnetic core has to provide a closed loop through the centre of the bobbins. With growing bobbin size a larger magnetic core should be used. As a consequence an additional (iron) mass adds to the mass budget.

Detailed optimization typically involves numerical field calculations by Finite Elements software (or similar) as shown in Figure 4-17.

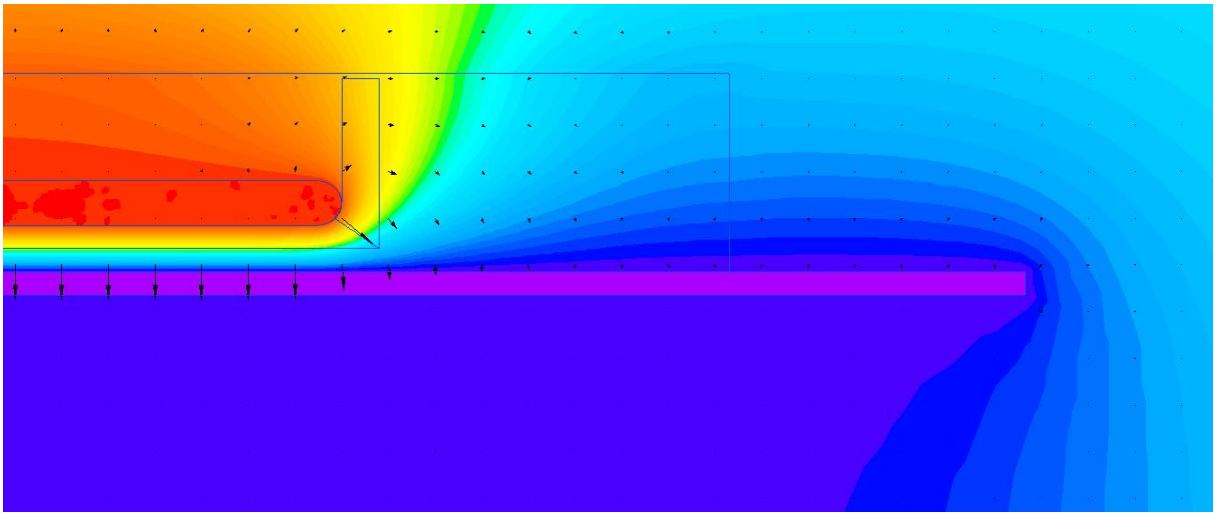


Figure 4-17: Example of a FEM calculation result: Equipotential Lines for a Plane-to-Plane configuration with spherical edges of the upper plane

Design optimization of the high voltage section can involve:

- modifications of sections and windings
- control of field enhancements by curvatures, wire diameters
- material selection

Further aspects to be considered for the transformer design are thermal conductivity of insulation material to ensure proper thermal design.

In an EPC there are typically two critical "hot spots":

The transformer windings: due to resistive dissipation we find typically the highest temperatures in this area – exceeding of the maximum temperature of the potting material should be excluded, otherwise insulation lifetime can be reduced significantly (thermal breakdown).

The rectifiers are the second "hot spot", usually not as critical for the potting material, but potentially critical for the semiconductor itself, since at high temperature a "run-away" effect can occur, which thermally overloads the rectifier.

A material with high thermal conductivity has the advantage to bring the temperatures down. Resins with a high percentage of high conductive filler are ideal for this purpose.

High temperature resistant materials, like silicone, can avoid thermal degradation of the isolation, but do not solve the problem of thermal runaway of semiconductors.

4.4.3 Electric propulsion

4.4.3.1 Electric propulsion overview

Electrical Propulsion is a complement or alternative to chemical propulsion. As outlined in Figure 4-18 electrical thrusters uses electrical energy to transform the inert fuel into mechanical energy (thrust), by accelerating the obtained charged particles to very high velocities instead of obtaining the acceleration from chemical reaction (hybrids of using both chemical and electrical energy are available, too: so-called Resistojets and Arcjets etc.).

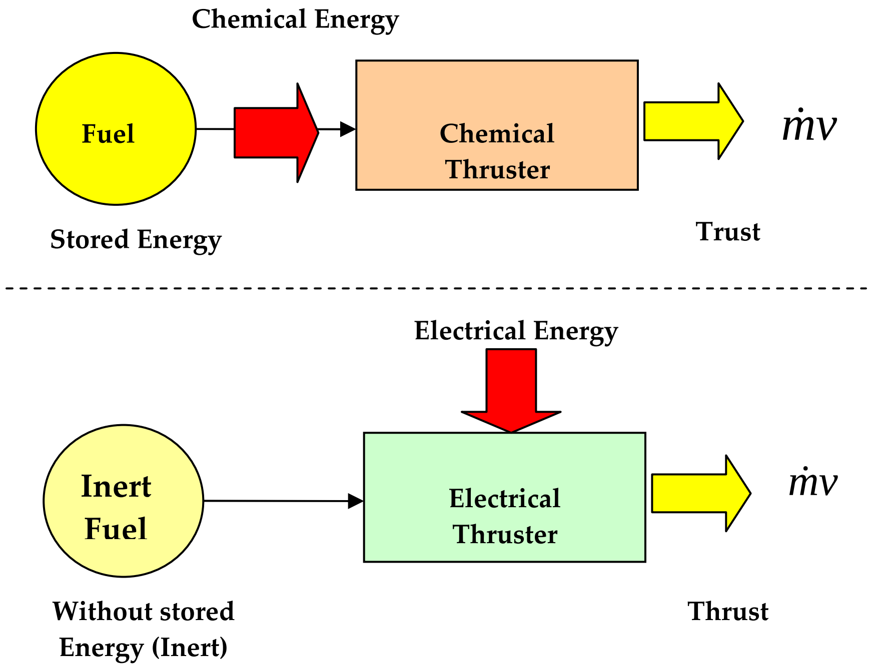


Figure 4-18: Principle of Electrical Propulsion vs. Chemical Propulsion

Categorized by the principle of mass acceleration, electrical propulsion systems distinguished into the following sub-groups:

- Electrothermal Thrusters
- Electrostatic Thrusters
- Electromagnetic Thrusters

An overview on the different types of thruster types and their electrical / physical parameters is given in Table 4-8.

Table 4-8: Overview on Electrical Propulsion Principles, Thruster Type and Electrical Physical Parameters

Principle	Fuel	Voltage (Main Power)	Power	Specific Impulse	Efficiency	Thrust
Electrothermal						
Resistojet	Ammonia, Argon, N_2, Xe	few volts	0,5 - 1,5 kW	300 s	80 %	
Arcjet	Hydrazine, Ammonia, Argon, H_2	> 1 kV ignition few V operation	0,3 - 100 kW	500 - 2000 s	35 %	
Electrostatic						
Ion	Xenon	1 - 2 kV	0,5 - 5 kW	3000 - 5000 s	60-80 %	10 - 200 mN
Plasma - Hall	Xenon	0,3 - 0,8 kV	1,5 - 5 kW	1500 - 2000 s	50 %	80 - 400 mN
Plasma - HEMP	Xenon	1-2 kV	0,5 - 1 kW	2000 - 3000 s	60-70 %	40 - 200 mN
FEEP	Indium, Cesium	5 - 15 kV	10 - 150 W	8000 - 12000 s	30-90 %	0,001 - 1 mN
Colloid	Glycerol, ionic liquids	2 - 5 kV	5 - 50 W	500 - 1500 s	60-90 %	0,001 - 1 mN
Electromagnetic						
Pulsed Plasma	Teflon	> 15 kV ignistion few kV operation	1 - 200 W	10000 s	5 %	1 - 100 mN
Magnetoplasma-dynamic	Ammonia, H_2	> 1 kV ignistion few 10 V operation	1 - 4000 kW	2000 - 5000 s	25 %	1 - 200 N
Variable I_{SP} Plasma Rocket	H_2		1 - 10 MW	3000 - 30000 s	< 60 %	1 - 2 kN

Typically an Electric propulsion (EP) system consists of one or more electrical thrusters connected to a power supply and (except for FEEP, colloid and pulsed plasma thrusters) to a gas feed system. The electric power supply unit of an EP system is typically called PPU (Power Processing Unit), PSCU (Power Supply and Control Unit) or simply PCU (Power Control Unit) and is providing various high voltage lines, heater lines and complex control functions to the thrusters.

The following discussion is focused mainly on the used or close to use (going to qualification) EP thruster principles, which are:

- FEEP (Field Emission Electric Propulsion) Thruster
- Plasma Thrusters (Hall effect type)
- Plasma Thrusters (HEMP type)
- Ion Engines (Ion Thrusters) - Kaufmann type
- Ion Engines (Ion Thrusters) - (Radio-frequency type

FEEP utilizes the field emission of metallic ions from a liquid metal surface, so there, the propellant being either Indium or Caesium. The plasma thrusters (Hall and HEMP) and ion engines all use Xenon gas as a propellant. The gas is ionized and the Xenon ions are accelerated, both ionization and acceleration are based on different principles depending on the thruster type.

For completeness to be listed, but not discussed here:

- thermo-electrical thrusters, i.e.
  - Resistojets typically not requiring high voltage
  - Arcjets, requiring high voltage for ignition only
- magnetoplasma thrusters i.e. typically requiring high current at low voltage
- pulsed plasma thrusters, typically requiring short duration high voltage pulses
- colloid thrusters, electrostatic thruster with similarities to the FEEP principle

4.4.3.2 FEEP thrusters

The basic FEEP thruster configuration is shown in Figure 4-19 (as an example), consisting of a sharp edged emitter (needle or slit) wetted with a liquid metal. The ion emitter voltage is used to force ion emission from the needle emitter by causing high electrical field strengths. The ion emission current - and as a consequence: the thrust - is determined by the applied voltage. The shield is biased with a moderate high voltage to control the ion trajectories of the ion beam.

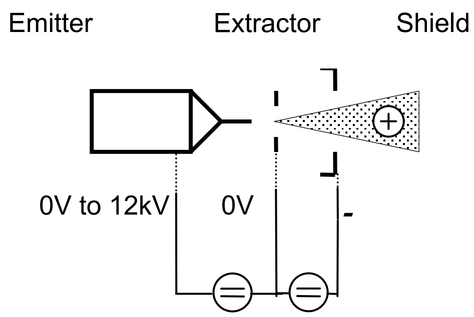


Figure 4-19: FEEP Ion Emitter Principle

The shield is a static load with a negligible current supplied by a small power source in voltage control mode. The emitter voltage drives the ion emission from the emitter sites. The emitter ignites after the ignition voltage is reached, typically the emission current can increase dramatically with slight voltage increase, so that passive resistors are switched in series. In order to control the thrust, the regulator loop is typically current-controlled.

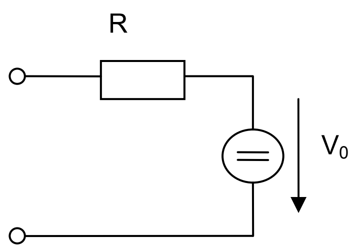


Figure 4-20: FEEP Ion Emitter Load – Equivalent Circuit

The voltage V_0 is in the range of 3 kV to 6 kV and the resistor R a few ten MΩ (which includes intentionally switched series resistors). In case that the series resistor is reduced, the element R becomes a non-linear Z. An inductive or capacitive load component is negligible.

FEEP thruster operation involves continuous sparking (breakdown), especially in the early operation phases, which need to be tolerated by the power supply up to a defined limit.

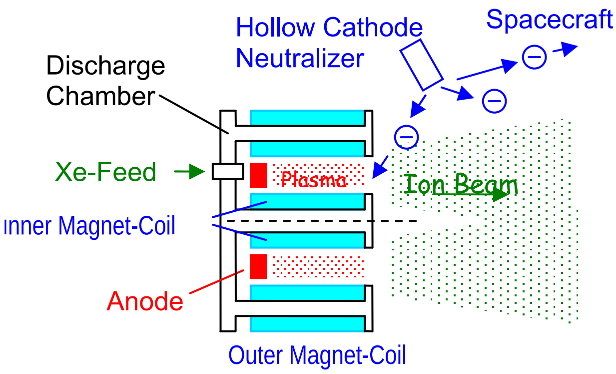
References are made to:

L. Ceruti, M. Magnifico, "Power Control Unit for µN Propulsion Subsystem", Proc. Seventh European Space Power Conference, Stresa, Italy, 9-13 May 2005, Proceeding ESA SP-589

M. Gollor, M. Boss „Micro-Newton Electric Propulsion Subsystems for Ultra-Stable Platforms"AIAA-2006-4825, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit', Sacramento, California, 9-12 July 2006

4.4.3.3 Plasma thrusters (Hall effect type)

The basic Hall-Effect thruster configuration is shown in Figure 4-21 (as an example), consisting of a discharge chamber fed with Xenon gas. A system of magnets creates a radial magnetic field; the anode voltage provides an electrical field vector mostly perpendicular to the magnetic field. Electrons dispensed from the cathode are attracted towards the anode and trapped in the radial magnetic field at the thruster outlet and there forced to spin on circular tracks, where they ensure good ionization of the Xe gas. From the generated plasma the ions are accelerated by the crossed electrical and magnetic field into the thrust vector direction.



Anode (red marked): pos. HV (appr. 300 V)

Figure 4-21: Hall Effect Thruster Principle

The Hall Effect Thruster power supplies consist of anode, magnet, heater, and igniters.

Magnet and Heater Supplies are serving a closed (linear) resistive conductor loop with some inductive component of the magnet circuit.

The Anode Supply is the high power source driving the ion beam. The voltage is in the order of typically 300-800V. It is operated normally in constant voltage mode up to a pre-defined current threshold, above the current limit the voltage is reduced proportionally. The anode supply is exposed to significant oscillations of the load (plasma oscillations: so-called "breathing mode") with a frequency in the order of 10-40 kHz. Typically, Hall Effect Thrusters are equipped with a filter (RLC-type) to avoid propagation of the load oscillations into the power supply and into the main bus. In addition, the power supply output can be designed with an inductive component. Further plasma oscillation can appear in the frequency range of 100 kHz to 1 MHz and above 10 MHz. Therefore the filter unit (RLC-filter) is proposed to be located as close as possible to the thruster in order to avoid conducted emissions (CE) from attaining the power supply as well as limiting the harness length that can act as an antenna. The plasma oscillations mentioned above are essentially determined by the harnesses; otherwise the radiated emissions (RE) go much further up in the frequency range, several GHz.

References are made to:

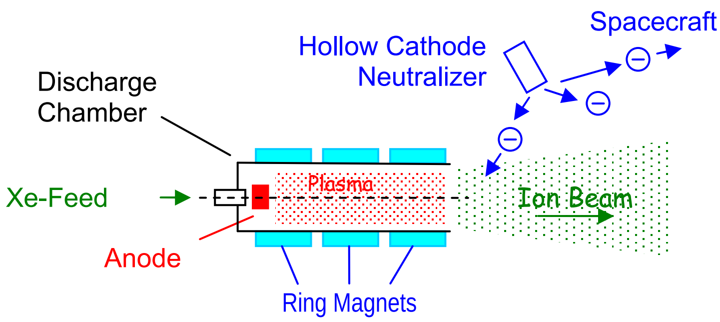
E. Bourguignon, T. Scalais, J. Thomas, "High Power Processing Unit for Stationary Plasma Thruster" Journal: Proc. 4th International Spacecraft Propulsion Conference (ESA SP-555). 2-4 June, 2004, Chia Laguna (Cagliari), Sardinia, Italy. p.65.1 ff.

S. Barral, J. Miedzik, E. Ahedo," A Model for the Active Control of Low Frequency Oscillations in Hall Thrusters", AIAA 2008-4632, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford, CT, July 21-23, 2008

S. Barral, E. Ahedo, "Theoretical Study of the Breathing Mode in Hall Thrusters", AIAA-2006-5172, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, July 9-12, 2006

4.4.3.4 Plasma thrusters (HEMP type)

The basic High Efficiency Multistage Plasma (HEMP) Thruster configuration is shown in Figure 4-22. The plasma chamber is surrounded by ring magnets forming a magnetic mirror field structure. Electrons from a hollow cathode are travelling following the E-Field towards an anode at the far end of the chamber, the interaction between magnetic field and electrical field ensures efficient ionization. Ions are moved uniformly into the main thrust vector direction.



Anode (red marked): pos. HV (appr. 1200 V)

Figure 4-22: HEMP Thruster Principle

Since the magnetic system is based on permanent magnets, there are only three power sources necessary:

- Heater (hollow cathode)
- Keeper (hollow cathode)
- Anode

The anode supply is the main power source, which is operated as a constant voltage source (typically 1-2 kV). The anode current of the thruster is a power supply load with a constant current, which is nearly independent of the anode voltage. The anode current is mainly driven by the Xe flow rate. Due to plasma effects, a significant current ripple is present of up to 60 % of DC current with a fundamental ripple frequency between 80 kHz to 120 kHz.

References are made to:

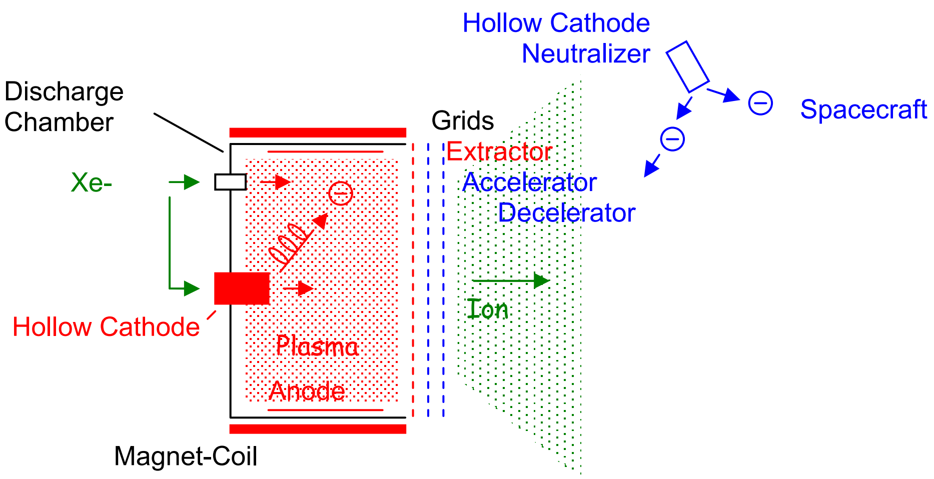
G. Kornfeld, N. Koch, H.-P. Harmann, P. Micheli, H. Meusemann, E. Gengembre, "High Power HEMP-Thruster Module, Status and Results of a DLR and ESA Development Program" AIAA-2006-4476, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, July 9-12, 2006

N. Koch, H. Harmann, G. Kornfeld, "First Test Results of the 1 to 15 kW Coaxial HEMP 30250 Thruster"AIAA-2005-4224, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, July 10-13, 2005

M. Gollor, M. Boss, et. al. "Generic High Voltage Power Supply – Next Generation", AIAA 2007-5215, Proc. 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinatti, OH, July 8-11, 2007, p. 4825 ff.

4.4.3.5 Ion engines (Kaufmann type)

The basic Kaufmann thruster configuration is shown in Figure 4-23 (as an example), consisting of a discharge chamber fed with Xenon gas. From a hollow cathode electrons are accelerated towards the anode. Due to the magnetic field generated by a coil system the electrons are trapped in this magnetic field and circulating in a spiral formed trajectory, thus ionizing the Xenon gas. The plasma is at a potential of 1000 V - 2000 V depending on the thruster class and type. A 2 (or 3) -grid system extracts and accelerates the ions from the thruster. Accelerator and decelerator grids are biased with a slightly negative high voltage (in the range 50 V - 300 V).



all red marked parts: pos. HV (1000-2000 V):
Hollow Cathode, Extractor, Anode
all blue marked parts: neg. HV (50-300 V):
Accelerator, Decelerator

Figure 4-23: Ion Thruster Principle (Kaufmann)

The number of required power supplies is high and comprises:

- Discharge and Neutralizer Cathode Keeper (Hollow Cathode)
- Discharge and Neutralizer Heater (Hollow Cathode)
- Anode Discharge
- Magnet

- Beam Supply (Extractor)
- Accelerator and Decelerator Grid

All mentioned sources are operated in current control mode, except the Beam Supply, Accelerator Grid and Decelerator Grid Supplies, which are operated in voltage control mode. The beam supply is the most powerful converter typically providing between a few 100 W and several kW´s.

For the characterization of the loads the following should be considered:

- Magnet and Heater Supplies are serving a closed (linear) resistive conductor loop; of course the Magnet Supply also has an inductive component.
- In a simplified electrical model for small signal response the anode supply operates against a series circuit of a constant voltage and a resistor, however, a negative V-I curve is possible under some conditions.
- The beam supply, which forms the primary high voltage supply and the accelerator grid are currently understood as "mostly" resistive load.

Disturbing effects for the power source are sporadic flashovers (arcing, "beam out") in the grid system due to surface contaminations and plasma oscillations in the hollow cathode and its interactions, typically with frequencies in the range of a few ten kHz, possibly also in the range of some MHz.

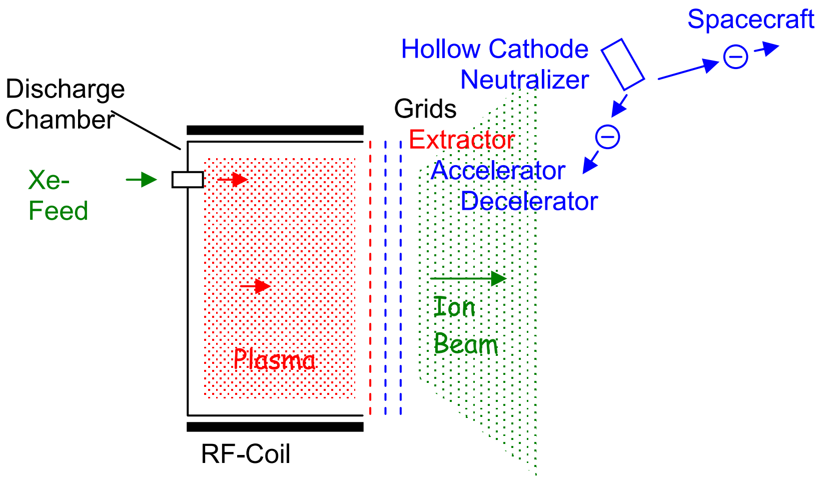
References are made to:

C.H. Edwards, N.C. Wallace, C. Tato, P. van Put, "The T5 Ion Propulsion Assembly for Drag Compensation on GOCE", Proc. "Second International GOCE User Workshop" ESA SP-569, European Space Agency, The Netherlands, June 2004

C. Tato, J. Palencia, F. de La Cruz, "The Power Control Unit for the Propulsion Engine of GOCE Program" Proc. 4th International Spacecraft Propulsion Conference (ESA SP-555). 2-4 June, 2004, Chia Laguna (Cagliari), Sardinia, Italy. p.64 ff.

4.4.3.6 Ion Engines (Radio-frequency type)

The basic Radio Frequency Ion Thruster (RIT) configuration is shown in Figure 4-24. Similar to the Kaufmann type ion thruster the ions are extracted from plasma by a 2 or 3 grid system. The main difference is the principle of plasma generation: the Xe-gas is exposed to a radio frequency field causing a high degree of ionization, therefore no cathode and no anode is necessary.



all red marked parts: pos. HV (1000-2000 V):
Extractor
all blue marked parts: neg. HV (0-300 V):
Accelerator, Decelerator

Figure 4-24: Radio Frequency Ion Thruster (RIT) Principle

The RF coil supply is a combination of a DC voltage regulator and followed by an active RF oscillator (700-1000 kHz). The grids are supplied by voltage controlled positive and negative high voltage sources, whereas the positive high voltage takes the main power load. The ion flow and therefore the load of the positive high voltage source are depending on the RF power fed into the plasma. As a consequence, the beam current is nearly constant (slightly increasing) over a wide range of extractor voltage.

Disturbing effects for the power source are sporadic flashovers (arcing, “beam out”) in the grid system due to surface contaminations.

References are made to:

S. Arcisto, M. Gambarara, A. Garutti, A. Trivulzio, A. Truffi, H. Bassner, H. Mueller, “Power supply and control unit (PCSU) for radio frequency ion thrusters (RIT)” ESA, Proc. 2nd European Spacecraft Propulsion, Noordwijk, The Netherlands, 27-29 May 1997 (ESA SP-398), pp 643-648

H. Leiter, R. Killinger, M. Boss, M. Braeg, M. Gollor, S. Weis, D. Feili, M. Tartz, H. Neumann, D. di Cara, ”RIT-µX - High Precision Micro Ion Propulsion System Based on RF-Technology” AIAA 2007-5250 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Cincinnati, OH, July 8-11, 2007

4.4.4 Microwave tubes

Microwave tubes are used in for RF signal amplification in terrestrial and for space applications, especially in cases where high RF power levels of several ten watts or higher are needed. For space applications some relevant examples are given in the following:

- 220 W –S-band –67 % efficiency (TWT)
- 220 W –Ku-band –67 % efficiency (TWT)
- 130 W –Ka-band –65 % efficiency (TWT)
- 5,5 kW –C-band –pulsed (TWT)
- 1,6 kW –W-band –pulsed (Extended Interaction Klystron).

The basic components of a Travelling Wave Tube (TWT) are sketched in the Figure 4-25. The electron gun contains the cathode for electron emission and forms an electron beam. The beam is feed through the helical delay line, which couple the electromagnetic field of the electrons with the signal fed into the input of the delay line (RF input). The interactions between both, the electron beam and the RF signal on the delay line interacts into signal amplification, such that a high RF power signal can be coupled at the RF output. The electron beam is partially collected in the collector stage, consisting of typically 4 or 5 collectors.

The cathode voltage is the most negative voltage with reference to the housing, resp. with reference to the helix. For communication TWT's the voltage is between 5-8 kV. The collector voltages are a fraction of the cathode voltage.

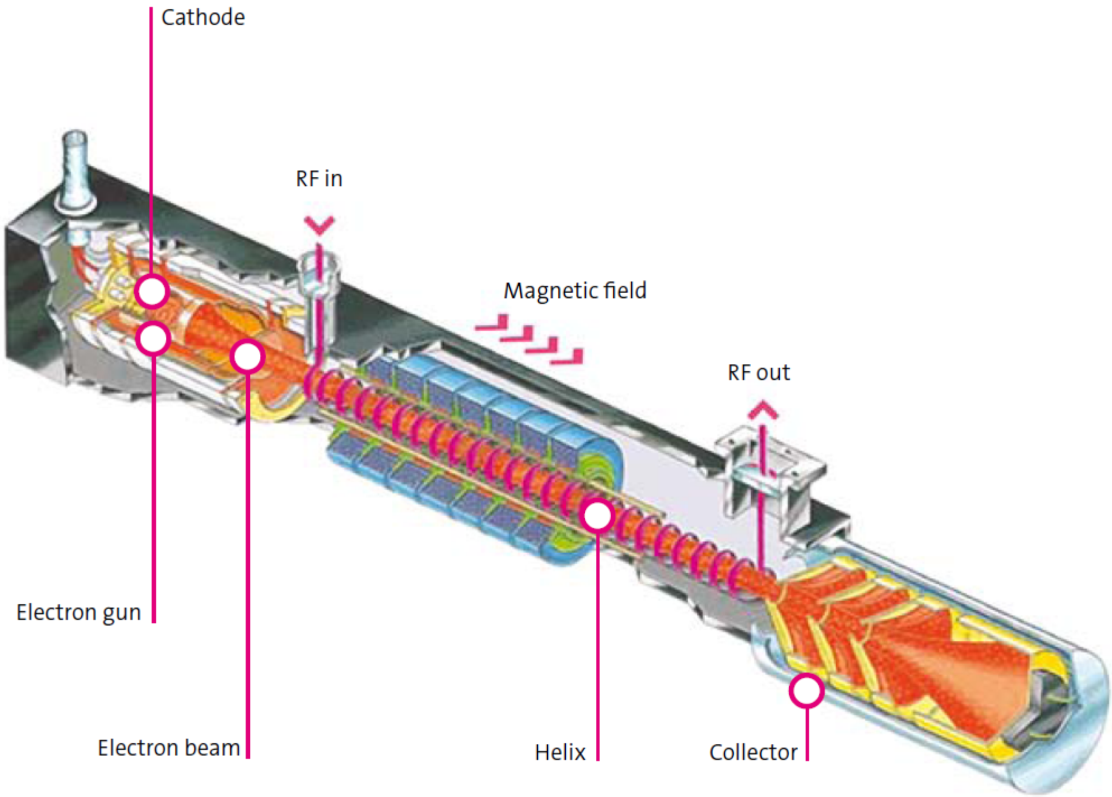


Figure 4-25: Schematic layout of a TWT

The electron gun principle is shown in Figure 4-26. The voltage V_F is needed to heat the cathode to allow emission. The anode voltages V_{A1} and V_{A0} are needed to extract the electrons from the cathode and to form the beam. The emission current is mainly depending on the voltage V_{A0} and a specific constant μ. Acceleration of the electrons is determined by the helix voltage V_H. Some characteristic values are given in the figure.

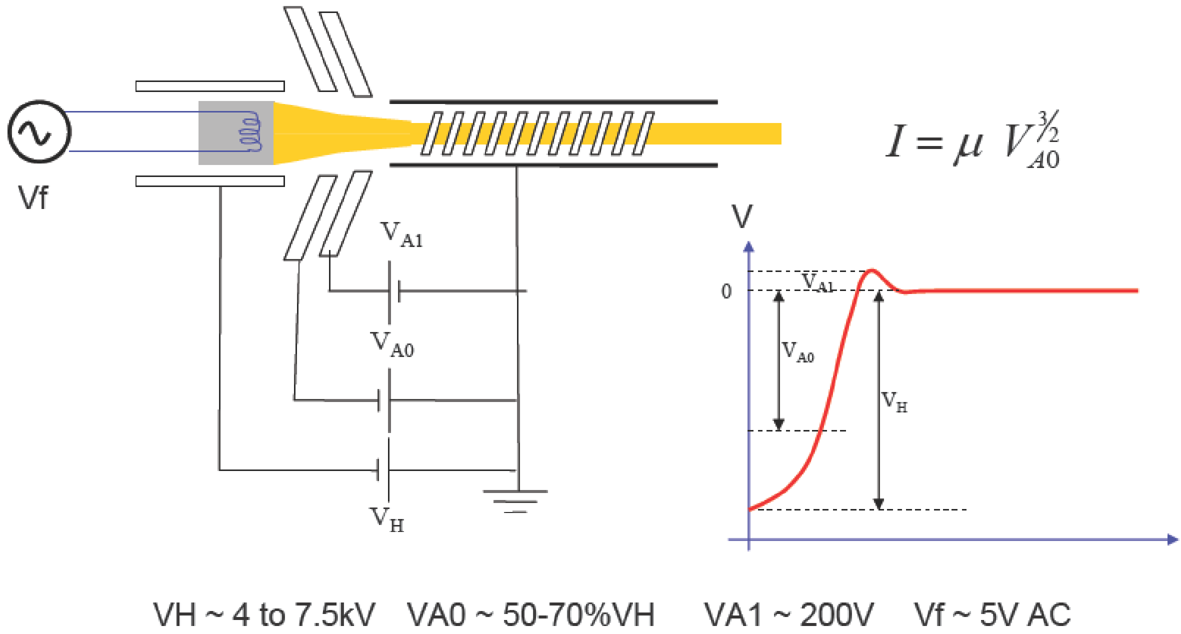


Figure 4-26: Principle of the electron gun of a TWT

The principle of the collector is described in Figure 4-27. It is needed to recuperate the unused energy of the electron beam in order to achieve a reasonable high efficiency of the TWT. The collector voltages are spread between the negative cathode voltage and the chassis/helix voltage (ground).

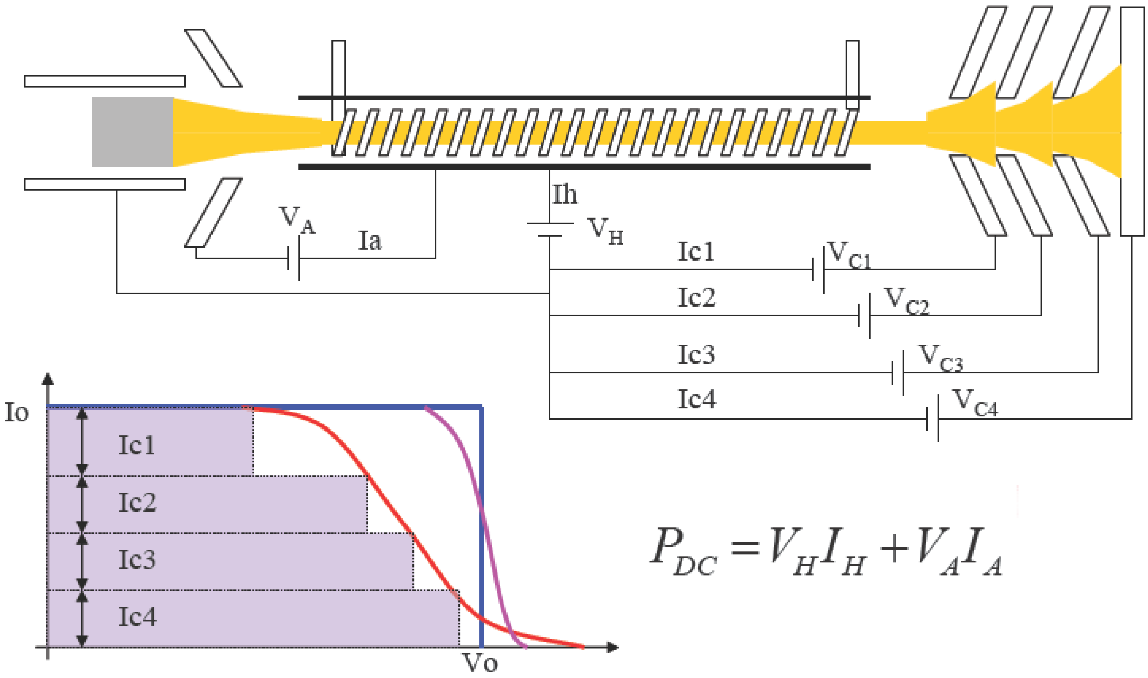


Figure 4-27: Principle of the collector stage of a TWT

From the point of high voltage insulation and design, the most relevant parts are the insulators/spacers, which fix the internal structures operated at high voltage potential. Furthermore, the high voltage feedthroughs from the vacuum inside the tube towards the ambient outside are the major aspects of the high voltage insulation.

Most of the internal insulators and the feedthroughs are made of ceramics in order to ensure a high quality vacuum inside of the tube. High voltage cables are connected externally to the ceramic high voltage feedthroughs. Typical high voltage cables used for TWTs are made of PTFE or FEP, in some cases silicon rubber insulation is used. Often the high wires are potted in the area of the ceramic feedthroughs by silicone rubber materials. Especially the temperatures of the collector are high due to the dissipation.

A special electrical breakdown phenomenon related to the presence of high electrical RF fields can occur in the RF high power conductors (waveguide) and is the so-called multipaction phenomenon. For details see ECSS-E-20-01A (Multipaction design and test standard).

4.4.5 Scientific instruments and experiments

Very specific applications for high voltage equipments exist in the field of scientific experiments and instruments. As this field is very wide, the needed power levels and characteristics are very heterogeneous. For an overview a course classification and description is given in the following:

- Laser Instruments
- Plasma Measurement Instruments
- Radiation and Particle Measurements Instruments
- Fluid Science Experiments

Laser Instruments are involving high voltage in two different ways: for the generation of a high power laser beam and for switched in the optical path. High power lasers have been studied for ESA missions with gas laser concepts (CO_2 lasers) using pulse voltage up to 150 kV for 10μs pulse length and 10 Hz repetition rate on breadboard study level. Optical Q-switches based on the Kerr-Effect principle use high voltage to change orientation of optical polarisation if optical crystals. These switches need fast change of a high voltage of 3-10 kV with rise/fall times in the nanosecond range. Q-switch drivers are often formed by a static DC power supply feeding into a high voltage push-pull stage. As the voltage ratings of semiconductor switches are limited, the high voltage push-pull stage is formed by an array of transistors switched in series. Gate signal drive is isolated via capacitive or transformer coupling. Related technologies have been developed for flight as part of the ESA Aladin (Earthcare mission) instrument and of the ESA ATLID instrument (Aelous mission).

Plasma Measurement Instruments are used to analyse various types of space plasma. Therefore typically a high voltage is applied between a set of electrodes. These electrodes are exposed to the free space and the "leakage" current through existing plasma is measured. The required voltages vary depending on the type and density of the investigated plasma from the range of a few hundred volts to a few kilovolts, DC, AC or with modulations. As currents are typically low in the nA or μA-range high voltages are often generated by high voltage multipliers as described in section 4.4.1. A reference is made to EFI instrument of the ESA Swarm Mission

Radiation and Particle Measurements Instruments detect charge generation caused by radiation or fast particles. These generated charges result into a current pulse when a high voltage field is applied by suitable electrodes. The needed high voltages are in the range of a few kilovolt up to the range of about 30 kV with low currents in the nA or μA-range. High voltages are often generated by high voltage multipliers as described in section 4.4.1. A reference is made to ESA Cluster mission and ESA Integral mission.

There have been flown a number of Fluid Science experiments on manned space missions for in-flight zero-gravity research using unique high voltages, here to mention:

- BDPU Bubble, Drop & Particle Experiment for Material Science Lab (ESA / Space Lab)
- Columbus FASES GEOFLOW onboard ISS (ESA)

Both experiments required high frequency ac high voltage with adjustable amplitude up to 15 kV-peak-to-peak. For BDPU the amplitude, the waveform and the frequency were adjustable, for GEOFLOW only the amplitude.

5
High voltage design principles

5.1 Basic design principles

Reliable high voltage design is based on principles avoiding a breakdown of the electrical insulation. These basic principles are the

- control of voltage
- control of electrical field strengths
- control of electrical field distributions
- control of partial discharges
- control of triple junction effects
- control of interferences

Most of the mentioned basis principles are linked to each other. Not all are relevant for all applications, however, all points should be checked for there relevance and their fulfilment. More explanations are given in the following sections.

5.1.1 Control of voltage

The typical destruction process is involving acceleration of electrons (in some cases ions) and its collision with matter. The maximum energy of an electron accelerated by an electrical field in a free path is given by the basic equation:

$$W_{kin} = e\,U \qquad [5\text{-}1]$$

where:

W_{kin} kinetic energy

e electron charge

U voltage

A collision of an accelerated electron with atom and ions can only be relevant for an electrical breakdown, if a certain kinetic energy is reached to cause displacements and ionization. As a simplified conclusion it can be deducted, that below a specific voltage threshold there is no specific high voltage related breakdown mechanism possible (to be distinguished from other – non-voltage related failure mechanisms).

The definition of a general threshold voltage is difficult as there are different insulation scenarios to be considered. Table 5-1 gives an overview of some critical high voltage related “thresholds”.

Table 5-1: Critical "thresholds" for high voltage

Gaseous insulation with low pressure ambient atmosphere (air) transition from ambient atmosphere into space "bad" space environment due to gas leakages and outgassing	
> 90 V	Paschen Breakdown in pure inert gas (Ar) atmosphere possible *)
> 240 V	Paschen Breakdown in pure nitrogen (N2) atmosphere possible *)
> 330 V	Paschen Breakdown in air (N2) possible *)
General for space applications	
> 200 V **)	electrical insulation becomes a design driver
Safety relevant	
> 60 V DC	hazardous voltage ***)
> 25 V AC	hazardous voltage ***)
*) see section 4.3.4 and 5.1.7 **) tentatively ***) see section 9	

As a general guideline the following voltage levels can be critical with respect to high voltage related phenomena and can require specific design precautions:

- Voltage > 200 V
  in general
- Voltage > 90V
  in specific low pressure gaseous environment
- Voltages < 90 V
  in specific cases for example if plasma and charging generated by external "source" (space plasma, ionizing source, electrical arcs etc.). This can potentially create conditions for an electrical breakdown even under low voltage. This should be taken into account at least for structures on the outer surface of a spacecraft (for example: solar generators).

NOTE High voltage breakdown develops in a timeframe of a few nanoseconds up to a few microseconds. Thus, for the final breakdown voltage always the peak value of an AC or pulse voltage is the design driver for the electrical insulation.

5.1.2 Control of electrical field strengths

5.1.2.1 Electrical Field Strengths Classifications

The electrical field is caused by an electrical potential. In the typical technical high voltage applications under consideration here, an applied electrical voltage across an insulating space results in an electrical field. The resulting electrical field can be a

- **Uniform electrical field**:

  the resulting electrical field strengths is constant in all locations of the insulating gap

- **Non-Uniform electrical field**:

  the resulting electrical field strengths varies depending on the locations in the insulating gap

Important for the characterization of an electrical field are the following field parameters:

- **Maximum electrical field strength**: $\boldsymbol{E}_{\mathbf{max}}$

  the *maximum value* of the electrical field strengths in the insulating gap

- **Mean electrical field strength:** $\boldsymbol{E}_{mean}$ **(or** $\overline{\boldsymbol{E}}$ **)**

  the *mean value* of the electrical field strengths in the insulating gap

- **Electrical field enhancement factor:** η

  the ratio of maximum electrical field strengths to mean electrical field strength

  $$\eta = E_{\max} / E_{mean} \qquad [5\text{-}2]$$

  Calculation methods and examples are given in section 5.1.2.9.

- **The most important parameter driving electrical breakdown of insulation is**

  the maximum electrical field strength $E_{\max}$

  since typically, in the zone of the maximum electrical field strength, discharges (and partial discharges) start triggering immediate or produce erosive breakdown.

As insulation typically is optimized to minimize size and mass of high voltage equipment, **the electrical field enhancement factor should be minimized to get an optimum distribution of the electrical field**, which means a very uniform field (see section 5.1.3).

If the maximum electrical field strength $E_{\max}$ is not kept below the electrical breakdown field strength E_d of the insulation material an electrical breakdown would occur:

$$E_{\max} << E_d \text{ .}$$

In practice the value of electrical breakdown field strengths E_d depends on:

- the applied profile of stress

  Alternating voltages (AC) causing polarity change of electrical fields lead to significantly lower electrical breakdown field strengths, than pure DC voltage (resp.) or combined DC+AC stress or pulse stressed.

- Long-term effects

  Long-term electrical breakdown field strengths (hours, months, years) is significantly lower than short term strengths (minutes, seconds and below).

Table 5-2 gives an orientation for maximum electrical field strengths typically used in high voltage applications (for space):

Table 5-2: Orientation "map" for maximum electrical field strengths in electrical insulation

Max. electrical field strength: E_{max}	Typical safe operating range	Remark
1 - 2 kV/mm	Air (ambient)	
5 - 8 kV/mm	high insulating and pressurized gaseous insulation (SF_6)	
0,5 - 2 kV/mm	solid insulating material (AC voltage)	
1 - 10 kV/mm	solid insulating material (DC voltage)	
5 - 20 kV/mm	thin layers of solid insulating material (i.e. dielectrics of capacitors)	
0,3 - 0,6 kV/mm	solid insulation creepage path	
1 - 10 kV/mm	vacuum insulation	

5.1.2.2 General control means for electrical field strength

The electrical field strength is dependent on:

- Voltage
- Geometrical parameters:
  - Distance (Insulator/Gap lengths)
  - Shape
- Dielectric properties (in conjunction with geometry)
  - Specific insulation resistance
  - Dielectric constant ε_r
- Space charges / Potential

5.1.2.3 Impact of voltage

The dependence of electrical field strengths E on voltage U is strongly linear as long as space charges (and equivalent phenomena) are not involved: However, in practice the voltage is defined by the system resp. application. Therefore a control (in terms of limitation) of electrical field strength by control of voltage is typically restricting the application. An example is shown in Figure 5-1, details on reference cases and calculation methods are given in section 5.1.2.2to 5.1.2.9.

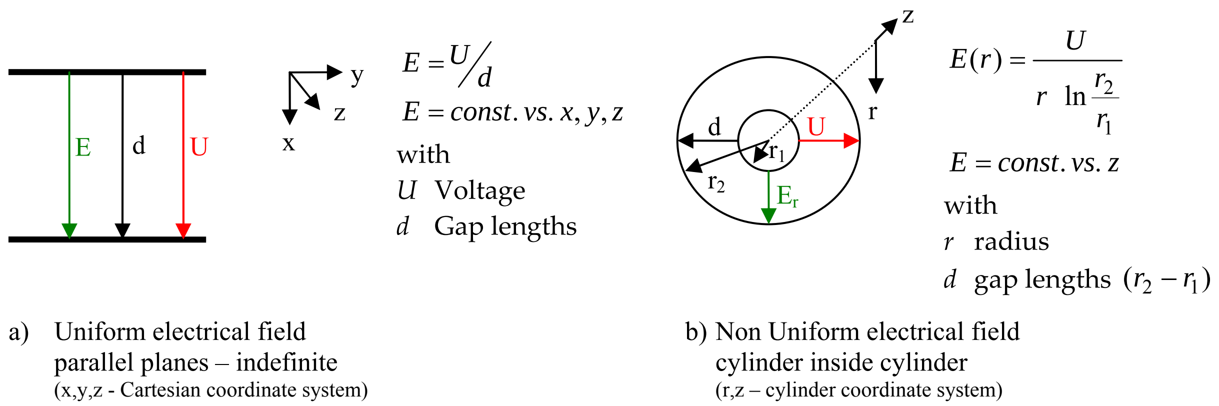


Figure 5-1: Electrical field strength depending on voltage and geometrical parameters (Examples)

5.1.2.4 Impact of geometry

As a geometry parameter the insulating gap length is determining the electrical field strength in the entire volume between two electrodes. Only in the case of a uniform electrical field, the electrical field strengths are everywhere the same and are clearly proportional to the gap length. In cases of a non-uniform field this relationship is not that clear. Although the mean value of the electrical field strengths E_{mean} still follows linearly the gap distance d, the local field strengths can increase or decrease in a non-proportional way with d and are more related to the radius of curvatures of electrodes as described in the following sections.

5.1.2.5 Geometry reference case: parallel planes

This basic case was already outlined in 5.1.2.1 is referenced here for completeness.

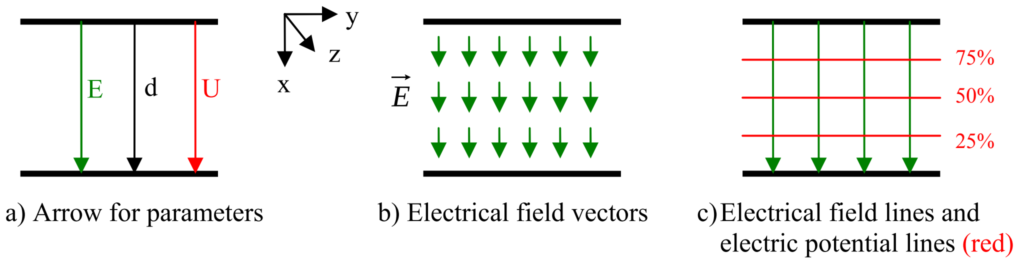


Figure 5-2: Uniform electrical field for indefinite parallel planes

The following equations are applicable.

$$E = U/d \quad [5\text{-}3]$$

$$\vec{E} = const._{x,y,z} \quad [5\text{-}4]$$

where:

U voltage

d gap lengths

$$E_{\max} = E_{mean} = U/d \quad [5\text{-}5]$$

As the electrical field strength is constant all over the uniform gap, the maximum electrical field $E_{\max}$ strength is equivalent to E_{mean}.

The indefinite parallel planes are not a full realistic case as the "real" planes have edges, where the electrical field is non-uniform. So the indefinite parallel plane is good approximation for the centre area of larger parallel planes, however, the field there appears differently and is higher at the curvatures.

5.1.2.6 Geometry reference case: spheres

Spherical geometries are a practical reference case for the following reasons:

- many non-uniform electrical fields can be analysed (at least by approximation) with spheres
- spheres are often intentionally used to control and limit electrical field strength

A geometrical model is described in Figure 5-3.

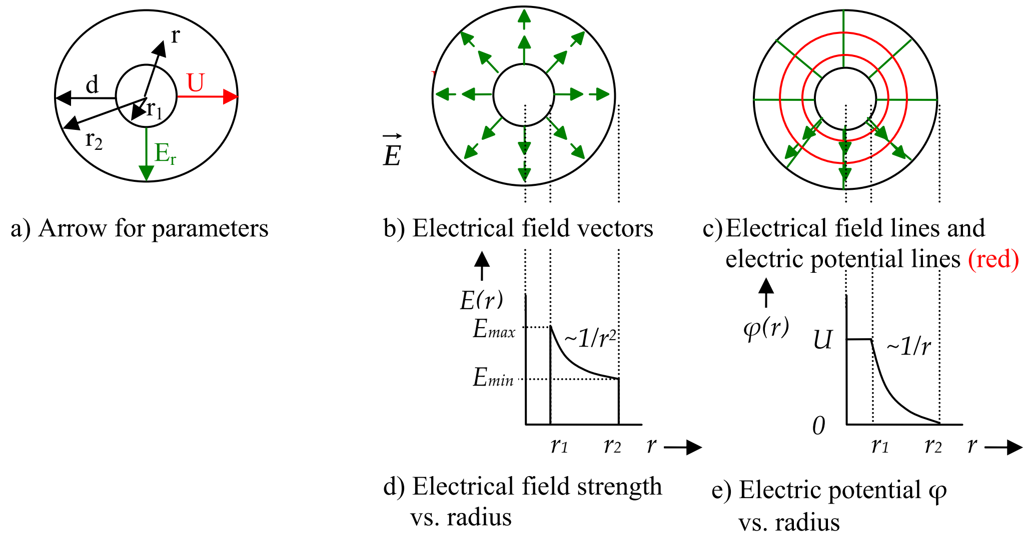


Figure 5-3: Sphere-inside-sphere electrical field

The following equations are applicable:

$$E(r) = \frac{U}{r^2\left(\frac{1}{r_2} - \frac{1}{r_1}\right)}$$ [5-6]

$$E_{mean} = U/d = \frac{U}{(r_2 - r_1)}$$ [5-7]

$$E_{\max} = \frac{U}{\frac{r_1^2}{r_2} - r_1}$$ [5-8]

where:

U: voltage,

r: radius (from centre),

r_1 radius of inner sphere,

r_2 radius of outer sphere

Conclusions for practical high voltage design with sphere-inside-sphere geometries are:

- the max. electrical field strengths increases to high values
  - — if the inner sphere is too small
  - — if the ratio between inner outer sphere (radius) is too small
- an optimum for the size of an insulation is reached, if the following condition is met:

$$r_2 = 2\, r_1$$ [5-9]

In case of a sphere in a free space the geometrical parameter $r_2 \to \infty$ results in a simplified set of equations:

$$E(r) = \frac{U}{r^2} r_1$$ [5-10]

$$E_{\max} = \frac{U}{r_1}$$ [5-11]

Conclusions for practical high voltage design with sharp edges structures are:

- select a minimum radius of a conductive high voltage structure to limit the maximum electrical field strengths – following $E_{\max}$ definition with equation [5-11] the resulting "law" is

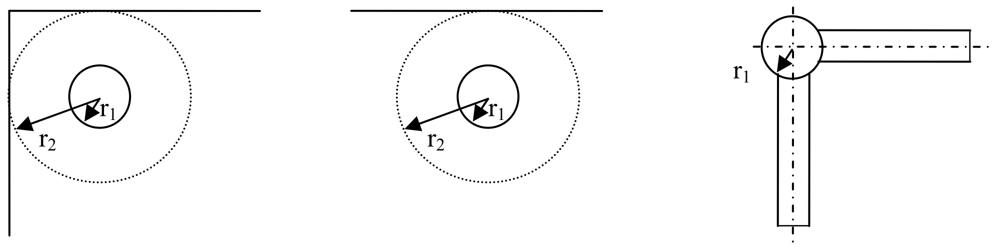
$$r_1 = \frac{U}{E_{\max}}$$ [5-12]

- this rule is valid as long as your counter-electrode is still far away from the spherical structure (means acc. to equation [5-9] is $r_2 >> r_1$).
- for a first assessment equations [5-8] and [5-11] can be used of critical field strengths in any design for sphere-like structures.
- Some examples for the selection of the proper radius are given in Table 5-3.

Table 5-3: Orientation values (examples) for selection sphere structures to limit the maximum electrical field of a high voltage assembly

Application	Max. electrical field strength: E_{max}	Max operating voltage 1kV	Max operating voltage 10kV
air (ambient)	for 2 kV/mm	r_1 = 0,5 mm	r_1 = 5 mm
pressurized gaseous insulation (SF_6)	for 5 kV/mm	r_1 = 0,2 mm	r_1 = 2 mm
solid insulating material (DC voltage)	for 10 kV/mm	r_1 = 0,1 mm	r_1 = 1 mm
thin layers of solid insulating material (i.e. dielectrics of capacitors)	for 20 kV/mm	r_1 = 0,05 mm	r_1 = 0,5 mm

The equation for spheres can be easily used to assess different practical situations or place field control measures in applications – examples are shown in Figure 5-4 and Figure 5-5.



a) Sphere in a corner b) Sphere-to-plane c) Sphere as "joint" for conductors

Figure 5-4: Examples for practical use of field equations for spheres

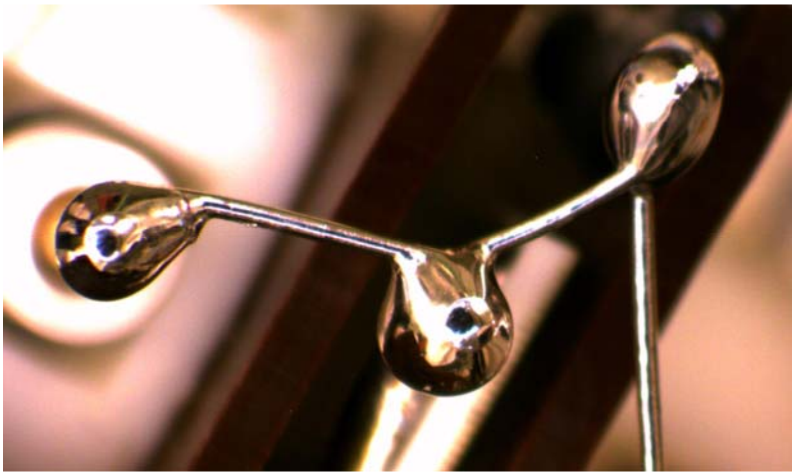


Figure 5-5: Examples for practical: connections of wires by using spherical solder joints

5.1.2.7 Geometry reference case: cylinders

Cylindrical geometries are a practical reference case for the following reasons:

- many non-uniform electrical fields can be analysed (at least by approximation) with cylinders
- cylindrical structures are the typical configuration of high voltage cables and wires.
- cylinders are often intentionally used to control and limit electrical field strength

A geometrical model is described in Figure 5-6.

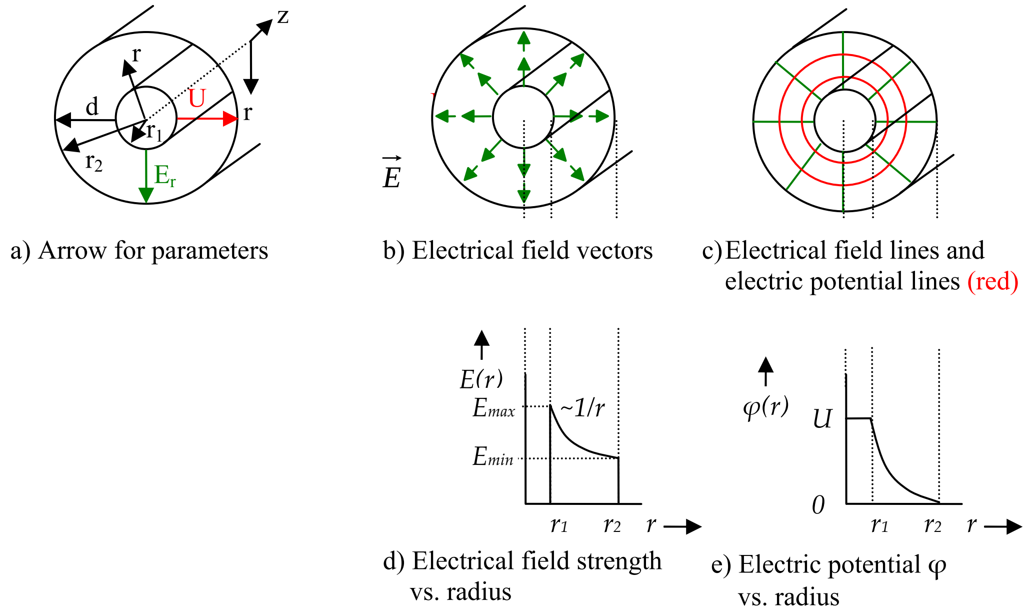


Figure 5-6: Cylinder-inside-cylinder electrical field

The following equations are applicable:

$$E(r) = \frac{U}{r \ \ln \frac{r_2}{r_1}} \qquad [5\text{-}13]$$

$$E_{mean} = U/d = \frac{U}{(r_2 - r_1)} \qquad [5\text{-}14]$$

$$E_{\max} = \frac{U}{r_1 \ \ln \frac{r_2}{r_1}} \qquad [5\text{-}15]$$

where:

U: voltage,

r: radius (from centre),

r_1 radius of inner sphere,

r_2 radius of outer sphere

Conclusions for practical high voltage design with cylinder-inside-cylinder geometries are:

- the max. electrical field strengths increases to high values
  - if the inner sphere is too small
  - if the ratio between inner outer sphere (radius) is too small
- an optimum for the size of an insulation is reached, if the following condition is met:

$$\frac{r_2}{r_1} = e \qquad [5\text{-}16]$$

5.1.2.8 Space charges

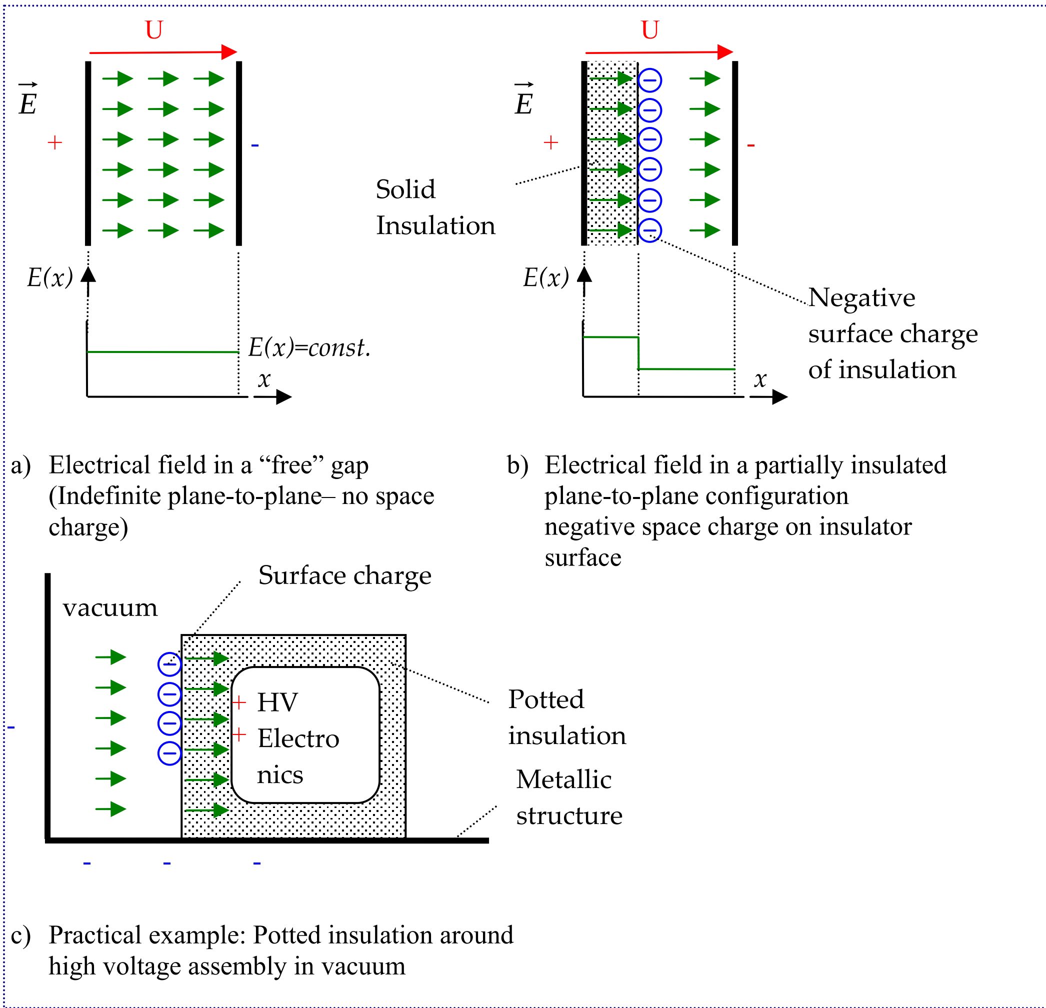
5.1.2.8.1 General

Space charges are able to alter the field distribution significantly. Space charges are zones, where electrons and ions are accumulated by free movements or "injection" due to electrical field forces. The resulting changed distribution of the electrical field is in practice difficult to predict, as the amount of charge accumulated and the place of accumulation is not precisely predictable in most cases. However, such cases should be known and considered if they appear to be applicable. Some relevant examples are shown in the following (see also ECSS-E-ST-20-06C).

5.1.2.8.2 Space charge on an insulating barrier

The situation described in Figure 5-7 is typical for many practical implementations of high voltage design:

- High voltage assembly with potted insulation in vacuum or gaseous insulation
- Interface between different insulating materials: solid-solid or vacuum-solid or liquid-solid or liquid-gas



a) Electrical field in a "free" gap (Indefinite plane-to-plane– no space charge)

b) Electrical field in a partially insulated plane-to-plane configuration negative space charge on insulator surface

c) Practical example: Potted insulation around high voltage assembly in vacuum

Figure 5-7: Space charge formation on an isolating surface

The impact of the space charge (in this case a surface charge) is an increase of the field strength in some areas. The increase of the maximum field strength is unknown, but typically limited to the maximum established for the situation, that the "counter-electrode" is directly placed at the surface.

Such a surface charge formation is favoured by insulation materials which allow easy movement of free charge carriers as it is the case for a vacuum environment.

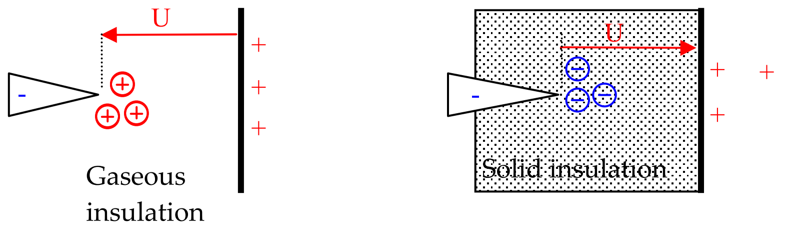
In highly insulating materials, which impede the movement of charge carriers, the formation of space charges is progressing slower, but on the contrary, if space charges are allowed to build-up over a long time in a highly insulating environment, they stay there for a long time. This can be problematic, if the voltage and especially its polarity changes in the meantime.

5.1.2.8.3 Space charge injection at a sharp edge

Space charges can appear in strongly non-uniform electrical fields by ionization effects. Two different typical examples are given in Figure 5-8.

In example a) the sharp-edge structure is shown as a tip with negative polarity in a gaseous environment. If the local electrical field strength exceeds the ionization threshold, the gas is ionized locally. Due to their high mobility the electrons disappear quickly flowing to the positive plane, while the less mobile remaining ions form a positive space charge in front of the negative tip – increasing the local field strengths.

As shown in example b) a charge injection into solid insulation is possible due to high electrical field forces and resulting displacements of the atomic structure. Especially very low conductive materials are vulnerable, as they maintain the state of space charge for a long time.



a) Negative polarity "tip" (sharp edge) in a gaseous insulation in front of a positive plane structure

b) Negative polarity "tip" (sharp edge) in a solid insulation in front of a positive plane structure

Figure 5-8: Space charge formation on sharp-edged structures in various environments

5.1.2.8.4 Surface charging along an insulator

Often solid insulators are used as spacers to separate different metallic (conductive) structure parts of a high voltage assembly. Driven just by mechanical needs, the surface of the insulator is more or less perpendicular to the electrodes and therefore in parallel with the electrical field vectors – as shown in Figure 5-9. Especially in vacuum environment "free" electrons can move along the electrical field lines and hit the surface of the space. Accumulated charges lead to distortion of the electrical field including local enhancement of electrical field strengths.

Typically surface charging of isolators lowers the electrical strengths of the assembly significantly.

The "free" moving electrons can come from an "external" source (space plasma) as well as from the surfaces of the assembly. Very critical are the triple-junctions as explained in section 5.1.9) Measures to control such effects are listed in section 5.3.8).

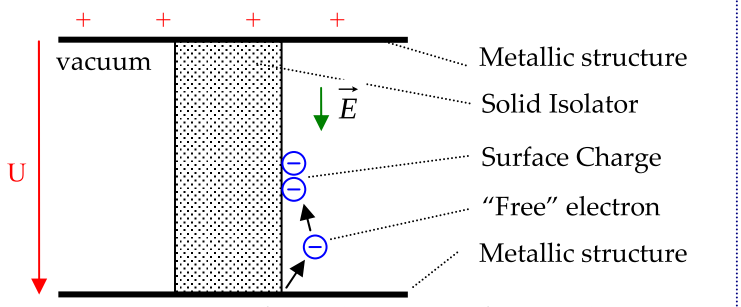


Figure 5-9: Surface charging of an isolator

5.1.2.9 Calculation Methods

5.1.2.9.1 General

Calculation methods for electrical fields and (most important) for maximum values are manifold. The most promising are presented below.

5.1.2.9.2 Analytical

Analytical methods to determine the electrical field are available for simple standard configuration as:

- Plane-to plane (basic equations - see section 5.1.2.5)
- Sphere-inside-sphere (basic equations - see section 5.1.2.6)
- Cylinder-inside-cylinder (basic equations - see section 5.1.2.7)

These equations can be used for rough order of magnitude assessments for similar configurations. Other equations for simple configurations can be found in many electrical engineering handbooks and tutorials.

5.1.2.9.3 Catalogue

Catalogues for dedicated more complex configurations can be found in various high voltage engineering handbooks. A useful set of tables and graphs is given in Annex A.

5.1.2.9.4 Numerical (FEM)

A number of commercial and non-commercial software tools are available to determine 2-dimensional or 3-dimensional electrostatic fields. Due to a lot of similarities to mechanical and thermal field calculation, the Finite Element Method software is widespread in use to determine high voltage electrical fields.

It is beyond any doubted, that actual FEM software is able to solve field calculations for very complex geometries. In order to avoid bad surprises it is strongly recommended to:

- cross-check critical results for maximum field strength analytically by similarity with simple configurations as mentioned in 5.1.2.9.2
- verify that sharp edged shapes and curvatures of the analysed model are sufficiently meshed. For curvatures in critical areas with high field strengths at least 8 to 10 elements should be allocated to a radius of $\pi/2$. Sharp edges should be represented by a representative radius. Examples are shown in Figure 5-10.

  NOTE Typically inexperienced users of Fem software rely on the automatic meshing functions of the software. This can lead to a sub-optimum meshing and potentially wrong results.

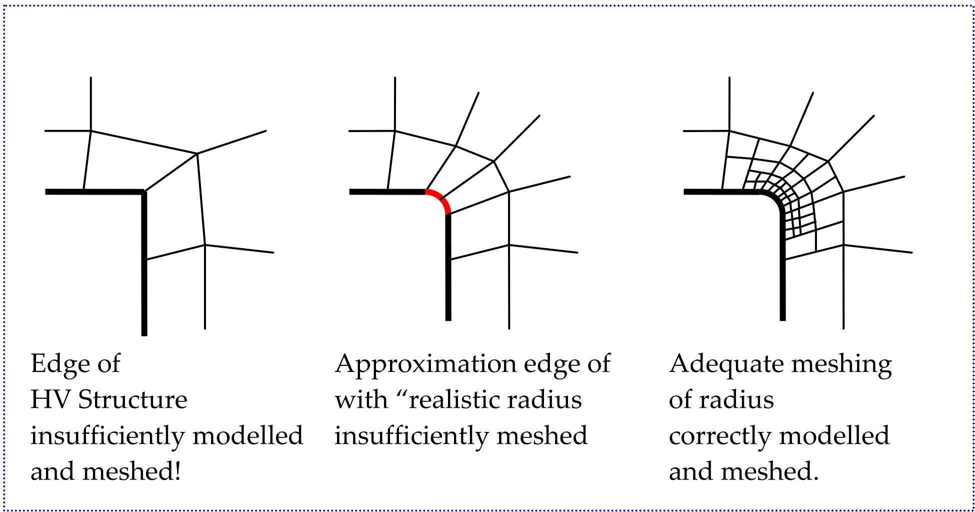


Figure 5-10: Correct meshing of shapes

5.1.3 Control of electrical field distribution

Although the maximum value of the electrical field strength is the most important driver for a breakdown electrical insulation in most cases, the field distribution is relevant for the following reasons:

- Achieving a high utilization of an electric insulation, respectively for reducing the size of an electrical insulation.
- Reducing the maximum electrical field strengths.

In view of these points it is important to reconsider the following basic law:

$$U = \int_{p1}^{p2} E(s)\, ds \text{ in a three-dimensional volume} \quad [5\text{-}17]$$

where:

U voltage,

E(*s*) electrical field strength at the location s (x,y,z),

p1 starting point (x,y,z),

p2 point (x,y,z), s: (any) path.

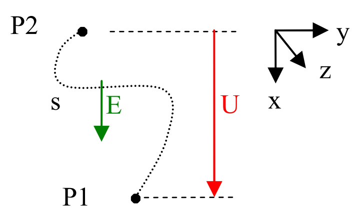


Figure 5-11: General: E-Field and voltage for a three-dimensional path

$$U = \int_0^d E(x)\,ds \text{ along an coordinate axis} \quad [5\text{-}18]$$

where:

U voltage,

$E(x)$ the electrical field strength at the location x,

d gap lengths.

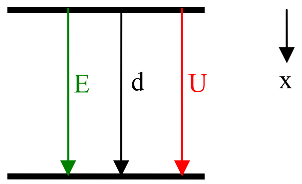


Figure 5-12: E-Field and voltage for gap lengths (straight path)

Concluding from the above equations [5-17] and [5-18] is that

- The mean electrical field strength for given gap d and voltage is always constant (in absence of space charge and in a homogeneous dielectric).
- Decreasing local high field strengths results in an increase of the field strengths in other locations of the electrical field.
- For design optimization in terms of mass and size it is desirable to keep the field enhancement factor η low (see eq. [5-2]).

Primary measures to control the distribution of electrical fields:

- Define radius for undefined sharp-edged structures of conductors
- Select optimized radius for defined structures of conductors to achieve optimum field distribution

Both measures can be performed with the rational and methods described in sections 5.1.2 and 5.1.2.6 (in specific: 5.1.2.7 and 5.1.2.9).

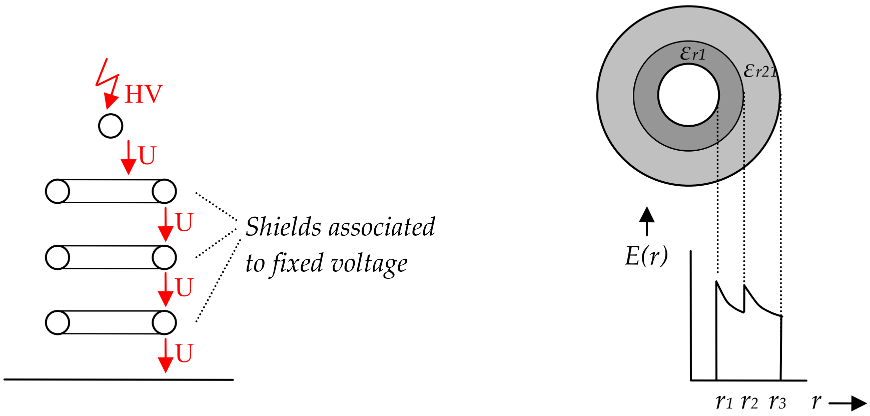
Note that an optimization of the electrical field distribution and field enhancement factor can lead to increased size of conductors, which can give counterwise penalties in mass, size. Thus an overall optimum should found. In typical case a field enhancement factor of 3 to 5 is reasonable, in large structures values beyond (higher) can be acceptable, too.

Additional measures to control the distribution of electrical fields are

- introduction of additional electrodes
- modification of insulation properties

The introduction of additional electrodes gives the opportunity to predefine fixed voltage potentials in a field and by this to change the distribution of the electrical field according to the needs. An example is given in Figure 5-13 a). In the example three shields are defined for electrical field control. The association of the electrodes to a fixed intermediate voltage is mandatory in most applications. Possible means are resistive dividers, capacitive coupling (for AC and pulse voltage) or by active control with high voltage sources.

The modification of insulation properties can be achieved either by change of electrical resistance or by change of the dielectric constant ε_r. The method of configuring electrical insulating materials with different ε_r is effective in case of AC or pulsed voltages. An example with a coaxial conductor configuration is shown in Figure 5-13 a). Controlling the specific electrical resistance of the insulation is more a theoretical possibility, because typically an electric insulation is very high ohmic and in the high ohmic regime the adjustment of small conductivity is difficult to achieve. Furthermore the high ohmic insulation resistance is significantly temperature dependent, so the field distribution can follow closely any temperature variation.



a) Control of E-field by introduction of additional electrodes

b) Control of E-Field by graduation of $\varepsilon_{r1} < \varepsilon_{r2}$ with applied AC voltage in coaxial conductor structure

Figure 5-13: Control of electrical field distribution - Examples

5.1.4 Control of insulation properties

5.1.4.1.1 General

In order to achieve good high voltage insulation, the control of insulation properties is a key element. Basically the following should be granted:

- Homogeneous composition of the insulation, especially:
  - No defects (cracks, voids, delamination)
  - No contaminations (water, corrosive substances, particles)
- Homogeneous distribution of :electric and dielectric properties, especially:
  - Specific electric insulation resistance
  - Dielectric constant

Homogeneous in the above mentioned context does not explicitly exclude, that properties are not allowed to change in a controlled way.

Some relevant principles are discussed below.

5.1.4.1.2 Gaseous insulation

For gaseous insulation the insulation properties are typically constant as the gas molecules equally fill a room (some exception of leakages or heavy dynamic gas flows are not discussed here).

5.1.4.1.3 Vacuum insulation

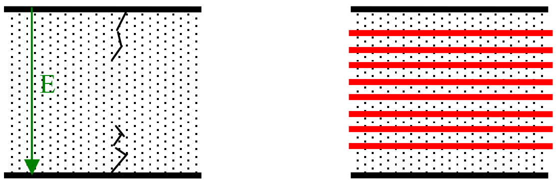
For vacuum insulation there is no issue regarding the insulation properties itself, however, surface and residual gases play an important role for breakdown. For details see section 5.2.5 and section 4.3.4.

5.1.4.1.4 Liquid insulation

For liquid insulation the following most important effects should be controlled:

- Fibres

  In order to achieve high electric strengths fibre and similar contaminations should be either strictly avoided or its impact in building fibre bridges should be suppressed. In most of the cases the introduction of barriers is an efficient measure (see Figure 5-14).



a) Liquid filled gap starting built-up of fibre bridges

b) Preventing of fibre bridges by barriers, here: insulation foils

Figure 5-14: Avoiding fibre bridging effect in liquid insulation

- Gas bubbles

  Formation of gas bubbles should be avoided. Gas bubbles can be the result of partial discharge or of transitioning the threshold of vapour pressure. So as countermeasures:

  - partial discharges should be avoided (see section 5.1.7 Control of corona effects)
  - the gas should be always under sufficient pressurization
  - if the bubble is small enough, the voltage across it is below the Paschen minimum, thus eliminating the problem of discharges
  - solved gases should be removed under low pressure
  - filling under absence of gases (i.e. under vacuum, if appropriate).

5.1.4.1.5 Solid insulation

For solid insulation the following most important effects should be controlled:

- Avoiding cracks and delamination

  Cracks and delamination in an area with high field stress is a starting point for breakdown of a solid insulation. Suitable countermeasures are:

  - Selection of a suitable manufacturing process

    Favourable manufacturing processes are:

    - moulding/potting,
    - sintering
    - extruding

    Additional advantage can be achieved with processes allowing

    - performance of essential steps of processing under vacuum to avoid inclusions of air (bubbles), respectively of air bubble size reduction after repressurization

- o gapless contact with electrodes and conductors.

— Selection of suitable materials

Favourable solid insulation materials should be compatible with the above mentioned favourable manufacturing processes. Important roles for high voltage design for space applications are playing the following materials:

- o Polymeric materials, most important epoxy resins, polyurethane resins, silicon resins, flour ethylene polymers (PTFE (Teflon ™), FEP), polyimide (Kapton ™, Vespel ™)
- o Ceramic materials
- o Mica

- Avoiding high electrical field stresses along interfaces

In many high voltage insulation applications it is unavoidable to have discontinuities in structure of the insulation. Reasons for such discontinuities can be:

— Composites of different materials for optimum properties of insulation (i.e. glass-fibre reinforced material for thermo-mechanical strength improvement)

— Sequential manufacturing steps (i.e. potting of an assembly in a series of moulding, potting, hardening steps)

— Interfacing of different materials with glue (etc.)

— Filling gaps between materials with glue (etc.)

— Wrapping or shrinking materials onto other materials

The consequences for design of high voltage insulations under such circumstances are the following:

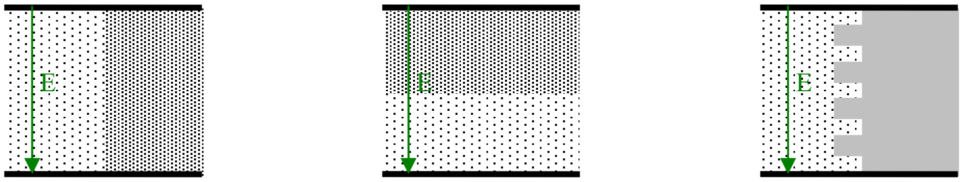
— Typically the breakdown strength is significantly lower, if the vector of the electrical field strengths is in the direction of the interface (between two insulations) – see Figure 5-15 a.

— Therefore the vector of the electrical field should be preferably perpendicular to the interface of the materials – see Figure 5-15 b.

— In case that a perpendicular orientation is not possible, an interleaved interface can be advantageous– see Figure 5-15 c. An interleaved interface can be more easily realized with potting materials, and is typically difficult to achieve with machined parts on both sides of the interface as gaps cannot be avoided.

— Otherwise the electrical field strengths applied should be significantly lowered compared to those of the “pure” materials.

— If an interface area is situated close to ground or to a high voltage electrode the field stress can be locally reduced by introduction of shield electrodes – these measures are identical to those proposed to control triple-junction areas and are explained there (see section 5.1.9).



a) Critical w.r.t. breakdown strengths: E-Field oriented parallel to the interface

b) Improved w.r.t. breakdown strengths: E-Field oriented perpendicular to the interface

c) Interleaved interface as a solution if the E-Field main orientation along the interface cannot be avoided.

Figure 5-15: Optimum design of interfaces between materials w.r.t. the electrical field

- Harmonized thermo-mechanical design

  The thermo-mechanical design of the solid high voltage insulation with all constituents and attached, embedded parts should be fully harmonized to avoid typical problems with cracking and delaminations. Some typical measures are:

  — Matching of thermal expansion coefficient as far as possible (i.e. using appropriate fillers for potting materials)

  — Avoiding sharp-edged interface structures

  — In case of potting materials (and similar materials) the hardening process takes place at high temperatures. Typically the potting material shrinks after cooling down and compresses embedded parts as long as these are ceramic or metallic materials with lower thermal expansion coefficients. This shrinking effect is beneficial as long as local mechanical forces are not getting too high. It is typically recommended to stay with the operating temperature below the hardening temperature of the potting material, as above this temperature the mechanical forces can reverse and can cause delamination.

- Cleanliness

  As high voltage insulation is sensitive with respect to irregularities in the structure of the material any contamination with particles can cause a weakness of the insulation. Cleanliness during the manufacturing process is mandatory as well as storage under clean conditions to avoid contaminations of surfaces. Standard clean room conditions (class 100.000) for space industry are usually sufficient. Lower standards can be acceptable in justified cases, however, in any case it is poposed to track and remove large particles even if not directly involved with the class 100.000.

5.1.5 Control of surface properties

This subject especially addresses surfaces of solid insulating materials in gaseous, liquid or vacuum environment.

For <u>vacuum</u> environment the surface properties are extremely important, especially:

- Sensitivity to surface charging (negative: highly ohmic/isolating, high coefficient for secondary electron emissions)
- Adsorption of gases (adsorbed gases should be avoided)
- Outgassing (should be avoided)

- Hydroscopic properties (should be avoided)
- Roughness (rough surface appears to be advantageous over flat surface)
- Shape (should prevent surface charging, see section 5.3.8)
- Particle contamination (should be avoided).

The relevant aspects are explained in section 5.2.5.

For gaseous environment the following surface properties are important:

- Hydroscopic properties (should be avoided)
- Wetting by water (should be avoided)
- Shape (should increase the lengths of a conductive path, see section 5.3.8).

For liquid environment the following surface properties are important:

- Hydroscopic properties (should be avoided)
- Shape (should increase the lengths of a conductive path, see section 5.3.8).

Possible methods to control surface properties in general:

- Machining
  provides the basic shape and can control the surface roughness.
- Polishing (mechanical)
  minimizes surface roughness
- Thermal treatment
  is useful for drying and quick removing of adsorbed gases under vacuum
- Plasma treatment
  removes surface layers and controls surface roughness
- Coating
  can alter the surface properties of the substrate material
  Examples: silicon coating to increase hydrophobic properties or conductive (high ohmic) coating to reduce surface charging effects.
- Additives
  to control surface conductivity
- Cleaning with fluids
  to remove surface layers and humidity

5.1.6 Control of partial discharges

Partial discharges should be kept under a maximum level to avoid continued erosion of the insulation causing a long-term breakdown. The critical levels depend on the type of material and typically range from 1 pC to 20 pC, for some partial discharge resistant materials (like mica) levels of a few 100 pC can be acceptable, too (see more details in section 5.3.2).

The measures to control the level of partial discharges are depending on the type of insulation.

In gaseous insulation the important factors are

- Electrical field strengths

  Limiting the (local) maximum electrical field strengths to a value below the breakdown field strengths is in most cases the only measure to avoid partial discharges in gaseous insulations. These values are in accordance with section 4.3.2.2 and cannot be changed only by changing the material (gas). A very useful strategy in many applications is to mix or replace "gases" by (or with) SF_6-gas.

- Particles

  Loose particles can be a problem in gas insulations with very high breakdown field strengths, which can by high compressed (few atmospheres) insulating gases like SF_6-gas. Particle movement can appear under high electrical field forces causing partial discharges – so called "particle bouncing". Cleanliness during manufacturing and integration of such insulation is a key factor to avoid problem to be caused by particles.

In liquid insulation the important factors are

- Electrical field strengths

  Limiting the (local) maximum electrical field strengths to a value below the breakdown field strengths is in most cases the only measure to avoid partial discharges in liquid insulations. As the on-set threshold for partial discharges is typically very much depending on contaminations the avoidance of particles and solved gas / gas bubbles is important.

- Particles

  Particles need to be consequently avoided by filtering of the liquid (before filling), cleaning of the surfaces being in contact with the liquid, using particle/abrasion free surfaces (coating if necessary).

- Gas bubbles (Solved gases).

  First, gas content in liquids should be avoided, if possible. Suitable measure can be degassing under low pressure and vacuum. Contact to gaseous environment (ambient air, etc) should be avoided after degassing (if possible by design and handling).

  If gas content is unavoidable, the liquid should be kept under sufficient pressure to avoid formation of gas bubbles.

In solid insulation the important factors are

- Electrical field strengths

  Limiting the (local) maximum electrical field strengths is useful in the way of achieving a most uniform electrical field distribution, respectively a homogeneous field. With a few exceptions (short lifetime equipments, partial discharge resistant materials, etc.) partial discharge should not appear, which means in practice partial discharge levels below a few to few ten Picocoulombs. The maximum operating field strengths should be selected in respect of this.

- Gas filled-gaps, delamination, gas bubbles, voids

  Irregularities inside the solid insulation and at the interface between insulation and the conductors/electrodes should be avoided, which means

  — Avoid gas filled volumes (enclosed gas bubbles, gaps, etc.)

  — Avoid enclosure of particles, especially metallic particles (abrasions) and inclusions with different dielectric properties than the original materials

  — Avoid structural changes of the material

    NOTE The strategy of avoiding enclosure of particles and structural changes does not ignore the fact, that some there is a suitable compound material (filled epoxy resin, mica compounds etc.) with a natural “content” of structural discontinuities, which can still achieve good dielectric strengths when exposed to a high level of severe partial discharges

In vacuum insulation partial discharges do not exist according to the definitions given in section 4.3.3. However, there are so called micro-discharges and pre-breakdown currents, which can be interpreted by a detector as partial discharges.

In general it should be noted, that AC applications are representing the most critical case w.r.t. partial discharges and its (long-term) erosive effects. In DC and in unipolar pulse application partial discharges appear less frequently, so the impact on ageing is less severe in most cases, but can never be neglected.

5.1.7 Control of corona effects

The expression “corona” is often used with different meanings. From the origin it means a light emitting discharge around a conductor. Such a phenomenon can be related to

- (Outer) partial discharges in a gaseous environment

  As outlined in sections 5.1.6 this effect can be avoided by

  — Geometry: increasing distance and large radius of curvature of electrodes in order to reduce the maximum field strengths

  — Mixture or substitution of the original gas with a stronger gas mixture with higher breakdown field strength

- (Inner) partial discharges in gas-filled gaps and voids of solid or liquid insulations

  Measures are outlined in section 5.1.6

- Paschen breakdown

  Measures are outlined in section 5.1.8

5.1.8 Control of Paschen breakdown

The Paschen breakdown is explained in section 4.3.4 and the critical voltage and pressure values can be taken from Figure 4-7 and Table 4-7. The Paschen breakdown is a phenomenon which is relevant especially for non-encapsulated equipments, exposed to the natural environment and undergoing the transition from ambient air pressure on ground to space vacuum environment during and after launch. Some more exotic conditions can appear for interplanetary missions entering in other planetary atmospheres with their specific atmosphere i.e. gas mixture and gas density.

In general the following aspects should be considered:

- Consider operation scenarios for high voltage equipment during/after launch or during outgassing.
- Define sufficient outgassing time of the spacecraft before switching high voltage equipment on (if possible by operations scenario) or make it independent from atmospheric environment (encapsulation, potting).
- Define safe operating conditions for high voltage equipment w.r.t. pressure and plasma. In typical space applications an often used definition is:

  Pressure $p < 10^{-5}$ mbar (10^{-3} Pa) and ambient atmosphere (Earth).
- Consider pressure increase by leakage (tanks, pressurized modules, thrusters).
- Perform test of the assembly in a critical pressure environment (if critical).
- Use complete encapsulation (potting, etc.), if voltage and critical pressure leads to unsafe or unstable operation of equipment – especially if the operating voltage is above the Paschen Minimum voltage and critical pressure cannot be excluded.
- Limit free gap length for vacuum insulated assemblies.

  As outlined in Figure 5-16 the free gap lengths can be limited by locating the critical HV assembly in a conductive cage (proper venting to be ensured!). The distance d should be properly selected in accordance with Figure 4-7 and Table 4-7 (or other valid data).

  For example according to Table 4-7 a limitation of the gap to 10 mm can avoid Paschen breakdown in air atmosphere for pressures below 7,3 10^{-02} mbar. Some safety margins (i.e. factor 10 at least) need to be added and verification by test is proposed.

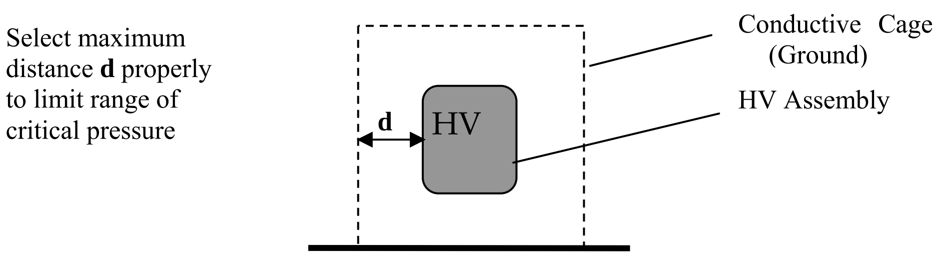


Figure 5-16: Limit critical Paschen breakdown pressure range by limitation of maximum gap

It is important to be aware, that some Paschen breakdown related phenomena can appear even with fully encapsulated high voltage equipment, if the encapsulation does not involve shielding as well.

Case 1:

A high voltage assembly is fully encapsulated by a solid insulation material to avoid a Paschen breakdown in the critical pressure range. In the example shown in Figure 5-17 the encapsulated HV assembly is surrounded by a gaseous / vacuum environment passing through the critical pressure range. As the electrical field is present inside and outside of the solid insulation, a partial breakdown in the gaseous zone is possible. In case of a DC high voltage such a discharge is typically only a single event, when the voltage is switched on or its level is changed. The reason is: as long as the solid insulation withstands, there is no energy transfer possible. Energy to sustain the plasma is only delivered from the capacitance given by the geometry of the configuration. The current flow through the solid insulation is negligible.

However, if the high voltage is an AC or pulsed voltage, the capacitive current flow can be sufficient to keep a permanent discharge alive, especially if high frequency high voltage is present, as is the case in many high voltage DC power conditioners. The effect of such a discharge is often negligible for many applications, as the capacitive current is low and can appear as an additional leakage current only.

A possible impact can be given in terms of degradation (erosion) of the surfaces being in contact. For short-term exposures the degradation can be low and the effect therefore can be acceptable, especially for the relatively short transition time of space equipment from ground to vacuum. A long time exposure should be avoided or in unavoidable cases further analysed by life-testing.

A proper way to avoid the effects described for this case, is a complete metallization (or metallic housing) of the outer surface of the solid encapsulation There should be no gaps between the metal shield and the solid insulation in order to avoid any partial discharges. The metal case resp. metallization should be kept properly grounded or connected an appropriate potential. However, it is worth noting that metallic encapsulations and metallizations require a more complex design of the HV assembly, especially if an external high voltage harness is connected. Furthermore it is considered, that the metallization applies a higher electrical field over lifetime, than insulation, where vacuum/air and solid insulation share the electrical field stress.

In view of electromagnetic compatibility it is highlighted, that such glowing plasma can be a source of radiated (electromagnetic) emission, too.

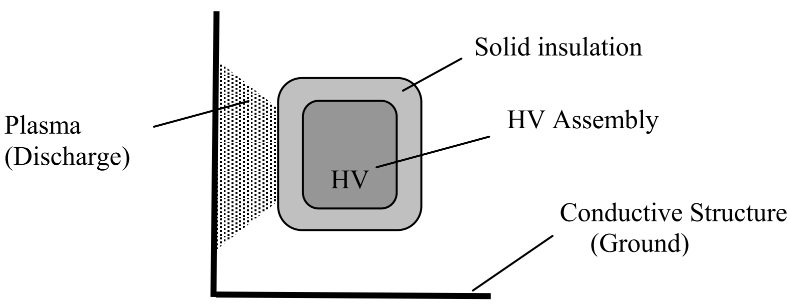


Figure 5-17: Paschen discharge in a gap between solid insulation and ground

Case 2:

The second problematic situation is related to the above described Case 1. Figure 5-18 shows the already described situation of plasma generated outside of a HV assembly which is encapsulate by a solid insulation. In the critical pressure range plasma is generated and well supplied by an AC HV source. A low voltage assembly with unprotected conductors is exposed to the plasma. As the plasma provides a conductive path it can trigger a breakdown between the conductors (resulting in a short circuit) even if the voltage is low.

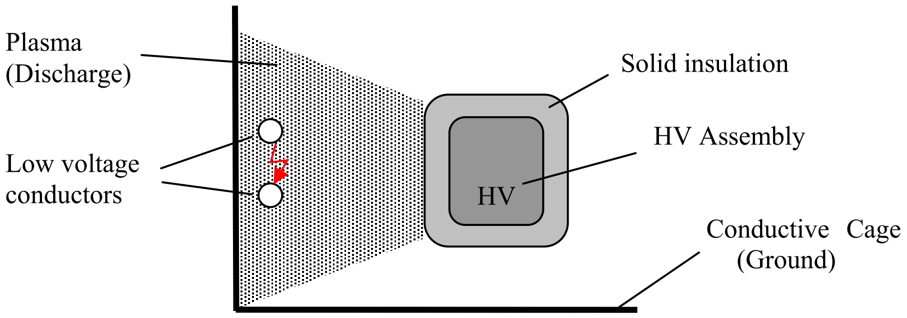


Figure 5-18: Triggered Paschen discharge in a gap between solid insulation and ground

Therefore it is quite essential, that low voltage assemblies exposed to high voltage fields should be properly encapsulated or coated with insulation material and/or shielded from the HV field (metallic potential controlled shield.)

5.1.9 Control of triple junction effects

The region of high voltage insulation, where three materials are joined together, is called the "triple junction" region. This critical region is typically formed by the interface between:

- Solid insulator – gaseous insulation – metal (conductor)
- Solid insulator - vacuum – metal (conductor)
- Solid insulator – liquid insulation – metal (conductor)

An example is shown in Figure 5-19.

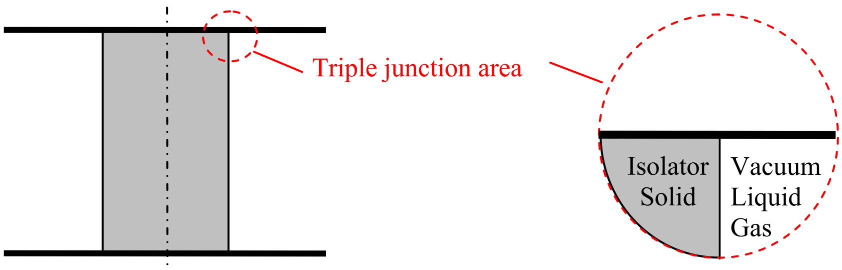


Figure 5-19: Critical triple-junction point/area in an interface between solid - gaseous/liquid/vacuum insulation - metal conductor

The triple-junction zone is critical:

- if the local structure is not ideal (perfect) due to manufacturing and assembly process. Small microvoids, delamination, gas, holes; cracks are likely to be present.
- if there is natural displacement of the morphological structure between metal and solid insulator as well as at the surface of both materials towards the gas/liquid/vacuum environment.
- when some local enhancement of the electrical field strengths is possible due to modifications of dielectric properties.
- in vacuum: this situation provides a lower threshold for electron emission (field emission), which can cause a leakage current or promote surface charging and resulting breakdown.
- in gas/liquid: in this situation partial discharge onset can occur at lower voltage than in other locations of the insulation.

Thus in conclusion, the triple junction interface can lower the overall strengths and lifetime of an insulation assembly, if not additional measures are taken to reduce the local electrical field strength especially for this zone. Some useful design variants are shown in Figure 5-20. Depending on the selected geometry the local electrical field can be reduced by an order of magnitude or more.

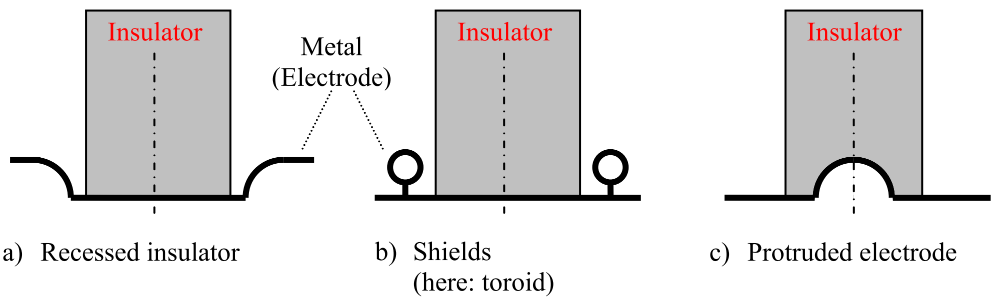
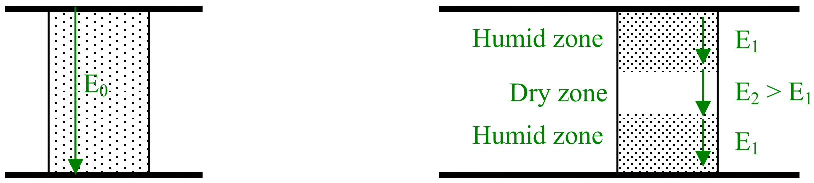


Figure 5-20: Methods to reduce the influence of the triple junction zone by design

5.1.10 Control of creepage path

The path along the surface of a solid insulator is called "creepage path". Depending on the application this surface can be exposed to a gaseous, liquid or vacuum environment. In all of these environmental cases it is possible that the surface of the solid insulator is contaminated by particles, dust, water film and other surface layers. (in vacuum additionally by adsorbed and absorbed gases). These surface layers can weaken the breakdown strengths significantly. Typically this is the case, if the ohmic conductivity of the surface is higher than that of the solid material and the surface conductivity is not constant. As shown in Figure 5-21 as an example, the electrical field distribution is uniform without surface contamination (a) and alters to a non-uniform electrical field distribution (b) in case of surface contamination with non-uniform distribution. The highly loaded zone can be overstressed and can partially breakdown. The partial breakdown can stay a while with varying flares, can disappear again or result in a final flashover. This effect is especially significant for air environment, with the natural humidity as an important influencing factor. As many space equipments are tested under ambient atmospheric conditions, it is important to consider this influence.

Furthermore, it is worth to consider, that an increasing conductivity across a creepage path can contribute to the overall leakage current of the insulation.



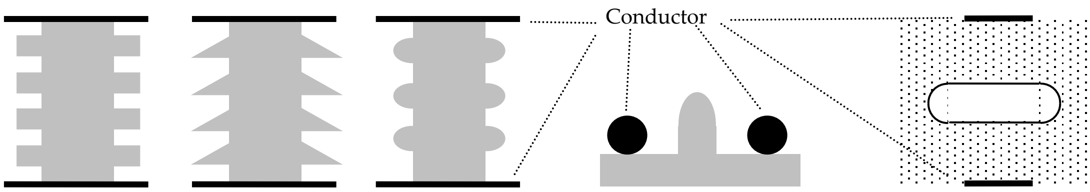
a) Ideal electrical field – uniformly distributed (no surface related effects)

b) Non uniform field caused by non-uniform surface conductivity (here: dry and humid zones)

Figure 5-21: Impact of creepage path on electrical field distribution

Suitable measures to reduce the impact of a creepage path can be the following:

- Increasing the length of the path (see Figure 5-22 a,b)
- Segmenting the path (see Figure 5-22 c)
- Interrupting the path (barrier see Figure 5-22 b)
- Removal of layers by proper cleaning
- Avoidance of layer formation by handling, storage and operation in a clean environment
- Reduction of humidity impact by handling, storage and operation in a dry environment
- Removal of humidity (bake out – where possible)



a) Various insulator shapes to increase the creepage path lengths

b) Barrier between terminals

c) Segmenting with slots

Figure 5-22: Designs to reduce impact of creepage path on electric insulation

5.1.11 Control of surface charging

Surface charging can be a relevant effect in highly insulating environments; the most critical case is a solid insulator surface in vacuum. The reason is that free charge carriers (mainly electrons) can be moved by the electrical field forces along a very long free path. For example, electrons emitted from the electrode surface can follow the electrical field lines and hitting an insulator surface, there either being attached or triggering secondary electron emission. Both effects can lead to formation of local surface (space) charges, which can alter the electrical field distribution and – in a worst case – trigger a full flashover.

Surface charging can also occur in (dry) gaseous environment or in liquid environment; however, in the more dense media the movement or free electrons is very limited and such charge carriers are easily captured by the surrounding molecules.

There are different techniques to avoid surface charging or to reduce the impact of surface charging:

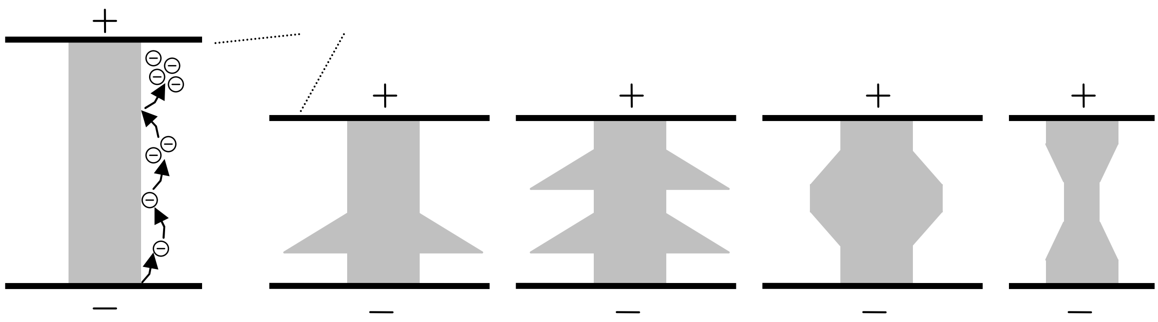
- Select solid insulating materials with a controlled surface resistivity
- Select an environment which is not promoting space charge formation
- Ensure defined controlled surface conductivity
- Select insulator surface shapes, which are less affected by surface charging
- Select insulator surface structures, which are less affected by surface charging
- Segment the insulator and control actively or passively the voltage/field strength per segment
- Avoid the source of free charge carriers, for example by relaxing electrical field strength at the triple-junction zones (see section 5.1.9).

Regarding the first two points, selecting the solid insulation material and the environment, there are typically restrictions: for example, the environment is typically given and the choice of insulation material is limited as it is driven by other design parameters (like process of manufacturing and assembly, mechanical/thermal constraints and lifetime requirements).

Ensuring a controlled defined surface conductivity is difficult, too. Because, finally the insulator should be of high electrical resistance (some 10 MΩ or GΩ), but especially in the high ohmic regime it is nearly impossible to produce layers (zones) with a constant, but controlled resistance value. Controlled deposition of metallic or carbon layers leads immediately to a drastic change of conductivity. There such a measure can be only appropriate in high power (or pulsed) HV equipments, where a high leakage current is acceptable (negligible).

Selecting an appropriate shape of the insulator surface is a suitable option. Especially in a vacuum environment a valid approach is to avoid a straight free path along a surface (electrical field vector parallel to the surface) in order to impede the build-up of avalanches involving secondary electron emission. Some scenarios (mainly applicable for vacuum applications) are outlined in Figure 5-23. The inclination of the surface with respect to the free path can reduce the negative surface charge effects, however, the effectiveness of different shapes depend very much on the material. For more details it is referred to in section 8 of the following publication:

R.V. Latham "High Voltage Vacuum Insulation" Academic Press, London, San Diego, 1996



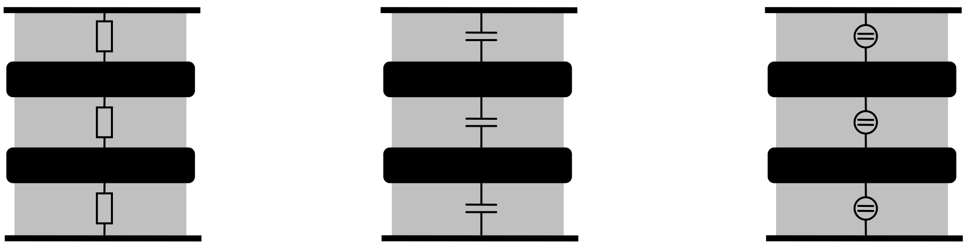
a) Surface charging with secondary electron generation along an insulator surface

b) Surface charging possible shapes with impact on surface charging and secondary electron generation.

Figure 5-23: Designs to reduce impact of surface charging on electric insulation

In addition to the shape, the structure can be relevant: roughening of a smooth surface (i.e. glass, ceramic) can raise the breakdown voltage, however, if the surface is made too rough, the effect can be the contrary, lowering the breakdown strengths.

Another approach is the segmenting of the insulator with a conductive intermediate shield as outlined in Figure 5-24. The electrical potential (voltage) of each section is controlled by different means: either by a resistive network (divider), a capacitive network (in some applications the stray capacitance can be sufficient), or by an active control using current sources, voltage sources or current sinks / voltage sinks. Introducing such an approach can implicate a complex design effort, if shield and networks need to be integrated for this purpose and should be traded carefully against benefits of potentially higher breakdown strengths. Implementation can be easier, in case that capacitive or resistive dividers or voltage/current generators (power supplies) with multiple stages are used anyway.



a) Insulator surface segmented by intermediate shields – controlled by resistors

b) Insulator surface segmented by intermediate shields – capacitive controlled (AC and pulse applications)

c) Insulator surface segmented by intermediate shield – actively controlled by voltage or current sources/sinks

Figure 5-24: Segmenting of insulator to influence surface charging

It is important to highlight, that the mechanisms of surface charging and charge triggered breakdown (especially in vacuum) are very complex. Therefore it is not predictable, which of the above proposed methods are effective and efficient (by costs, design, and complexity). Thus it should be checked for each application individually, if there is a measurable positive effect (by test) and if it worth to spent the effort.

5.1.12 Control of interferences

The presence of high voltage can result in significant problems of interference in terms of:

- Electrical field emission
- Electromagnetic field emission
- Conducted electromagnetic emissions

The measures typical used to avoid interferences are:

- Shielding
- Galvanic isolation
- Limitation of discharge energy
- Limitation of discharge current
- Overvoltage suppression

The pure electrical field emission should be checked w.r.t. spacecraft requirements. In most cases the E-field emission can be significantly reduced by introducing electrostatic shields, preferably placing the HV assembly in a completely shielded box or cage. In case of transient fields or AC application the shield should be grounded properly via a low inductance path.

Electromagnetic field emission and conducted emission come along with alternating and transient voltages/currents in high voltage circuits. These alternation/transients are either caused by the natural function of the HV circuit (AC or pulsed operation) or exceptional events (partial or full discharges, breakdowns, flashovers, etc.). It is clear, that the normal operation should be covered by design; however, special attention should be paid to the non-nominal cases as well. Especially in gas and vacuum environment discharges (flashovers, breakdowns) are not completely avoidable. Therefore the design should be resistant to such events as explained in the following.

An electrostatic shield (as proposed above to limit E-field emission) is also effective to limit high frequency electromagnetic emission. Only in the low frequency domain the magnetic field is difficult to shield as it can require investing a significant mass for metal shielding purposes.

Galvanic insulation is strictly recommended to be placed between high voltage circuits and low voltage circuits (especially towards spacecraft interfaces). Preferred is the use of

- isolation transformers for power and control functions (including an electrostatic shielding as well)
- optocouplers / opto-links for control functions
- high impedance differential link for control (not a preferred solution due to difficult implementation and the fact, that it is not providing a full galvanic isolation).
- Separation of grounding on high voltage side and low voltage side

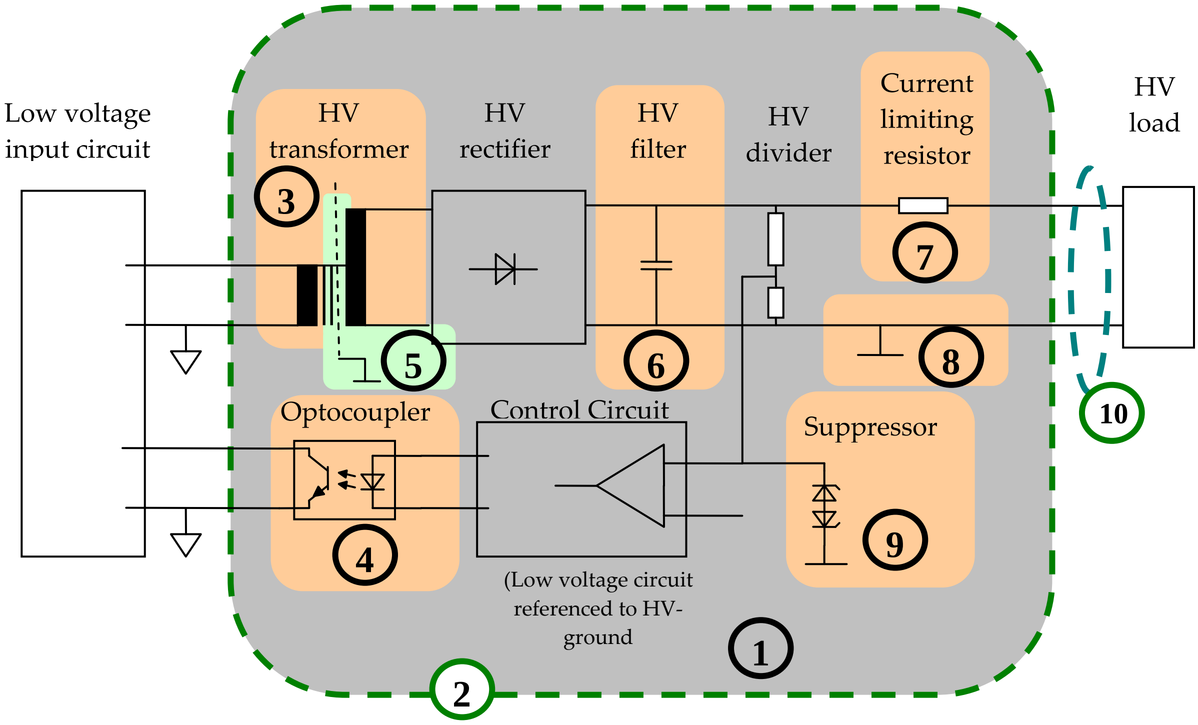
In case, that flashovers and breakdown in the HV circuit or in its load cannot be completely avoided (vacuum or gas-insulated set-ups, electron tubes etc.) the discharge energy and/or the discharge current should be limited. As most of the discharge energy available is related to the filter capacitors of a high voltage conditioner it is worth to limit the value of (output) capacitance to a reasonable value in compromise with the other functional requirements to the circuitry (as its filtering capabilities). It is worth to highlight here, that the discharge energy W_C of a capacitor is $W_C = 0{,}5 \cdot CU^2$ linearly depends to the capacitance *C* and to the square of the applied voltage *U*.

Alternatively or in addition to a limitation of the capacitance, a limitation of the discharge current is proposed for implementation. The simplest means is a limitation by a series resistor. In some cases an inductor is appropriate as well. Of course active current limitation (regulators) can be useful as well, however, they are difficult (complex, expensive) to implement into the output circuitry of a high voltage supply and often they cannot be fast enough. In general, the discharge current limitation concentrates the discharge energy to an element which would be designed to sustain it: the limiting resistor, inductor or semiconductor. For resistors agglomerated carbon resistors are preferred due to their good capability to absorb pulse energy.

For low voltage circuits connected to the high voltage circuit the use of protection devices is proposed to avoid damages from overvoltage. The protection can be achieved by fast suppressor diodes or RC-filters (capacitor and resistor). The device(s) are designed to withstand the maximum dumped energy.

Furthermore an electrostatic shield is useful to protect low voltage parts in the neighbourhood of a high voltage discharge (arcing).

The Figure 5-25 outlines a typical high voltage conditioner design with implementation considering the above measures to minimize interference problems.



Possible interference protection measures

1	HV insulation	6	Limitation of discharge energy (max. C)
2	Shield (metal or metallised)	7	Limitation of discharge current by resistor
3	Transformer for galvanic isolation of power path	8	Secondary ground on HV side separate from low voltage side
4	Optocoupler for galvanic isolation of signal path	9	Suppressor circuits to protect low voltage devices from overvoltage
5	Electrostatic shield between primary and secondary	10	Electrostatic shield for connection to load

Figure 5-25: Implementation of design measures minimizing interference problems for a typical high voltage power conditioner (regulated DC-DC converter for high voltage as an example)

5.2 High voltage assemblies

5.2.1 Solid insulation: potted modules

5.2.1.1 General

For space applications the most widely used type of solid insulation is the potted insulation forming the:

- potted modules

The advantages of such potted insulations are their capability:

- to embed and isolate complex assemblies, as printed circuit boards and transformers
- to provide a mechanically stabilized encapsulation
- to allow multiple encapsulations in a sequence (typically)
- to avoid space vacuum related effects, ground related effects (ambient atmosphere) and transition effects (between both) -if adequately designed
- to provide a good thermal interface (depending on the selected material)
- to provide a compact design (size) due to high insulation strengths

Their disadvantages can be found in their

- mass
- sensitivity to thermo-mechanical ageing and partial discharges

However, these disadvantages can be compensated by an optimization of the shape (to optimize mass), a proper design (to minimize thermo/mechanical ageing effects) and suitable potting process (to avoid any local areas affected by partial discharges).

5.2.1.2 Materials

5.2.1.2.1 Overview

In general, there are three classes of potting materials acceptable for use in spacecraft:

- epoxy resin-based materials
- silicone materials
- polyurethane (PUR) materials

From, each of these groups there are candidates available, which show a low outgassing rate, being compatible with contamination requirements. All mentioned materials are belonging to the chemical group of polymer materials formed by large structures of organic molecules.

Epoxy and PUR belong to the class of thermosetting resins, forming an inherently stable material after curing. Silicone resins typically form an elastic material after curing (rubber-type elastomer).

Potting materials allow compact designs enabling high field strengths inside of the insulation. As a consequence, the insulation should be free of defects, especially free of voids, cracks, delaminations and particles. Such defects are a source accelerating ageing and limiting lifetime. Partial discharges are a very relevant part of the ageing mechanism under AC voltage, but also a non negligible ageing contributor for DC and pulsed voltage. In order to minimize the risk of degradation by insulation defects the design of potted high voltage modules and the potting process needs to be adequate and well defined.

The processing of the potting material typical involves the mixing and processing of different components, at least

- the resin (not cured)
- a curing agent (hardener)

and for many resin products additives as

- flexibilisators
- accelerators (for curing)
- fillers.

Some commercial products are offered as pre-mixture of at least a 2-component system or a 3-component system. Often a user is optimizing his ″own″ resin composition of multiple components.

A brief summary on the different materials is given in the following.

5.2.1.2.2 Epoxy Resins (EP)

Epoxy resins are molecules containing C_2H_3O groups (epoxy groups) at the end of each molecule chain. The quantity of epoxy groups is expressed by the so called EEW value, the epoxy equivalent weight. It describes the quantity of resin in grams which contains 1mol oxygen (of epoxy groups). Resins of low viscosity have EEWs of less than 200 g.

Two groups of epoxy resins have become more dominant for high voltage applications. The bisphenol Resins are mainly used for indoor insulation whereas cycloaliphatic resins are used for outdoor insulation.

Furthermore, it is distinguished between epoxy resins hardening at high temperatures by anhydride hardeners and epoxy resins hardening at about room temperature by amine and amide hardeners. For long-term high voltage applications it is preferred to use the anhydride hardened epoxies.

Epoxy resins are used often with fillers. For space applications the typical filling material is a quartz powder (silica powder). The purpose of the filler is to

- match the thermo-mechanical expansion coefficient with the embedded components,
- increase heat conductivity
- reduce the material shrinkage effect during curing.

The filler needs to be very well optimized with the resin to ensure the proper viscosity for moulding and to avoid sedimentation during curing. A well optimized mixture of different glass particle sizes is important. The use of “silanized” fillers ensures that the particle surface is hydrophobic and thus dielectric properties are not worsened by humidity.

The unfilled epoxy material is transparent in most of the cases, which makes it easier to detect defects and void after processing, which is typically not possible by visible inspection with filled epoxy materials.

Other new minerally filled epoxy systems are still under development and actually not in use for space applications: as the use of “core shell tougheners” to reduce cracks and fractures under mechanical shock and the use of nanotechnology and nano-materials (n-fillers).

The main assets of epoxy materials are their excellent electrical properties, good mechanical properties, low water absorption, good adhesion to metals, and low mould shrinkage. Furthermore, they have a low outgassing characteristics and low vapour pressure. These properties are affected by treatment and processing technique.

5.2.1.2.3 Silicone Resins (SIR)

Silicones are water repellent, heat stable, and very resistant to chemicals. Silicone polymers offer superior electrical properties and excellent thermal properties especially in terms of a low degradation at high temperatures. Main applications of silicon elastomer are curing and potting and flexible insulations, i.e. cables. As the material is a "rubber" it is usually soft and therefore it is not suitable for exposure to high mechanical loads.

Silicones used for insulation purposes have a good resistance against partial discharges and X-ray. A problem is the insufficient adhesion to metals and other organic materials which can be improved by using primers.

The outgassing of silicones is an area of concern especially for space applications. Newer formulas with less low molecular weight siloxane molecule groups can reduce the mass loss significantly. Potting materials of this type are extremely expensive and therefore are suitable only for small volume applications.

5.2.1.2.4 Polyurethanes (PUR)

Polyurethane is a polymer consisting of a chain of organic molecule groups joined by urethane links Polyurethane (PU) is produced in a variety of textures and harnesses by varying the particular monomers and adding other substances. Softer polyurethane can be made by adding flexible Polyethylene glycol segments between urethane links.

Careful control of viscoelastic properties can lead to memory foam, which is much softer at skin temperature than at room temperature. Polyurethane foam (including foam rubber) can be produced by adding a small amount of water to one of the liquid precursors of polyurethane before they are mixed together. This modifies the polymerisation reaction, causing carbon dioxide to be released as the material cures. Gas is generated throughout the liquid, creating relatively uniform bubbles which then harden to form solid foam as polymerisation progresses. However, the use of foams is critical for high voltage insulation due to their "natural" content of void featuring partial discharges.

Therefore the typical PUR application for high voltage insulation in space applications is PUR as an inherently stable thermoset material. Low glass transition temperature, good electrical values and very good reparability makes the PUs suitable for the potting of high voltage components in a temperature range of –50 °C to +120 °C. Nevertheless many unfilled polyurethanes have problems to comply with typical outgassing requirements of spacecraft. Another critical point is the temperature resistance or the ageing of PU under the presence of oxygen.

Additional characteristics of the polyurethanes comprise good electric properties (in terms of high voltage dielectric strengths), a good adhesion to most materials, low exothermic temperature rise during curing, low mould shrinkage, long pot life, and easy reparability. The linear thermal coefficient of expansion is greater than epoxies but smaller than the silicones.

A typical encapsulation problem is the mechanical stress developed between the encapsulant and the embedded parts due to elevated temperatures, temperature differences, and encapsulant shrinkage. In many applications the use of fillers can be helpful to bring different mechanical properties in agreement. In general the fillers increase the value of thermal conductivity and decrease thermal expansion.

The handling of the polyurethanes should be performed with care since the pre-polymers and curing agents can be health hazardous.

5.2.1.2.5 Fillers

In high voltage applications inorganic fillers are used in casting resins where they fulfil various functions:

- improvement of mechanical properties like CTE (coefficient of thermal expansion), elastic modulus, hardness, tensile strength, elongation at break
- influence on the electrical properties like dielectric constant and dissipation factor, resistivity, dielectric strength
- reduction of exothermic reaction during curing process
- improvement of thermal properties like of thermal conductivity, thermal expansion and capacity
- cost reduction of cast resins (important for large volume applications).

Density and particle size are the most important parameters. In practice fillers with a particle size of less than 50 µm (µ-fillers) are often used. Popular fillers are quartz/silica, quartz/silica based materials, alumina and glass fibres.

Regarding ageing effects the internal interface between filler and resin plays an important role. The quality of the insulation system depends evidently on the adhesion between filler and resin. A low adhesion leads to accelerated ageing processes caused by moisture, partial discharges and electromechanical forces. These effects can be classified by loss factor measurements and partial discharge analysis.

These ageing mechanisms related to interfacial phenomena can be influenced by special preparation of the fillers and filler surfaces. Examples are:

- hydrophobic additives (silane treatment)
- additives to improve adhesion
- plasma treating
- ‘pure’ filler with low impurities.

Most important fillers are quartz/silica powder often improved by silane treatment. Other (for space applications less relevant) fillers are wollastonit and chalk which are cheap in production. New types of fillers like boron nitride or aluminium nitride, which are not very common in use and (today) not offered as established mixture from the available suppliers. Users, which are interested in resin trimmed with these “sophisticated” fillers, have the choice either to develop the filled system themselves or to request this from specialized industrial service providers.

A new interesting family of fillers are the nano-scaled fillers (n-fillers). Particle sizes from 1 nm to 100 nm are achieved and new insulation systems are still under development.

Advantageous effects of nano-materials are related to microscopic interactions between the surface of the filler particles and the resin. The smaller the particle size the more atoms are located on the surface. Particles with diameter of 20 nm contain 10 % of the atoms at the surface and 1nm particles contain 99 % of the atoms at the surface. This results in a stronger interfacial linkage between the atoms on the particle surface to atoms in the particle and atoms of the resin. Concluding, even with low filler content (10 % - 30 %) the physical properties of the composed material can change significantly.

With the small size of the n-fillers the more important become the proper mixing between filler and resin. Only with special high speed mixers it is possible to achieve a smooth dispersion. For analysis (particle distribution) and characterisation of the filled system only REM and TEM with highest resolution, X-ray structure analysis and high sophisticated optical methods can be used.

Another disadvantage of n-fillers is a limited mixing ratio of resin/filler. The higher the filling degree the more viscous becomes the system. Low filler content results in even lower thermal conductivity properties. The right way can be a development of a mixture of n-fillers and µ-fillers depending on the requirements. Whereas only specialised companies are able to develop such a filled potting system.

Since research on composites with nano-fillers is a new field, the impact on all the different thermal, mechanical and electrical properties is not very well known, actually.

Silanes are additives to fillers (like silica/quartz powder) and form a compound of silicon and hydrogen. As mentioned above the interface between resin and filler is a weak point in a potting system. To increase the bonding capabilities of the resin and the filler particles silanes are used very frequently. Most advantages are:

- easier mixing and smoother distribution of filler particles
- better bonding between particles and resin
- hydrophobic capabilities.

Silane treated silica (quartz powder) are often used for outdoor applications like power transformers, bushings, isolators etc.

UV-absorbers are normally used in clothing, cosmetics, paints and also very often in thermoplastics, elastomers and insulators for outdoor use. The reason for the use in insulators is the bond energy of C-C bonds which is lower than the radiation energy of sun light. A new aspect for the use of UV-absorbers is the reason for the damage effect of partial discharges. Not the destruction due to thermal decomposition is the main reason; the short wave radiation energy due to a discharge breaks the molecular chains. But it should be verified if UV-absorbers have a significant influence on the PD behaviour of insulators.

5.2.1.3 Design

5.2.1.3.1 General

The design of a potted module follows some basic rules but depends also on the purpose and content. Some basic design cases and design rules are explained along with a number of examples:

- Modules with embedded structures
- Modules with electronic parts and components
- Modules with PCB's
- Components
  - high voltage transformers
  - filter modules
  - isolators
- Feedthroughs (conductors, insulated wires)
- Mixed modules (transformer and components).

The following design examples are dedicated to certain general design aspects.

5.2.1.3.2 Potting of structures

A very general case is the potting of mechanical structures in a module, for example: embedded electrodes, embedded conductors or terminals for interconnection. However, this case represents also the packaging of more complex assemblies with HV components and PCB's.

The basic sequence is always the same as shown in Figure 5-26: in Phase 1 the item to be encapsulated is prepared in a mould, in Phase 2 the mould is filled with resin, followed by a curing process and in Phase 3 the mould is removed. In detail there are many more detailed processing steps with variations. More details on the processes and variants are explained in section 5.2.1.4.

In relation to the potting process, there are some important factors to be considered in order to prevent negative consequences of thermo-mechanical effects as well as of high voltage field effects.

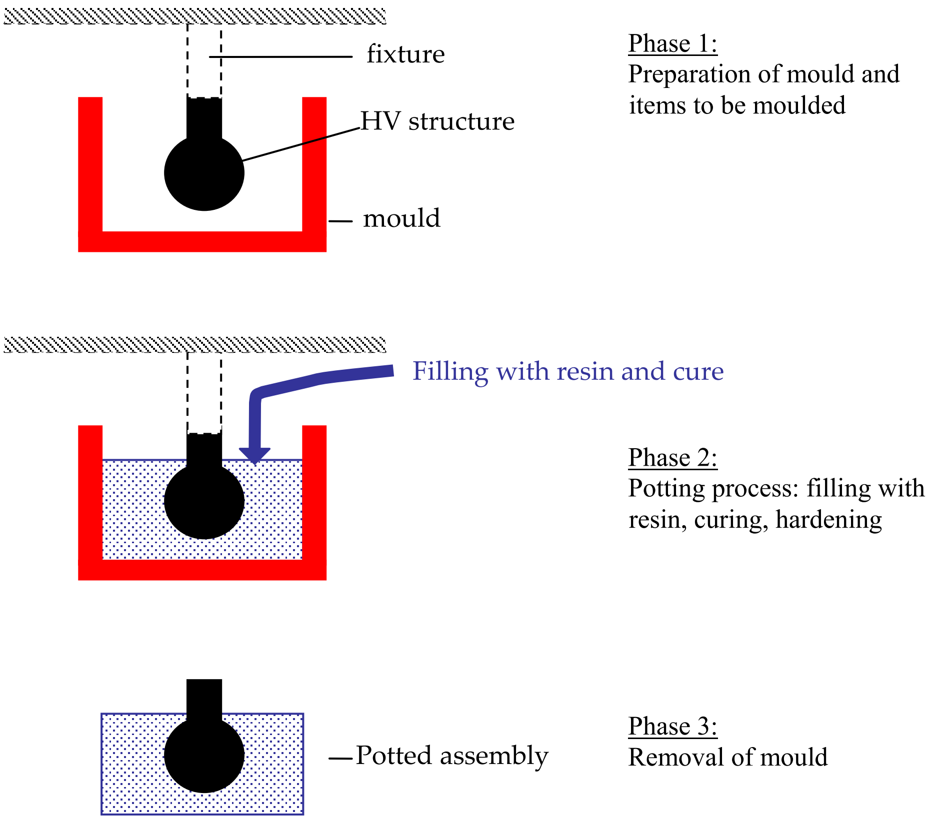


Figure 5-26: Designs example: potting of embedded aluminium structure, i.e. an HV terminal

In the following some very important general design aspects are addressed and are outlined in Figure 5-27.

A) Mechanical compression forces:

Compression forces experienced by the encapsulated HV items are advantageous as long as these forces are not overstressing the item. Normally the compression forces ensure that the potting material is always in contact with the HV item/electrodes and therefore no delamination and gaps can occur. Related to this wanted compression effect, the following needs to be highlighted:

- The expansion coefficients of most potting materials are higher than those of metallic and ceramic materials.
- Often the curing process is performed at elevated temperatures.
- In order to avoid delamination in the interface between the encapsulating resin and the embedded component, it can be advantageous to ensure the embedded components always

experience a compression force from by the encapsulating resin. A suitable way to achieve this behaviour is to ensure two major conditions: 1) the potting process is performed at higher temperatures than the maximum operating condition of the potted item and 2) the thermal expansion coefficient of the resin is higher than of thermal expansion coefficient of the embedded item.

- However, the compression forces can be critical / especially in combination with thermal cycling, if the embedded item is not able to withstand it. Especially combinations with glass and ceramic can be critical; as such material can crack easily. Furthermore, some potting materials themselves are brittle and tend to crack, often in the low temperature range.
- If compression forces are not perpendicular to the surfaces of the embedded items, delamination can occur due to shear forces.

B) Mechanical detaching forces:

Detaching forces often appear when the potting material is filled into an outer containment (of lower thermal expansion coefficient): for example, when the resin is cured at elevated temperature in a metallic containment, then detaching forces occur at curing (due to material shrinkage) and at decreasing temperatures. A formation of a gap can occur. To a certain extent, the adhesive forces of the potting material can withstand these forces.

However, delamination should be considered as a failure case and the consequences analysed carefully. An alternative could be the use of soft, but insulating filling material (i.e. silicon), however, the required process and design can be much too complex.

C) Local mechanical peak forces:

An encapsulation of sharp-edged structures is critical. Mechanical and thermo-mechanical forces can be very high at such points and be the cause of crack initiation, leading to a mechanical failure and subsequently, to an electrical failure. Therefore, soft-shaping of embedded items is essential from a mechanical point of view as well as a means of reducing the electrical field stress (see D).

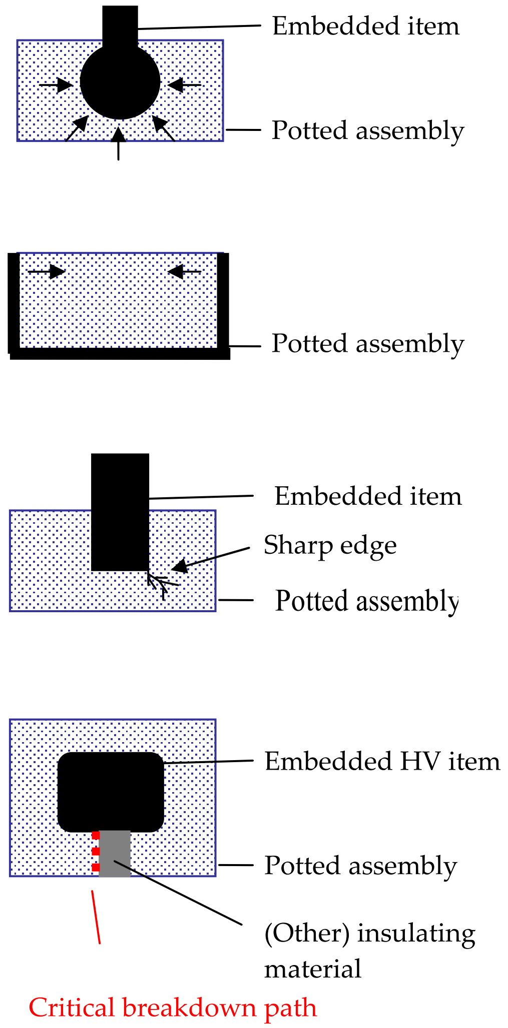
D) Local peak electrical field strengths:

Sharp-edged structures of embedded HV conductors are critical as well. The resulting electrical field strength can be high (see section 5.1.2) and cause partial discharge favouring growth of "electrical trees". Organic potting materials are sensitive to such a life-limiting destruction process. For orientation values of maximum electrical field strengths see Table 5-2 and Table 5-3.

E) Critical lateral electrically stressed interfaces:

Often, the manufacturing process of a potted module requires a sequence of potting steps (potting of one part and after curing followed by a subsequent potting) and/or the combination of different insulating materials. In many cases insulating spacers are needed to position the item, which is foreseen to be encapsulated. In such a case the interface should not be exposed to a significant electrical field along (lateral) to the interface area. This forms a "critical breakdown path. As a consequence:

- The electrical field strength of such an interface (regarding the field component lateral to this interface area) should be significantly lower than that one applied to the homogenous insulation material surrounding it.
- If such interface conditions cannot be avoided:
  - place such interfaces in areas with no or low electrical field strengths or assure a perpendicular orientation of the interface with respect to the electrical field.
  - select process and potting material with good adhesion to each other.



A) Mechanical compression forces
In this typical case the embedded items are exposed to compression forces.
+ Prevents delamination
- Critical if overstressing embedded items

B) Mechanical detaching forces
Detaching forces are critical as they can cause delamination (not recommended, but possible if marginal mismatching of CTE)

C) Local mechanical peak forces
Sharp edges cause cracking due to mechanical and themo-mechanical forces – to be avoided!

D) Local peak electrical field strengths
Sharp edges cause partial discharges and treeing due to electrical field – to be avoided.

E) Critical lateral electrically stressed interfaces
In case that interfaces of different insulating materials or same materials combined in sequential production steps are used, the interface should not be exposed to significant electrical field along (lateral) the interface area. This forms a “critical breakdown path (see doted red line).

Figure 5-27: Designs example: potting of embedded aluminium structure, i.e. HV terminal

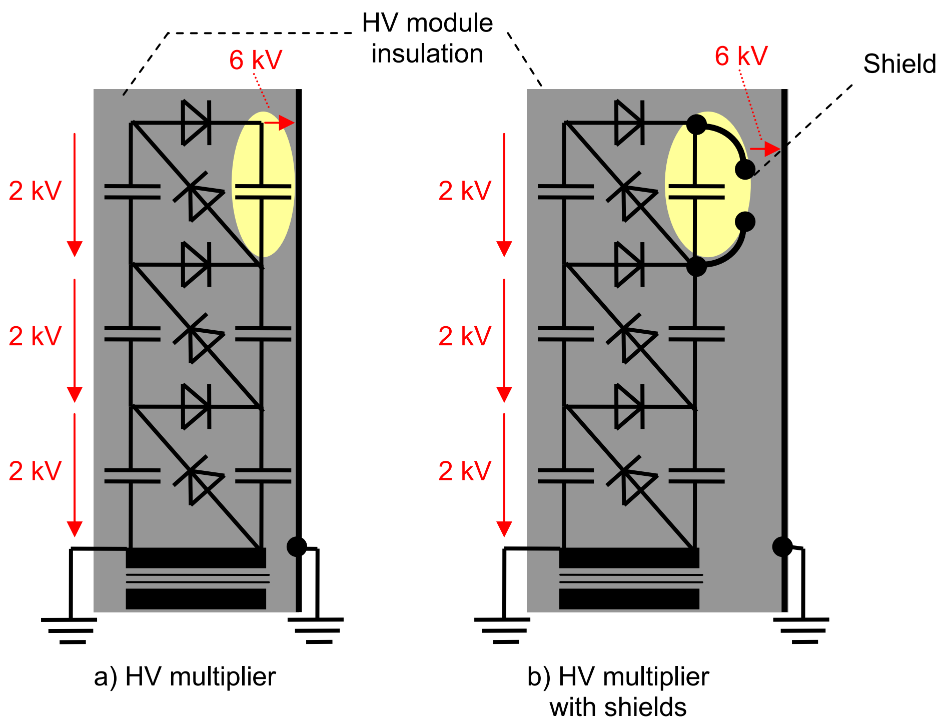
5.2.1.3.3 Modules with electronic parts and components

In electronic power conditioning for high voltage typically many types of electronic parts are used like capacitors, inductors, transformers, diodes, transistors etc. These electronic parts are sometimes specifically designed for high voltage applications or sometimes used at floating high voltage potentials (with low internal electrical field stress.

There are some aspects to be considered for the design of potted modules embedding electronic parts and components:

- The potted components should be compatible with the electrical and mechanical stress cases as explained in section 5.2.1.3.2 "Potting of structures". The compatibility should be investigated by analysis or/and test. Special attention should be observed to parts like:
  - diodes in glass packaging
  - ceramic capacitors
  - ferrite magnetic cores
  - thin conductors (flexible PCB’s, thin wires of transformers and inductors).

- Outgassing of the parts during the curing process is a potential problem, which can occur, if there is a trapped gas volume, which slowly degasses during the curing phase of the potting process. These gas volumes can then form gas voids in the surrounding potting material after curing. Typical sources of such gas volumes are insulated wires (often with stranded conductors) embedded in the resin or embedded foams. Another reason can be a chemical incompatibility.
- Chemical incompatibility of materials with the potting material can be a potential source of gas formation (see above). Furthermore, it is possible due to a chemical reaction or diffusion that the properties of the original potting material change.
- A shielding for the purpose of controlling the electrical field can be necessary if an electronic part is exposed to an improper electrical field stress. An example is shown in Figure 5-28.
- Interconnecting parts can be performed in different ways:
  - Interconnecting using PCB's (Printed Circuit Boards) – for detailed discussion see section 5.2.1.3.4 "Modules with PCB's" and section 5.3.10. Interconnecting via PCB's has its limitation (in terms of voltage level) due to high electrical field strengths appearing at the edges of conducting tracks.
  - Free wiring using the existing wires attached to the parts, or connecting with additional external wires, rails and structures. Since typical wires are "round" they principally lead to lower local electrical field strengths than sharp-edged copper tracks of PCB's. However, it is important, that solder joints (or equivalent joints) are rounded properly, a "ball type" solder joint - covering the sharp-cut ends of wires – is proposed. An example is shown in Figure 5-5. Further details are given under section 5.2.1.3.7 "Solder Joints".



Explanation: The electric part – a capacitor C– is used in the circuit. Although the voltage across the part is nominal, it is used floating at a high voltage level. When this assembly is potted, it should be ensured, that the part is not exposed to unusual local electrical field strength. In such a case a local electrostatic shield attached to the local potential of the part can help to reduce the local field strengths or at least give a better control.

Figure 5-28: Shielding necessary to avoid exposure of an electronic part to excessive electrical field stress

5.2.1.3.4 Modules with PCB's

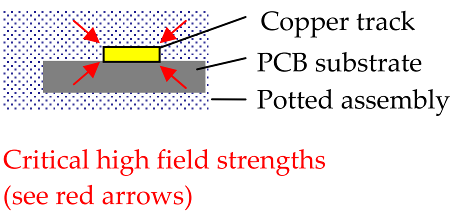
Potting of PCB's – rigid or flexible - is a practical method to simplify the production process, but can lead to a complex thermo-mechanical design, especially if different types of electrical components are soldered onto the PCB. Typically, local stress cases and the influence of thermo-cycling on lifetime cannot be easily predicted; therefore thermo-cycling with the applicable load cases together with the high voltage stress is essential.

From a pure electrical point of view, there are different design cases to be considered:

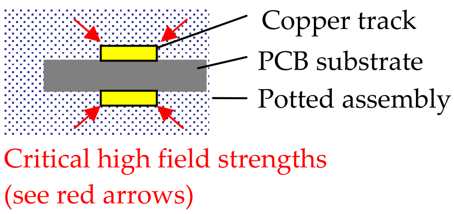
- The circuit on the PCB is "low voltage", but everything is electrically floating and associated to a high voltage potential. Between tracks – inter-layer and intra-layer – the voltage is low. In such cases high electrical field strength can appear only on the boundary tracks to the outside. Local shielding or global shielding is needed, if local electrical field strength is too high (see Figure 5-28-b for global shielding and for local shielding Figure 5-29).
- The circuit on the PCB is carrying "high voltage". In this case local shielding is needed, if local electrical field strengths are too high (see Figure 5-29 A-D). Furthermore, cut-outs in the PCB can help to improve the interface between PCB and potting material (see Figure 5-29 E,F) Additional information is given in section 5.3.10.

Potting of a PCB typically requires surface treatment to control adhesion of the resin to the PCB assembly (see section 5.2.1.4).

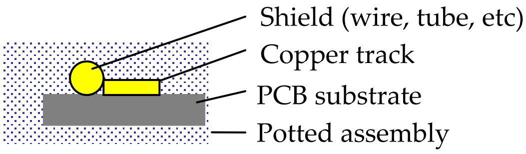
Furthermore, it is pointed out, that instead of complete potting of PCB's in some applications coatings or condensed layers are used (see section 5.3.10).



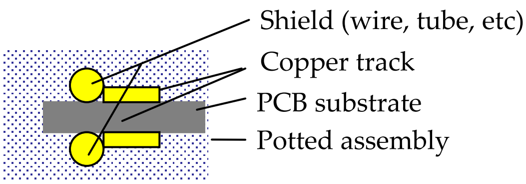
A) Sharp-edged copper tracks
High local electrical field strengths appear at the edges of PCB copper tracks, if the track conducts high voltage with respect to other PCB tracks, to the outside or towards parts mounted on the PCB. This situation may be acceptable for high voltages up to a few kV.



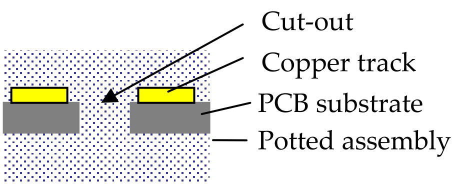
B) Copper track on both sides
“Doubling copper tracks associated to the same potential removes (most of) the electrical field stress of intra-PCB insulation, but high local electrical field strengths appears still at the “outer” edges of PCB copper tracks. Small improvements w.r.t A). Better with low PCB thickness.



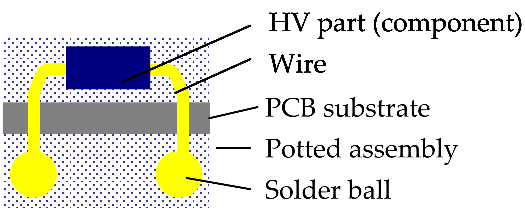
C) Shielding a sharp-edged copper track
High local electrical field strengths appear at the edges of PCB copper tracks, if the track conducts high voltage with respect to other PCB tracks, to the outside or towards parts mounted on the PCB. Radius selection in accordance with chapter 5.1.3.



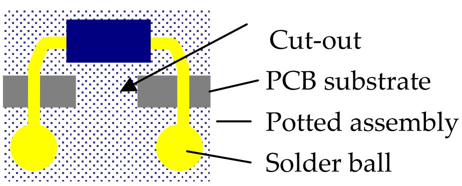
D) Shielding of sharp-edged double-sided copper track
Same as C), but slightly better field distribution and max. field strength reduction.



E) Cut-out at critical PCB locations
In case that a significant HV field is present between two copper tracks (lateral to PCB), cut-outs in the PCB may aid to avoid a straight “creepage” path. The cut-out are filled with resin. An improvement (if any) depends on selected material, process an electrical field.



F) PCB without tracks as “carrier” only
In case that a significant HV field is present between two copper tracks (lateral to PCB) another design option is to use the PCD without track (only through-holes) and to make interconnection by round wires and solder ball. This design give maximum control of the peak electrical field.



G) PCB without tracks with cut-out
Combines the advantages of F) and E). Problem could be the mismatch of the thermal expansion coefficients.

Figure 5-29: Potting of PCB`s: typical design aspects

5.2.1.3.5 Components

Typical components used in high voltage electronics are:

- HV transformers
- filter modules

Both are typical parts of high voltage power conditioners used in space electronics. A transformer to step-up from low voltage to high voltage using high frequency AC voltage (often between few ten kHz and few hundred kHz) and a rectifier/filter module to produce a "smooth" DC voltage.

For completeness, it should be emphasized here, that the combination of a HV transformer and a HV filter module is an example for any other combination of high voltage function integrated into modules. So the presented considerations are transferable to many other combinations of components and modules.

High voltage transformers and filter modules can be built as potted modules or partially potted. Non-potted alternatives are either limited to the lower high voltage range (few hundred volts and non subject to Paschen breakdown) or need to involve other high voltage insulations like oil or pressurized gas (however, both methods are not well established in space environments. More detailed aspects of these topics can be found in sections 4.2.3, 5.3.1, and 5.3.8.

As both components are used together with an electrical interface, there are some design options for potting.

- Two different modules in "open" connection (see Figure 5-30)

  The advantage is an individual potting of each module (one filter, one transformer), which can be very well matched to the embedded items. Thermo-mechanical stresses and the risk of encapsulating a defect is less critical due to lower potted volume (compared to combing both in one module). Furthermore it is easily possible to test each module individually for function, performance and high voltage insulation. Good reparability and maintainability can be obtained as each module. Can easily be exchanged

  Disadvantages are higher mass, size and the need for "open" terminal for interconnection. Furthermore the modules need an "outer" insulating environment as gas, liquid or vacuum.

- Two different modules with potted HV harness (see Figure 5-31)

  Similar configuration as above, however, the interconnecting high voltage harness is potted, thus the outer environments do not play an important role for overall insulation. This independence of the environment is at the expense of a more complex potting sequence: either the modules are potted individually and only the interconnecting harness is potted in a second step, or the harness is potted in the same step (which comes close to the situation described below "Common module").

  When the harness is potted in a second step, there is typically the need for a small mould. Often it is possible to foresee a "niche" in the potted module which fulfils the function of a "natural" mould; otherwise it is necessary to place an external mould with sealing.

  It is obvious, that the disconnection of the potted harness can be difficult or not possible at all. If soft potting materials (like silicone or soft polyurethane) are used, it is easier to make the connection accessible again by removing material, thus rendering the connection point accessible and after repair, allow re-potting of the connection.

  Regarding the harness treatment see also 5.3.5. The design of the harness potting needs to respect sufficient strain in order to avoid detachments and delamination of the harness insulation from the surrounding potting material. Furthermore, it is typically the case, that the harness needs special treatment (cleaning, etching etc.) to ensure proper interfacing with a potting material. In addition, it is worth consideration that the harnesses typically have some gas volume enclosed amongst the stranded wires, shields etc, careful attention should be given so that gas is not released during the curing process, that would forms gas filled bubbles in the resin.

- One common module assembled in two or more potting sequences (see Figure 5-32)

  Very efficient in terms of mass and volume is the approach to place all necessary components (transformer, filter stages etc.) in one module. This avoids interconnecting harnesses, connection terminals and specific module elements as insulation, fixations, etc.), that then can be shared. So there are some synergies for such an approach. On the other hand, this combined compact module is more complex, requiring a sequence of potting steps. Furthermore, the access to the embedded function after potting is typically not possible, the testability and the reparability are very limited.

  In some cases a single potting of the entire module is possible in one step. However, often first the transformer is encapsulated and then the already potted transformer is integrated with the rest of the assembly. The first and second (and other subsequent potting) can be made with the same material or with different. Often a hard material like epoxy resin is used for the transformer and a softer material (like polyurethane) is used for the overall potting. Sometimes filled and unfilled materials are combined, whereas the filled material is used in areas with higher heat loads.

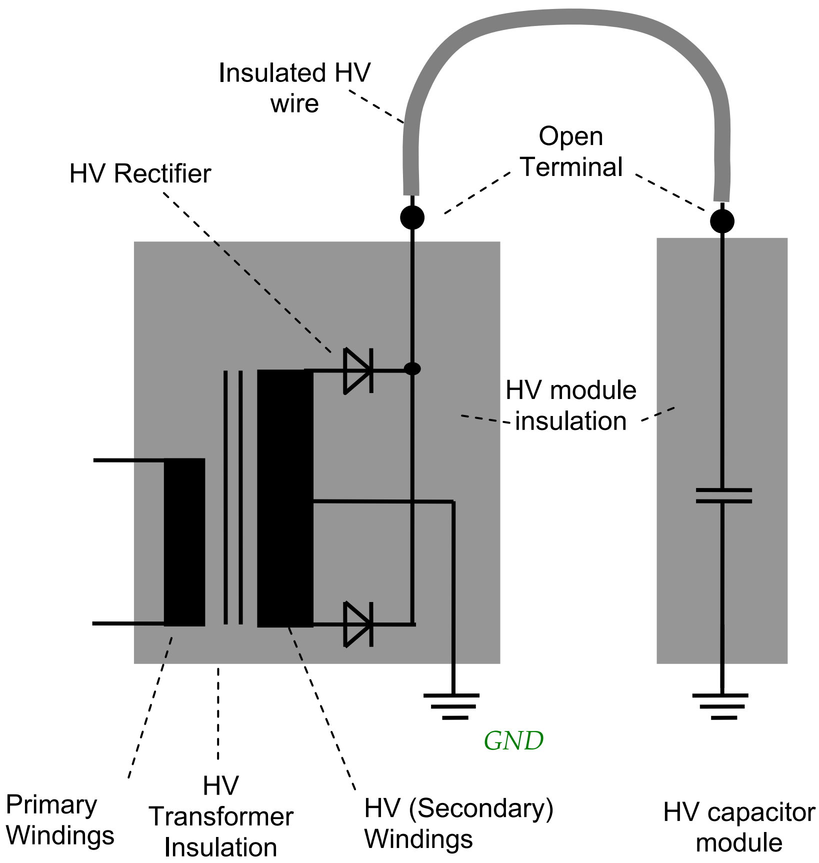


Figure 5-30: Transformer with rectifier and filter designed as two separate modules using open terminals for interconnecting HV harness

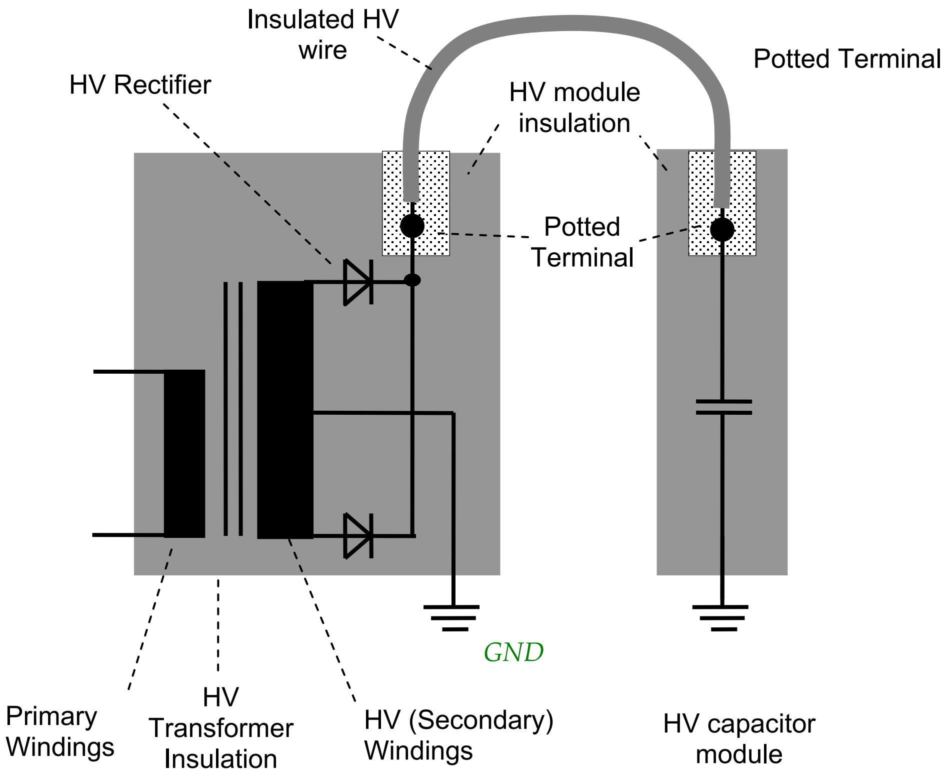


Figure 5-31: Transformer and rectifier filter designed as two separate modules using potted terminals for interconnecting HV harness

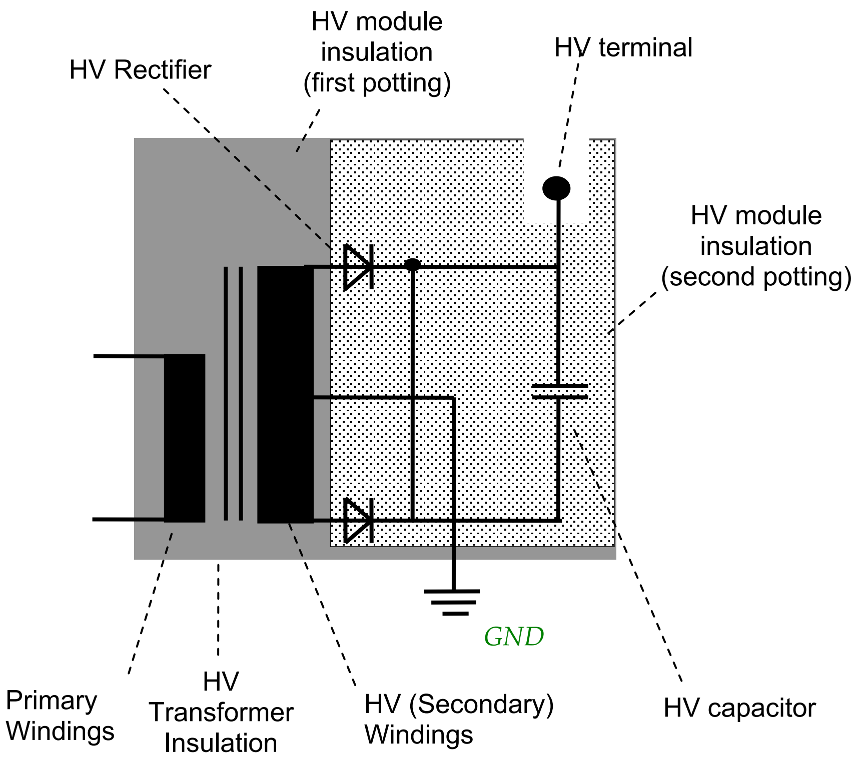


Figure 5-32: Transformer and rectifier filter designed as one combined module potted in (a) one or (b) two and more sequential potting processes

5.2.1.3.6 Insulators and Feedthroughs (conductors, insulated wires)

Insulators and feedthroughs can be made of potting materials. There are two practical ways to create a shaped insulator or a feedthrough:

- Moulding of simple specimen as a raw base potting material and shaping it by milling and drilling
- Using fit-to-shape moulds

The shaping by milling, drilling etc. is usually possible if hard potting materials like epoxy resin are used and allows very complex shapes depending on the material. However, some filled resins – i.e. glass filler, quartz, alumina fillers requires special machining tools with diamond plated cutting blades. In addition the machining could cause cracks in the insulating material, thus a dedicated inspection process after machining should be used.

Moulding into a shaped mould avoids complex machining, however, it requires some effort to produce specific moulds. On the other hand it is easily possible to embed electrodes for electrical field stress relaxation at triple junction points.

For further details see section 5.3.8 (Insulators and spacers).

5.2.1.3.7 Solder Joints

Solder joints which are located inside potting materials and which are exposed to high electrical fields need to be shaped in a more or less spherical manner in order to limit the local electrical field strength to an uncritical value (see Figure 5-33).

This type of treatment for solder joints is proposed, if the operating voltage exceeds a threshold of 5 kV-10 kV for DC and 2,5 kV for AC operation.

Recommendations for shape radius can be obtained from section 5.1.2.6, with specific attention to equation [5-11] and Figure 5-5.

There are two practical ways to implement spherical solder joints:

- Shaping the hot flowing solder material (manual soldering) in an appropriate shape. This requires some experience of the person performing the soldering and is not fully reproducible. However, this method can be acceptable for “lower” high voltages (up to a few kV) and if the number of units/solder joints to be produced is not too high to be treated and inspected individually. Visual inspection by an experienced high voltage engineer or quality assurance person is strongly recommended.
- Using pre-manufactured metallic spheres with embedded structures (i.e. holes) to embed the to-be-connected wires. The conductive interface can be made by conductive glue or by a soldering process.

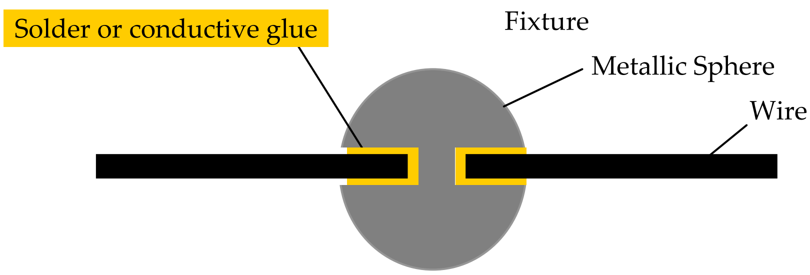


Figure 5-33: Designs example: Spherical solder ball

5.2.1.4 Potting Process

For the production of potted high voltage modules a well defined and suitable potting process is the key factor for providing a high performance and long-life electrical insulation.

A major encapsulation problem (to be avoided) is the occurrence of cracks, voids, delamination and particles in the material. In these areas the presence of strong voltage gradients leads to inception of partial discharges and reduces the lifetime of the insulation. By taking care on the selection of an encapsulant and of the related processing technique the problem can be minimized. A substantial aspect of this technique is vacuum degassing of the encapsulant material before mixing, then mixing and pouring in vacuum.

Although there are various possible processes depending on the material, for a high quality potting process it is proposed to involve the following process steps:

1. Outgassing of potting material constituents
2. Mixing (if two or more component resins or fillers are used)
3. Warming up of resin mixture (if hot curing resin is used)
4. Pre-heating of moulds (if the process requires high temperature and especially if metal moulds are used)
5. Outgassing of moulds (if the process requires high temperature)
6. Casting under vacuum (preferred)
7. Casting under ambient pressure (not preferred)
8. Pressurizing to ambient
9. Pressurized curing (Autoclave)
10. Applying a temperature profile curing (stand-alone or in combination with pressurized curing).

It is highlighted, that a high quality potting process has to ensure, that within the steps 1-6 the vacuum environment is always present and is never interrupted (by pressurization) in this process chain.

In order to achieve better mixing results, the potting components are warmed up before mixing. The process steps could be the following:

- Warming up and outgassing of potting material constituents
- Mixing
- Warming up of resin mixture.

After filling up the mould with resin, the vacuum can be removed (step 8) and the applied ambient pressure squeezes the remaining gas bubbles enclosed in the still low viscose resin and can possibly go into dilution. Applying additional high pressure is promoting this effect (step 9) – thus performing the curing process in high pressure chamber (step 9), which is a further advantage.

Applying a thermal profile (step 10) is useful, especially if the curing takes place under elevated temperature. At the end of the curing process it can be beneficial to stay for hours at elevated temperature level before reducing the temperature stepwise.

Casting under ambient (step 7 instead of step 6) is not recommended, but can be unavoidable depending on the selected potting material or due to restrictions of the circuitry/items to be potted. If the casting is performed under ambient, it should be ensured, that the pre-processing (steps 1-4) are performed in vacuum.

Filling a mould with the resin can be performed in different ways, depending on the construction of the mould:

- Filling a mould from the top
- Filling a mould from the bottom.

Filling the mould from the top is very practical as the viscose resin is just following the gravitational forces to fill the mould. However, as potentially residual gases have to escape in the opposite direction (against the flowing resin) it is possible, that gas bubbles become trapped in the cured resin. This often happens when the geometries of the embedded components and the mould are complex.

Filling-up the mould from the bottom more easily ensures, that trapped gases have the possibilily to escape, if a suitable opening on the top side of the mould is foreseen.

As the resin is typically shrinking during curing it is useful to provide some extra resin volume in the supply and riser piping. After curing removal of the mould, these "appendices" typically are removed by milling or cutting.

Regarding the mould, there are two basic constructions:

- Flexible moulds, typically made of silicon resin
- Rigid moulds, typically made of aluminium (or other metallic materials or polymers).

Flexible moulds (especially if made of silicon) can be easily produced by encapsulating a "shape dummy" of the intended specimen as a "positive shape". Removing the dummy specimen after curing of the silicon resin gives a properly shaped mould. As the material is soft, the accuracy of the dimension is limited. However, the soft mould is easily suitable to cope with expansion and shrinkage of the resin content. The reuse of such moulds is limited.

Rigid moulds give a precise mechanical shape of the specimen, but they are more expensive to produce, but they are reusable many times. As the processed resin typically tends to glue with the surfaces of the mould, there is the need of using non-adhesive surfaces, as made of PTFE (Teflon) or silicone making handling more complex.

However, rigid moulds made of metal give the opportunity to heat the mould. As the curing reaction of most resins is "exothermal" they tend to start curing from the centre of the body. By external heating the curing can be controlled in a better way: more homogeneous curing starting from the walls, avoiding uncontrolled shrinkage.

Regarding the filling of the mould with resin there are different approaches:

- Filling from the top side (free flowing or dropping)
- Filling from the bottom side
- Filling through nozzle with pressure.

Filling from the top side allows box-like mould which can be easily filled by casting or dropping of the liquid resin with or without any additional means. However, potentially trapped gas bubbles need to evacuate into the opposite direction and can be captured somewhere in the filled mould, thereby creating a critical source for partial discharges. Bottom-up filling reduces the risk of entrapping gases, but requires more complex resin feed systems and often require more expensive rigid moulds. However, the filling can be controlled in a better way.

Nozzles systems give a lot of flexibility to fill a mould in an optimum way – thereby avoiding trapped gas bubbles and a more easily controlled curing process." The effort to install and operate such a system is higher compared to the alternatives, however, the gain of this optimized potting process is highly rewarding.

For some resins it is possible to perform more than one sequential potting step, for example: first to pot and to cure one part of the assembly and afterwards to pot and cure another section of the assembly. With many epoxy resins as well as with polyurethanes and combinations of both, this is feasible. Difficulties can be expected if silicone resins are used, as the surfaces can have some difficulties in gluing together.

There are numerous effects and problems to maintain under control for a potting process, some of these are listed in the following:

- Sedimentation of fillers
- Gas bubbles (in general)
- Gas bubbles cause by encapsulated components (chemical reaction with surface and materials, i.e. especially yarns, tapes and glues)
- Delamination due to shrinkages caused by thermal effects or due to mass loss during the curing process
- Cracks due to shrinkage
- Embedding of harnesses presents a risk, where a stranded wire surrounded by insulation, can contain significant amounts of trapped gas, which can slowly escape during the curing process as gas bubbles
- Multiple material moulding has to handle different expansion cycles and coefficients causing mechanical stress (cracks, delamination) and needs to ensure a good interface between materials (adhesion).

In many case a partial discharge test is performed to characterize the quality and integrity of the potted insulation. It is proposed to check the design of a potted assembly for the suitability of being tested against partial discharges. Especially in complex assemblies with grounded structures the partial discharge test configuration is not fully identical to the intended operational configurations. In such cases the insulation can be modified to fit to the test scenario as well as to the operational scenario. An example is shown in Figure 5-34.

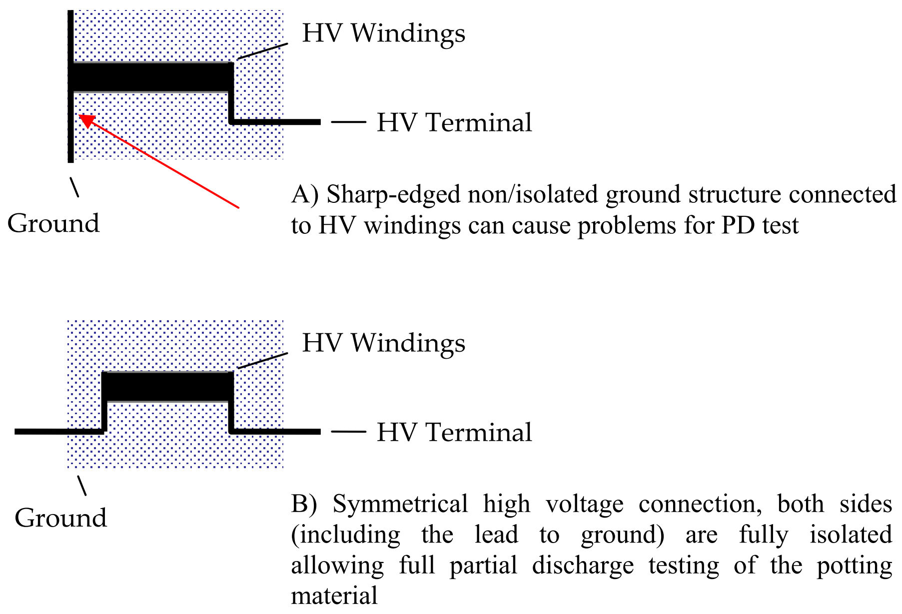


Figure 5-34: Fitting a potted assembly to partial discharge testing (Example of a potted transformer winding)

5.2.1.5 Life Limiting Factors

The major life limiting factors for potted assemblies are:

- thermo-cycling
- high temperature
- low temperature
- radiation (cosmic and ultraviolet)
- humidity.

Thermal cycling is a most important ageing factor especially for hard potting materials as the thermo-mechanical stresses can result in cracking and delamination after a while.

High temperature is critical in general, as the chemical destruction and electrical ageing progresses faster than at lower temperatures.

Low temperature increases the brittleness of most potting materials resulting in cracking.

Radiation in the ultraviolet range or hard cosmic radiation can result in destruction of polymeric chains, making the material more brittle with time. Cosmic radiation can cause space charges inside of the material increasing local electrical stress.

Humidity as an environmental factor on ground can increase the electrical loss factor.

5.2.1.6 Thermal management

Often dissipating components are embedded in the potted insulation. As the thermal conductivity of the potting material is low compared to metallic materials, the draining of heat is often a problematic issue. The maximum operating temperatures of these insulation materials is typically between 80 °C and 120 °C – depending on the limitations given by the stress-lifetime curve.

Basically there are two means of increasing the heat drain capability of a potted module (see Figure 5-35).

- Using a high conductive filler
- Embedding a high conductive drain structure made of metal (copper, aluminium) or ceramic.

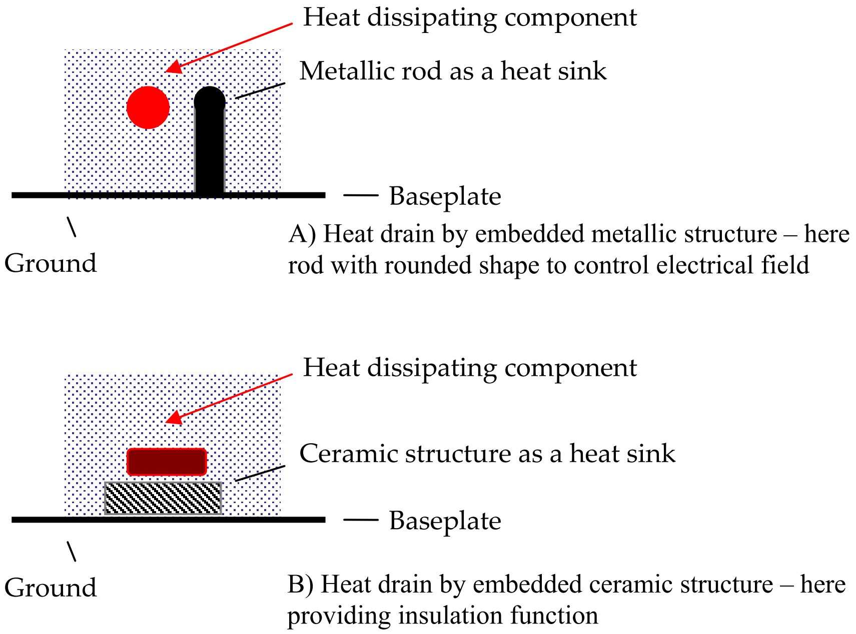


Figure 5-35: Examples for thermal drains embedded in potted modules

High conductive fillers are quartz (glass), boron nitride and alumina. However, to achieve good results the percentage of fillers, the grain size of fillers and the potting process need to be very well matched. Highly optimized potting materials for high voltage insulation can achieve thermal conductivity in order of 1 W/m K.

Thermal drain structures made of metal or ceramic can help to improve the heat flux from high dissipating embedded components. If metal structures are used, special care should be taken to avoid implications with high electrical field strength, as the embedded metal structure reduces the insulation distance to high voltage conductors. The use of ceramic structures can increase thermal conductivity as well, however, not as well as a metallic structure. However, the ceramic does not weaken the insulation so much. Of course, there is an impact, that the embedded ceramic modifies the electrical field distribution; this provides a weak surface between the ceramics and potting material interface.

This should be carefully matched with the thermal expansion of the embedded material.

5.2.1.7 Thermo-mechanical matching

In a perfect case, the thermal expansion coefficient of the embedding potting material is equally matched to the embedded component inside the potting material. For embedding of electronic components this is difficult to achieve, as substrate materials are typically made of ceramics and as conductor materials are typically metallic or silicon, both have lower thermal expansion coefficients than typical potting materials. Using fillers for the potting material can help to reduce the mismatch in coefficients. Suitable fillers are quartz (glass), boron nitride and alumina. Often it is advantageous using a process which cures at higher temperatures than the maximum operating temperature of the potted module, as to allow shrinking of the insulation material onto the embedded components. This can help to prevent delamination in the interface; however, pressure forces generally need to be controlled to avoid cracking.
It is highlighted, that one is careful when curing of potted material is made with temperature sensitive components embedded in the potting. Not only “active” components are at stake here, even “passive” components / materials can be negatively affected if the curing temperature is too high.

5.2.1.8 Other aspects

Special attention regarding design should be addressed to the following points:

- Control of surface charging – see section 5.1.12
- Control of interferences – see section 5.1.11
- Control of corona effects – see section 5.1.7

5.2.1.9 Long-term stability

The long-term stability of potted high voltage insulation is excellent under the condition that they are

- properly designed
- using a high quality materials and processes.

Lifetimes of 15-20 years and longer can be assumed as a standard.

5.2.1.10 Reparability

Potted insulations are difficult to repair – in flight anyway there is no possibility, on ground only in very exceptional cases, for example when an easily removable soft potting material is used, which then can be mechanically removed and replaced.

5.2.1.11 References of potted insulations

For space missions solid insulations are "state of the art" for EPC´s in communication and radar applications, worldwide they have a heritage of more than 30 years.

5.2.1.12 Costs

The production of potted insulations require a well established process for obtaining a high quality insulation, a facility that allows for the preparation, mixing and moulding under vacuum conditions is beneficial. Furthermore, specially designed tools (moulds) are used. Therefore non-recurring costs for potted insulations are typically high, but some benefits can be achieved for non-recurring cost in serial production.

5.2.1.13 Recommendation for use

Potted insulation is the preferred solution for any kind of spaceborne high voltage equipment up to a certain volume/size. Limitations when the moulded item gets too bulky – exceeding for example a few kilogram of mass or the operating temperatures at the insulation hot spot exceed the range of 80 °C - 110 °C. Potted insulation can be of lower preference if the application uses another insulation concept (i.e. liquid, gas, vacuum).

5.2.2 Solid insulation: others

5.2.2.1 General

5.2.2.1.1 Polymers (other)

In addition to the potting materials (see section 5.2.1) the following polymers are used in some applications:

- PMMA - Polymethylmetacrylat (Trademarks: "Acryl")
  used for spacers and insulators
- PEEK -Polyetheretherketone
  used for spacers
- PI – Polyimide
  used for cable insulation up to 600 V (currently)
  rarely used for higher voltages on cables,
  also used for high voltage PCB's
- PTFE, FTE – Polytretrafluorethylene
  used for cable insulation and spacers
- PE – Polyethylene
  used for cable insulation

All these materials are delivered as pre-manufactured raw materials and shaped by milling and cutting. They are typically used as spacers, or feedthroughs, and are not suitable for full encapsulation like potting materials.

For special considerations regarding pre-manufactured raw materials see section 5.2.2.1.8 “General aspects of raw insulation materials”.

5.2.2.1.2 Ceramics

While porcelain is the standard ceramics for terrestrial applications, for space applications typically ceramic materials based on Alumina (Aluminium Oxides) are used.

Some of these ceramic materials are “soft’ enough, that pre-manufactured raw materials (like rods and boards) can be cut and milled to achieve the required shape. Other ceramics with “hard” structure need to be shaped before the sintering process and can furthermore be slightly trimmed afterward by especially hardened tools (diamond). The sintering process is typically performed on site of a specialized ceramics supplier. In some cases, ceramic adhesives are available, which can be processed by the users themselves.

For special considerations regarding pre-manufactured raw materials see section 5.2.2.1.8 “General aspects of raw insulation materials”.

As ceramic materials are very brittle, cracking of the raw material and of the manufactured insulator is a typical problem. Inspections and proper mechanical interfacing is strongly recommended.

5.2.2.1.3 Glass

Glass is sometimes used as packaging for semiconductors and of tubes. As it needs to be molten and shaped at high temperatures it is used for a very limited range of applications.

5.2.2.1.4 Insulation by dispensing, spraying, or dipping

For low mass insulation it appears to be very attractive to dispense insulation in thin layers on high voltage assemblies, especially on PCB structures. The problem areas for such kind of insulations are:

- Ensuring a defined (minimum) thickness of all surfaces including at sharp edges and “hidden” areas.
- Avoiding inclusion of voids.
- Suppressing surface charging effect of the outer insulation surface and avoiding partial discharges / corona if the assembly is operated under AC in gaseous or in low pressure environment.

In practice, the key problem is to ensure a defined minimum thickness of the insulation as the processed material needs to be ‘liquid” enough to be dispensed, sprayed or dipped, but then has to adhere immediately to cure at the right place. Sharp edges and corners increase theses difficulties. The difference from potted insulation, where the dimension of the insulation is clearly defined by the filling of the mould, here a method is used to verify the required thickness. This is more important at higher voltages (above a few kV), where the insulation thickness needs to be in the range over a few tenths of a millimetre or millimetres.

5.2.2.1.5 Sintered insulation

Polyimide (Trademarks of polyimide films include Apical, Kapton, UPILEX, VTEC PI, Norton TH and Kaptrex and polyimide parts and shapes include P84 NT, VTEC PI, Meldin, Vespel and Plavis) and PTFE (Polytetrafluoroethylene, Trademark: Teflon) are typically processed by sintering at suppliers premises. One way of making such material is in the format of rods and boards to be machine later by the user. Another method is used by the manufacturers of specific cables, where tapes of such a material are wound around a conductor. The resulting multi-layer assembly is sintered at high temperature to form a mostly homogeneous insulation. More information about high voltage cables is given in section 5.3.5.

5.2.2.1.6 Chemical vapor deposited polymers insulation

An interesting method is the vapour deposition of a polymer on a surface forming thin high voltage insulation. Such a method is practically given by vapor deposited poly(p-xylylene) polymers mostly used under the trademark Parylene. In the military/aerospace market there are two variants mostly used, the Parylene C and the Parylene HT. Due to the vapor deposition, a pinhole free layer can be established. Critical is the stability of the material, especially with respect to ultraviolet irradiation, where only the HT variant seems to be significantly less sensitive.

The result is a very low mass insulation; however, the problem areas for such kind of insulations are the same as for Insulation by dispensing, spraying, or dipping (see section 5.2.2.1.4). The use of the process can be subject to restrictions (for HT) and can be only possible to be performed at supplier's premises.

5.2.2.1.7 Powder insulation

In order to take advantage of a good heat transfer from highly dissipating electronic parts is filling a box containing the electronic circuitry with a ceramic power, like boron nitride or alumina. The powder should be a well composed mixture of particles with different particle sizes, and the filling has to combine a compression process with high forces and vibration to ensure a high degree of filling. In combination with space vacuum and after appropriate outgassing time the powder insulation can grant suitable high voltage withstanding capability. A risk with the inclusion of air is if the outgassing is not sufficient, resulting in partial discharges and degradation.

A reference is made to:

F. Boer, BN100 filler technology, ARTHE Engineering Solutions S.R.L., 2004,

ESA Contract 18697/04 and European Patent Application EP0993238

5.2.2.1.8 General aspects of raw insulation materials

In case that high voltage insulation is made on the basis of pre-manufactured raw material, a high quality of high voltage insulation can be ensured only under the following conditions:

- the material is suitable for high voltage insulation
- the production process ensures that the material does not contain voids, holes, included contamination and equal distribution of dielectric properties.
- the raw material is subject of a dedicated incoming inspection
- the machining and use of the raw materials is performed by a process which does not result in cracking and delamination of the material, or changes the electrical insulation properties.
- The use of the material respect the rules described in section 5.1 "Basic design principles" – especially avoiding critical electrical field stresses.

5.2.3 Gaseous insulation

5.2.3.1 General

The design of gaseous insulations is comfortable in so far as there is no significant electrical ageing of the gas and the insulation strengths is clearly predictable. Degradation is mostly related to pressure loss (gas leakage) of pressurized containments or chemical degradation.

The design cases are driven by the boundary condition of the gases. An overview of insulation properties of typical gases is given in Table 4-2. Either the gas is a natural environment, as it is for ambient air on earth or in manned space vehicles, or is a selected gas in a pressurized containment.

Natural gas environments:

- Air
- Carbondioxide, Methan on some planets and moons

Often used artificial gas environments:

- Nitrogen (often selected for insulation purposes)
- Carbondioxide (e.g. lasers)
- Inert Gases: Helium, Xenon, Neon (e.g. for laser, electric propulsion)
- SF_6 Sulfurhexafluoride (high performance insulation gas)

The electric strength of a gaseous insulation depends significantly on the pressure. The breakdown voltage of a uniform-field gap in a gaseous environment can be expressed as a function of gas pressure times the gap length. This characteristic is known as the Paschen's law and expressed in the Paschen curve (see Figure 4-7 in section 4.3.4). The law of the breakdown voltage U_{bd} can be written in the form:

$$U_{bd} = f(pd)$$

where p is the gas density and d the distance between parallel plates. The pressure corresponding to minimum breakdown strength depends on the spacing of the electrodes. Detailed curves and tables are given in section 4.3.4.)

When the pressure is increased to values greater than two atmospheres, or when the field exceeds 100 kV/cm, Paschen's law is no longer satisfied. The breakdown strength E_d can be estimated by the following equation

$$\frac{E_d(p)}{E_d(p_0)} = \left(\frac{p}{p_0}\right)^a \qquad [5\text{-}19]$$

where:

$E_d(p)$ Breakdown field strengths at pressure p

$E_d(p_0)$ Breakdown field strengths at reference pressure p_0

a Exponent typically between 0,6 .. 0,8

In non-uniform electrical fields the breakdown voltage depends on the non-homogeneity and the polarity of the gap. A characteristic value is the utilization factor which is defined as the ratio of the average to the maximum gradient across the gap. High values of the utilization factor cause a low flashover voltage.

Gaps with an unsymmetrical non-uniform field of positive polarity (at the electrode where the higher field strength is present) have a lower breakdown voltage as such with negative polarity. Indeed negative unsymmetrical gaps show partial discharge at lower voltages but the total breakdown occurs at much higher values (for more details see section 5.1.2).

A list of properties of selected gases can be found in Table 4-2. Despite of the typical air environment or nitrogen, most interesting are gases like the fluorocarbons and SF_6. They have outer rings deficient of one or two electrons. These molecules are able to capture free electrons forming heavy and relatively immobile negative ions. Gases forming such ions – so called electronegative gases – owe a high dielectric strength because they prevent the formation of electrical discharges normally initiated by mobile free electrons.

A point of interest for space applications is the condensation temperature of the gas insulation. Typically a gas with high electric breakdown strength has also higher condensation temperatures. While "classic" gases like air and nitrogen condense at uncritical low temperatures SF_6 is not so far beyond the typical operating temperature range of satellites.

Especially fluorocarbon can need additional temperature control in some space applications. The condensation problems become much more important if the insulating gas is pressurized higher than 1 bar.

5.2.3.2 Nitrogen (N2)

Nitrogen has a good chemical stability, is non toxic, non flammable, and forms no dangerous decompositions in presence of electrical discharges. The dew point is very low so that there are no problems in the low temperature range for space applications. At atmospheric pressure the breakdown strength is nearly the same as in air. There are no special requirements for handling of N_2, except to take care on human safety w.r.t. high concentrations of N_2 at the human workplace. Thus nitrogen is a dielectric for space applications of gas insulated systems without extraordinary high electrical field strengths.

5.2.3.3 Sulphur Hexafluoride (SF_6)

SF_6 gas is chemically inert, non toxic, non flammable, and has a good thermal stability. It can decompose chemically when it is disposed to partial discharges or arcs. In the presence of small quantities of water this decomposition leads to a formation of hydrofluoric acid, a very aggressive fluid. This makes it necessary to avoid all kinds of discharges in an encapsulated gas volume.

The heat transfer and the dielectric properties of SF_6 gas are comparatively excellent. Already mixtures of other gases with small parts of SF_6 improve the dielectric behaviour significantly. As shown in Figure 5-36 a part of 30 % by volume of SF_6 in N_2 gives 80 % electrical strength of pure SF_6.

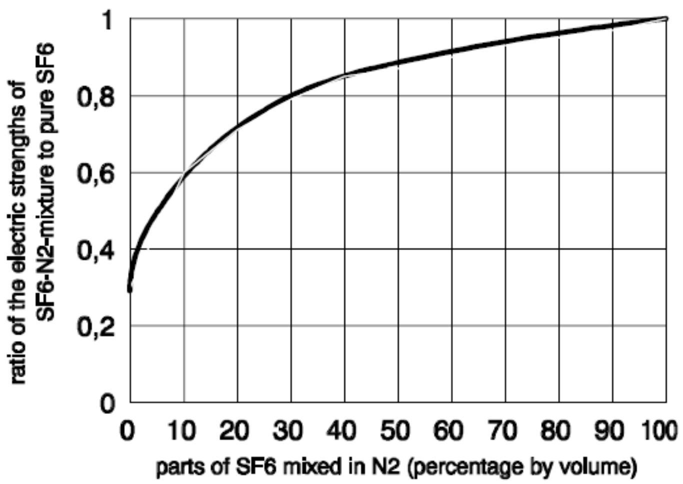


Figure 5-36: Relative Dielectric Strength of a SF_6-N_2-Mixture versus Composition of the Mixture

The dew point of a SF_6-N_2 gas mixture is important for pressurizing. Some dew points of SF_6-N_2-mixtures are given in Table 5-4.

Table 5-4: Dew point of SF_6-N_2-mixtures versus pressure and depending of composition

Composition (Vol. %) SF_6/N_2	SF_6/N_2 Mixture Dew Points (°C) 1 atm	3 atm	5 atm
0/100	-110	-	-
20/80	-92.1	-77.1	-68.9
40/60	-82.4	-66.9	-57.3
60/40	-76.7	-59.6	-50.5
80/20	-72.8	-54.7	-44.1
100/0	-68.7	-50.1	-37.7

For some applications with low environmental temperatures a heater should be installed to prevent condensation of the gas.

5.2.3.4 Construction elements

For the purpose of a gaseous insulation, there is typically the need using solid insulators and spacers as construction elements for mechanical support to high voltage conductors. Such elements can be designed as self standing parts or being functionally combined with other high voltage components (for example: a high voltage capacitor with fixation point for high voltage wires.

Shaping of insulator can be kept with minimum effort (see section 5.1.10) as long as surface contaminations and humidity can be excluded, allowing the use of straight surface paths or with small barriers. However, in case of high pressurized gases of high electric strengths or in case of highly contaminated environment or humid environment, strong shaping is recommended.

Surface charging needs only to be taken into consideration, when insulating atmospheres with high electric strengths are used, as high pressure SF_6) Measures see section. 5.1.11.

Homogeneous fields should be ensured in the vicinity of construction elements, see section 5.1.4.

Surface properties of insulating construction elements need to be considered as well, See section 5.1.5.

5.2.3.5 Long-term stability

A significant problem for use of gaseous insulation in long-term missions is the leakage rate of the containment. Only soldered or welded metal/ceramic housings can ensure such low leakage rates, so that the long-term stability of the atmosphere over 10-15 years is ensured.

5.2.3.6 Reparability

Gaseous insulations are self-healing. After a discharge typically the full insulating capability recovers. Nevertheless, repair can require breaking the hermetically sealed containment.

5.2.3.7 Mass/Size

As an alternative to a potted insulation, a conservative design limit of 6 kV/mm for the electrical field strength and with a safety factor of 1,5 this implies a final breakdown strength of 10 kV/mm.

This can be obtained with ≈3,5 atmospheres of N_2 or with ≈1,5 atmospheres of SF_6.

In this case, the EPC size would be in the same order of magnitude as conventional EPC's with potted HV circuits, but requiring a pressure load.

5.2.3.8 References of Gaseous Insulations

In space missions, gaseous insulations have been used for:

XSAR / SRTM HPA

This X-Band radar was flown on a common DLR/NASA radar earth observation mission (1993/1998). The HPA was built by Dornier System (now EADS Astrium) and is based on the ERS-design (vacuum insulated design, see section 5.2.5.10). Maximum high voltage is 17 kV.

Since the mission was scheduled on several US Space Shuttle flights, the High Power Amplifier (HPA) with the high voltage power conditions has been kept in a sealed container under 1 atmosphere of N2. The lid of this assembly is equipped with a metal sealing and is removable. Operation was in the open payload bay of the US space shuttle – mission time was a few ten days in space environment.

Communication TWTA

Some approaches are known from the FIAR company (now Selex Galileo) in the 1980´s to build EPC´s for communication TWT´s with voltage up to 6 kV in hermetically sealed containments (welded lids) pressurized with SF6. These EPCs have been flown on OTS and EUTELSAT I (former ECS) satellites. A pair of TWTA's has been flown on the ESA/NASA mission Ulysses with a flight to Jupiter being operational from 1991 till 2008.

FSL BDPU

FSL BDPU was an scientific experiment flown on US Space Shuttle in a manned ESA/NASA mission (1998), providing a fluid science experiment. An alternating high voltage of 20 kVpeak (frequency 0 kHz - 10 kHz) was isolated in an SF_6 filled containment (1,1 hPa pressure). The supplier was Dornier Satellite Systems (now Astrium).

FASES GeoFlow

FASES GeoFlow is a scientific experiment planned flown on the International Space Station (as part of the European Columbus module), providing a fluid science experiment. An alternating high voltage of 10 kV-rms. (frequency 1 kHz - 10 kHz) is isolated in an SF6 filled containment (1,1 hPa pressure). The supplier is EADS Space (now Astrium).

5.2.3.9 Costs

Compared with conventional EPC´s with potted HV, there is some cost saving with the absence of complex potting process. Nevertheless, it can be difficult, to replace all potted parts by "open" parts (difficult for transformer windings), so partial potting is still necessary. The need of a hermetically sealed house can at least compensate the cost saving in potting.

5.2.3.10 Recommendation for use

The hermetically sealed containment necessary for the gaseous insulations is a risk for long-term missions. The cost and mass savings by reduction of EPC potting is expected to be (over-) compensated by penalties of the housing. Therefore gaseous insulation appears suitable only for some "niche" applications in short-term / mid-term missions or manned space flight.

5.2.4 Liquid insulation (Oil)

5.2.4.1 General

Liquids insulations are self healing – with some restrictions. After a temporary overvoltage the affected area of a breakdown path is immediately reinsulated by fluid flow, nevertheless often some degradation remains. Often, liquid dielectrics are used in conjunction with solid insulations such as parts, films, and composite materials. By eliminating enclosed gases, the strength of a liquid insulation system is improved significantly.

The operating temperature of a liquid dielectric affects its life and stability. A pure liquid, in the absence of water or oxygen, should be very stable at rather high temperatures. With increased temperatures, fluid viscosity decreases and the higher mobility of the ions implies increased conduction. Refining techniques, additives, and blending of liquids are used for thermal upgrades.

Moisture reduces the reliability of liquid insulation. Water usually decreases dielectric strength and increases dielectric loss. Polar contaminants dissolved in oil give moisture its greatest degradation effect on dielectric strength.

The effect of gas absorption and liberation should be considered for long-term, successful operation. Changes in pressure can make dissolved gases evolve from a liquid. Also, temperature affects the solubility of gas, so heating can cause dissolved gas to evolve from the liquid. Partial discharges start in the evolved gas bubbles, leading to eventual breakdown.

Especially for space borne liquid insulated systems it should be taken care that the liquid is kept pressurized so that gas bubbles do not form.

In selecting a liquid dielectric, its properties should be evaluated in relation to the application. The most important are dielectric strength, dielectric constant and conductivity, flammability, viscosity, thermal stability, purity, flash point, chemical stability, and - very important - compatibility with other materials of construction and the local atmosphere.

On ground, mineral oils are most commonly used for high voltage equipment insulation. Silicones are necessary for specialized applications with fire resistance requirements and high operating temperatures. However, the use of oil-based insulation is a strong penalty for satellite level testing as there is a risk of severe contamination of the test chamber and of the satellite equipments in case of leakage, especially when thermal vacuum testing is performed.

5.2.4.2 Long-term stability

Liquid insulation can degrade by chemical decomposition, partial discharges, dissolved gases and increased water content. Decomposition due to radiation is possible, too. As there is no knowledge about space borne liquid insulated high voltage equipment it is therefore not possible to give a clear indication of long-term stability. As a global indication, liquid insulated high voltage systems are suitable for stable operation from a few weeks to a couple of years, without maintenance therefore being more life limited than solid insulations.

5.2.4.3 Reparability

Due to a limited self-healing capability, a pure liquid insulation recovers its strength after a breakdown; however, degradation is likely, especially after repeated discharges. If after a breakdown the insulation is degraded, it is possible to replace (refill) the liquid (on ground). In composite liquid/solid insulations (impregnated foils) the reparability is much more limited, as the solid insulation parts can be damaged as well and those do not recover.

5.2.4.4 References of Liquid Insulations

The only available reference is the scientific experiment FASES GeoFlow been flown on the ESA mission onboard the ISS (two flight missions in 2008 and 2010). A part of the experiment is isolated by a liquid. Parameters are a high voltage of 10kV-rms. (frequency 1-10 kHz). Operation was short-term a couple of days.

5.2.4.5 Costs

The costs for liquid insulated system are in the mid range. There are basic costs associated with the need of a sealed containment, whereas the overall design of the high voltage elements is simpler and therefore at lower costs, compared with solid insulation.

5.2.4.6 Recommendation for use

Due to the complexity given by the use of a hermetically sealed and pressurized assembly, the use should be limited to experimental equipment and large high power equipment in cases where potted insulation are critical due to bulk effects.

5.2.5 Space vacuum insulation

5.2.5.1 General

The natural environment of space, the vacuum, appears to be ideally suited for high voltage insulation. The "pure" high vacuum is an excellent insulator. Using the natural vacuum of space certainly can aid to mass savings, since solids and liquid dielectrics are minimized. In addition the problem of providing a reliably sealed containment for gas or liquid is avoided. Conduction currents in vacuum are very low as long as no pre-breakdown effects appear (see section 4.3.2.5).

There are some important facts to consider for vacuum insulation design:

- It is very difficult to achieve a vacuum insulation, which is completely free of discharges and sporadic breakdown.
- Therefore a vacuum insulated design and the surrounding electrical circuitry needs to be tolerant and hardened to survive sporadic flashovers, for example by introduction of:
  - discharge energy or current limitations to prevent overload of the affected electrical circuit
  - suitable EMC design to avoid disturbances in case of breakdown
  - shields to prevent discharge to inject energy into sensitive electric lines
  - overvoltage suppression devices to prevent mitigation of failures into sensitive parts of the electronic circuit
- The breakdown strength of vacuum is drastically lowered, when insulating surfaces are present in an area of high electrical field strengths. The reduction is difficult to predict, as it depends on surface properties, including surface layers, absorbed gases, micro particles, properties w.r.t electrical charging (secondary electron emission coefficient of insulation, field emission behaviour of electrical conductors, electrical surface conductivity), temperature, residual gas pressure, shapes and aspects of the triple-junction zone.
- The sensitivity to such "degrading" effects depends significantly on the voltage as in the free path the energy of accelerated electrons is linearly increasing with the voltage. Practically one

can say, that in the lower range of voltage up to a few kV the strengths of an vacuum insulation is very good and not much depending on “degrading effects”, however, the voltage range up to 10 kV is getting much more demanding and above 10 kV a vacuum insulated design requires significant effort in investigation about the above mentioned effects.

- Another sensitivity is given by the environment: space plasma, free charge carriers (electrons, ions), residual gases i.e. from depressurization during launch, degassing from surfaces; gas leakages etc. can cause a partial or full loss of the insulation capability.

An important reference giving an overview of all vacuum insulated research is given in:

R. V. Latham “High Voltage Vacuum Insulation”, Academic Press, London (UK), 1996

5.2.5.2 Insulator surfaces

Vacuum insulation naturally coexists with solid insulators as the high voltage electrical conductors and components need to be mechanically fixed. In view of this, the aspect of solid insulation should be considered (see section 5.2.2) as well as the aspect of the surface properties (see section 5.1.5). Due to the ability of “free” electrons and ions to move in the vacuum environment without collisions with other residual gas matter (long free path corresponds to low probability of collisions):

- charges can be transported over long distances and accumulate at insulator surfaces.
- electrons and ions can be accelerated to high speeds and impact with high energy on surfaces.

When free moving charge carries hit an insulator surface they can both attach and then create a local surface charge, or with high energy impacts could generate secondary electrons. The secondary electrons can move and collide at elsewhere. Like sketched in Figure 5-37, an avalanche process can be triggered causing a flashover across the surface. This discharge can result either in a small current pulse or a full breakdown of the insulation.

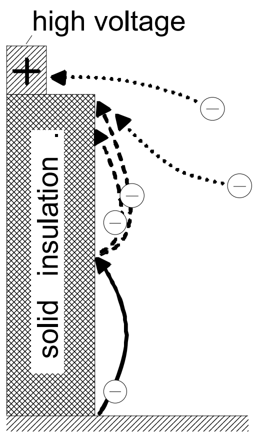


Figure 5-37: Surface flashover process in a vacuum environment

The surface flashover process is depending on a number of parameters and is not fully understood. Thus the following list is only a limited collection of possible effects:

- illumination and radiation (of high energy) causes degradation but only at untypical high intensity
- magnetic fields can either increase or decrease the surface flashover strengths, depending from where the charge carriers “fly-in” and where they are deflected – of course preferably away form any surface

- surface treatment is important, but its effect is difficult to predict. Often however, it has been observed that a specific surface roughness is advantageous in comparison to polished surfaces – as long as the roughness is not too deep and associated with loose particles. Furthermore, a slightly conductive surface is helpful to avoid surface charging, but is in practice, difficult to establish as in the high ohmic domain, it is difficult to keep a low homogenous conductivity. Sometimes a work-around can be to install intermediate shields to control the electrical field distribution and superimposing field distortions by surface charges (see implementation example in Figure 5-24).
- the applied waveform can give some advantage for pulsed voltages in the μs-range and less, lowest strengths is typically obtained for AC voltages with ms sinus period and in most cases a higher value for DC voltages.
- geometry is an important driver as the inclination of the surface (surface angle) determines if a surface is hit by electrons; in combination with material surface properties this determines further the triggering of secondary electron avalanches. Some examples of shapes are shown in Figure 5-38. Typical results shown most critically for slightly negative cone angles θ, presumably as the electrons can easily hit the surface and the avalanche can “slide” along it. Good results are likely (but nor guaranteed) for cone angles θ in the order of 45 degree. Several combinations of surface angles, materials and waveforms are presented in Table 5-5.
- triple-junction zones are the possible emission sites in the “corner” between the solid insulator, the vacuum and metal especially at the cathode: therefore it is important to reduce the electrical field in this zone (i.e. Figure 5-38: cylinders with inserts).
- pre-stress of a set-up has an effect on the strengths, especially after a polarity change from a negative to a positive voltage and vice versa a reduction of the breakdown strengths can appear – most likely caused by the build-up of space charges.
- conditioning is a frequently found effect, meaning, that after a surface flashover has occurred, subsequent flashovers happen at higher voltages – as long as the dumped energy does not destroy the set-up significantly.
- the material has an impact on surface flashover strengths of insulators in vacuum – however, results of studies are often contracting. Some important observations are: first, that homogeneous materials tend to make better insulators, and second, that there is an inverse relationship of voltage strength to the relative permittivity (epsilon) of the material. Most likely materials with a higher permittivity tend to concentrate the field more in the triple-junction zone, which eases the emission of electrons and consequently weakens the insulation.
- surface gases play a role, if they are easy to release – therefore the best is to release any surface gases by baking out and/or sufficiently long exposure to a good vacuum environment.
- a temperature increase lowers the breakdown strengths, typically

The Table 5-6 summarizes some theoretical predictions to improve the electrical strengths of insulator surface in vacuum in relation to practical measures.

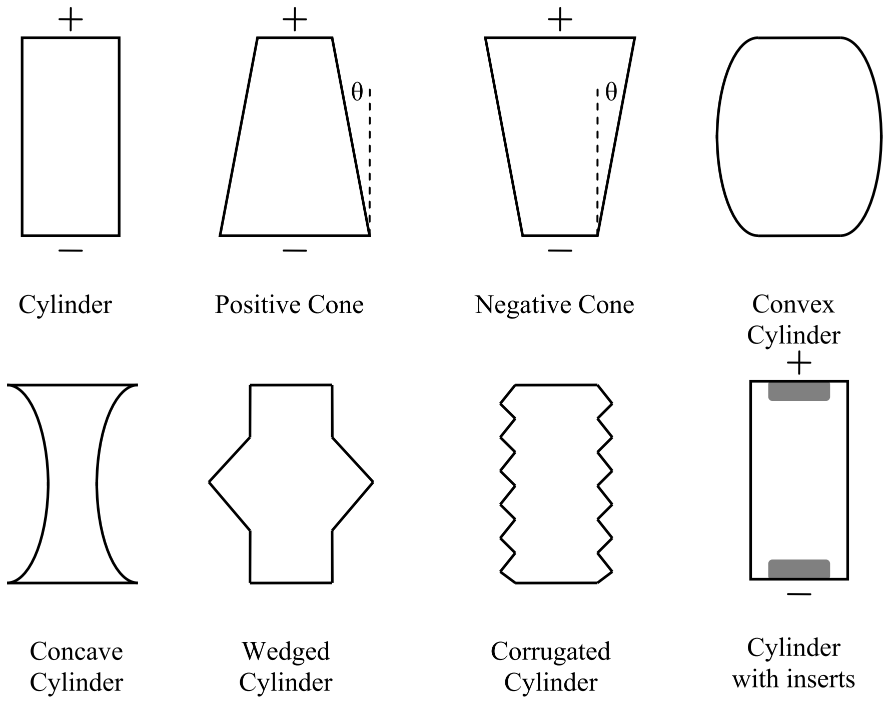


Figure 5-38: Surface shapes for insulators

Table 5-5: Surface shapes for insulators in combination with selected materials comparing the relative surface flashover strengths of +/- 45 degree cone insulators for various voltage waveforms w.r.t pure cylindrical shapes

Voltage waveform	Material	Relative Flashover Voltage		
		Cylinder	-45° Cone	-45° Cone
10 ns	PMMA	1	3,5 x	4,0 x
30 ns	7740 glass	1	+ 3 %	2,2 x
	7070 glass	1	+12 %	2,2 x
30 ns	Epoxy resin	1	3 x	5 x
	PMMA	1	-	3 x
	Glass	1	-	1,6 x
50 ns	PMMA	1	+15 %	2,25 x
75 ns	Epoxy resin	1	2,5 x	3,0x
0,75 μs	Oiled PMMA	1	1,7 x	2,4 x
0,8 μs	PMMA	1	2 x	3 x
	Glass	1	+ 15%	2 x
1,2/50 μs	Glass-ceramic	1	+ 10 %	+ 27 %
2/50 μs	PMMA	1	2,5 x	3,5 x
5 μs	7740 glass	1	3 x	6 x
	PMMA	1	5 x	6 x
	Polycarbonate	1	4 x	6 x
	Polystyrene	1	3 x	3,5 x
10/50 μs	7740 glass	1	2,5 x	3 x
DC	7070 glass	1	1	+ 10 %
DC	Glass-ceramic	1	+ 60 %	+ 30 %
DC	PMMA	1	+ 24 %	+ 38 %
DC	Ceramic	1	+ 24 %	+ 38 %
60 Hz	PMMA	1		+ 67 %
60 Hz	Porcelain	1	+ 55 %	Corrugated Cylinders
60 Hz	Glass-ceramic	1	Little effect	
50 Hz	Glass-ceramic	1	+ 55 %	Convex Cylinders
50 Hz	Ceramic	1	+ 65 %	

(Ref.: R. V. Latham "High Voltage Vacuum Insulation", Academic Press, London (UK), 1996)

Table 5-6: Theoretical predictions and experimental consequences of methods to improve the surface flashover strengths in vacuum

Theoretical predictions	Practical measures
Importance of cathode triple junction	
Decrease macroscopic field	Shape electrodes Recess Insulators Install metal inserts in insulators Use external metal shields
Decrease microscopic field	Minimize voids at junction Pressure in soft insulators Smooth interfaces Bonded interfaces Graded permittivity
Importance of desorbed gases for final stage of flashover	
Minimise quantities of absorbed gas	Fire insulators before assembly Bake out system Condition insulator
Minimise sites available for adsorption	Original formation of insulator Minimise surface damage during fabrication
Maximise binding energy for adsorbed gas	Chemical treatment of insulator Quasi-metalizing

(Ref.: R. V. Latham "High Voltage Vacuum Insulation", Academic Press, London (UK), 1996)

5.2.5.3 Conditioning effects

For pure vacuum gaps as well as in the presence of solid insulator surfaces, it is often noticeable, that after an initial breakdown / flashovers or after a series of such events the breakdown strength increases. Similar effects can sometimes be observed when applying some pre-stress at lower voltage level.

5.2.5.4 Cleaning and preparation

A good preparation of material surfaces either conductors or solid insulators are important to grant high breakdown strengths. The following aspects need to be considered:

- Polishing is positive for metallic electrode surface, especially a sequence of mechanical polishing followed by chemical polishing (or plasma treatment).
- Cleaning and polishing with plasma is useful as well for metallic surfaces.
- Roughening of the surface is better for solid insulator surfaces exposed to vacuum; sometimes good results can be achieved by sand blasting and plasma treatment. Grinding is critical as scratches can go to deep and particles remain.
- Cleaning agents like alcohol can have negative effects, so the thorough removal of the cleaning agent is important.
- Degassing is of high importance and should allow removal of absorbed and enclosed gases in the vacuum insulated assembly – allow sufficient time and appropriate high temperature.

- Bake-out of vacuum insulated systems is very positive and works well for ceramic and other temperature withstanding materials.
- The presence of particles is critical and should be avoided by the manufacturing and cleaning process.

5.2.5.5 Leakage currents and triple-junction effect

Significant leakage current can occur already below the breakdown threshold of a vacuum insulated system. The reason for this is small emission sites for electrons that can be found at locations with surface inhomogenities (particles, defects, micro-protrusions, sharp edges etc.). A very critical emission site is typically found in the triple-junction zones of the interface between conductor, solid insulator and vacuum. Therefore it should be ensured by design and verified by test, that only negligible emission currents are flowing.

5.2.5.6 Control of pressure

The control of pressure is most important for a vacuum insulated assembly, if the voltage exceeds the minimum of the relevant Paschen curve (see Figure 4-7), that is for air above 300 V and for inert gases above 80 V. For this purpose the following aspects are of importance:

- For most of the practical applications a vacuum environment of lower than 10^{-3} Pa resp. 10^{-5} mbar is well suited – in the non-metric world this is often modified into $1{,}3 \cdot 10^{-3}$ Pa resp. $1{,}3 \cdot 10^{-5}$ mbar (coming from 1 Torr (0° C) = 133,322 Pascal (N/m^2)).
- With some margin in practical applications a vacuum environment of lower than 10^{-2} Pa resp. 10^{-4} mbar is acceptable.
- Very high vacuum of lower than 10^{-5} Pa resp. 10^{-7} mbar is very well suited for long term stability, but only achievable in sealed containment without the presence of organic material and requiring a dedicated bake-out process. This is applied in electron tubes, for example.
- Higher pressures, 10^{-2} Pa resp. 10^{-4} mbar need to consider the Paschen breakdown as a limiting factor (see section 4.3.4). Operation of vacuum insulated equipment should be considered only, if this is driven by specific user constraints, for example in laser equipments or with electric propulsion systems.

5.2.5.7 On ground testing

Ground testing of vacuum insulated equipments, which are not completely sealed, can be performed in:

- a suitable vacuum chamber
- ambient air conditions, if the design allows this kind of operation and if in addition to the design rules of vacuum insulation also the design rules for gaseous insulations are fulfilled
- specific gas environment which provide a similar good strength as the vacuum insulation. Possible ideas is bagging the setup and filling the containment with pure SF_6 or a SF_6-air mixture.

5.2.5.8 Long-term stability

Under the assumption, that infrequent spurious effects (flashover, breakdown) are acceptable for the user, the long-term stability of vacuum insulation is excellent as there are no degradation effects. After a spurious event the insulation properties recover or often improve. Well designed systems operating in a safe pressure environment, well outgassed and/or baked out can withstand many years without spurious events. In order to ensure long-term stability a low pressure (see section 5.2.5.6) and protection against electron / ion flow is recommended to be employed.

5.2.5.9 Reparability

Vacuum insulation is self-healing after a breakdown, so typically no repair is needed even after a failure. Furthermore, there is no degradation. If a vacuum insulated system is kept open – like individual high voltage modules interconnected in an open design, parts can be easily exchanged for maintenance. This is of course different, if the vacuum insulation is kept in a sealed vessel, like it is for example the case for electron tubes.

5.2.5.10 References of vacuum insulations

In space mission vacuum insulations have been used for:

ERS C-Band Radar - this type of C-Band radar was flown on two ESA radar earth observation mission ERS1 (1991 till 2000) and ERS-2 (from1995 on). Maximum high voltage was 15 kVDC. Potted high voltage modules have been interconnected via open (vacuum insulated) connection points.

RADARSAT C-Band Radar -This type of C-Band radar was flown on a Canadian radar earth observation mission. The HPA was built by Dornier (now EADS Astrium) based on the ERS design.

INTERGRAL ACS Power Front-end -An array of front-ends with 2 kV operating voltage have been built for the instrumentation.

5.2.5.11 Costs

As no specific containments are needed – despite the advantage having some shielding around – a vacuum insulated system is comparably cheap, especially for recurring designs. For higher voltages (tentatively over 5 kV) there is considerable effort (no-recurring costs for design and verification) necessary to investigate an optimum design and materials composition to reduce the risk of spurious effects (discharges, flashovers).

5.2.5.12 Recommendation for use

Vacuum insulation is a cost and mass efficient solution for all high voltage systems

- which are not operated in the critical pressure regime (safe pressures below 10^{-2} Pa) and
- which can accept spurious effects (flashovers, discharges).

5.3 High voltage components

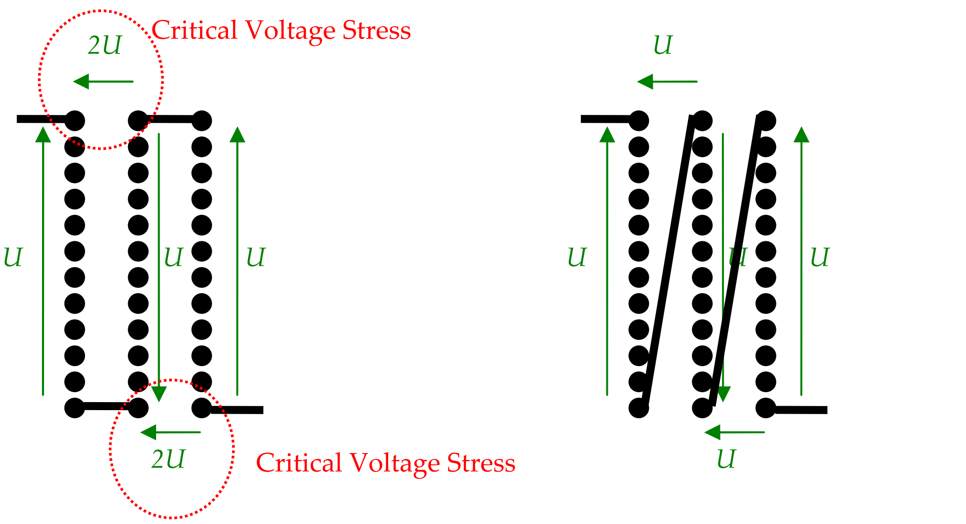
5.3.1 Transformers and inductors

High voltage transformers are needed to step-up an AC voltage and to transfer AC electrical power by magnetic coupling between circuits while keeping DC isolation. The design required for typical applications is characterised by the following principles: A core of magnetic material is employed to create enough primary inductance without too many windings and copper losses. The core losses, depending on flux density, frequency and volume, are tailored by a trade-off between number of windings, frequency and dimensions. The magnetic circuit can be gapped by a calibrated spacer to control the inductance. The core is electrically and mechanically isolated from the coils. The transformers thus consist of one or more isolated primary coils with their coil formers and terminals, one or more isolated sets of secondary coils with their coil formers and terminals, the core, means to deviate dissipated heat and devices for fixation and mounting. The coils and terminals are impregnated by a potting material. The attached rectifier/filter module has to process a high AC voltage and is often integrated with the transformer.

The electrical field is determined at the time of highest AC voltage for either polarity, assuming the relevant output rectifiers in conduction, such that the windings are biased with the potential of the output circuitry.

Important design aspects are the following:

- the electrical field of the high voltage coils inside the potting material is proposed be controlled by shaping not to exceed given limits under consideration of field enhancement effects (see sections 5.1 and 5.2.1). This applies in particular to the coils, windings, wires and terminals.
- at least one electrostatic shield useful to be inserted between the primary and secondary windings. It is proposed to provide complete electrostatic shielding around the secondary coils.



A) Double layers of windings, interconnecting wire at outer side – high stress at one the end of each layer

B) Single layers of windings, interconnecting wire inside layers – lower stress between winding but complex routing of interconnecting wire

Figure 5-39: Arrangement of cylindrically layers of windings

A typical high voltage transformer consists of a primary winding operating at low voltage and one or more high voltage windings. For the high voltage side typically a high number of turns/windings are required and the currents are low, thus the selected diameter of the wire is relatively low. The thin wire in a stack of windings cause usually an inhomogeneous field, depending how the wire is routed, and the related field stress can be very high. Some design aspects are explained in the following:

- Layers of windings can be arranged in a cylindrical way as shown in Figure 5-39. The different layers of winding can be placed directly one above each other, either using a layer of insulation material in-between or without. Having no inter-layer insulation results in a high stress between individual wires of different layers due to a high voltage difference, which can be too excessive for the wire insulation. The typical wire insulation is a coating or foil. Using an inter-layer insulation improves the situation. This additional insulation can be a foil or a sheet of fibre material, which is later impregnated with a resin. In the example A) of the Figure 5-4 the layers of windings are arranged as double layers, which are easy to produce, however, this configuration causes a higher insulation stress to every other ends of the windings layers. A lower stress can be achieved by guiding an interconnecting wire always to the opposite end of the windings space in-between two layers of winds as shown in example B). However, routing of the interconnecting wire requires more effort in manufacturing.
- Layers of windings can be alternatively arranged in discs (sections) as shown in Figure 5-40. Each disc of windings is placed in a slot of a bobbin. The layers in the different discs can be arranged differently: One possibility is the layout of double windings as shown in Figure 5-40 A) another possibility is the layout of single windings switched in series as shown in B).
- The distribution of voltage stress are different for cylindrical and sliced windings and the advantages/disadvantages of each need to be assessed on a case-by-case basis considering AC stress as well as other parameters as stray capacitance.
- Critical zones of high electrical field strengths typically are found at the "high side: of a configuration of windings (see example in Figure 5-40 C). A compact stack of wires typically shows a moderate electrical field strength inside, however, special attention should be paid to:
- Corners of a stack – see zone (a) in Figure 5-40 C)
- Freestanding wires interconnecting to the "outside" - see zone (b) in Figure 5-40 C)
- Displaced wires " - see zone (c) in Figure 5-40 C)

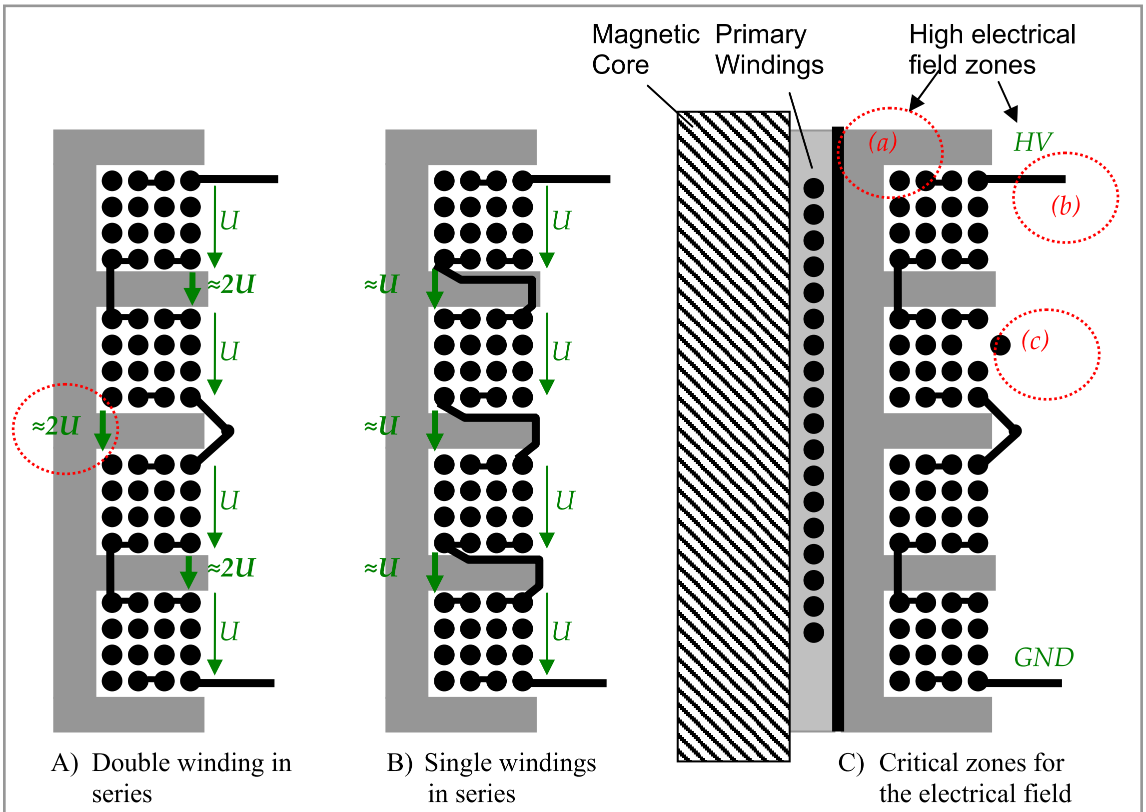


Figure 5-40: Arrangement of windings in discs of a bobbin

For the design of a high voltage transformer the following recommendation can be given:

- Primary and secondary windings should preferably be separated.
- An electrostatic shield between primary windings and high voltage windings is useful. Such a shield should be not floating and thus better connected to a fixed potential (ground or other useful reference).
- Floating high voltage windings and other floating structure elements (i.e. magnetic cores) should be avoided or it should be demonstrated by analysis or test that there is no undefined critical electrical field.
- Electrical field stress can be reduced by
  - a suitable selection of disc or cylindrical windings
  - ensuring a homogeneous dense stack or layer of windings
  - avoiding displaced single wires
  - increasing the diameter of wires in general or at critical locations (at corners, at exposed connections wire, at the "high side" of a winding
  - shaping the slots of bobbing in a way that a curved structure of the winding stack is achieved
  - placing shields (toroids) at critically field loaded spots of windings
  - using spherical shields or solder balls for interconnection of wires in exposed locations.

- It is important to ensure by a well defined process and inspections, that the elements of a high voltage transformer are properly placed and in the specified condition.
- A partial discharge test can be essential to demonstrate the quality of a manufactured transformer (see section 6.1.6).

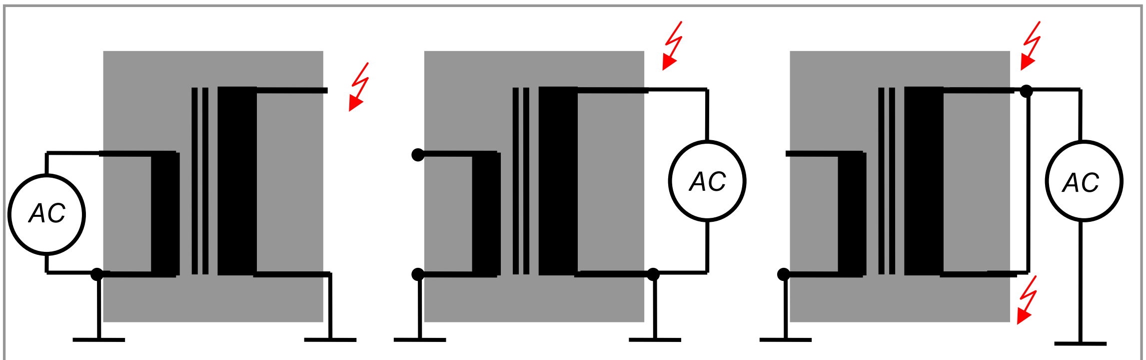


Figure 5-41: Partial discharge test aspects of a high voltage transformer

- The high voltage transformer design can consider the test methods, especially in case, that a partial discharge measurement is performed in a different configuration as the nominal one. Often the untypical field stress of a test case can require additional design for electrical field control at the low side of the transformer. As shown in Figure 5-41 the test configurations a) and b) provide nominal high voltage field loads to the transformer, however, in some cases (for example high frequency transformers tested with low frequency) a test configuration similar to c) can be selected. Although this configuration gives a more limited visibility of the insulation this can be the only option with respect to adequacy of test effort. However, configuration c) requires that also the low end of the high voltage winding has to withstand loads similar to the high voltage end. In view of this the insulation should be designed accordingly including feedthroughs, shields and probes.

5.3.2 Capacitors

High voltage capacitors for space electronics application are typically made of

- Impregnated epoxy resin (typically: reconstituted mica)
- Ceramics

Such capacitors are available in space qualified version from various manufacturers according to standards:

- ESCC 3001 for ceramic capacitors
- ESCC 3006 for mica capacitors
- Some known manufacturers are: Eurofarad, Reynolds, Custom Electronics, AVX

It is important, that such devices undergo specific inspections to exclude defects in the insulation Proposed tests are:

- Partial discharge test
- Ultrasonic scanning or X-ray scanning

Comparing ceramic capacitors and reconstituted mica capacitors it should be highlighted, that the partial discharge thresholds for acceptance can be very different. For ceramics, partial discharge levels below 5 pC (pico Coulomb) are typically applied, whereas for mica capacitors such acceptance levels can be much higher as the material has a strong isotropic and brittle structure but is very resistant against partial discharges.

Series switching of capacitors can ensure, that the distribution of voltage to the capacitor is well balanced ensuring to be within the derating for static and repetitive stress cases and within rating for transient stress cases. A useful measure is to switch bleeding resistors in parallel to each capacitor if no other voltage control measures are applied. The dependence of the capacity to the applied voltage is taken into account. For ceramic capacitors, the capacity decreases with an increasing voltage. In a series of capacitance the lowest capacity supports the highest voltage that in turn decreases the capacity increasing moreover the voltage imbalance.

Pulsed discharge currents typically should be limited in accordance with the parts specification. If high pulse discharge currents are needed, parts with low inductivity should be preferred.

The environment around the capacitor should be properly controlled as most of the capacitors used for high voltage electronics are not enclosed in metallic housing. This results in significant high electrical fields (outside) around the parts. For a proper design this means:

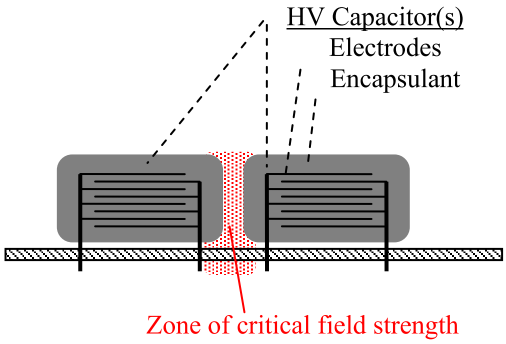
- Control the distance to neighbouring parts and structure elements including metal walls
- Control the atmosphere around the component to avoid Paschen breakdown at critical pressure or corona and to suppress partial discharges in general.

Some examples of critical cases and recommendations are shown in Figure 5-42.

Despite the applications in electronic circuitry it is worth to mention that some of the capacitor technology used in ground-based high voltages applications are in principle suitable for space applications as well, in specific:

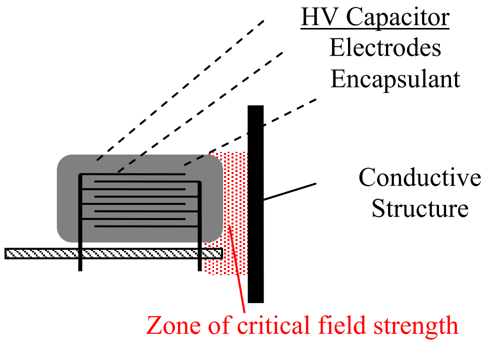
- Pressurized gas-filled capacitors (low capacitance with high stability and low loss factor)
- Liquid impregnated foils (like mineral oil/paper, mineral oil/ polymer foil).

Adaptation to space environment should especially consider adequate pressurization and leakage free design and as well as radiation resistance.



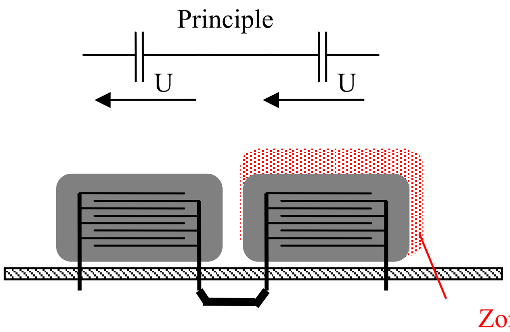
A) Critical electrical field stress between two PCB mounted capacitors

Due to proximity of both components and since the encapsulation is non metallic a high electrical field may result overstressing the insulation in the gap or of the encapsulation itself.



B) Critical electrical field stress between a high voltage capacitor and a conductive structure

Due to proximity of both components and since the encapsulation is non metallic a high electrical field may result overstressing the insulation in the gap or of the encapsulation itself.

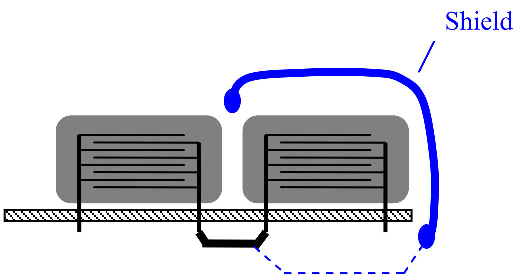


C) Critical electrical field stress between series-switched (or at high potential mounted) capacitors

Due to series switching (capacitive multipliers, multi-windings transformers etc.) the elements at the "high side" are exposed to much higher electrical fields (in the encapsulation and in their surroundings) than the elements at the low side.

Recommended Measures:

1) Check that critical electrical field strengths in the surroundings of a component are not exceeded (breakdown field strengths, max. field strength for lifetime)
2) Check that critical electrical field strengths in the encapsulant of a component are not exceeded (breakdown field strengths, max. field strength for lifetime)
3) Use shield to control electrical field stress (especially for case C).



D) Example: placement of a shield to control electrical field

A local shield referenced to a suitable potential of the circuitry can aid to reduce electrical field stress in the surroundings of a component (Improvement of Case C). However, as a consequence the electrical field strength inside the capacitor may increase.

Figure 5-42: Critical electrical field stress in the surrounding of high voltage capacitors and proposed measures

5.3.3 Resistors

High voltage resistors for space applications are typically made as:

- Film resistors
- Bulk resistors

Film resistors are made of a film of metallic oxide composite material deposited on a substrate (typically) ceramics as shown in Figure 5-43 a)– often final trimming of the resistor is made by laser abrasion to achieve high accuracy. A serpentine structure of the film is advantageous to achieve a low inductance design. The longitudinal separation between the different tracks is important as well to avoid high voltage differences and electrical fields between the individual tracks. Such construction can achieve resistance values between a few hundred Ohm to some Gigaohms.

Bulk resistors are made of carbon composite material typically formed in cylindrical shape as shown in Figure 5-43 b). Such construction can achieve resistance values between a hundred Ohm to some Megaohms. Advantages are the low inductance and the high pulse overload capability due to the good heat distribution in the bulk material. Bulk carbon resistors are able to sustain energies of some Joules (for example a typical 0,5 W type : 6,4 J). In comparison other film resistors can sustain only mJ. This allows using bulk carbon resistor as a current limiting devise in case of arcing.

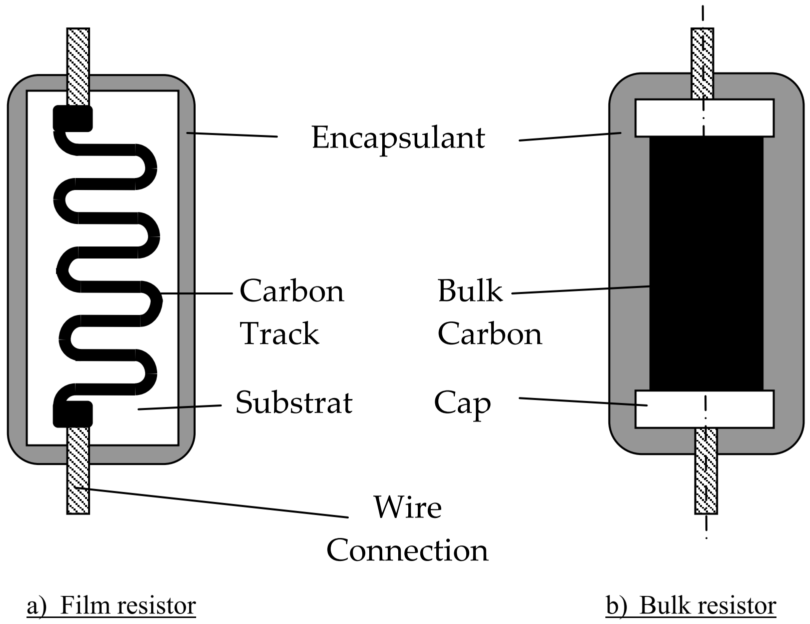


Figure 5-43: Basic high voltage resistor design variants

The encapsulation of such high voltage resistors is typically made of epoxy type resins or they are simply coated.

Such resistors are available in space qualified versions from various manufacturers according to standards:

- GSFC-S-311-P-796C
- MIL-R-39008C

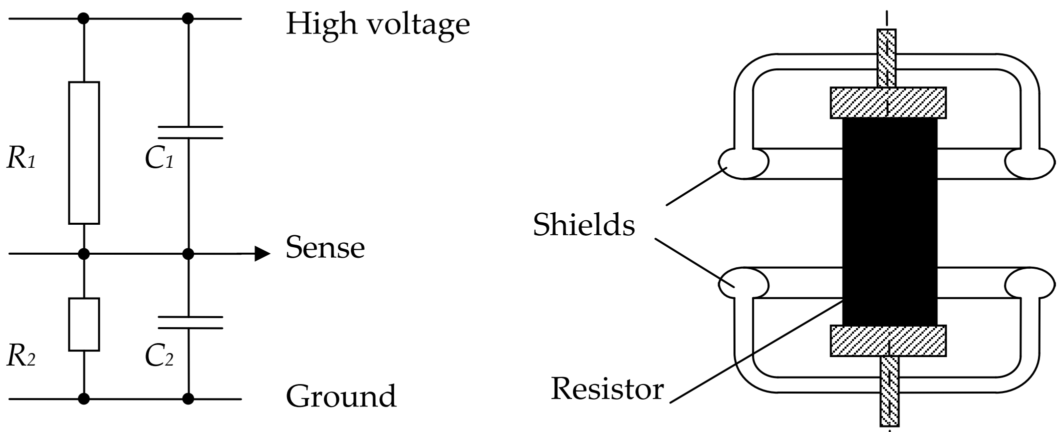
Some known manufacturers are: Caddock for metallic oxide serpentine (GSFC-S-311), RCD for agglomerated carbon bulk resistors (MIL-R-39008C) and wire-wound surge resistors.

The environment around the resistor needs to be properly controlled. This results in significant high electrical fields (outside) around the parts. For a proper design this means:

- Control the distance to neighbouring parts and structure elements including metal walls
- Control the atmosphere around the component to avoid Paschen breakdown at critical pressure or corona and to suppress partial discharges in general.

Critical design cases and recommendations are similar to those which have been shown in Figure 5-42 for capacitors. Furthermore the following aspects should be considered as well:

- Pulse overload – in case of flashovers (spurious effect, breakdown) resistors in the discharge current path are designed to handle this overload in terms of change of voltage distribution and peak current load.
- High voltage divider precision: using a matched pair of high voltage resistor(s) and of an equivalently manufactured low voltage resistor helps to increase accuracy and reduces temperature drift.
- High voltage settling time: a high ohmic high voltage divider has typically low response time, switching it in parallel with a capacitive divider can help to improve the high frequency response. In some cases it might be advantageous to uses shielding structures to control the parasitic electrical field. Examples are shown in Figure 5-44.



$$\frac{R_1}{R_2} = \frac{C_2}{C_1}$$

a) Capacitively compensateds resistive high voltage divider

b) HV resistor with electrostatic shield

Figure 5-44: High voltage resistor design aspects

Despite the applications in electronic circuitry it is worth to mention that some of the resistor technology used in ground-based high voltage applications are in principle suitable for space as well, in specific:

- Wire-wound resistors (for pulsed loading with low or medium impedance values)
- Electrolytic liquids (for pulsed loading with low or medium impedance values)

For adaptation to space environment it is recommended especially to consider the adequate pressurization and leakage free design, as well as radiation resistance.

5.3.4 Semiconductors

High voltage semiconductors for space electronics applications are typically

- High voltage diodes/rectifiers (typically rated to several kV)
- High voltage transistors (typically MOS-FET´s rated up to 1000 V)

Such semiconductors are available in space qualified versions from various manufacturers according to standards:

- MIL-PRF-19500P

Some known suppliers are: Microsemi (US), Sensitron (US), VMI (US)

As long as such semiconductor components are not completely encapsulated and sealed in a metallic housing the environment around the component should be properly controlled. As most semiconductors used for high voltage electronics are not enclosed in metallic housings, there can be significant high electrical fields present (outside) around the parts. For a proper design this means:

- Control the distances to neighbouring parts and structure elements including metal walls
- Control the atmosphere around the component to avoid Paschen breakdown at critical pressure or corona and to suppress partial discharges in general.

Some examples of critical cases and recommendations are shown in Figure 5-42 (demonstrated here for capacitors).

It is worth to highlight also that leakages of some μA can impair the functionality well before the electrical field breakdown.

Despite the applications in electronic circuitry it is worth to mention that some of the semiconductor technology used in ground-based high voltages application is in principle suitable for space as well, in specific:

- IGBT´s
- Thyristors

Adaptation to space environment should especially consider adequate thermo-mechanical design as well as radiation resistance.

5.3.5 Wires and cables

High voltage wires for space electronics application are typically made of

- PTFE (Polytetrafluarethylene, Trademark: Teflon)
- FEP (Fluorinated Ethylene Propylene)
- Polyimide (Trademark: Kapton) - typically for lower voltages (< 600 V)
- PE - Polyethylene (few applications)
- Silicone elastomer

In fact, for most of the DC applications in space PTFE and FEP wires are used for a voltage range of some kV up to the order of 20 kV. Polyimide is only used in the voltage range of a few hundred volts. In a few exceptional applications silicone and PE insulations have been used. Sometimes, a silicon material is used in combination with FEP to complement the properties of both. However, silicon insulations are mechanically sensitive, whereas PE is critical with respect to radiation. Nevertheless both can be attractive for AC applications, as it is possible to produce homogeneous conductive layers at the inner and outer insulations surfaces homogeneously linked with the insulation. This construction can help to avoid any gas filled gap between conductors and insulation ensuring a partial discharge free insulated wire.

Insulated wires are often assembled as cables or harness with braided shields and with an outer cable jacket. Many combinations are available from various manufacturers according to the following standards:

- ESCC 3901 (with supplementary requirements for HV application)
- NASA-STD-8739.4 (change notice 6)

Some known manufacturers are:

Axon, Gore, Teledyne (Reynolds), Raychem

It is important, that in addition to the basic testing required by the SCC and MIL specifications, high voltage cables and wires are subject to specific inspections to exclude defects in the insulation Proposed tests are:

- Partial discharge test (performed on the whole production lot)
- Progressive voltage stress test (performed on samples of a production lot)

A partial discharge test of a complete production lot is usually done by slowly moving the insulated wire though a cylindrical electrode. When this electrode is grounded the inner conductor of the insulated wire is connect to the test voltage. In order to ensure a close contact of the wire surface to the electrode a non-conductive liquid is proposed. An example for a suitable setup is shown in Figure 5-45. For cables the test should be preferably performed on the (unshielded) single insulated wire before assembling the cable.

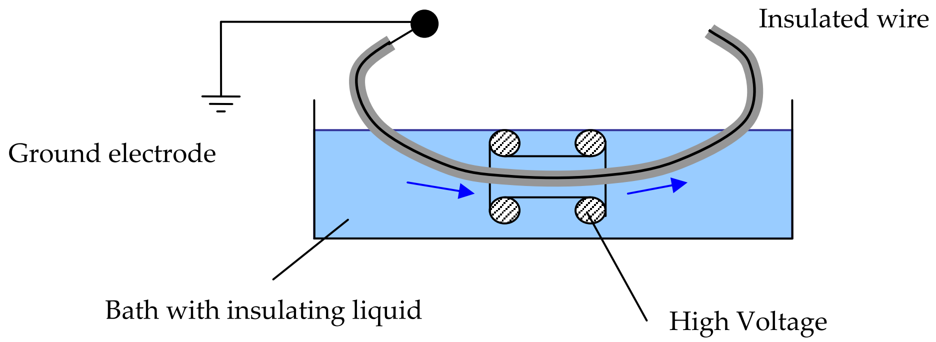


Figure 5-45: Suitable partial discharge test setup for high voltage wires

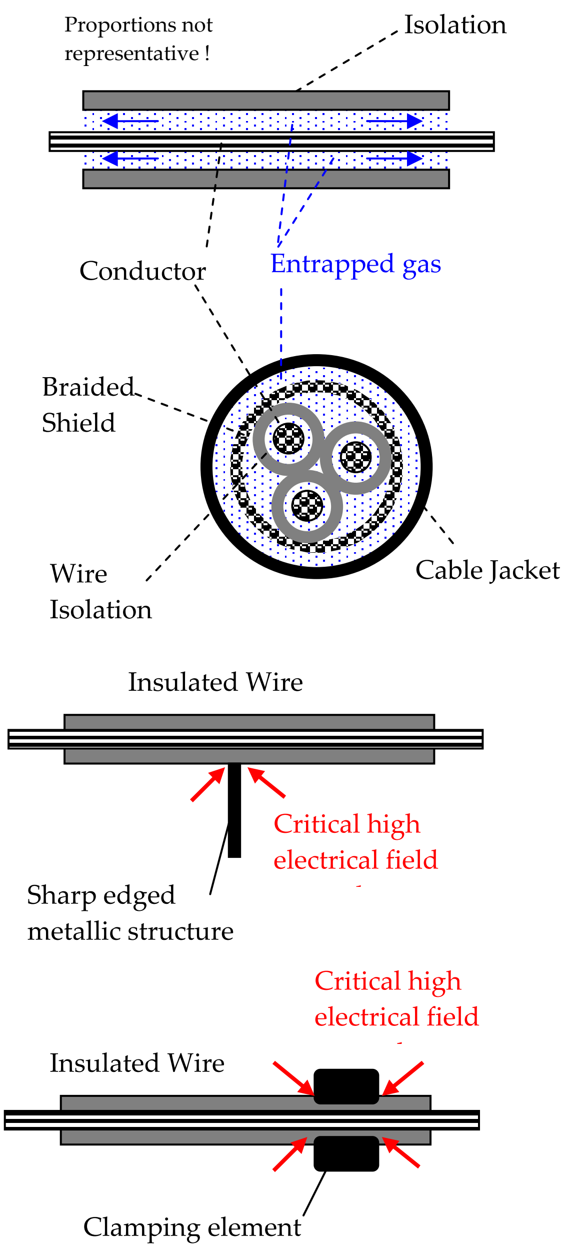
In case, that insulated wires with conductive surface layers are used the above mentioned test setup is not useful, the PD test can be made just by applying voltages between the centre conductor and the outer conductive layer/shield.

For the use of insulated high voltage wires and cables there are important aspects to be considered:

- The bending radius defined by the supplier should be respected with sufficient margin. Especially in combination with high voltage additional gap and delamination cause by too small bending radius can decrease the breakdown strengths and lifetime of the cable/wire.
- Entrapped gas volumes need a path and time for outgassing after transition from ambient conditions to vacuum (valid for non-encapsulated designs). As shown in Figure 5-46 a) and b) the entrapped gas in the (stranded) centre conductor, in braided shields and in the gap between insulated wires of a cable has to escape through the end of the cable/wire. It is therefore

essential to allow suitable venting paths or ensure for the intended application, that this kind of outgassing is uncritical for the envisaged lifetime and stress.

- Insulated wires (without outer shield) should not be routed across sharp edges of metallic (conductive) structures to avoid excessively high electrical field stresses to the cable insulation (see Figure 5-46 c). The use of insulated spacers or the proper shaping of insulation contacting structures is mandatory.
- Fixations and clamps used for mounting insulated wires and cables should be properly shaped and designed to avoid high electrical field stress and quenching of the insulation (see Figure 5-46 d). Sharp edges and excessive compression should be avoided.



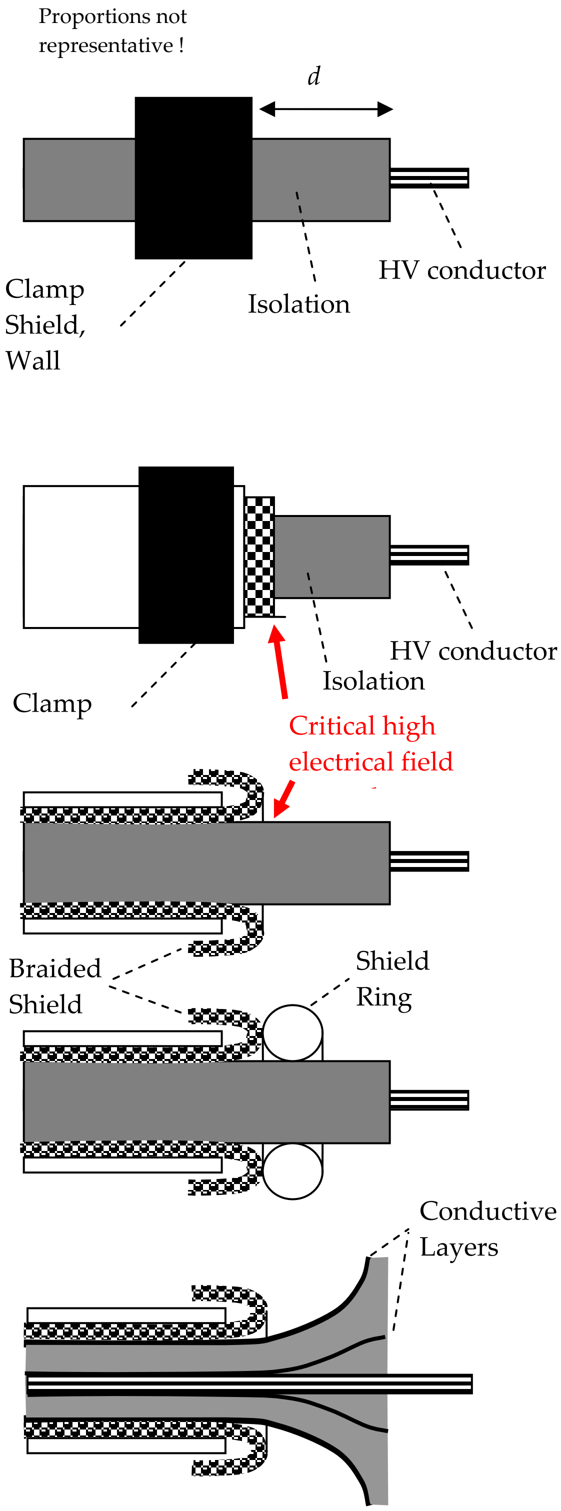
a) Entrapped gas volumes (Example: single insulated wire)
Between insulation and conductor and inside stranded conductor wires there is a entrapped gas volume which during transition into vacuum may disappear slowly – between some minute and some days.

b) Entrapped gas volumes (Example: Cable with multiple wires and shield)
In cables with multiple wires and shielding - there are entrapped gas volume as well.

c) Insulated wire facing sharp-egded metallic structure
Sharp-edged structures touching or pointing in close distance on the surface of the insulation of a (non-shielded) high voltage wire cause critical high electrical field strengths

d) Insulated wire quenched by clamping element
Unsuitable clamping elements may squeeze an high voltage wire resulting in a reduction of breakdown path.
Additionally if the clamping device is sharp-edged and metallic it will cause critical high electrical field strengths like in example c)

Figure 5-46: Critical stress cases for high voltage wires



a) Critical distance *d* across insulation path
At the termination of the wire it is important ensure sufficient distance d between the high voltage conductor and any metallic clamp, wall, or shield in longitudinal direction.
A flashover path is possible across the surface as well as inside of the insulation material.

b) Critical: Sharply-cut shield
Cutting a (braided shield) and leaving as it is leads to unacceptable high electrical field stress due sharp edges and protruding spliced metal fibre.

Critical solution – not acceptable!

c) Still Critical: Foldback of shield
Folding back of the shield does give a little improvement vs. situation b) but the risk of unacceptable high electrical field stress due sharp edges and protruding spliced metal fibre is still present.

d) Improved: Foldback of shield with field control
Using an additional suitably shaped shield like toroids help to reduce critical field strengths.

Acceptable!

e) Optimized termination with field control by conductive layers
Towards the inner conductor and towards the braided shield a conductive layer is gap-free interfacing with the high voltage insulation. At the termination this layers widen up field-controlled smoothly to any excessive electrical field strength.
Requires a dedicate process to glue or to integrate the conductive layer into the inslulation.

Optimium!

Figure 5-47: Critical stress cases for high voltage wires terminations

For the termination of high voltage wire there are as well some important aspects to consider:

- At the cut end of a high voltage wire the distance d between the inner conductor and the cut shield or to any other related structure should be sufficient to avoid
  - Surface flashover
  - Internal breakdown of the insulation in lateral direction

  (see Figure 5-47 a).

  As an orientation the field strengths in lateral direction should not exceed 400V/mm (air, high vacuum and equivalent surroundings) under worst case assumption for tolerances of workman ship. It is highlighted, that even embedding of this termination into a potting material gives a vulnerable interface, and excessive field loads should be strictly avoided.
- For shielded wires – especially with a braided shield – attention is paid to the fact that the shield is not just cut, as the cut region naturally forms a sharp electrode close to the insulation surface and a single protruding strand causes an (additional) increase in the local electrical field. The Situation as shown in Figure 5-47 b) should be strictly avoided.
- Back folding of the shield (as shown in Figure 5-47 c)) can give a slightly improved situation, however, the real curvature cannot be well controlled and the splicing and protruding of single strands cannot be avoided systematically.
- A shield electrode (as shown in Figure 5-47 d)) can help to "shade" the critical area of shield termination, however, zones with gaps between shield/electrode and insulation can be vulnerable to partial discharge inception.
- For higher DC and AC voltages it is necessary to glue or to integrate a conductive layer (i.e. carbon) into the interface to the conductor and to the braided shield - as shown in Figure 5-47 e). This design avoids any gap between conductor and insulation. Both layers should be opened up at the termination, thus increasing the distance while limiting the electrical field strength. Such complex integrated shields require a suitable production process of the HV wire and of the termination. Extruding processes of silicon or polyethylene insulation are suitable for such type of field control. Insulations built up with tapes and layers are suitable as well. This type of field control is proposed for AC voltage higher than 1 kV and DC voltage higher than 20..30 kV (orientation values!).

Often the termination of a high voltage wire is embedded into a potting material, where some specific aspects (in addition to the above mentioned) should be taken into consideration:

- A good adhesion between the wire insulation and the potting material should be ensured. Often a primer is used for this purpose (with FPA, PTFE, Silicone insulated wires). Surface roughening for example with plasma treatment can be useful in some cases. Proper cleaning and outgassing (before potting) is clearly mandatory as well.
- A good mechanical compatibility should be ensured, especially when potting wire with a soft insulation material into a hard potting (silicone-epoxy, PTFE epoxy). Sometimes shrinkage sleeves are used as a stress-relief – however, it needs to be controlled, that this construction is not weakening the electrical strengths.
- In order to prevent that mechanical forces on the wire leading to delaminate it from the potting material, it is proposed to glue or tie-base the wire on the potting surface.

5.3.6 Connectors

High voltage connectors for ground operation (ambient pressure) are available in many variants for voltages up to a few ten kV, for higher voltages as single-pin for moderate and low voltage as multi-pin connectors.

For operation in vacuum the choice of suitable connectors is very limited. The main problem for the design of such a connector is the interface between the interlaced insulation of the plug and the receptacle. Three strategies for the design of this interlaced interface should be taken into consideration:

- Gapless interface of plug and receptacle insulation, by using slightly conical structures with a soft insulation material in-between
- Interface with vented gap
- Interface with hermetically sealed gap

The gapless interface is difficult to achieve as it requires high precision of the manufacturing and a suitable soft insulation material for the interface.

Using a connector with a vented gap is only operating stably, if the critical pressure range in the interface can be avoided, i.e. by sufficient outgassing time in a high vacuum environment before applying high voltage. The vented gap becomes critical under ambient environment if the inception threshold for partial discharges is exceeded and especially if an AC voltage is applied.

A hermetically sealed interface can grant stable operating conditions for short-term independent of probably critical pressure outside, however, can reach a critical pressure due to leakage after long-term exposition in space vacuum.

In general, it should be highlighted, that the availability of space-qualified connectors is very limited.

As a conclusion, the appropriate connector design (if available) is depending on the intended use. Gapless interface and hermetically sealed gap interface can be suitable for short-term applications (more) independent of the pressure environment, whereas vented gaps for long-term operation are better if used after a good outgassing in a high vacuum environment.

In addition to the interface between plug and receptacle, the interface between plug/socket and the attached cable is very essential. Typically a gap-free interface should be achieved, for example by a suitable potting/gluing process. As this interface is very critical and requires a very well defined process it is mostly unavoidable to procure a connector assembly together with the cable from one supplier. Matching cables and connectors from different sources is very risky and typically not reliable.

Space suitable high voltage connectors seem today only available from the company Teledyne incorporating the former entities Rowe and Reynolds. Although there have been single products used on European space missions (from the "600 series" and from "PeeWee series"), there is no general space-qualified product available.

It is important, that in addition to the basic testing required by the SCC and MIL specifications, high voltage connector-cable assemblies are subject to specific inspections to exclude defects in the insulation Proposed tests are:

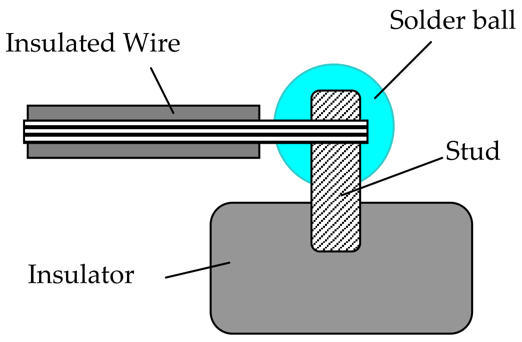
- Partial discharge test (performed on the entire production lot)
- Progressive voltage stress test (performed on samples of a production lot)
- Leakage current measurement (performed on the entire production lot)
- Life test on samples considering the typical environmental conditions (temperature and pressure).
- Burn-in test on assemblies dedicated to be used on flight.

5.3.7 Interconnections

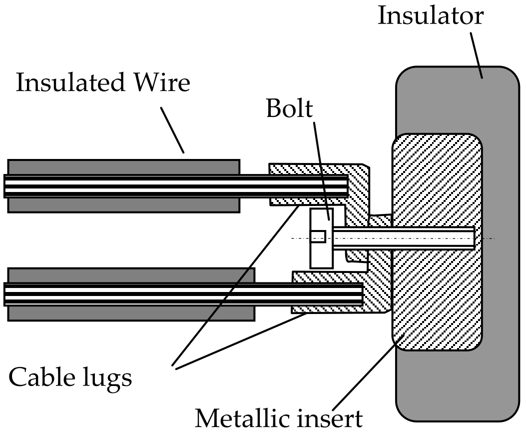
As an alternative to high voltage connectors there are other methods of interconnection which can have the advantage of simplification and lower risk – if properly selected and applied.

- Solder terminals
- Screwed of clamped terminals
- Flying leads (soldered or crimped)

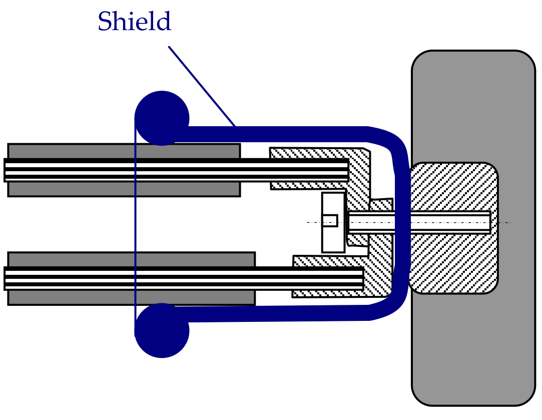
Terminals dedicated to solder joints or to bolted/clamped fixation as shown in Figure 5-49 a) and b) are suitable if used in a high vacuum environment (or if designed for that) under ambient conditions. For solder joints with a spherical shape of the solder joint is proposed. Especially for voltage higher than a few kV and addition shield should be used (see example in Figure 5-49 c). In principle these kinds of connections are detachable. Additional encapsulation with a potting material makes the connection suitable for critical pressure environment, however, is not limiting the reparability.



a) Connection via solder terminal
Important to reduce field strength by spherical solder joints, if field control is not achieved by other means



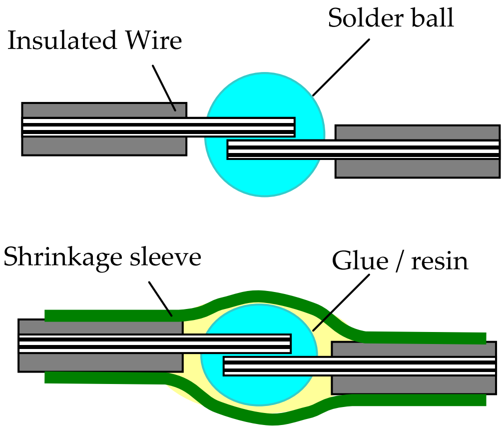
b) Connection via screwed terminal
Important to reduce field strength by spherical shaping and "over sizing of the metallic insert



c) Connection via screwed terminal with additional shield
The additional shield reduces the electrical field strengths at the sharp-edged cable lugs and bolt as well as at the wire termination

Figure 5-48: Interconnection of high voltage harness via soldering or crimping/bolting at terminals

Flying lead interconnections are very simple and can be made via soldering or crimping. Some examples are shown in Figure 5-49. Spherical solder joints are proposed. If the joint is not kept away from other structures by spacers, an additional insulation is used. Some solution with shrinkage sleeves as shown in Figure 5-49 are suitable for lower or moderate high voltages (below 10 kV for orientation). The sleeve can be used in multiple layers to improve the insulation strengths. Filling with glue/resin further improves the insulation strengths and avoids partial discharges. However, the filling with glue should be performed preferably under vacuum to avoid inclusion of air bubbles. It could be considered to replace the shrinkage sleeves by tubes of insulation material.



a) Flying lead with soldering
Important to reduce field strength by spherical solder joints, if field control is not achieved by other means

b) Flying lead with soldering and shrinkage sleeve
The shrinkage sleeves ensures continued insulation, filling with glue/resin may avoid partial discharge (need to be process under vacuum to avoid air bubbles insude)

Figure 5-49: Flying lead interconnections

It is important to consider an adequate strain relief for all solutions.

Interconnecting shielded wires require specific means to avoid critical electrical stress at the area of the joints– for details see section 5.3.5. For interconnection purposes the shield can be continued in coaxial structure around the interconnection zone – if required for EMC reasons.

5.3.8 Insulators and spacers

Insulators and spacers have to fulfil mechanical and electrical needs and can be designed in many shapes and geometries. However, for a good design it is referred to the rules and aspects:

- Table 5-2: Orientation "map" for maximum electrical field strengths in electrical insulation
- Figure 5-19: Critical triple-junction point/area in an interface between solid - gaseous/liquid/vacuum insulation - metal conductor
- Figure 5-20: Methods to reduce the influence of the triple junction zone by design
- Figure 5-22: Designs to reduce impact of creepage path on electric insulation
- Figure 5-23: Designs to reduce impact of surface charging on electric insulation
- Figure 5-24: Segmenting of insulator to influence surface charging
- Figure 5-25: Implementation of design measures minimizing interference problems for a typical high voltage power conditioner (regulated DC-DC converter for high voltage as an example)

Typical and simple geometries are based on cylindrical shapes as shown in Figure 5-50. Variant a) outlines an example of a straight cylindrical shape. In order to reduce the electric field in the triple-junction zones the metal armature has a recessed shaping. Contact to the electrodes can be made by mechanical compression, gluing or potting. The straight shape can give disadvantage in vacuum (for higher voltage above a few kV) and in humid or polluted air environment.

The variant b) in Figure 5-50 outlines an insulator with inserts in combination with recessed electrodes, giving an optimum for avoiding critical electrical fields in the triple-junction zones. The insert should be embedded into the insulator without gaps and voids, for example by potting under vacuum. The corrugated shape of the insulator increases the creepage path length.

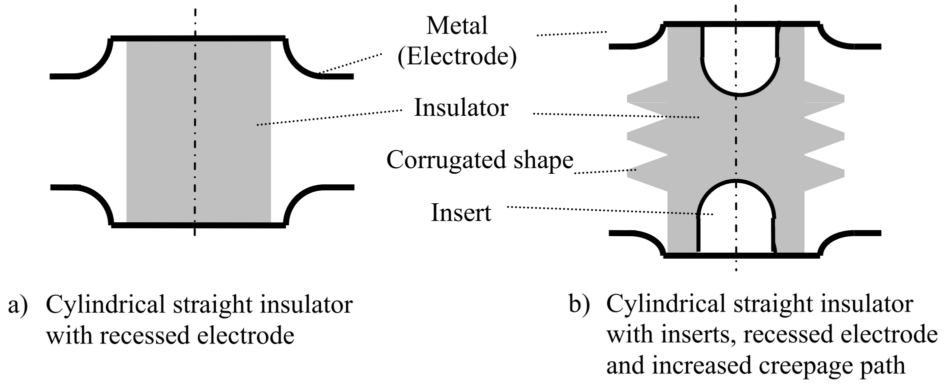


Figure 5-50: Suitable insulator design variants

High voltage spacers and insulators are proposed to be designed under consideration of electrical field analysis.

Materials for use are typically ceramics or potting materials (epoxy resin) with adhesives based on silicone or PUR. For some space applications, polyimide or PTFE materials are used as well (limited to the lower voltage range, up to a few kV tentatively. Some ceramic materials offer the possibility to be soldered to metallic armatures.

It is proposed to consider the following essential tests:

- Partial discharge test (performed on the entire production lot)
- Progressive voltage stress test (performed on samples of a production lot)
- Leakage current measurement (performed on the entire production lot)
- Life test on samples considering the typical environmental conditions (temperature and pressure).

5.3.9 Feedthroughs

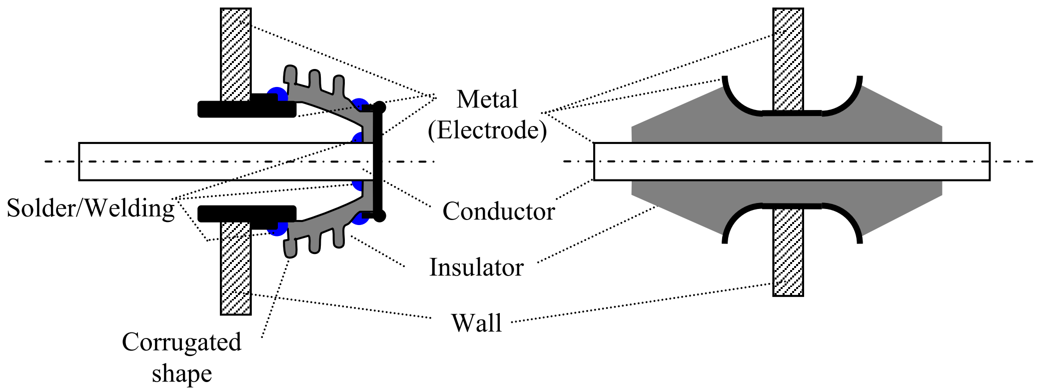
Feedthroughs have to fulfil mechanical and electrical needs and can be designed in many shapes and geometries. However, for a good design it is referred to the following rules and aspects:

- Table 5-2: Orientation “map” for maximum electrical field strengths in electrical insulation
- Figure 5-19: Critical triple-junction point/area in an interface between solid - gaseous/liquid/vacuum insulation - metal conductor
- Figure 5-20: Methods to reduce the influence of the triple junction zone by design
- Figure 5-22: Designs to reduce impact of creepage path on electric insulation
- Figure 5-23: Designs to reduce impact of surface charging on electric insulation
- Figure 5-24: Segmenting of insulator to influence surface charging

Typical and simple geometries are based on cylindrical shapes as shown in Figure 5-51.

Variant a) in Figure 5-51 outlines an example of a hermetically sealed hollow construction, based on ceramic materials. The ceramic insulator is soldered with the metal fittings ensuring low leakage rate sealing. This type of feedthrough is often used for vacuum-to/air and vacuum-to-vacuum connections. Sharp edges are avoided close to the insulator or located in an area shaded by a shield electrode. The corrugated shape of the insulator increases the creepage path length.

Variant b) in Figure 5-51 outlines an example of a bulk insulation material construction, typically based on potting materials. Inner and outer electrodes are round-shapes for better electrical field control. With proper potting material the mechanical interface between insulation and conductors relies on adhesive forces.



a) Sealed vacuum feedthrough with ceramic corrugated insulator

b) Potted bulk material feedthrough with shield

Figure 5-51: Suitable feedthrough design variants

High voltage feedthroughs are proposed to be designed under consideration of electrical field analysis.

Materials for use are typically ceramics or potting materials (epoxy resin). Silicone or PUR can be used if the constructions are exposed to low mechanical loads only. For some space applications polyimide or PTFE materials are used as well (limited to the lower voltage range, up to a few kV tentatively. Some ceramic materials offer the possibility to be soldered to metallic armatures.

It is proposed to consider the following essential tests:

- Partial discharge test (performed on the entire production lot)
- Progressive voltage stress test (performed on samples of a production lot)
- Leakage current measurement (performed on the entire production lot)
- Life test on samples considering the typical environmental conditions (temperature and pressure).

5.3.10 Printed circuit boards

Printed circuits are useful to simplify production of high voltage electronic circuits and to provide mechanical support to high voltage electronic components; however, their use should be considered with special care and can be acceptable for the range of low and medium high voltage levels. The following basic options are available with restrictions given by the applications.

Substrate materials are typically:

- Fibre-reinforced epoxy (i.e. FR4)
- Polyimide
- Ceramics

The use of this material can be made

- without copper tracks
- with copper tracks on one surface only
- with copper tracks on both sides (double-sided)
- with multi-layer

in combination with the various environments

- air, gas
- vacuum.
- liquid
- potting

It should be mentioned, that the typical environments for space applications are air and vacuum, or encapsulation with a potting material. Liquid environments are rarer.

Table 5-7: Application matrix for PCB with high voltage

	Fibre-reinforced epoxy	Polyimide	Ceramics
Without copper tracks	Suitable for potted PCB's. Range: up to some 10 kV-DC *) Limited suitable for non-potted PCB's. Range: up to some 10 kV-DC *)	Suitable for potted PCB's. Range: up to some 12 kV-DC *) **)	Suitable for uncoated PCB's in vacuum and air, behaviour in vacuum depends very much on surface properties. Range: up to some 10 kV-DC *)
Single sided copper tracks	Suitable for potted PCB's. Range: up to some 10 kV-DC *)	Suitable for potted PCB's. Range: up to some 12 kV-DC *)**)	Suitable for uncoated PCB's in vacuum and air, behaviour in vacuum depends very much on surface properties. Range: 0-30 kV-DC *)
Double sided copper tracks	Suitable for potted PCB's Range: up to about 10 kV-DC *) after careful evaluation	Suitable for potted PCB's. Range: up to some 12 kV-DC *) **)	No experience exists for high voltage
Multilayer (>2)	Suitable for potted PCB's. Range: up to about 10 kV-DC *) after careful evaluation.	No experience exists for high voltage	Complex, unknown

*) Tentative value for orientation only -requires always careful evaluation of material and process. Due to partial discharges the acceptable AC values for use are typically a fraction (between 10% and 50%) of the DC-values.

**) Experimental experience shows that double-sided PCB's in Polyimide with 12 kV between some superposed tracks (1,6 mm) at 125 °C can be operated for 10000 h without any failure

An overview of possible PCB's used for high voltage applications is given in Table 5-7. In practice there have been made some use of ceramic PCB's for high voltage (single layer copper tracks) exposed to air and vacuum environment. In such cases the surface should be left without coating. Careful consideration to the evaluation and selection of the material used should be given, as the vacuum flashover can be significantly influenced by the surface properties.

Most of the applications use PCB's with reinforced epoxy material, which is typically compatible with epoxy and polyurethane potting materials. Using PCB's without tracks – just as a mechanical support structure for mounted components - enables the use up to a few ten kV DC voltage. Mounting can be eased by small through holes and solder pads. Single layer and double layer constructions can be used typically up to 12 kV-DC (rough order of magnitude) however, preconditions are very well evaluated and controlled material and processes. The design aspects outlined in Figure 5-29: "Potting of PCB`s: typical design aspects" should be regarded.

PCB's with copper tracks on both sides rely on the crack-free, void-free insulation between both sides represented by the board. This requires high attention to quality insurance by a well controlled production process of the board, and inspections or test. Suitable means are

- ultrasonic scanning
- X-ray scanning
- partial discharge testing of the copper covered board before etching.

As in many cases the PCB's are procured items from external suppliers it is essential to have visibility on the board production process and introduce necessary inspections and tests.

Multi-layers PCB's with more than 2 layers usually use layers "sandwiches" of prepreg (impregnated glass fibre mesh) and polyimide sheet to separate the different copper layers. As it is difficult to produce such insulation structure void-free it is not recommended to use such technology for voltages higher than about 100 V. In general attention should be paid to vias and through holes as they can create a significant lateral field stress to neighbouring copper layers. This constellation is very sensitive and weak.

Non-specific for high voltage the ECSS-Q-ST-70-10C and ECSS-Q-ST-70-11C apply however, additional process control, screening and testing is proposed.

It is proposed to consider the following essential tests:

- Partial discharge test (performed on the entire production lot)
- Progressive voltage stress test (performed on samples of a production lot)
- Leakage current measurement (performed on the entire production lot)
- Life test on samples considering the typical environmental conditions (temperature and pressure).

The partial discharge test is often difficult to perform on an etched and finished PCB it can be an option for a raw double-sided or for a single-sided PCB to perform such a test before etching, this can ensure, that the bulk insulation is checked to be free of partial discharges.

5.3.11 Other components

Other possible high voltage components onboard spacecrafts are:

- Electron tubes for RF amplification
- Electron tubes for high power switching
- Gas lasers.

In general for these complex devices the guidelines of this document about insulation, design and materials apply in general, however, their specific application is subject of the knowledge and experience of the manufacturers of these devices.

6
High voltage testing

6.1 Non-Destructive Testing

6.1.1 Insulation Resistance Test (INR)

6.1.1.1 Applicability

This test is a general test for all types of insulations. It can be used for the characterization of pure insulations as well as for integrated circuitry. The insulation resistance test is useful to be done prior and after high voltage testing to compare the state of insulation as well as initial test after integration of high voltage circuits before applying high voltage.

6.1.1.2 Objectives

This test is used to characterize the quality of the insulation and to determine the critical state of the insulation which makes risks visible of early failure or breakdown/short circuit.

6.1.1.3 Rationale

The test should be performed before applying high voltage for testing purpose or before first nominal operation.

6.1.1.4 Method

The insulation resistance is tested by applying a low voltage (50 V to 100 V DC) to the insulation. An instrument sensitive enough to detect picoamperes (pA) measures the resulting current and the insulation resistance is calculated from Ohm's law (either by the measurement device or manually).

6.1.1.5 Acceptance Criteria

Insulation resistance should be higher than 1000 MΩ for a "pure" insulation.

This criterion can be modified accordingly, if the insulation is embedded in an environment which makes it impossible to achieve this value, for example: if the insulation is part of an electronic circuitry which provides low conductive paths in parallel to the insulation (e.g. resistors, semiconductors, conductive layers).

6.1.1.5.1 Accuracy

Resistance: 5 %

6.1.1.5.2 Nonconformances

A failure of this test can require detailed investigations about the reason. Application of high voltage to the circuit should be avoided, except in case of a failure investigation plan.

6.1.2 Bulk Resistance Measurement (BRM)

6.1.2.1 Applicability

Characterization of samples of insulation materials (raw materials, typically specially designed test samples).

6.1.2.2 Objectives

This test is used to characterize insulation resistance of a material in order to cope with the analysed project requirement.

6.1.2.3 Rationale

The test should be performed for new materials introduced into a space borne high voltage equipment

6.1.2.4 Method

The bulk resistance measurement is described in the electrical standard IEC60093. The bulk resistance is tested by applying a low voltage 1000V DC to the insulation The set-up requires a guard ring electrode to decouple the insulation current through the bulk insulation from the current flow across the surface (see Figure 6-1).

An instrument sensitive enough to detect picoamperes (pA) measures the resulting current and the insulation resistance is calculated from Ohm's law (either by the measurement device or manually).

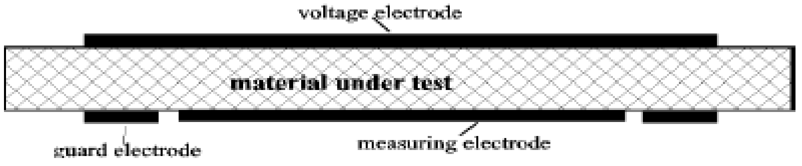


Figure 6-1: Guard ring test set-up for bulk resistance measurement

6.1.2.5 Acceptance Criteria

Typically there is no acceptance criterion as the measurement is used for material characterization, but the acceptance is referred to the application and its environment. However, a good insulation material should have a bulk resistance better than 10^{12} Ω cm

6.1.2.5.1 Accuracy

Resistance: 5 %

6.1.2.5.2 Nonconformances

Not applicable.

6.1.3 Surface Resistance Measurement (SRM)

6.1.3.1 Applicability

Characterization of samples of insulation materials (raw materials, typically specially designed test samples).

6.1.3.2 Objectives

This test is used to characterise the surface resistance of a material.

6.1.3.3 Rationale

The test should be performed for new materials introduced into a space borne high voltage equipment.

6.1.3.4 Method

The surface resistance measurement is described in the electrical standard IEC60250. The surface resistance is tested by applying a low voltage 1000 V DC to the insulation The set-up requires a guard ring electrode to decouple the insulation current through the bulk insulation from the current flow across the surface (see Figure 6-1).

An instrument sensitive enough to detect picoamperes (pA) measures the resulting current and the insulation resistance is calculated from Ohm's law (either by the measurement device or manually).

6.1.3.5 Acceptance Criteria

Typically there is no acceptance criterion as the measurement is used for material characterization, but the acceptance is referred to the application and its environment. However, a good insulation material should have surface resistance better than 10^9 Ω.

6.1.3.5.1 Accuracy

Resistance: 5 %

6.1.3.5.2 Nonconformances

Not applicable.

6.1.4 Polarisation and Depolarisation Current Measurement (PDC)

6.1.4.1 Applicability

This test is a general test for all types of insulations. It can be used for the characterization of whole insulation systems. The polarisation (relaxation) test is useful to be done prior and after ageing/burn in to compare the state of insulation.

6.1.4.2 Objectives

This test is used to characterize the quality of the insulation and to determine the critical state of the insulation which makes risks visible of early failure or breakdown/short circuit.

6.1.4.3 Rationale

The test should be performed in nominal environment e.g. vacuum.

6.1.4.4 Method

The relaxation current is measured by applying a high voltage pulse (e.g. up to 2xUnom DC) to the insulation. An instrument sensitive enough to detect picoamperes (pA) measures the resulting current. For low capacitance high insulating DUT the duration of the high voltage should be no less than 10 minutes. After switching off the voltage, the depolarisation current can be measured for additional information.

6.1.4.5 Acceptance Criteria

Insulation current should be not greater than 100 pA after 10 minutes for low capacitance insulation devices. No discontinuous current changes should occur.

This criterion can be modified accordingly, if the insulation is embedded in an environment which makes it impossible to achieve this value, for example: if the insulation is part of an electronic circuitry which provides low conductive paths in parallel to the insulation (resistors, semiconductors, conductive layers, etc.).

6.1.4.5.1 Accuracy

Current: 5 %

6.1.4.5.2 Nonconformances

A failure of this test can require detailed investigations about the reason.

6.1.5 Dielectric Loss Factor Test (DLF)

6.1.5.1 Applicability

The dielectric loss factor measurement is used for characterization of samples of insulation material (raw material, typically specially designed test samples) or of high voltage components like high voltage cable, insulators and capacitors.

6.1.5.2 Objectives

This test is used to characterise insulation loss factor of a material or a component.

6.1.5.3 Rationale

The test should be performed for new materials introduced into a space borne high voltage equipment or selected components.

6.1.5.4 Method

The dielectric measurement is described in the electrical standard IEC60250.

6.1.5.5 Acceptance Criteria

Typically there is no acceptance criterion as the measurement is used for material characterization, but the acceptance is referred to the application and its environment. However, a good insulation material should have dielectric loss factor better than 0,01 at 1 kHz.

6.1.5.5.1 Accuracy

Loss factor: 5 %

6.1.5.5.2 Nonconformances

not applicable.

6.1.6 Partial Discharge Test (PDT)

6.1.6.1 Objective

The objective is to qualitatively assess the insulation for presence of voids, cracks, particles, delamination and workmanship.

6.1.6.2 Rationale

Partial discharge testing can be performed with AC voltages, DC voltages and ramp voltages. Typically the use of an AC voltage is the most efficient method to detect voids and cracks within insulation.

Testing with AC voltage should be the first choice, even if the nominal operation of the high voltage device under test is not an AC voltage. However, if AC voltage is used instead of a DC voltage it should be ensured that the electrical stress to insulation and embedded components does not exceed the rated maximum voltage, and is from the electrical field strength equivalent to the original stress situation.

It is important to ensure, that the background noise level of the facility are adequately low to allow a precise measurement. For most cases, background noise levels below 1 pC are only achievable with a high effort.

A criteria for a measurement is the acceptance of less than 5 pC, the facility should achieve a background noise levels below 2 pC.

6.1.6.3 Method and Acceptance Criteria

The general principle and test method is described under:

IEC 60270:2000/BS EN 60270:2001 "High-Voltage Test Techniques - Partial Discharge Measurements" should be used.

The test is divided into two phases: addressing two different levels of testing:

- Level 1 testing is used for general acceptance testing of assemblies with high voltage circuits or to “sensitive” modules, for example modules including electronic components which can be excessively stressed. Test level can be adjusted, if justified by a suitable rational
- Level 2 testing is used to demonstrate design margins, for example for qualification of new high voltage insulation design. However, level 1 testing should be performed always in addition on the same sample – typically prior to the level 2 test or in combination with level 1 test, meaning: characterize first at level 1 and increase voltage to level 2.

The test profiles for the different test levels and for the different choices of AC or DC test voltage are listed in Table 6-1.

A suitable set-up is shown in Figure 6-2. It consist of a

- partial discharge free high voltage source
- partial discharge free high voltage connections
- partial discharge free coupling capacitor (for coupling of the detector)
- partial discharge detector.

As the time range of a pulse discharge is ~1-5 ns, which then is integrated by the effective capacitor, it is the amplitude of the integration value which is measured, therefore a bandwidth of 20 kHz-800 kHz should be used (narrow band). Detectors with a bandwidth of 200 kHz – 20 MHz (wideband) are available on the market, but more difficult for the interpretation of the result in a noisy environment.

The partial discharge detector should allow pulse evaluation directly indicating the charge Q_{pulse} per event and should allow recording of pulses Q_{pulse} over time.

It is highlighted, that each individual partial discharge measurement requires a calibration. Calibration is typically done by injecting pulses with a defined charge with a calibrated low voltage pulse source. The charge value should be selected in accordance with the measured pulse range. Note, that some detectors can require recalibration, if the measurement range is changed.

Furthermore it is essential to perform a measurement of the basic noise level before performing the partial discharge measurement with the device under test.

In most cases, a partial discharge test needs to be performed in an electrically shielded environment, for example in an EMC chamber to guarantee a sufficiently low background noise environment. Good power line filtering is proposed to avoid noise entering through the power source.

6.1.6.4 Aspects of implementation and test environment

For partial discharges measured with AC voltage the location of the pulses with respect to the phase can be used to discriminate the location of a partial discharge. Especially in series production and related testing the comparison of pulse patterns can be used to identify location and type of failure. In case of prototypes and small series this failure evaluation is more difficult.

It is important to know, that discharge pulses close to or at the peak of the AC sine wave can be caused by outer partial discharges, for example caused by the test setup. This can lead to the consequence of improving the test setup or the way of testing the device under test.

In Figure 4-1 some options for insulation characterization are proposed by the example of a high voltage transformer. In order to test the high voltage insulation of the secondary (high voltage) winding) the transformer can be supplied differentially – as shown in Figure 4-1 a). In this configuration the insulation is stressed nominally if the voltage source is representative in terms of voltage waveform. In most of the high voltage condition applications for space this cannot be achieved as the transformer is typically excited with a higher frequency than the normal power line frequency. In practice, the effort to achieve a representative power source and performing measurements with higher switching frequencies than the normal powerline frequency is very high. Furthermore, the complex design of high voltage transformers for power conditioning in space power supplies is rather complex, containing rectifiers and other electronic parts. In most of the cases it is more efficient to perform the partial discharge measurement with a kind of common mode excitation as shown in Figure 4-1 a). The set-up is not fully representative to the nominal voltage distribution and field stress, but allows a minimum of insulation quality assessment. It should be highlighted, that the device under test needs to be designed for such kind of test, ensuring that also the part of the insulation, which is nominally only exposed to low field stress is designed for the maximum test voltage in a partial discharge free process. The design should be carefully checked for any disturbing design elements, as non suitable feedthroughs and low voltage wires.

Another important aspect is the test environment. Although it is preferred to perform the partial discharge test in the nominal environment of the device under test, it can limit the test effort and improve the result of the test, if a different environment is selected.

Example: a potted high voltage module (i.e a high voltage transformer) should be analyzed w.r.t. its insulation quality of the core insulation (of the potting material). A measurement in ambient air can give erroneous results due to external partial discharges in air, which are not representative for the in-flight environment of vacuum. In order to suppress this misleading external partial discharge the test can be performed alternatively in

- Vacuum
- Insulating Liquid (oil, flour-carbon insulating liquid)
- High insulating gas (SF_6, compressed nitrogen)

Performing the test in vacuum requires the effort of a suitable vacuum chamber with partial discharge free feedthroughs.

Insulating liquid allows a quick setup in a container filled with liquid, which can be in a simple case a plastic or glass vessel. Classical transformer oil is simple to use but requires cleaning effort. Good experience has been made by using Fluorocarbon insulating liquid (for example: Flour-inert FC77 of 3M)

Compressed gas requires a pressurized vessel and therefore a higher effort. Simple with good results is the bagging of the device under test (simple plastic bag) and filling/flushing with SF6 gas. As explained in section 5.2.3.3 even non-perfect mixtures of SF6 with air can give an improvement of insulation strengths by a factor of 2 to 3 and therefore suppress external partial discharges efficiently.

6.1.6.4.1 Accuracy

- Voltage: 2 %
- Calibration charge: 10 %

6.1.6.4.2 Nonconformances

A failure of this test can require detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

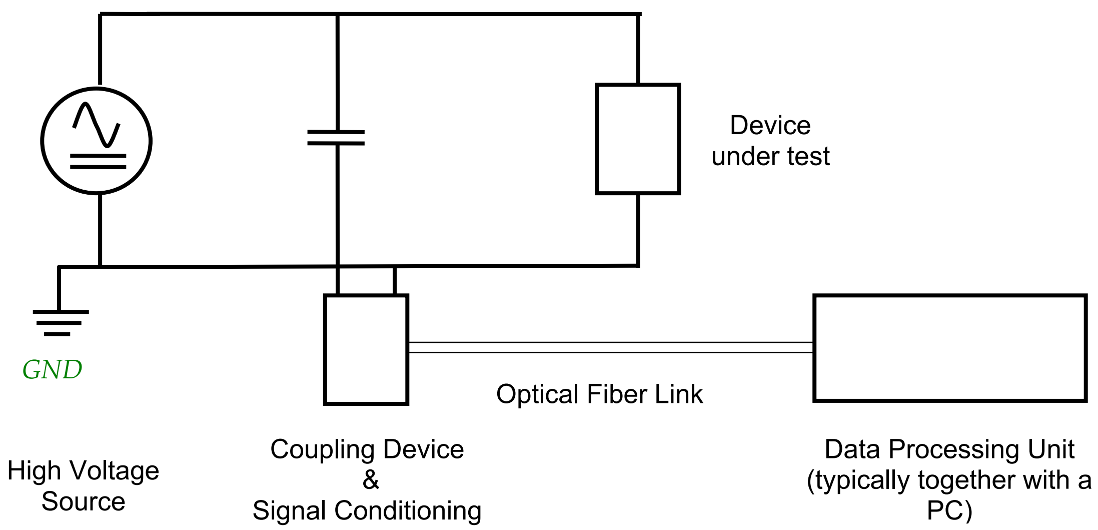


Figure 6-2: Partial discharge test set-up

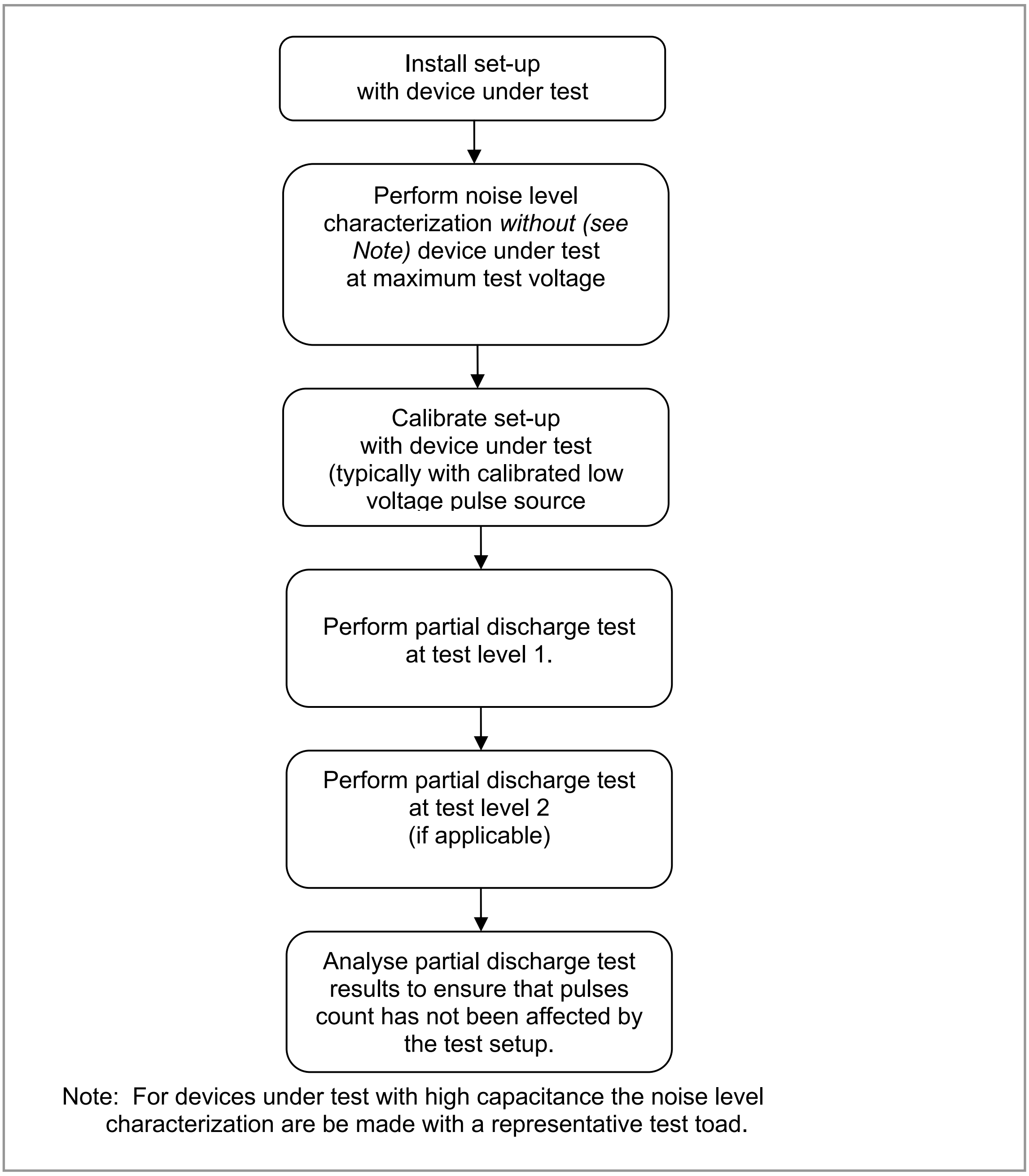


Figure 6-3: Typical partial discharge test flow

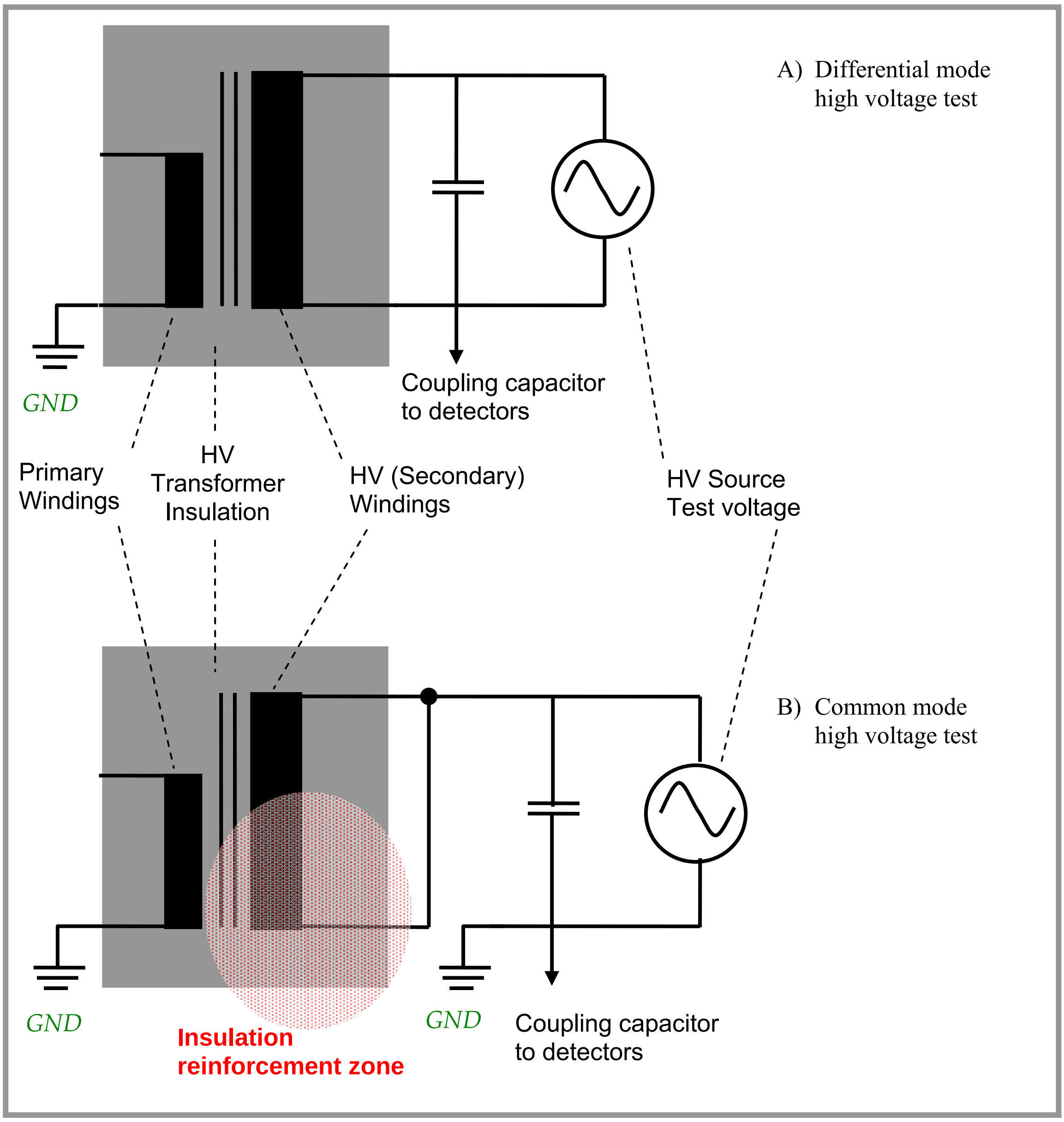


Figure 6-4: Partial discharge testing aspects. Example: High voltage transformer

Table 6-1: Test methods, levels and acceptance criteria for partial discharge testing

Method	Test Voltage	Test Duration	Pass Criteria
AC (Level 1)	AC sinusoidal voltage $\widehat{U}_{ac-test} = 1{,}3\ U_{nom-\max}$ AC peak voltage $\widehat{U}_{ac-test}$ equal to 1,3 times the sum of nominal DC voltage and any AC peak voltage or superimposed AC peak voltage or peak pulse voltage. Frequency to be selected to standard 50 Hz or 60 Hz from power line or to be selected with justification in accordance with the application.	10 min before and after ramp up/down from 0 V to test voltage $\widehat{U}_{ac-test}$	no pulses per 10 min above 5 pC *)
AC (Level 2)	AC sinusoidal inception voltage $\widehat{U}_{ac-test} = 1{,}5\ U_{nom-\max}$ AC peak voltage $\widehat{U}_{ac-test}$ equal to 1,5 times the sum of nominal DC voltage and any AC peak voltage or superimposed AC peak voltage or peak pulse voltage. Frequency as above	10 min increase from level 1 test Or perform as an additional self-standing test ramp up/down from 0 V to test voltage $\widehat{U}_{ac-test}$	no pulses per 10 min above 10 pC *)
DC (Level 1)	DC voltage $\widehat{U}_{dc-test} = 1{,}3\ U_{nom-\max}$ DC peak voltage $\widehat{U}_{dc-test}$ equal to 1,3 times the sum of nominal DC voltage and any superimposed AC peak voltage or peak pulse voltage.	24 h before and after ramp up/down from 0 V to test voltage $\widehat{U}_{dc-test}$	no pulses per 60 min above 5 pC *)
DC (Level 2)	DC inception voltage $\widehat{U}_{dc-test} = 1{,}8\ U_{nom-\max}$ DC peak voltage $\widehat{U}_{dc-test}$ equal to 1,8 times the sum of nominal DV voltage and any superimposed AC peak voltage or peak pulse voltage.	24 h increase from level 1 test Or perform as an additional self-standing test ramp up/down from 0 V to test voltage $\widehat{U}_{dc-test}$	no pulses per 60 min above 10 pC *)

*) In case the HV component or module under test contains any capacitor of reconstituted mica or of similar material, higher partial discharge levels can be tolerated. The charge limits given above should be adjusted to the actual "capacitance of the sample" (C-sample) as follows:.

C-sample up to 100 pF	5 pC (level 1) / 10pC (level 2)
C-sample 1000 pF	50 pC (level 1) / 100 pC (level 2)
C-sample 10000 pF	500 pC (level 1) / 1000 pC (level 2).

Scale accordingly for C- samples with higher values, the value of the test setup coupling capacitor should be taken into account with the equipment under test.

MIL-PRF-49467C adjustments for equipment using mica ceramic multilayer capacitors is almost identical to this.

6.1.7 Dielectric Withstanding Voltage Test (DWV)

6.1.7.1 Objective

High voltage tests are intended to detect insulation flaws, discontinuities, ageing cracks, and deteriorated or weak insulation.

6.1.7.2 Rationale

Repeated application of high potential test voltages can reduce the dielectric strength and life of the insulation. Any significant reduction in dielectric strength depends on the number of tests, the insulation material, and the insulation thickness. Up to ten high-potential tests can probably not permanently damage the insulation.

6.1.7.3 Method

Proposed test conditions are:

- Environment: to be selected in accordance with representative stress of the insulation
- Duration: 60 s
- Test Voltage: DC, AC, pulse: voltage U_{test} :
  - for Level 2 test: $U_{test} = 3\,U_{nom}$ *)
  - for Level 1 test: $U_{test} = 2\,U_{nom}$ *)

  where the nominal voltage U_{nom} is maximum voltage of operation

*) The test level should be adjusted (lowered) carefully for hardware used later for flight, or protoflight assemblies, if there is the danger that the high test voltage contributes to significant pre-aging or other applicable ratings of involved components are exceeded.

Level 2 testing is proposed to demonstrate design margin assuming that a high voltage device is operated with a derating factor of 0,5 and tested at 1,5 times the rated voltage. Level 2 testing should not be repeated too often as it can overstress the insulation. Therefore it is proposed for qualification test and an initial test at acceptance. Repeated test on flight hardware should follow Level 1 conditions.

The voltage waveform should be selected according to the real application, so for DC operation a DC voltage test should be selected.

A proposed electrical set-up is shown in Figure 6-5.

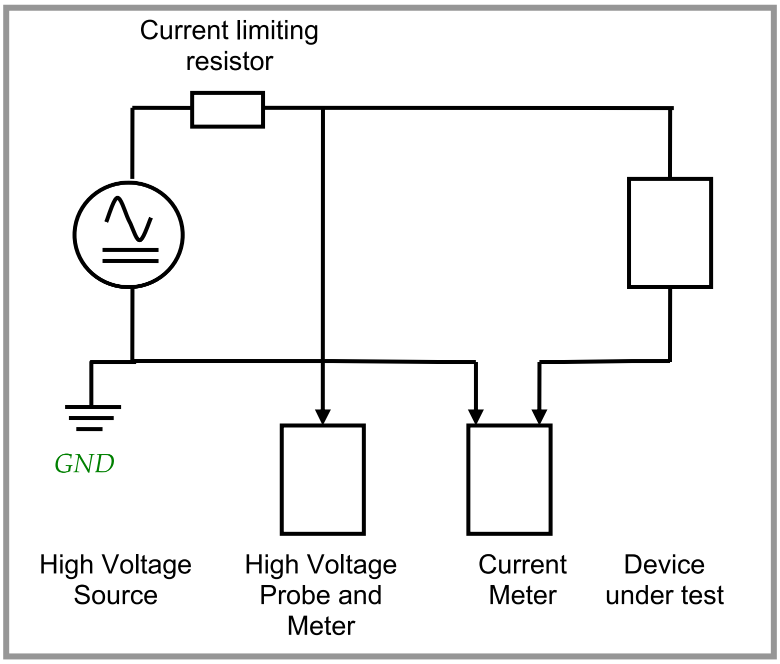


Figure 6-5: Dielectric Withstand Voltage Test Electrical Schematic

6.1.7.4 Acceptance Criteria

A justified current level should be defined depending on the insulation resistance and attached circuitry, typically in the range of µA… mA.

6.1.7.4.1 Accuracy

- Current 5 %
- Voltage: 2 %
- Time: +5 % / -0 %

6.1.7.4.2 Nonconformances

A failure of this test can require detailed investigations about the reason, design and processes should be checked. If the failure was not destructive an assessment should be performed about continuation of test and use.

6.1.8 Triple Junction Test (TRJ)

6.1.8.1 Applicability

This test is primarily dedicated to vacuum insulations in order to ensure that with applied high voltage no leakage currents are present due to surface conductivity and electron emissions caused by local electron emission sites present on surfaces, especially at sharp-edged metallic structures and at triple-junction zones.

6.1.8.2 Objective

The test detects leakage currents due to degradation of vacuum insulation, when high voltage is applied. It can detect problems due to design, processes and workmanship after assembly and integration.

6.1.8.3 Rationale

The test should be applied at module and/or equipment level after initial insulation characterization, however, it can be inserted or repeated in any test sequence or operational life cycle.

6.1.8.4 Method

This test is applicable to test for potential failure modes due to leakage currents in vacuum. Such leakage currents often occur from emission sites on the surface of electrodes at locations with high field strengths. Critical zones for emitters are the triple junction zones of electrical insulations as well as sharp edged structures of the conductors. Contamination by gas layers, particles etc. promote this effect. The effect is voltage and temperature dependence and can be time dependent as well.

The test is performed by applying a high voltage for a significant length to the device under test.

Proposed test conditions are:

- Pressure: in Vacuum Chamber with pressures lower than 10^{-4} mbar.
- Temperature: at high level, equivalent to maximum operation temperature for acceptance or qualification.
- Duration: 36 hours
- Test Voltage: DC voltage U_{test} :
  - for Level 2 test: $U_{test} = 2\,U_{nom}$
  - for Level 1 test: $U_{test} = U_{nom}$

  where the nominal voltage U_{nom} is maximum voltage of operation

*) The test level should be adjusted (lowered) carefully for hardware used later for flight, or protoflight assemblies, if there is the danger that the high test voltage contributes to significant pre-aging aging or other applicable ratings of involved components are exceeded.

Level 2 testing is proposed to demonstrate design margin on single "non-sensitive" modules, for example for simple insulators. Level 1 testing is proposed for assemblies of high voltage circuits or for "sensitive" modules, for example modules including electronic components. Test level should be adjusted, if justified by a suitable rationale.

A proposed set-up is shown in Figure 6-6 comprising a high voltage source, high voltage meter and a sensitive current meter.

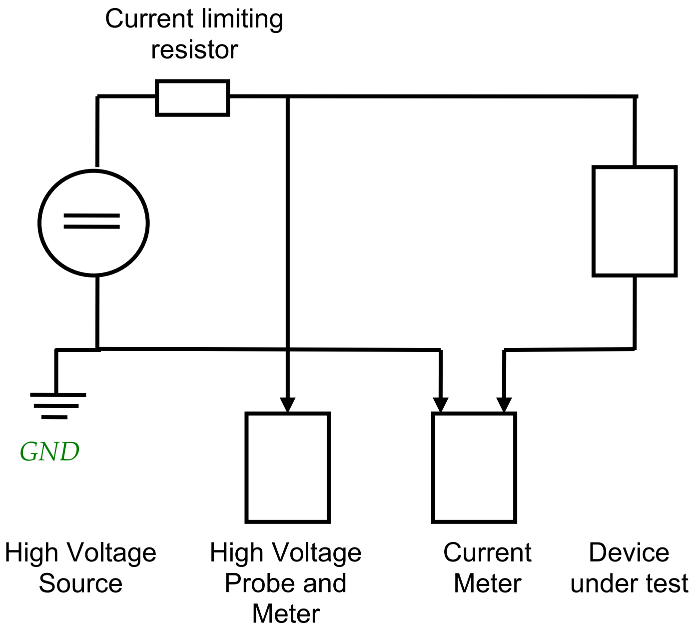


Figure 6-6: Triple Junction Test Electrical Schematic

6.1.8.5 Acceptance Criteria

The leakage current should not alter by more than the error of the measurement during the test.

6.1.8.5.1 Accuracy

- Current 5 %
- Voltage: 2 %
- Time: +10 % / -0 %

6.1.8.5.2 Nonconformances

A failure of this test can require detailed investigations about the reason. Check especially for correct design and for process/workmanship with attention to contamination issues.

6.1.9 Critical pressure testing/Corona testing (CPT)

6.1.9.1 Objective

Critical pressure testing (often called: Corona Testing) is used to ensure, that a component, an equipment or a subsystem can be safely operated at critical pressures according to the Paschen Curve (see sections 4.3.4 and 5.1.8).

6.1.9.2 Rationale

There are different classes of items under test:

- Class 1: For test items which are not fully encapsulated (high voltage conductors not exposed to the vacuum) to demonstrate margin and/or safe operation.

  In this case it should be taken care, that the electrical test environment, which is exposed to the same low pressure environment as the item under test is safe for operation at low pressure.

- Class 2: For test items which are fully encapsulated (high voltage conductors exposed to the vacuum) to demonstrate margin and/or safe operation.

  In this case the test requires completely encapsulated high voltage equipment operated in a high voltage chamber. This includes all high voltage connections and set-up used as a test environment, too.

6.1.9.3 Method

Proposed test conditions are:

- Test environment: Test performed in a vacuum chamber
- Pressure:
  - starting pressure $p_{high} = ambient \approx 10^5\ Pa$
  - end pressure $p_{low} = ambient \leq 10^{-2}\ Pa$
- Duration: Pressure variation (sweep) from p_{high} to p_{low} within 10 min to 15 min.
- Margin demonstration:

  Design margin can be demonstrated either by voltage or pressure.

  - Test Voltage: DC, AC, pulse: voltage U_{test}:
    - for Level 2 test: $U_{test} \leq 2\,U_{nom}$ *)
    - for Level 1 test: $U_{test} = U_{nom}$

      where the nominal voltage U_{nom} is maximum voltage of operation

    NOTE *) for qualification the level of voltage should be carefully selected according to the specific application.

— Pressure:

- o for Level 2 test: $p_{test} = 2\ p_{\max - low}$
- o for Level 1 test: $p_{test} = p_{\max - low}$

  where the pressure $p_{\max - low}$ is maximum pressure specified when increasing the pressure from good vacuum.
- o range of corona-free operation is proposed to be defined according to the applications.

Level 2 testing is proposed to demonstrate design margins assuming that a high voltage device is operated with a derating factor of 0,5. Typically Level 2 can only be performed with test samples and not with operational equipments. Therefore it is proposed for qualification test and for special requests at acceptance.

Level 1 testing can be typically performed with operational condition and therefore can be foreseen as a standard test for acceptance.

The voltage waveform should be selected according to the real application, so for DC operation a DC voltage test should be selected. For Level 1 testing, equipment can be used self-powered.

A proposed electrical set-up for testing of not-self-powered devices under test is shown in Figure 6-7. Self-powered equipment is operated in a dedicated suitable electrical test environment, while monitoring the relevant performance parameters.

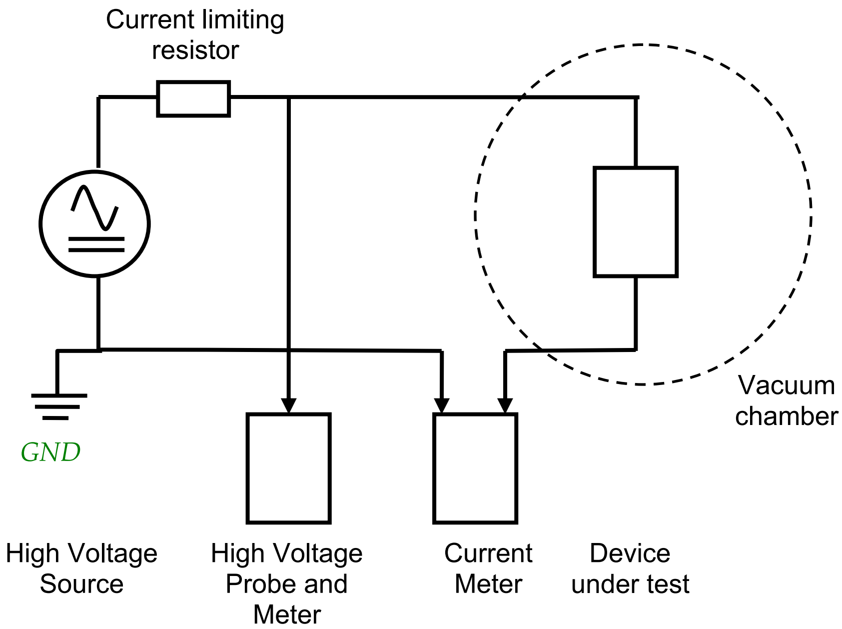


Figure 6-7: Critical Pressure Test Electrical Schematic

6.1.9.4 Acceptance Criteria

A self-powered equipment should be checked against its performance criteria defined in the applicable requirement specification and accuracy level selected suitable to that. For externally powered devices under test the following acceptance criterion levels can be considered.

Leakage current should not increase during pressure sweep.

6.1.9.4.1 Accuracy

A self-powered equipment should be checked against its performance criteria defined in the applicable requirement specification and accuracy level selected suitable to that. For externally powered devices under test the following accuracy levels can be considered.

- Time: 5 %
- Voltage: 2 %
- Current: 3 %

6.1.9.4.2 Nonconformances

A failure of this test can require detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

6.1.10 Life testing (LIT)

6.1.10.1 Objective

Life testing should ensure that a high voltage equipment, module or component is capable to achieve the specified lifetime requirements.

6.1.10.2 Rationale

Life testing is proposed to be performed for all new high voltage equipment, module or component to be qualified. A strategy should be applied according to an evaluation plan to decide, on which level (subsystem, equipment, module, component) needs to be performed, covering the maximum level of stress from nominal operation.

6.1.10.3 Method

Proposed test conditions are:

- Test environment: Selection in accordance with the nominal operational scenario of the device under test. Simplifications – for example replacing thermal-vacuum by thermal test in air – are only proposed if well justified, i.e. if the representative environment is covered by another test or if it can be demonstrated, that the replacement environment does not endanger the objectives of the test.
- Duration: Life time plus margin.
- Remark: Duration can be adjusted to ensure adequate development cost and schedule. In this case the can be only an adequate fraction of the operational mission time.
- An often used duration for long term mission is: 1500 h.
- Operating: Representative sequence of operating modes
- Temperatures:
- Qualification temperatures including temperature cycles and cold start
- Measurement: Performance parameter according to specification. Monitor insulation current, where necessary and/or where no performance parameter available.

6.1.10.4 Acceptance Criteria

No failure and no degradation of performance against specification considering the applicable drifts including end of life.

6.1.10.4.1 Accuracy

Adequate accuracy is proposed to ensure measurement of performance parameters better than their tolerances including drift and ageing.

6.1.10.4.2 Nonconformances

Complete failure like partial and full breakdown lead to fail of test. Untypical performance degradation (out of spec measurements) requires detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

6.1.11 Accelerated life testing (ALT)

6.1.11.1 Objective

Accelerated life testing should ensure that a high voltage equipment, module or component is capable to achieve the specified lifetime requirements.

6.1.11.2 Rationale

Accelerated life testing is proposed to be performed for all new high voltage equipment, module or component to be qualified. A strategy should be applied according to an evaluation plan to decide, on which level (subsystem, equipment, module, component) needs to be performed, covering the maximum level of stress from nominal operation. An acceleration factor is defined in accordance with an applicable stress lifetime law (see section 4.3.5 - Ageing).

As the accelerated life test often requires increase of operating conditions (voltage, temperatures, etc.) beyond the nominal settings of equipment, it is often proposed to perform the accelerated life test on module or component level, if well justified.

6.1.11.3 Method

Proposed test conditions are:

- Test environment: Selection in accordance with the nominal operational scenario of the device under test. Simplifications – for example replacing thermal-vacuum by thermal test in air – are only proposed if well justified, i.e. if the representative environment is covered by another test or if it can be demonstrated, that the replacement environment does not endanger the objectives of the test.
- Duration: Adequate according to applicable stress-lifetime law.

  In the case the stress-lifetime relation is not known or confirmed, an evaluation program for identification of the stress-lifetime curve should be performed in advance.
- Operating: According to stress life time law.
- Temperatures: According to stress life time law.
- Measurement: Performance parameter according to specification. Insulation current, where necessary and/or where no performance parameter available.

6.1.11.4 Acceptance Criteria

No failure and no degradation of performance against specification considering the applicable drifts including end of life.

6.1.11.4.1 Accuracy

Adequate accuracy is proposed to ensure measurement of performance parameters better than their tolerances including drift and ageing.

6.1.11.4.2 Nonconformances

Complete failure like partial and full breakdown lead to fail of test. Untypical performance degradation (out of spec measurements) requires detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

6.1.12 Burn-in testing (BIT)

6.1.12.1 Objective

Burn-in testing should ensure that a high voltage equipment, module or component is not subject of so-called "infant mortality".

6.1.12.2 Rationale

Burn-in testing is proposed to be performed for all high voltage equipment, module or component to be delivered as flight hardware. A strategy should be applied according to an evaluation plan to decide, on which level (subsystem, equipment, module, component) needs to be performed, covering the maximum level of stress from nominal operation without reducing the expected lifetime significantly.

6.1.12.3 Method

Proposed test conditions are:

- Test environment: Selection in accordance with the nominal operational scenario of the device under test. Simplifications – for example replacing thermal-vacuum by thermal test in air – are only proposed if well justified, i.e. if the representative environment is covered by another test or if it can be demonstrated, that the replacement environment does not endanger the objectives of the test.
- Duration: A negligible fraction of life time ensuring to address "infant mortality" sufficiently. An often used duration for long term missions is: 100 h and/or 3 full temperature cycles according to acceptance level.
- Operating: Representative sequence of operating modes
- Temperatures: Acceptance temperatures including temperature cycles and cold start
- Measurement: Performance parameter according to specification. Insulation current, where necessary and/or where no performance parameter available.

6.1.12.4 Acceptance Criteria

No failure and no degradation of performance against specification considering the applicable drifts including end of life.

6.1.12.4.1 Accuracy

Adequate accuracy is proposed to ensure measurement of performance parameters better than their tolerances including drift and ageing.

6.1.12.4.2 Nonconformances

Complete failure like partial or full breakdown lead to fail of test. Untypical performance degradation (out of spec measurements) requires detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

6.2 Destructive Testing

6.2.1 Breakdown Voltage Test (BVT)

6.2.1.1 Objective

The objective of this test is to obtain the margin between the nominal application voltage and the rupture voltage.

6.2.1.2 Rationale

The test is typically performed on component level and is destructive. As far as possible the test should be performed on a number of samples to be statistically relevant, typically 3 to 10 samples. If this cannot be justified due to a trade-off in risk efforts, a lower number of samples might be selected.

6.2.1.3 Method

The test conditions should be:

- Environment: to be selected in accordance with representative stress of the insulation
- Voltage applied: from 0 V or nominal voltage increase to breakdown voltage in steps of 1 kV every 20 s

The voltage waveform should be selected according to the real application, so for DC operation a DC voltage test should be selected.

A possible setup is shown in Figure 6-8.

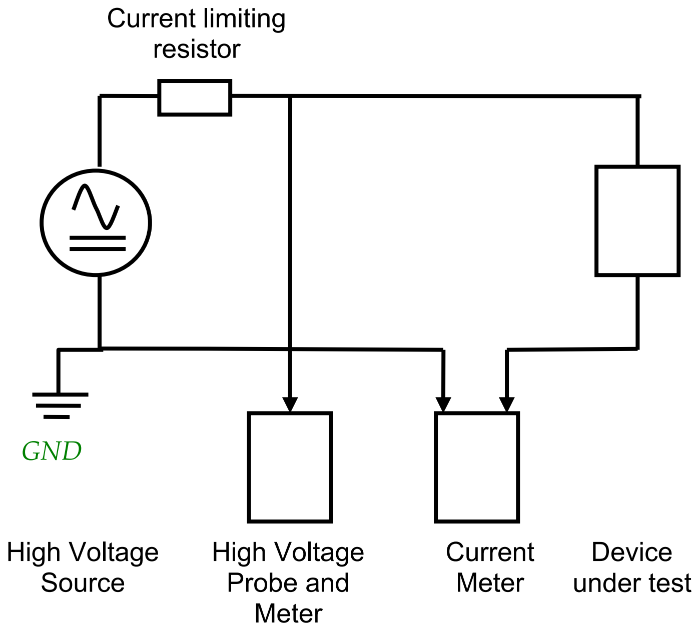


Figure 6-8: Breakdown Voltage Test Electrical Schematic

6.2.1.4 Acceptance Criteria

A design margin should be adequately defined in view of the tested component/material.

6.2.1.4.1 Accuracy

- Voltage: 2 %

6.2.1.4.2 Nonconformances

A failure of this test can require detailed investigations about the reason. The design and processes should be checked as well as the selection of design margins.

6.2.2 Lifetime evaluation testing (LET)

6.2.2.1 Objective

Evaluation of a stress life-lifetime relation in order to predict lifetime of a high voltage device.

6.2.2.2 Rationale

A suitable number of samples need to be tested under different stress conditions to determine a stress-lifetime law. Possible relations are described in section 4.3.5. A strategy should be applied according to an evaluation plan to decide, which stress parameters are evaluated and which type of samples (design) and which number of samples should be tested at various stress level until loss of insulation or relevant function.

6.2.2.3 Method

Proposed test conditions are:

- Test environment: Selection in accordance with the nominal operational scenario of the device under test. Simplifications – for example replacing thermal-vacuum by thermal test in air – are only proposed if well justified, i.e. if the representative environment is covered by another test or if it can be demonstrated that the replacement environments does not endanger the objectives of the test.
- Duration: Adequate according to applicable stress-lifetime law.
- In case the stress-lifetime relation is not known or confirmed, an evaluation program for identification of the stress-lifetime curve should be performed in advance.
- Operating: According to stress life time law.
- Temperatures: According to stress life time law.
- Measurement: Performance parameter according to specification. Insulation current, where necessary and/or where no performance parameter available.

6.2.2.4 Acceptance Criteria

Not applicable.

6.2.2.4.1 Accuracy

Adequate accuracy is proposed to ensure measurement of performance parameters better than their tolerances including drift and ageing.

6.2.2.4.2 Nonconformances

Not applicable.

6.3 Supplementary Methods

There are several methods to support high voltage testing and/or to ensure a proper quality of insulation.

a. Ultrasonic Scanning

Ultrasonic scanning allows detection of voids or cracks inside insulation, especially for small and thin items.

b. X-Ray Scanning

X-Ray scanning allows detection of voids or cracks inside insulation and is useful for bulky items. Evaluation becomes more difficult with multiple layers of components and with complex metal parts like transformer windings.

c. Visual Inspection

Visual inspection is a standard measure before and after test to identify visible defects and contaminations.

d. Audible Detection

Audible detection is useful to identify partial discharges especially on the outside of conductors and HV assemblies, which are not fully encapsulated. It is useful as well to identify unwanted discharges in a test environment/test set-up.

e. Visible Detection

Visible detection is useful to identify partial discharges especially on the outside of conductors and HV assemblies, which are not fully encapsulated. It is useful as well to identify unwanted discharges in test environment/test set-up. Visible detection requires typically a dark room or chamber.

f. Chemical Analysis

Chemical analysis can be useful to ensure the quality of a liquid or gaseous insulation. The initial status before use and changes after testing or operation can be stated and compared to a reference.

6.4 Testing strategy

An adequate testing strategy should be selected depending on the application and on the scope of the test campaign. The following table provides an assessment of the various test methods and a recommendation, where to apply:

Table 6-2: Assessment of test methods w.r.t. its application

Test method	Item under test	Apply for
Insulation Resistance Test (INR)	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Bulk Resistance Measurement (BRM)	Samples	Material Selection Process Evaluation & Validation
Surface Resistance Measurement (SRM)	Samples	Material Selection Process Evaluation & Validation
Dielectric Loss Factor Test (DLF)	Samples Subassemblies	Material Selection Process Evaluation & Validation
Polarisation and Depolarisation Current Measurement (PDC)	Samples Subassemblies	Material Selection Process Evaluation & Validation
Partial Discharge Test (PDT)	Samples Subassemblies Assemblies,	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Dielectric Withstanding Voltage Test (DWV)	Samples Subassemblies Assemblies	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Triple Junction Test (TRJ)	Subassemblies Assemblies, Units	Only for items in vacuum with non-encapsulated high voltages: Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Critical pressure testing/Corona testing (CPT)	Subassemblies Assemblies, Units	Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items

Test method	Item under test	Apply for
Life testing (LIT)	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Accelerated life testing (ALT)	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Burn-in testing (BIT)	Subassemblies, Assemblies, Units	Acceptance of Testing of Items
Breakdown Voltage Test (BVT)	Samples	Material Selection Process Evaluation & Validation Qualification Testing of Items
Lifetime evaluation testing (LET)		Material Selection Process Evaluation & Validation
Supplementary methods:		
Ultrasonic Scanning	Samples Subassemblies	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
X Ray Scanning	Samples Subassemblies	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Visible Inspection	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items
Audible Detection	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation
Visible Detection	Samples Subassemblies Assemblies, Units	Material Selection Process Evaluation & Validation Failure Investigations
Chemical Analysis	Samples	Material Selection Process Evaluation & Validation Qualification Testing of Items Acceptance of Testing of Items

7
High voltage product aspects

7.1.1 Best practice for materials and processes selection

It is proposed that materials selected for high voltage insulations dedicated to qualification and to flight products is performed in accordance with the following criteria:

- High electric strengths
- A good material should allow continuous operation with field strengths higher than 6 kV/mm over lifetime for DC applications and higher than 2 kV/mm for AC applications. Short-term breakdown strengths (typical material data sheet values) should not be lower than 20 kV/mm
- Low dielectric losses (high insulation resistance, low loss factor for AC applications)
- Low degradation over lifetime
- Free of partial discharges and/or resistant against partial discharge (low degradation)
- The material itself or the process of manufacturing / application of the material needs to ensure insulation without cracks, voids, gas bubbles, and delamination
- Radiation resistance
- Compatible with temperature range of use (including qualification)
- Compatible with space environment including radiation

Table 7-1 provides an overview of material properties, standard test methods and typical minimum requirements to be considered for selection of materials.

It is proposed to perform selection under the following aspects:

- Material selection based on ranking of properties
- Process for procurement of the material (requirements, incoming inspections)
- Process to produce the material (for self produced material, for example by potting process)
- Process for use of the materials (treatments, cleanings)

As a guideline the following reference can be used:

- Annex B.1: High Voltage Evaluation Plan
- Annex B.2: Materials Evaluation
- Annex B.3: PID – Process Identification Document

Table 7-1: Typical material properties and reference test methods for high voltage insulation materials

Properties	Applicable for G=Gases L=Liquids S=Solids	Minimum Requirements and Applicability	Method Standard
General	-		-
Heritage	all		-
Appearance	L,S		-
Number of Components	S	For composite materials	-
Kind of Filler	S	For composite materials	-
Physical Data			
Outgassing Data	S	Fulfil	ECSS-Q-70-71A
Density (g/cm³)	all	Low	ASTM-D-2240
Elastic Modulus (MPa) -35 °C - +150 °C	S		ASTM-D-695
Shore Hardness At room temperature	S		ASTM-D-2240
Tensile Strength (MPa) at room temperature	S		ASTM-D-638
Thermal Conductivity (W/m K) At room temperature	all		ASTM-D-2214
Glass Transition Temperature (°C)	S	For potting materials: should be higher than max operation temperature	ASTM E831 - 06
Thermal Expansion (10^{-6}/K)	S		ASTM E831 - 06
Radiation Resistance	all	Depending on mission requirement	
Service Temperature (°C)	all	High	ASTM-D-794
Electrical Data			
Dielectric Constant 50Hz 1kHz 1MHz	all	Low	ASTM-D-150
Dissipation Factor 50Hz 1kHz 1MHz	all	Low	ASTM-D-150

Properties	Applicable for G=Gases L=Liquids S=Solids	Minimum Requirements and Applicability	Method Standard
Specific Volume Resistance (Ohm cm)	all	High	
Surface Resistance(Ohm)	S		
Dielectric Strength (kV/mm)	all	High	
Resistance To Partial Discharge	all	High	
Dew Point	G		
Vapour Pressure	L		
Vapour Temperature	L		
Condensation Temperature	G		
Freezing Temperature	L		
Viscosity	S,L		
Gas Absorption	L		
Water Absorption	L		
Process Data			
Pot Life	S	For potting materials	-
Viscosity (mPa s)	S	For potting materials	-
Curing time	S	For potting materials	-
Storage Life of components	S	For potting materials	-

7.1.2 Best practice for design

Best practice for design can make use of the following recommendations:

a. Electrical field strength of high voltage insulations should be properly controlled by means of

- shaping and geometry
- selection of suitable distances compliant with the breakdown field strength of the material under consideration taking into account the required lifetime and applying justified margins for derating of voltage resp. electrical field

  NOTE Values from general datasheets of materials should not be taken as reference unless it is unambiguously clear, that they are reflecting the intended case of application in terms of stress and lifetime.

- use of methods described in section 5.1 - Basic design principles.

b. Potted modules should be designed with

- Material selection of process controlled and evaluated materials (for material and process selection see section 7.1.1)

— It is preferred to base maximum permitted electrical field strengths and maximum permitted average field strength on detailed life test evaluation. If these are not available the following general rules can be applied:

Maximum permitted electrical field strengths

- o for DC voltages: 6 kV/mm
- o for AC voltages: 2 kV/mm

to be applied for qualified materials like epoxy, polyurethane and silicone.

Exceeding of these design values can be accepted if justified by sufficient evaluation including adequate life testing and/or heritage of the process owner. The process needs to be clearly identified by a PID (see section 7.1.1).

Lower limits can be applicable, if the selected material is obviously not capable to be compliant with such stress under consideration of applicable lifetime requirement and/or the process is not controlled.

If the process control is limited, the following maximum permitted electrical field strengths should be applied

- o for DC voltages: 2 kV/mm
- o for AC voltages: 700 V/mm

c. Electrical field across surfaces in ambient air or high quality vacuum

— a maximum permitted electrical field strengths are

- o for DC voltages: 600 V/mm
- o for AC voltages: 200 V/mm

Exceeding these design values can be accepted if justified by sufficient evaluation including adequate life testing and/or heritage of the process owner. Improvements can be achieved by suitable shaping of the insulator surface (see section 5.1.10). The process of manufacturing needs to be clearly identified by a PID (see section 7.1.1).

Lower limits can be applicable, if the selected material is obviously not capable to be compliant with such stress under consideration of applicable lifetime requirement and/or the process is not controlled.

d. High voltage and low voltage electronic circuits should be separated sufficiently by means of

— galvanic isolation

— spacing

— electrostatic shield

— overvoltage suppression at critical inputs of sensitive low voltage circuits

e. High voltage circuits sensitive to critical pressure conditions (i.e. vented modules with non-encapsulated high voltage lines) should be designed in accordance with the following rules:

— The worst case pressure should be assessed, taking into account the outgassing rates and quantities of the materials used and the flow restriction of the openings of shields and insulators for a molecular stream.

— The electrode distance should be selected in accordance with the Paschen law.

— For all applicable pressure conditions during operation the electrode separation should be selected to ensure a design margin of factor 2, which means the design should withstand two times the nominal maximum operating voltage.

— Venting hole size of enclosing structures should be selected to >2 cm^2 per 1000 cm^3 of enclosed volume, if no detailed venting analysis is performed.

— Where applicable, attention should be paid to the venting hole size as well as the maximum individual hole size, so that radiation does not enter into the equipment and jeopardizes the functionality of the equipment, due to radiated susceptibility (RS) aspects. This is particularly important when EP (electrical propulsion) is used on the spacecraft."

f. High voltage connectors should not be used in harnesses exposed to critical low pressure or vacuum unless they are qualified for this purpose.

g. For high voltage insulation made of potting materials the glass transition point should be outside of the applicable (qualification) temperature range or instead it should be confirmed, that the change of physical properties across this transitions is compatible with the selected design.

h. High voltage wires should be used under the following aspects.

— The maximum voltage applied should be 50 % of the manufacturer's rating. The maximum AC voltage should be 5 % of the DC rating if not otherwise specified by the manufacturer.

— The minimum bend radius should be 5 times the manufacturer's recommendation for PTFE insulated wires and equal to the manufacturer's rating for other types.

— Unshielded high voltage cables should not be routed near any sharp edges to avoid local field concentration.

— Splices should not degrade the voltage withstanding characteristics of the assembly below the rating of the cable.

— High voltage cable bundles which are not field controlled should operate partial discharge free in vacuum, i.e. the sheath should allow adequate venting of the outgassing products.

7.1.3 Best practice for qualification

Note: under cover of this headline "qualification", the specific needs for qualification to high voltage technological items are addressed; general rules for qualification are given in ECSS-E-ST-10-03C.

Best practice for qualification should be distinguished between part/components and module, assemblies, for example.

For parts and components qualification should follow the relevant ECSS, ESCC and MIL Specification for HiRel space parts/components. Where these are not specific to high voltage at test the following elements should be added:

a. Analysis of the electrical field and voltage stress.

— Calculation of maximum electrical stress

— Verification of suitability of design and materials with respect to electrical stress, in specific

o demonstration of design margins (see section 7.1.2)

o assessment of lifetime.

b. Demonstration of margins by test for dielectric withstanding voltage (see section 6.1.7) with a factor of 2 against maximum nominal operating voltage (including ripple and transients).

c. Partial discharge test (see section 6.1.6).

d. Life test (according to section 6.1.10.

For high voltage modules, assemblies and equipments the qualification should include:

e. Presentation of a high voltage evaluation plan according to section 7.1.7.

f. Documentation of all processes relevant for ensuring the quality of the high voltage insulation by individual Process Identification Documents (PID) according to section 7.1.6.

g. Analysis of the electrical field and voltage stress.
   - Calculation of maximum electrical stress
   - Verification of suitability of design and materials with respect to electrical stress, in specific
     - demonstration of design margins (see section 7.1.2)
     - assessment of lifetime.

h. Testing under consideration of the following sequence:
   1. functional test
   2. vibration
   3. functional test
   4. cold storage in air - 24 hours
   5. hot storage in vacuum - 250 hours
   6. functional test
   7. thermal-vacuum test (see section Life testing (LIT) 6.1.10)
   8. functional test.

i. Thermal vacuum test sequence performed under h) with the following elements:
   - The thermal-vacuum test should have a minimum duration of 1500 hours and consist of a minimum of 100 cycles. The cycles should have a full temperature excursion between qualification operating limits with hot operation at the maximum qualification temperature during the remaining time.
   - The cycling should go on continuously with a maximum rate of change of 1 degree/minute and a minimum stabilisation time of 2 hours at temperature extremes. The stabilisation time can be adapted to the real time constants of the item under test, if useful.
   - Ten cold starts at the cold start temperature should be included at regular intervals in the cycling sequence with 2 hours prior stabilisation times in cold storage condition.
   - For the first and the last test cycle the pressure should be deliberately raised to 10^{-3} mbar, in order to verify a margin of one decade, assuming worst case satellite pressure of 10^{-4} mbar.
   - The above mentioned definition of number of cycles assumes that the item under test experiences only a few full temperature cycles in its operational life (reference geostationary telecom satellite with 15 years mission duration). The number of test cycles should be increased if the specified number of operational cycles is higher.
   - The above mentioned definition of number of cycles and total test duration can be reduced, if well justified for missions of very short durations.
   - The thermal –vacuum test can be replaced by a thermal test, if well justified that the vacuum environment is not relevant for this test (for example: if the operating environment is not vacuum).

7.1.4 Best practice for flight acceptance

Best practice for flight acceptance should be distinguished between part/components and module, assemblies etc.

For parts and components acceptance should follow the relevant ECSS, ESCC and MIL Specification for HiRel space parts/components. Where these are not specific to high voltage at test the following elements should be added:

a. Partial discharge test (see section 6.1.6).

b. Burn-in test (according to section 6.1.12).

For high voltage modules, assemblies and equipments the acceptance should include:

c. Traceability that all process relevant for ensuring the quality of the high voltage insulation have been performed in accordance with individual Process Identification Documents (PID) according to section 7.1.3.

d. Testing under consideration of the following sequence:
   1. functional test
   2. vibration
   3. functional test
   4. cold storage in air - 24 hours
   5. hot operation in vacuum - 250 hours
   6. functional test
   7. thermal-vacuum test (see ECSS-E-ST-10-03 or any customer requirement)
   8. functional test.

e. Thermal vacuum test sequence performed under c) with the following elements:
   1. The thermal-vacuum test should have a minimum duration of 250 h and consist of a minimum of 10 cycles. The cycles have a full temperature excursion between acceptance operating limits with hot operation at the maximum acceptance temperature during the remaining time.
   2. The cycling should go on continuously with a maximum rate of change of 1 degree/minute and a minimum stabilisation time of 2 hours at temperature extremes.
   3. One cold starts at the cold start temperature should be included at regular intervals in the cycling sequence with 2 hours prior stabilisation times in cold storage condition.
   4. For the first and the last test cycle the pressure should be deliberately raised to 10^{-3} mbar, in order to verify a margin of one decade, assuming worst case satellite pressure of 10^{-4} mbar.
   5. The above mentioned definition of number cycles assumes that the item under test experiences only a few full temperature cycles in its operational life (reference geostationary telecom satellite with 15 years mission duration). The number of test cycles should all be increased if the specified number of operational cycles is higher.
   6. The above mentioned definition of number of cycles and total test duration can be reduced, if well justified for missions of very short durations.

      NOTE The thermal –vacuum test can be replaced by a thermal test, if well justified that the vacuum environment is not relevant for this test (for example: if the operating environment is not vacuum).

7.1.5 Best practice for verification

A best practice table for verification is given in Table 7-2.

As a guideline the following documentation should be established to define and to document the verification flow:

- 7.1.7 Evaluation Plan
- 7.1.6 PID

Supplemented by:

- Test Plan, Test Procedures and Test Reports
- Analysis Reports
- Inspection Reports

Specific recommendation for qualification and acceptance testing are given in the section 7.1.3 and 7.1.4

Table 7-2: Best practice of verification for high voltage design aspects

Best Practice Item	Proposed Method of Verification	Proposed Verification Point	Comment
7.1.1	RoD, A	PDR, CDR, T *)	*) Evaluation test program proposed for new materials and processes
7.1.2a	A, INS	PDR, CDR	
7.1.2b	RoD, A	PDR, CDR	FEM Analysis for complex geometries proposed
7.1.2c	RoD, A	PDR, CDR	FEM Analysis for complex geometries proposed
7.1.2d	RoD	PDR, CDR	
7.1.2e	RoD, A, T	PDR, TRB, CDR	Venting analysis for complex structures proposed
7.1.2f	RoD	PDR	
7.1.2g	RoD	PDR	
7.1.2h	RoD, INS	PRD, CDR, DRB	
SRR: System requirements review PDR: Preliminary design review CDR: Critical design review TRR: Test readiness review TRB: Test review board DRB: Delivery review board		RoD: Review of design T: Test A: Analysis INS: Inspection	

7.1.6 PID

Processes used to manufacture qualified flight high voltage equipments and modules should be documented and authorized through a dedicated Process Identification Document (PID) Requirements. Each individual process should be covered by an individual PID. An example for the content of a PID is given in Annex B.3. Change of the qualified process w.r.t the PID typically leads to a re-qualification.

7.1.7 Evaluation Plan

An Evaluation Plan should be produced, planning the thorough investigation and characterisation of the technologies and materials proposed for integration into HV equipments. For each technology a categorisation should be used to determine, based on existing heritage if any, the work that should be performed. An example for the content and scope of an Evaluation Plan is given in Annex B.1.

8
Specific problem areas

8.1.1 High voltage converters

The typical problems of high voltage converters are related to

- EMC issues (see section 8.1.5)
- Flashover (in open circuit)
- Effects related to critical pressure (Paschen breakdown)

In general it is proposed to a have a clear galvanic insulation between primary and secondary voltages of a power conditioner which means galvanic insulation though a transformer in the power path. It is furthermore valuable to have an electrostatic shield between primary and secondary windings (with a slit to avoid short-circuit winding). Auxiliary power paths should be separated by the same means.

For signal paths, a galvanic separation via transformer or optocoupler/optical fibre transmission is proposed. In some cases (for telemetry signals) it can be considered to use differential amplifiers with a very high ohmic resistance in the differential path to ensure a galvanic insulation. However, in case of transients (i.e. flashovers) in the high voltage section, common mode transients can overstress this signal path.

Charge and discharge currents in the high voltage circuitry should be limited, in most of the cases serial resistors can be used, taking into account, that the resistors see a high voltage transient in case of a short-circuit (flashover) and they should be able to withstand this stress. Powerful high voltage converters typically need active elements for current limitations.

Under the assumption of galvanic insulation of primary and secondary side of the high voltage converters it is simple to avoid differential mode disturbances caused by high currents over the return paths, as long as a single point grounding concept is followed. A good point for grounding is close to the power source, as shown in Figure 8-1. In some cases this is not possible due to the configuration of the load, when the ground should be connected at the load side. In such a case it is proposed to limit or to harden the high voltage grounding of the power conditioner against differential mode disturbances as shown in Figure 8-2. In some cases (very often for electric propulsion applications) a floating ground used, however, either by clamping device or by other means it should be ensured, that the floating ground potential does not raise to critical levels.

Over long distances between load and power conditioner the connection between should be routed via a shielded cable. If the return path is via the shield an additional electrostatic shield should envelope the cable (i.e. by triax cable or similar), see Figure 8-3.

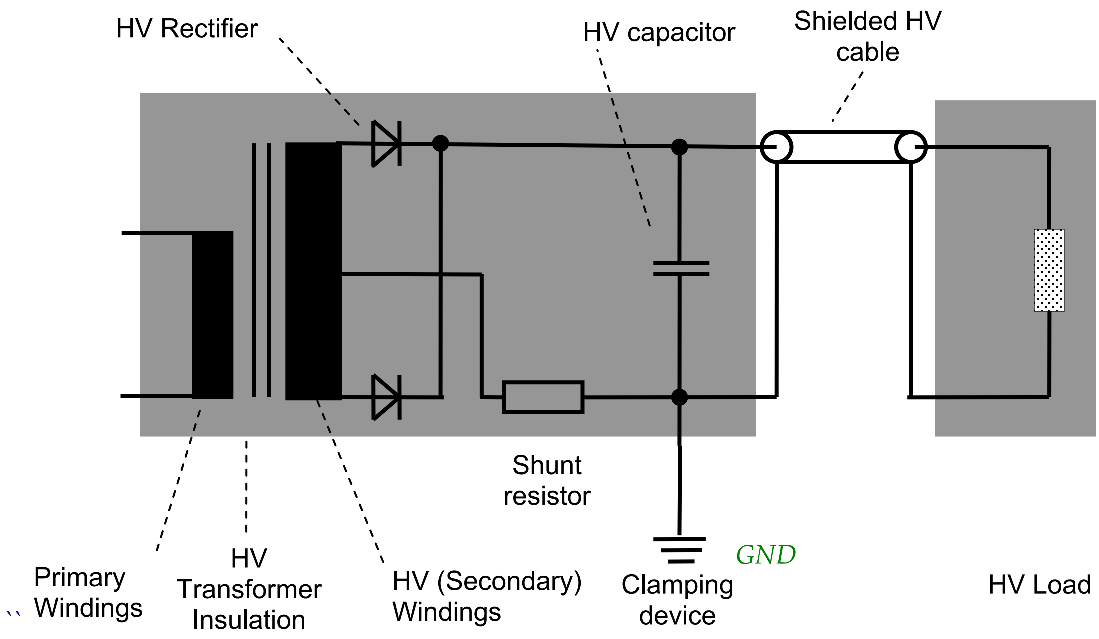


Figure 8-1: High voltage conditioner with grounding at converter – load floating

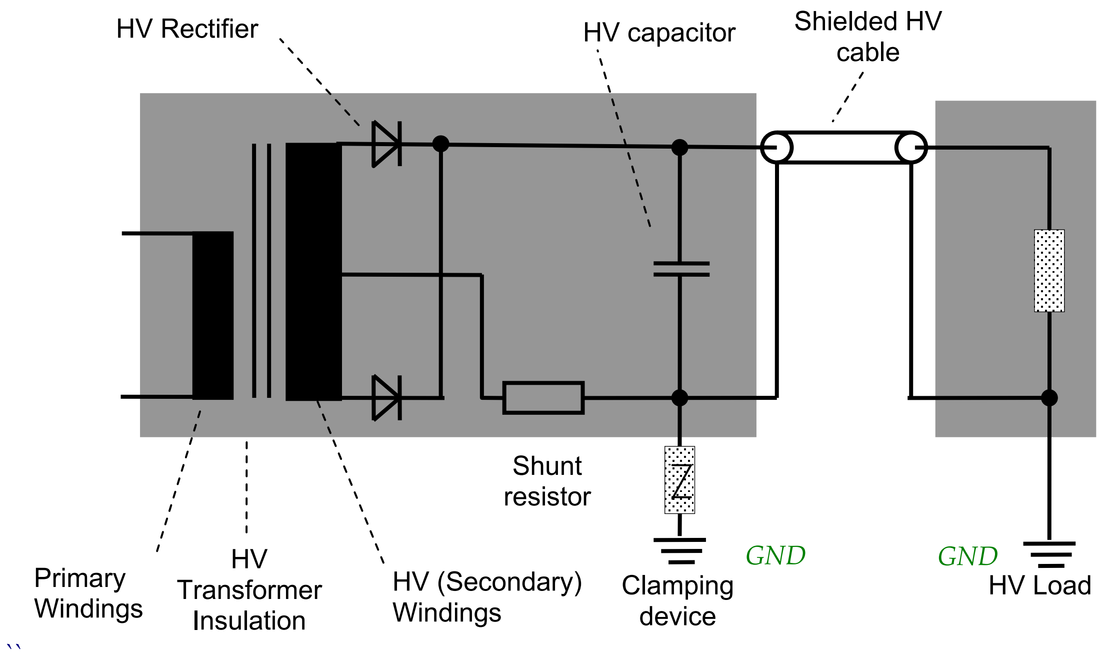


Figure 8-2: High voltage conditioner with grounding at load side – including a clamping device at the conditioner

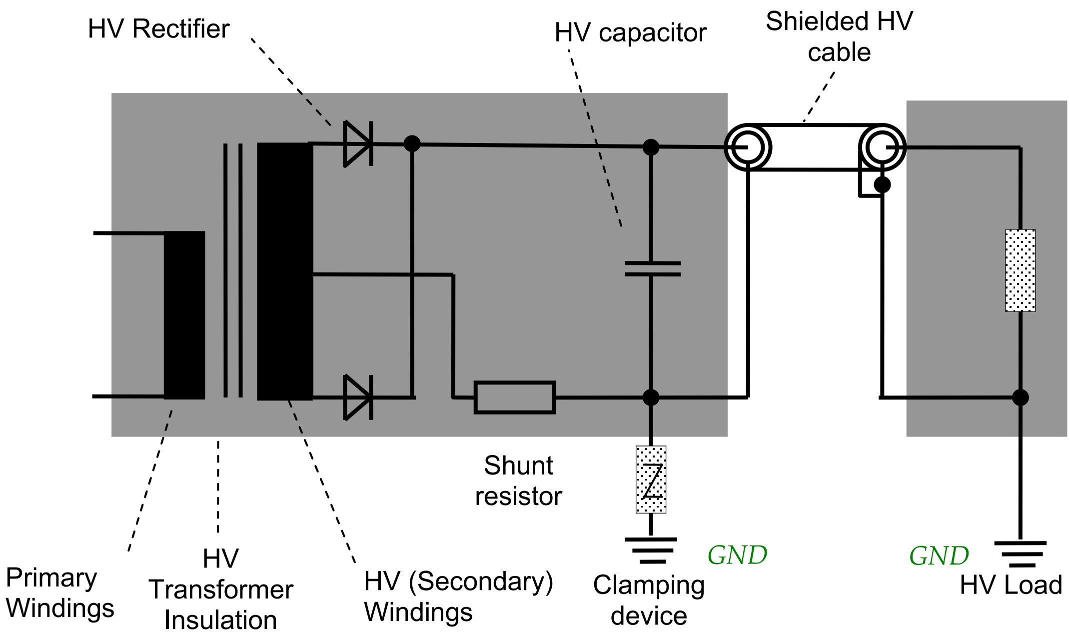


Figure 8-3: High voltage conditioner with grounding at load side – including a clamping device at the conditioner and triax HV cable for load connection

The above described measures allow to limit disturbance caused by normal operation of the high voltage as well as avoidance of and failure propagation in case of abnormal operation, for example with occurrence of flashover.

Intended operation during critical pressure can be typically controlled only by encapsulation, in a few cases by control of distances (limit free gap lengths). Also here the above described measure limit disturbances in case of unintended low pressure operation.

8.1.2 Electric propulsion

8.1.2.1 Criticality of load characterization

The EP thrusters and the power conditioner for thruster operations are typically developed separately. In most cases, the thruster designers use standard laboratory supplies for testing, especially in early development phases. Often, these laboratory power supplies are oversized in terms of power; they use large filters and they are not tailored to the application. In contrary, the power conditioner developer is recommended to follow an efficient approach, optimizing mass and efficiency and considering long-term degradation caused by ageing and radiation. Furthermore, the power supply designers need to demonstrate the margins in terms of thermal and long-term drift, including stability of the control loop. Especially, highly optimized resonant topologies can be sensitive to load variations.

Therefore, there is an essential need for sufficient characterization of the EP load with the following objectives:

- Minimize verification of thruster supplies testing with real thruster due to high costs (test facility)
- Obtain correct load model to perform conclusive stability analysis
- Establishing thruster loads models for integration into the simulation models of the power supply

- Control loops can be optimized during development
- Allow analysis based on electrical terms and methods but not on plasma-physical effects

The wish-list of the power supplier for load parameters to be specified is long; however, in practice it can be difficult to provide everything in advance to a coupling test.

Basic parameters to be specified are of course:

- Max./min. operating voltage
- Overvoltage, undervoltage
- Max. voltage ripple
- Max. output current
- Overload/short/circuit conditions and behaviour
- Voltage accuracy
- Current accuracy (in current control mode)

As the above parameters are easy to be specified by the thruster developer, the next group of load parameters is more difficult to determine:

- Static I/V curve (current vs. voltage)
- Impedance vs. frequency curve

In some cases, it can also be useful to define:

- Load capacitance
- Load inductance

Difficulties to provide these data can be reasoned by

- Limitations to operate the thruster with a large variation of voltages and currents
- Unavailability of access point or lack of test equipment to inject and measure frequency dependent load impedances.

The situation can be even more complex due to the fact, that

- Thruster can be affected by sporadic arcing and discharges
- Multiple power supplies are coupled through the thruster
- Plasma effects inside the thruster can cause oscillations.
- Plasma effects outside of the spacecraft can interfere with the thruster and can cause oscillation type of interference.

Therefore it depends strongly on the thruster type and on the maturity of the thruster design, which thruster interface data can be provided to specify the powers supply correctly.

8.1.2.2 Electromagnetic compatibility of EP

The situation of EMC (Electromagnetic Compatibility) should be illuminated regarding the different "classical" aspects

CS – Conducted susceptibility

RS – Radiated Susceptibility

CE – Conducted Emission

RE – Radiated Emission

RFC – Radiated Autocompatiblity

For CS the nominal spacecraft operating case is uncritical for high power thruster as the PPU usually has a power converter and a filter which can be designed properly to cope with the S/C power bus emissions. However, a special situation should be considered for transients. Those can be caused by different effects: typical are fuse blowing transients (voltage to zero for few ms) or TDMA modes on telecom satellites (3-8 V repetitive transients of few ms duration). These transients can be challenging for the design of high power conditioning in the range of some kW. To accommodate such transients there a different strategies:

- Sizing the PPU filter and regulation appropriately can result in significant mass penalties.
- Switching-off in case of fuse blowing transients can be acceptable, but interrupts thrusting.
- Transferring the transient to the thruster without filtering requires an agreement with the thruster concept, as voltage, current and thrust can run out of nominal range, but can be acceptable if thruster is not damaged and no specific fine thrust regulation is needed.

RS is typically not an issue for EP.

With respect to conducted emissions (CE) the following aspects can be relevant:

- The plasma oscillations of many thrusters are causing high frequency currents at least on the power line between PPU and thruster. As often these power lines are floating, potential impacts are differential mode emissions as well as common mode emissions. The differential mode emissions can be controlled by filtering and the use of twisted shielded pairs for the supply lines. The common mode emissions are more difficult to control as the return path can involve the structure. In some cases this emission can be reduced by placing a proper snubber circuit between floating power return line and structure.
- Transients as a result of thruster switch-off can be caused by contaminations in grid and on insulator surfaces. Often such effects are difficult to predict and for some EP technologies these spurious effects are part of the nominal operation. In most cases the spurious effects are representing a kind of short circuit. So the PPU has to react either with a complete switch-off or with a current limitation mode. For high power thrusters the sudden switch-off can cause a problem when the EP is the main load of the spacecraft power bus. Attention should be paid, that the bus voltage is not stepping up uncontrolled with the EP switch-off. The current limitation mode can result in an extra load step pulling the bus voltage down. Attention should be given that the current rise does not trigger the protections of the spacecraft bus.
- Transients as a result of non-nominal flashovers are a risk to be considered for many thruster principles where a surface flashover across insulators in vacuum environment cannot be avoided by design. Impact on the spacecraft can be reduced, if a robust grounding concept is implemented and the high voltage secondary power is sufficiently isolated from the primary input power of the PPU.

RE can be an artefact of plasma oscillations being present in steady state as well as of transient plasma effects (flashovers, beam-outs), all of these effects depending on the thruster type. As these types of emission appear in conjunction with conducted current, a proper shielding of the harness between thruster and PPU is useful including double shielding (triax cables or equivalents).

Regarding RFC the impact of plasma on RF transmission should be addressed for the satellite architecture).

Another effect to be considered is the magnetic emission, see impact is discussed 8.1.2.3.

8.1.2.3 Satellite Architecture Aspects

Despite the fact that of course EP is different from chemical/cold gas propulsion with impact on the s/c architecture; there are some very specific points to make system architects aware:

- Magnetic fields
- Floating EP Ground
- Contaminations
- RF Shielding
- Command and control
- Flow control and valves
- High Power Concepts
- High Voltage Harness Specification

Some EP thrusters are using magnetic fields for controlling the plasma or to accelerate the ions. These magnetic fields can substantially interfere with the attitude control system of the satellite, especially in the low earth orbit, where interactions with the earth's magnet field are likely. The situation becomes more complex, when the magnet field is not static (i.e. produced by a permanent magnet) but is variable depending on thruster modes. As shielding cannot provide a very efficient solution, compensation can only be achieved by optimizing the orientation of the magnetic fields and by considering this effect in the attitude control budgets.

The floating ground of some electrical thrusters is necessary to achieve positive or negative biasing of the emitted plasma. As the floating voltage can reach some hundred volts, sufficient isolation should be ensured for all floating parts including harnesses as well as proximity to MLI thermal shields.

Further, is should be highlighted, that the emitted plasma (ion beam) represents high energy (accelerated) particles. The impinchment of the beam on satellite surfaces can cause significant erosion on a long-term scale. Critical is the erosion on solar arrays. For these not only the cover glasses are very sensitive, but the inter-cell connections as well as optical surfaces (mirrors, lenses). The emission direction is often not limited to a narrow field of view as the plasma plume often has a wide angel.

Another effect to consider is the shielding effect of the plasma beam, which can be less transparent for radio frequencies and therefore can impact the performance of RF transmissions.

In view of both phenomena, the plasma erosion as well as the RF shielding, a good characterization of the plasma beam is necessary to be aware of the plume angel, energy distribution and shielding characteristics. Based on this information, the location of thrusters on the satellite can be better defined, avoiding critical configurations.

Regarding the command and control architecture a lot of additional functions are required to operate the thruster, including power supplies for neutralizer, heaters and valves. This subsystem needs an internal control to manage all the functions and to allow control by the spacecraft. Depending on the complexity of the control tasks, the electric propulsion subsystem requires either hardwired control logic or a powerful microcontroller. The more autonomy is given to the subsystem, the higher the effort to spend – in terms of complexity and cost. In case that control algorithms are transferred into the responsibility of the satellites onboard computer (rather than in the PPU) it is necessary to foresee an adequate AIT strategy as a closed loop test of EP and satellite, is difficult to arrange (see section 8.1.2.4).

In view of control it is worth to mention, that the EP concepts based on ionized gases require regulation valves to control the gas flow at very low rates. Their characteristic is very non-linear and imposes some complexities in the regulation algorithms.

In case, those high power thrusters of several kW are embarked on satellites, the satellites power system architecture could be revised in specific cases. For example: it may not be useful to combine a regulated spacecraft bus with a power conditioner using an individual wide range regulator as well. For some electrical thrusters the question should be asked, to which extend a regulation is necessary, or if for certain spacecraft modes a wider drift of voltage and currents is acceptable for the EP system. Also the fusing concept can be adapted, especially if electronic fuses, LCL's (latching current limiters) are used. For high power thrusters it can be difficult to tailor the protecting latching current limiters of the satellites power system. Instead, the protection function can be transferred to the power conditioner, which is dedicated to control higher power and current.

The high voltage harness typically connects the PPU, which is located inside the spacecraft, to the thruster(s) which is/are located outside of the spacecraft. A proper specification is needed to cover the specific aspects of high voltage (levels, ratings), possible high temperatures in vicinity of the thruster (everything above 120 °C can be critical), need of insulated connection terminals (as suitable high voltage connectors typically are not available), high radiation environment outside of the spacecraft, bending flexibility (if thruster pointing mechanisms are used), need of shielding and floating ground operation (can need triax shielding), and safety aspects.

8.1.2.4 Assembly, Integration and Test Issues of EP

The AIT (Assembly, Integration and Test) of EP systems on satellites is affected by the fact, that end-to-end testing of the propulsion subsystem is limited and by the specifics of high voltage and high power use.

As it is not possible to run the thruster together with the spacecraft in a vacuum facility, testing of the subsystem should be "sliced". On subsystem level, the thruster is typically first characterized with the aid of lab power supplies and later tested coupled with the PPU. On satellite level the thruster cannot be operated, thus the PPU should be integrated onto the satellite using a thruster simulator respectively a load simulator. The thruster simulation should be done with a representative load simulator. It should be highlighted, that the load simulator can be a challenging development as it has to handle high voltage and high power (for some EP systems several kW). To be representative regarding EMC aspects the load simulation should be highly dynamic and possibly include transient and high frequency ripple simulation (plasma oscillation).

In view of EMC testing on subsystem and on unit level it should be highlighted, that the Line Impedance Simulation Network (LISN) is typically not suitably defined for high power loads as like large EP systems. The definition of this item should be tailored in a suitable way.

As a last point it should be pointed out, that the high voltage harness used for most of the EP systems introduces some complexity for satellite AIT, as suitable high voltage connectors are not available for space application (only for some ground testing). A typical workaround is the use of splice blocks and terminals to perform cable interconnections. Consequently, such solutions are not "plug-and-play", because they require specific procedures and checks, and not to forget: some safety hazards due to accessible open high voltage.

Last but not least and worth to mention: the high power thrusters for EP suffer from high temperatures at the thruster interfaces. Often for the selection of a suitable high voltage cable, the difficulty occurs that qualified HV cables for operation beyond 180 °C are often not available.

8.1.3 Electron devices (tubes)

Electron devices like travelling wave tubes or klystron are equipment with highly optimised high voltage insulations. As in space projects they are typically used as qualified equipment according to their dedicated design rules here only the effects affecting the interface to the high voltage power conditioners are highlighted.

Most relevant for the interface is the effect of “spurious”, which means that it cannot be excluded, that breakdowns or pre-breakdowns occur in the high voltage vacuum insulation of the tube. Although the events are typically rare, the power conditioner should be hardened against this by:

- Implementation of current limiting element (for example: resistors)
- Consideration of changed voltage and field distribution in the insulation as a consequence the “spurious”
- Measures to maintain EMC

Furthermore, electron devices are typically manufactured with flying leads for the high voltage interface. As high voltage connectors are not available and are avoided, the flying leads are connected to the power conditioner either via “open” terminal blocks (in the minority of applications) or are “potted” with the HV insulation of the electronic power conditioner (the typical case). Potting on both ends gives some limitation on reparability, integration and testability (after potting).

8.1.4 Scientific instruments and experiments

In the frame of scientific instruments and experiments the following case of high voltage application can require special attention:

- AC high voltage sources

AC high voltage sources are sometimes requested with modulated frequency and amplitude. The main problem is that the high AC voltage can cause significant degradation of the high voltage insulation by partial discharges. The insulations should be specially designed for this kind of stress. High voltage cables (and HV insulation in general) typically requires a gap free interface between conductor and insulation. High voltage transformers are single staged and need careful control of the electrical fields by proper shaping and shielding.

8.1.5 EMC aspects

Related to high voltage the following EMC effects need to be taken into consideration and to be assessed:

- High electrical field strengths in the environment of the high voltage circuit
- High magnetic field strengths in presence of high currents (transients, breakdown)
- High electromagnetic field strengths in presence of high currents (transients, breakdown)
- High currents on return lines (structure)
- High ripple on high voltage lines
- Propagation of high voltage into low voltage circuitry in case of failure

As a consequence the following general recommendations are given:

a. High voltage and low voltage electronic circuits should be separated sufficiently by means of

— galvanic isolation

— spacing

— electrostatic shield

— overvoltage suppression at critical inputs of sensitive low voltage circuits

— for more details see section 8.1.1.

b. Discharge currents and energies should be limited (resistors or actively).

c. High voltage supply lines and their return lines should be routed close together in case of risk of high currents

d. Shielded high voltage lines should be used (as far as possible) when power harness is routed outside of the high voltage equipments.

e. High voltage units should be shielded in general (as far as possible) by metallic or metallized structures with proper grounding.

f. Floating high voltage grounds should be avoided – and if floating, limit the floating range by clamping devices.

9
Hazards and safety

9.1 Hazards

The typical hazards related to high voltage and its applications are:

- Electrical Shock

In some cases:

- Acoustic noise
- X-Ray Radiation
- Explosions

The electrical shock is applicable if certain levels of voltage or current or energy are exceeded (see section 9.2).

Acoustic noise or explosion are possible typically in case of high voltage breakdown, sparks and arcing, either due to destruction of high voltage insulations or by ignition of explosive substances (if present).

X-Ray radiation can be generated if high voltage is applied in a high vacuum and a sufficiently high current is flowing through the vacuum insulation caused by arcing, plasma or surface discharge. The effect depends on the voltage, on the current and the interacting surface material.

9.2 Safety

Safety can be ensured by respecting the applicable safety standards and performance of adequate risk assessments with implementation of measures for risk reduction.

- It is proposed to address all high voltage related risks in a risk management plan and in critical items list.

As a specific standard for testing with high voltage it is proposed to respect

- European Standard: “Erection and Operation of Electrical Test Equipment” (EN 50191:2000)

With respect to the standard it is worth to mention, that the standard is applicable to the erection and operation of fixed and temporary electrical test installations under the following conditions:

- Voltages at frequencies below 500 Hz are higher than 25 V AC or 60 V DC.
- The resulting current through a 2 kΩ resistor exceeds 3 mA(r.m.s.) AC or 12 mA DC.
- The resulting current for voltages at frequencies above 500 Hz exceeds the values defined in the EN.

Or

- The discharge energy exceeds 350 mJ.

In case of ambiguities between the EN standard and this text, the standard is always applicable.

Annex A High Voltage Field Calculation Tables

A.1 Principles of field efficiency factors for spheres and cylindrical geometries

Often geometries with spheres and cylinders can be easily assessed by using the field efficiency factor (Schwaiger factor) η according to Schwaiger, which is defined as the ratio between mean electrical field strength E_{mean} in relation to the maximum electrical field strength $E_{\max}$.

$$\eta = E_{mean} / E_{\max}$$

The factor is expressed as a function of one or two geometrical parameters

$$p = \frac{d + r}{r} \text{ and } q = \frac{R}{r}$$

where:

- d shortest distance between electrodes
- r radius of the smaller electrode
- R radius of the larger electrode

For a given geometry the maximum electrical field strength $E_{\max}$ can be calculated for a given voltage U according to the following equation:

$$E_{\max} = \frac{U}{\eta \, d}$$

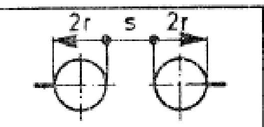
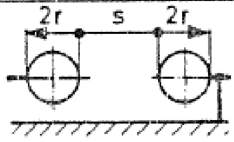
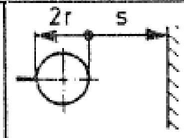
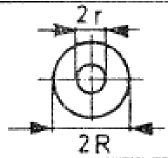
Tables and graphs for determination of the field efficiency factors (Schwaiger factors) are given in the following sections.

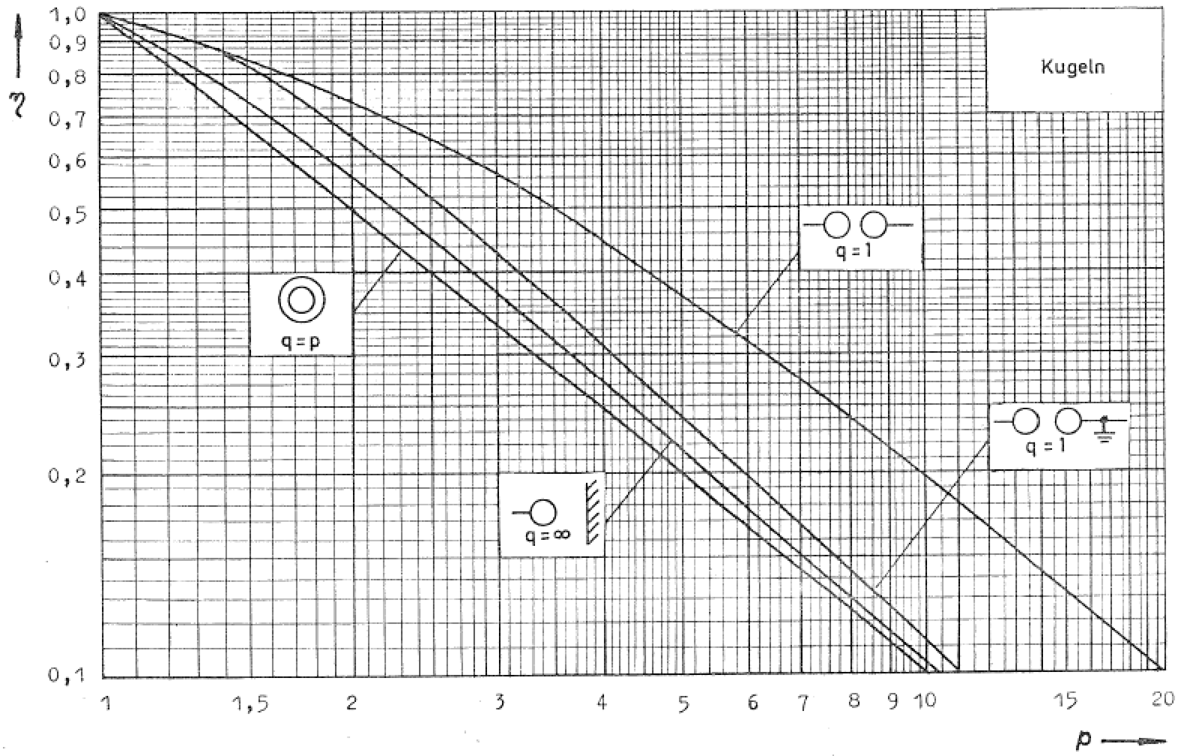
Reference is made to:

A. Schwaiger: Elektrische Festigkeitslehre, Springer Verlag Berlin 1925

A.2 Spherical geometries

Table A-1: Sphere geometries

				
p	q = 1	q = 1	q = ∞	q = p
1,0	1	1	1	1
1,5	0,850	0,834	0,732	0,667
2	0,732	0,660	0,563	0,500
3	0,563	0,428	0,372	0,333
4	0,449	0,308	0,276	0,250
5	0,372	0,238	0,218	0,200
6	0,318	0,193	0,178	0,167
7	0,276	0,163	0,152	0,143
8	0,244	0,140	0,133	0,125
9	0,218	0,123	0,117	0,111
10	0,197	–	0,105	0,100
15	0,133		–	–



Parameter p can be determined from Table A-1

Figure A-1: Field efficiency factors (Schwaiger factors) η as a function of geometry parameter p for spheres

A.3 Cylindrical geometries

Table A-2: Cylinder-parallel-to-a-cylinder geometries

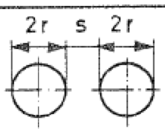
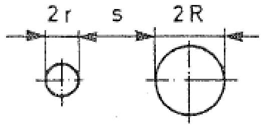
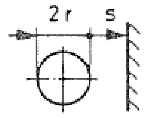
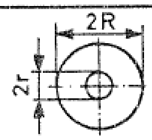
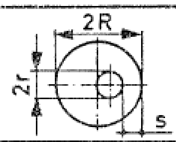
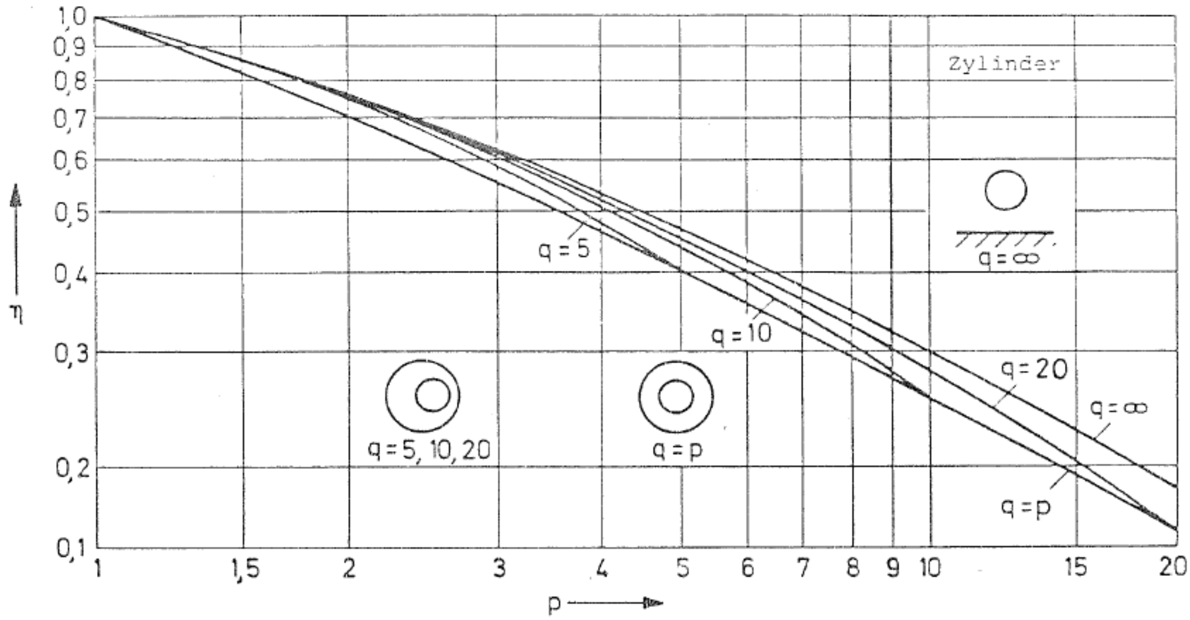
							
p	q = 1	q = 2	q = 3	q = 5	q = 10	q = 20	q = ∞
1	1	1	1	1	1	1	1
1,5	0,924	0,894	0,884	0,878	0,871	0,864	0,861
2	0,861	0,815	0,798	0,783	0,772	0,766	0,760
3	0,760	0,702	0,679	0,658	0,641	0,632	0,623
4	0,684	0,623	0,595	0,574	0,555	0,548	0,533
5	0,623	0,564	0,538	0,513	0,492	0,486	0,468
6	0,574	0,517	0,488	0,469	0,450	0,435	0,419
8	0,497	0,447	0,420	0,401	0,377	0,368	0,349
10	0,442	0,397	0,375	0,352	0,330	0,324	0,301
15	0,349	0,314	0,296	0,277	0,257	0,249	0,228
20	0,291	0,263	0,248	0,232	0,214	0,202	0,186
50	0,1574	–	–	–	–	–	0,0932
100	0,094						0,0537
300	0,038						0,0214
500	0,025						0,0138
800	0,0168						0,00922
1000	0,0138						0,0076

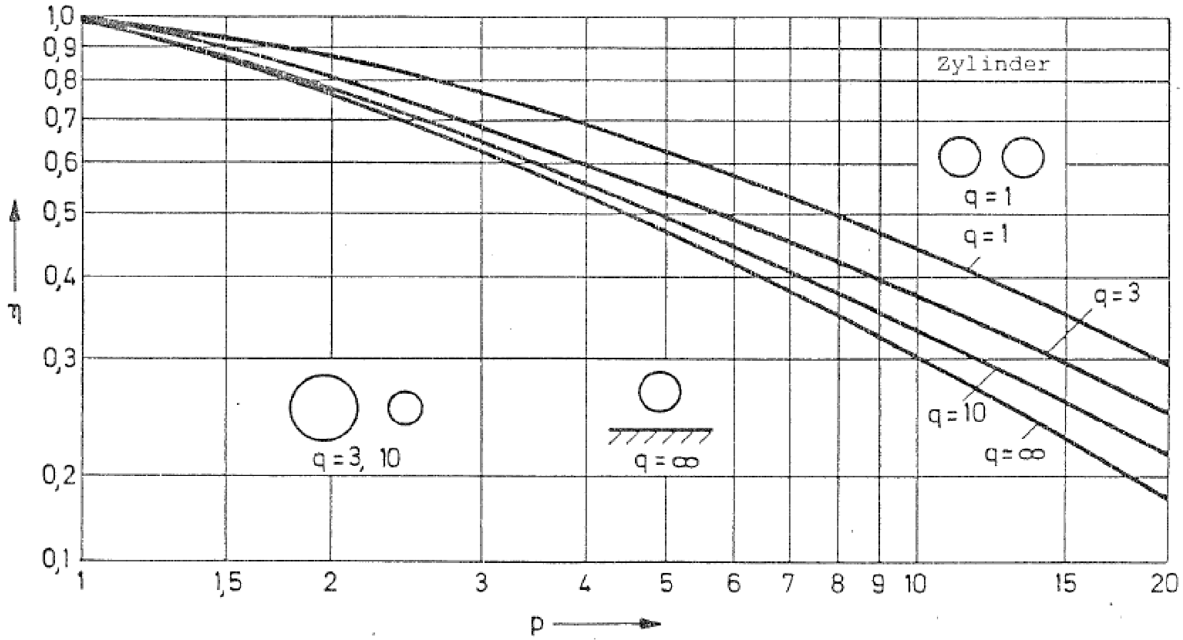
Table A-3: Cylinder-inside-a-cylinder geometries

					
p	q = p	q = 3	q = 5	q = 10	q = 20
1	1	1	1	1	1
1,5	0,811	0,831	0,847	0,855	0,857
2	0,693	0,717	0,735	0,748	0,754
3	0,549	0,549	0,582	0,604	0,614
4	0,462	–	0,478	0,507	0,521
5	0,402		0,402	0,439	0,454
6	0,358		–	0,386	0,404
8	0,297			0,310	0,331
10	0,256			0,256	0,281
15	0,193			–	0,204
20	0,158				0,158
50	0,0798				–
100	0,047				
300	0,019				
500	0,0125				
800	0,0084				
1000	0,0069				



Parameter p can be determined from Table A-2

Figure A-2: Field efficiency factors (Schwaiger factors) η as a function of geometry parameter p for cylinders



Parameter p can be determined from Table A-3.

Figure A-3: Field efficiency factors (Schwaiger factors) η as a function of geometry parameter p for cylinders

Annex B
Best Practice References

B.1 High Voltage Evaluation Plan

B.1.1 Evaluation Activities

For new equipments, modules and components/parts used in flight hardware, an evaluation should be established and the agreed/proposed tasks should be performed to ensure and safeguard a proper qualification of the subjected item.

B.1.2 Evaluation Plan

An Evaluation Plan should be produced planning the thorough investigation and characterisation of the technologies and materials proposed for integration in HV equipment. For each technology a categorisation should be used to determine, based on existing heritage if any, the work that should be performed. This categorisation should follow the guidelines of Table B-1. A short Requirement Specification should also be established as a guide for the Evaluation objectives.

Evaluation should be performed on individual parts, materials and processes including subassemblies and modules.

The Evaluation Plan should include where appropriate:

- The characterisation of ageing behaviour,
- The temperature behaviour in conjunction with neighbouring technologies and materials,
- The performance in partial pressure,
- The influence of electrical parameters such as voltage, field, power, AC and DC.

Every effort should be made to ensure that the technologies and materials are flight compatible and relevant in terms of, for example, outgassing and properties over flight temperature range, radiation environment, availability, practical implementation, quality control of process and supplier, prior to beginning the evaluation.

The Evaluation plan should be agreed with the procuring entity.

A Test plan should be produced for each evaluation planned. The number of samples evaluated should be sufficient to allow parallel tests, including where appropriate “control” samples, with a view to reducing the cost and time associated with the test facilities; and to ensure that the results are reliable. A minimum of 3 samples, and preferably 5, should be used to “majority vote” important results.

The output of this segment should be:

- An agreed Evaluation plan.
- An agreed Requirement Specification for each Technology
- An agreed Test Plan for each Technology

B.1.3 Manufacturing of Evaluation Samples

The required relevant number of samples of the various technologies and materials that should be tested should be manufactured. At the end of manufacturing, an Evaluation TRR should be held on the basis of Test Procedures generated from the Test Plans.

The output of this segment should be:

- An agreed Test Procedure for each Technology
- Manufactured Evaluation Samples
- Successful Evaluation TRR.

B.1.4 Test and Characterisation

Following the manufacturing of Evaluation samples these samples should be tested according to Test Procedures agreed in the Evaluation TRR.

The output of this segment should be

- Raw Test Results

B.1.5 Evaluation Review

The work performed in this Task should be submitted to the Agency for approval in a dedicated Evaluation Review.

The Review data package should include an Evaluation Report, in which the test results are summarised. They should be reviewed for their compliance to the requirement specifications. Results should be discussed with respect to the agreed objectives of the Evaluation Plan, and analysed with respect to available 'state of the art' scientific knowledge.

Wherever possible, all statements made in the report, including predicted trends and assumptions, should be justified with detailed discussions at a technical level.

The output of this segment should be:

- The Evaluation Review data pack
- A successful Evaluation Review
- Agreed technologies and materials to be qualified.

Table B-1: Product categories according to heritage (Ref.: ECSS-E-ST-10-02C)

Category	Description	Qualification programme
A	Off-the-shelf product without modifications and • subjected to a qualification test programme at least as severe as that imposed by the actual project specifications including environment • produced by the same manufacturer or supplier and using the same tools and manufacturing processes and procedures	None
B	Off-the-shelf product without modifications. However: It has been subjected to a qualification test programme less severe or different to that imposed by the actual project specifications (including environment).	Delta qualification programme, decided on a case by case basis.
C	Off-the-shelf product with modifications. Modification includes changes to design, parts, materials, tools, processes, procedures, supplier, or manufacturer.	Delta or full qualification programme (including testing), decided on a case by case basis depending on the impact of the modification.
D	Newly designed and developed product.	Full qualification programme.

B.2 Materials Evaluation

A typical material evaluation should consider

- Physical property tests
- Electrical property tests
- Technology sample tests

A typical flow is shown in Figure B-1.

Physical and electrical properties should be determined to standard methods applicable for the type of material. For determination of electrical parameters like electrical breakdown strengths a suitable sample design needs to be selected. Some options are:

- Rogowky profile electrodes (to be embedded in potting materials) – see Figure B-2
- Close-to-application electrodes, for example crossed wire electrodes - see Figure B-3
- Material disk between shaped electrodes - see Figure B-4

The electrode separation is 1 mm.

A statistical relevant number of samples should be selected. For breakdown tests 10 samples per test parameter should be used as a minimum.

After determination of physical and electrical properties the material selection should be confirmed and further evaluated by “technology samples”.

These samples should be designed close to the application, for example:

- Representative part of a transformer coil including insulation
- Printed circuit board equipped with parts.
- Representative insulator

The number of test samples should be selected to be statistically relevant.

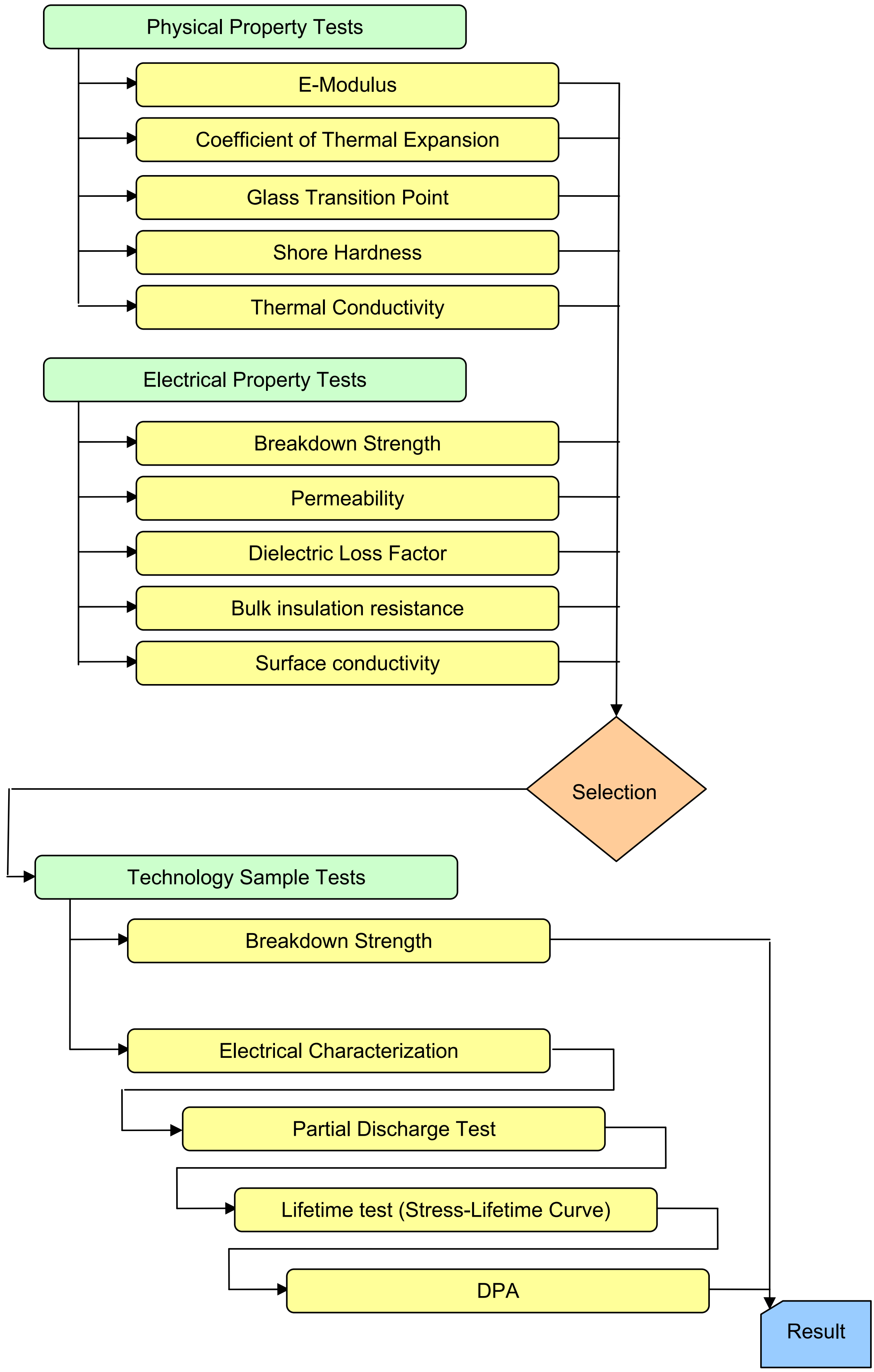


Figure B-1: Typical material evaluation flow

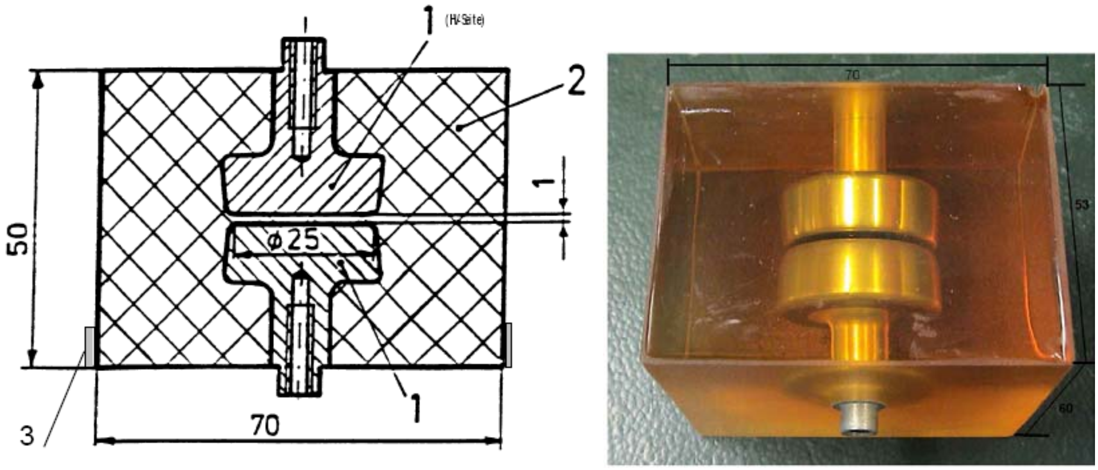


Figure B-2: Potted Rogowsky-profile electrodes

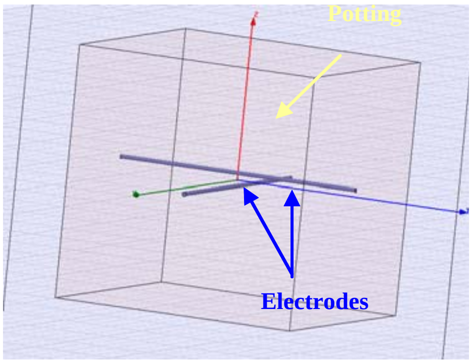


Figure B-3: Crossed wire electrode

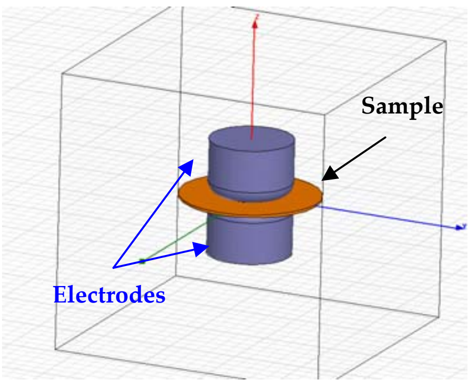


Figure B-4: Material disk between electrodes

B.3 PID – Process Identification Document

In order to avoid redundancy with other internal company documents, a PID could consist of a list of configured documents (manufacturing+tests, control, other if any). The PID then only points to the relevant documents (and chapter), where the required information can be found.

The PID should consist of the following documentation:

Section 1:

- Reference documents
- Short description of the concerned technologies
- Application area of the technologies.

Section 2:

- Manufacturing flow chart taking into account all the different steps as well as all intermediate quality control steps. All processes should be properly configured

Section 3:

- Configured Items Data List including document reference number, version and issue:
- Listing of the quality system,
- Listing of the procurement specifications
- Listing of all the manufacturing processes
- Listing of the quality control processes

Section 4:

- Organigram of the company
- Description of the different key personnel (optional)

Section 5:

- Description of the different steps used to manufacture the product. An example of the log sheet and or travel sheet is preferred.

Section 6:

- List of all materials used to manufacture the final product

Section 7:

- Working area description (a map is sufficient)

Section 8:

- Listing of all equipment used to manufacture the final product:
  - Manufacturing equipment
  - Control equipment.

Section 9:

- Listing of all the test facilities

All deviations from the PID should be considered as being outside qualification.