estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

Passive Component Dossier
ESCC Component Technical Board

Table of contents:

1 INTRODUCTION

This is the first edition of the Passive Components Strategic Dossier. The overall purpose of this document is to determine the European R&D strategy for the development activities and qualification programs associated with passive components for space applications. As such, the dossier aims at identifying the main activities to be launched in the short to medium term (5-year time horizon) to ensure that strategic passive components and products are available for future European space applications. This document has been compiled by the Passive Component Technology Board Working Group (PCTBWG) with additional inputs taken as a result of discussions and meetings with space industry representatives (users, component manufacturers, agencies).

Part 2 of this document describes the background and the scope and give a brief introduction to the role of the PCTBWG.

In part 3 and 4, the general trends and main space constraints are briefly presented.

The part 5 provides the status of the each major family of passive components. Each family is divided into the different technologies available.

Based on user needs, on manufacturer capabilities or innovative solution and on future applications, the development, the evaluation and the qualification activities have been listed and prioritised according to user and agencies inputs and classified according the main advantages brought by each development. Annual Qualification Plan will be derived by the progress of each activity. This is presented in part 6.

2 SCOPE

The definition of passive component may vary depending on manufacturer, users or applications. As a typical definition, Electronic, Electrical and Electromechanical (EEE) components who do not require electrical power to operate are called passive components. Passive component are not capable of power gain or not capable of energy production. In this document, the passive components covered are: capacitor, resistor, thermal sensor, heater, inductor, transformer, cable, connector, relays and quartz.

The Passive Components Strategic Dossier has been written on behalf of the CTB, and covers all families and products of passive component with the following additions and exceptions:

- RF passives are not included in this dossier and will be considered in a dedicated dossier
- Optical Fibers and Optical Connectors are not included in this dossier and will be considered in a dedicated dossier
- Crystal oscillators are included
- Piezzo ceramic components are included

Inductor and transformer technologies and needs will be described in the next revision of the dossier.

2.1 The Passive CTB Working Group

The CTB is a subordinate body to the SCSB (Space Components Steering Board) and is responsible for the formulation of strategic programmes and work plans for technology research and development in the area of European EEE space components.

The Passive Working Group is one of seven sub-groups established by the CTB. The other working groups cover the following domain: Silicon, Hybrids, Microwave, MNT, Photonics and Radiation Effects.

The Passive Working Group members are representatives from space industry system and equipment manufacturers, components manufacturers and Space Agencies.

Passive Component Dossier	ASTRIUM, Toulouse
ESCC Component Technical Board	
Frédéric MONCASSIN	TAS, Toulouse
Marc BARDONNAUX	TAS Charleroi,
Thomas GAUL	TESAT, Backnang
Manuel MORALESs	ALTER
Denis LACOMBE	ESA
Olivier PERAT	ESA
Jean-Paul BUSSENOT	CNES
Bertrand Marty	CNES
Jean-Baptiste SAUVEPLANE	CNES

2.2 Reference documents

RD 1	EQPL ((https://escies.org/webdocument/showArticle?id=166&groupid=6)
RD 2	EPPL (https://escies.org/webdocument/showArticle?id=166&groupid=6)
RD 3	"POWER MANAGEMENT AND DISTRIBUTION" Harmonisation Technical Dossier
RD 4	Electrochemical Energy Storage" Harmonisation Technical Dossier

2.3 Acronym

AIT	Assembly, Integration and Testing
AQP	Annual Qualification Plan
CDR	Critical Design Review
CTB	Component Technology Board
DCL	Declared Component List
DML	Declared Material List
DPL	Declared Process List
ECSS	European cooperation for space standardization

EEE parts	Electronic, Electrical and Electromechanical parts
EM	Engineering Model
EPPL	European Preferred Parts List
EQPL	ESCC Qualified Parts List
ESCC	European Space Components Coordination
ESR	Equivalent Serie Resistance
FM	Flight Model
PCTBWG	Passive Component Technology Board Working Group
PDR	Preliminary Design Review
SCSB	Space Components Steering Board
SMD	Surface Mount Devices
TRL	Technology Readiness Level
WG	Working Group

3 GENERAL TREND FOR PASSIVE EEE

The next section provide accurate information about the current offer and limitations about EEE passive Components for space applications.

In chapter 7, a list of activities is proposed to bridge the gap between current and future needs and the available range of components.

This list has been consolidated by the PCTBWG to address all technologies and types of Passive EEE components and to identify key requirements and developments of the European space industry.

These activities have been defined to respond to an identified need or drive :

1. *To ease procurement by reducing procurement cost and delivery time while guaranteeing quality and reliability of products, thanks to EPPL/EQPL introduction :*

   Although all EEE parts might be considered under concern, this is particularly applicable to oscillators or cable assembly that were considered in the past more as equipment with all associated heavy acceptance process and reviews (PDR, CDR, EM, FM, DML, DCL, DPL, etc.) than EEE parts. Parts listed in EPPL or QPL can be procured with a reduced (EPPL) or no (QPL) additional testing (LAT) to validate their use in space project (see ECSS standard).

2. *To increase industry competiveness through European non-dependence*

   Several parts are only available outside Europe with the required quality level or qualification status. This lead to difficulties in procurement (exportation licence such ITAR) and support when problem or failure occurred (NDA, …). It is the case for fuse, oscillators, platinum sensors, etc.

3. *To achieve miniaturisation*

   Mass and size saving is always an objective during development of equipment. Passive components represent more than 70% of EEE parts used in space project. As for other non space application, new technologies are used to reduce the space dedicated to passive components. General reduction in size is a trend share with every electronic devices. Passive parts follow this trend with the reduction of size of connector, chip capacitor and resistor, used of SMD design and improvement of key parameters like ESR for tantalum capacitor (reduction of number of capacitor used).

4. *To anticipate long term needs by disruptive technology evaluation*

   Disruptive technology are driven by different factors then difficult to classify. We would like to highlight what we consider the most interesting one:

   - New materials:
     - Base Metal Electrode for ceramic capacitor allow a potential extension of the capacitance value by a factor 5 to 10
     - Silicon capacitor with a drastic reduction of size for the same capacitance value and potential use at high temperature
     - High temperature cable for specific mission or power application
     - Nano materials for wire (in insulation material for ESD improvement or as conductor for weigh improvement), for supercapacitors, etc.

- New components driven by new needs like high data rate or backplane connectors with the revision of SpaceWire standards and implantation of SpaceFiber standards.
- New design or concept like embedded component (size reduction) and modular connector (ease AIT operations)

5. *To increase performances of Space EEE parts ranges :*

Evolution of constraints lead to the necessity of increasing the performances of EEE parts.

Since Ariane V, the level of shock and vibration have increased. Passive parts are not usually sensible to this type of constraint with the exception of the electromechanical relays. Failure due to excessive vibration or mechanical shock are the main cause of failure for relays and the current range is not always adapted to the new requirement which lead to adaptation of the equipment to damp the mechanical constraint “see” by these parts.

In the future, GaN based application may become a standard. The high power capability of GaN lead to thermal dissipation issue. One solution envisaged is to increase the temperature base plate of some board or equipment. Operating temperature of capacitor, resistor and potentially connector may increase by 30 to 50C with a drastic reduction of reliability. Specific passive parts are already used in automotive and drilling applications where high temperature is one of the main constraint. These parts should be evaluated to assess their capability to answer to our need with the required reliability.

6. *To define accurately recommendation of uses*

When technology boundaries are nearly reaches a way of improvement is the accurate definition of use of the components such as derating rules or mounting recommendation. Experience shows that derating rules for cables and connectors or relays might be defined more accurately and that could lead to consequent mass saving in a spacecraft. Mounting validation is also a critical points that shall be addressed during EEE parts evaluation.

The activities, presented in chapter 6, are defined in order to get sufficient confidence in the products to introduce it in EPPL II after a successful ESCC evaluation (TRL 3) or in EQPL after a successful ESCC qualification (TRL 6). The introduction of a product in EPPL or EQPL will ease the procurement of parts by decreasing the cost and delivery time while providing to the users all guarantees of ESCC qualification system (traceability, audit, non-conformance, periodic testing).

4 SPACE CONSTRAINTS AND REQUIREMENTS

As any other component, passive parts shall meet space requirements. :

Space Constraints	Characteristics and requirements
Vaccum	ECSS Q-70-71 TML< 1.0% CVCM< 0.1%. Low pressure
Forbidden Material	Cd, Zn , Sn (pure), etc.
Thermomechanical	Vibrations, shocks, thermal cycling
Radiation	Effect on some polymers (wires, cable assemblies) Thin film materials Oscillator add-on active parts

Table 1 : Main space constraints and requirements

Specific requirements for each passive component type are provided in the dedicated section.

5 PASSIVE COMPONENT FAMILY AND TECHNOLOGIES

5.1 Resistors

5.1.1 Overview

A linear resistor is a two-terminal, linear, passive electronic component that implements electrical resistance as a circuit element. The current through a resistor is in direct proportion to the voltage across the resistor's terminals. Thus, the ratio of the voltage applied across a resistor's terminals to the intensity of current through the resistor is called resistance. This relation is represented by Ohm's law:

$$I = \frac{V}{R}$$

Resistors are common elements of electrical networks and electronic circuits and are ubiquitous in most electronic equipment. Practical resistors can be made of various compounds and films, as well as resistance wire (wire made of a high-resistivity alloy, such as nickel-chrome). Resistors are also implemented within integrated circuits, particularly analogue devices, and can also be integrated into hybrid and printed circuits.

The electrical functionality of a resistor is specified by its resistance: common commercial resistors are manufactured over a range of more than nine orders of magnitude. When specifying that resistance in an electronic design, the required precision of the resistance may require attention to the manufacturing tolerance of the chosen resistor, according to its specific application. The temperature coefficient of the resistance may also be of concern in some precision applications. Practical resistors are also specified as having a maximum power rating which must exceed the anticipated power dissipation of that resistor in a particular circuit: this is mainly of concern in power electronics applications. Resistors with higher power ratings are physically larger and may require heat sinks. In a high-voltage circuit, attention must sometimes be paid to the rated maximum working voltage of the resistor.

Variable resistors are not taken into account in this chapter as not used in space applications. The technology presentation is based on the application note “Basics of Linear Resistors” from Vishay.

<u>Film resistor</u>

Film resistors in general are characterized by a resistive layer on a ceramic base.

The resistive element of thick films is 1000 times thicker than thin films, but the principal difference is how the film is applied to the cylinder (axial resistors) or the surface (SMD resistors).

Thin film resistors are made by sputtering (a method of vacuum deposition) the resistive material onto an insulating substrate. The film is then etched in a similar manner to the old (subtractive) process for making printed circuit boards; that is, the surface is coated with a photo-sensitive material, then covered by a pattern film, irradiated with ultraviolet light, and then the exposed photo-sensitive coating is developed, and underlying thin film is etched away.

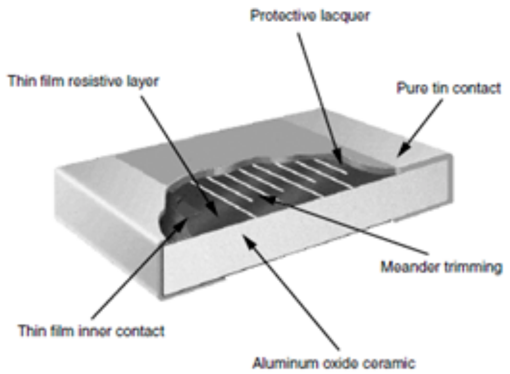
Because the time during which the sputtering is performed can be controlled, the thickness of the thin film can be accurately controlled. The type of material is also usually different consisting of one or more ceramic (cermet) conductors such as tantalum nitride (TaN), ruthenium oxide (RuO_2), lead oxide (PbO), bismuth ruthenate ($Bi_2Ru_2O_7$), nickel chromium (NiCr), and/or bismuth iridate ($Bi_2Ir_2O_7$).

Thick film resistors are manufactured using screen and stencil printing processes. Thick film resistors may use the same conductive ceramics, but they are mixed with sintered (powdered) glass and some kind of liquid so that the composite can be screen-printed. This composite of glass and conductive ceramic (cermet) material is then fused (baked) in an oven at about 850 °C.

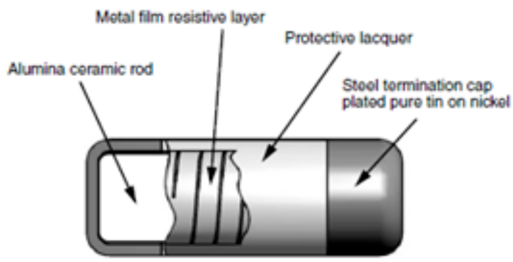
The resistance of both thin and thick film resistors after manufacture is not highly accurate; they are usually trimmed to an accurate value by abrasive or laser trimming. Thin film resistors are usually specified with tolerances of 0.1, 0.2, 0.5, or 1%, and with temperature coefficients of 5 to 25 ppm/K. Additional important difference, thick film resistors have a noise level 10-100 times greater than thin film resistors.

Thick film resistors, when first manufactured, had tolerances of 5%, but standard tolerances have improved to 2% or 1% in the last few decades. Temperature coefficients of thick film resistors are high, typically ±200 or ±250 ppm/K; a 40 kelvin (70 °F) temperature change can change the resistance by 1%.

Thin film resistors are usually far more expensive than thick film resistors. For example, SMD thin film resistors, with 0.5% tolerances, and with 25 ppm/K temperature coefficients, when bought in full size reel quantities, are about twice the cost of 1%, 250 ppm/K thick film resistors.



Metal film chip resistor



MELF resistor

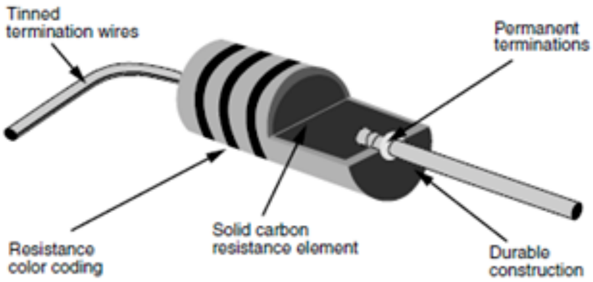
The last film technology used a carbon film which is deposited on an insulating substrate, and a helix cut in it to create a long, narrow resistive path. Varying shapes, coupled with the resistivity of amorphous carbon (ranging from 500 to 800 μΩ m), can provide a variety of resistances. Carbon film resistors feature a power rating range of 0.125 W to 5 W at 70 °C. Resistances are available in range from 1 ohm to 10 Mohm. The carbon film resistor has an operating temperature range of -55 °C to 155 °C. It has 200 to 600 volts maximum working voltage range. Special carbon film resistors are used in applications requiring high pulse stability. This technology is not really use in space applications.

Carbon composition

Carbon composition resistors consist of a solid cylindrical resistive element with embedded wire leads or metal end caps to which the lead wires are attached. The body of the resistor is protected with paint or plastic. The resistive element is made from a mixture of finely ground (powdered) carbon and an insulating material (usually ceramic). A resin holds the mixture together. The resistance is determined by the ratio of the fill material (the powdered ceramic) to the carbon. Higher concentrations of carbon, a weak conductor, result in lower resistance. Moreover, if internal moisture content (from exposure for some length of time to a humid environment) is significant, soldering heat will create a nonreversible change in resistance value. Carbon composition resistors have poor stability with time and were consequently factory sorted to, at best, only 5% tolerance.

The advantages of the composition resistor are its very good high-frequency characteristics and the high capability to overload relative to the component size.Values ranged from fractions of an ohm to 22 Mohms. Because of the high price, these resistors are no longer used in most applications. However, carbon resistors are used in power supplies and welding controls.

This technology is still available at a few manufacturers but is almost obsolete.



Wirewound resistor

Wirewound resistors are commonly made by winding a metal wire, usually nichrome, around a ceramic, plastic, or fiberglass core. The ends of the wire are soldered or welded to two caps or rings, attached to the ends of the core. The assembly is protected with a layer of paint, moulded plastic, or an enamel coating baked at high temperature. Because of the very high surface temperature these resistors can withstand temperatures of up to +450 °C. Wire leads in low power wirewound resistors are usually between 0.6 and 0.8 mm in diameter and tinned for ease of soldering. For higher power wirewound resistors, either a ceramic outer case or an aluminium outer case on top of an insulating layer is used. The aluminium-cased types are designed to be attached to a heat sink to dissipate the heat; the rated power is dependent on being used with a suitable heat sink, e.g., a 50 W power rated resistor will overheat at a fraction of the power dissipation if not used with a heat sink. Large wirewound resistors may be rated for 1,000 watts or more.

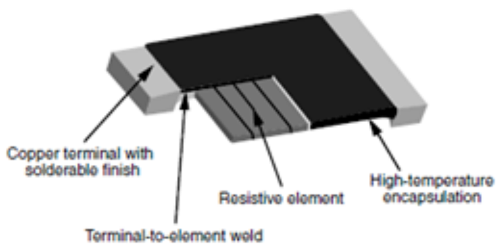
Because wirewound resistors are coils they have more undesirable inductance than other types of resistor, although winding the wire in sections with alternately reversed direction can minimize inductance. Other techniques employ bifilar winding, or a flat thin former (to reduce cross-section area of the coil).

Applications of wirewound resistors are similar to those of composition resistors with the exception of the high frequency. The high frequency of wirewound resistors is substantially worse than that of a composition resistor.

Precision wirewound resistors are no longer used in space application.

Power Metal Strip resistor

Power Metal Strip resistor construction consists of solid, self-supporting, resistance element which is welded to copper terminals. The resistive element is trimmed to a desired resistance value by increasing the current path. Finally the resistor body is encapsulated and the terminals plated for solderable connection. Power Metal Strip resistors are characterized by very low resistance values (1 Ω to 100 μΩ), tight resistance tolerance (± 1 % standard, ± 0.5 % available), low temperature coefficient (TCR) (below 75 ppm/K) and low thermal EMF (below μV/K).



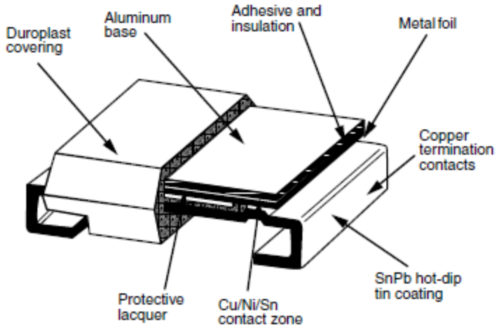
Power Metal Strip resistors are commonly used as shunt resistors.

Foil resistor

The metal foil resistor consists of an electrically insulated etched metallic foil mounted on a material of high heat conductivity. Metal foil resistors are used today in large quantities as low-ohm current sensing resistors, as well as precision resistors for measurement applications.

The most important requirements for these applications are high precision, low temperature coefficient, low thermo-electrical potential difference with reference to copper, and high long-term stability.

These requirements are met extremely well by foil resistors manufactured by etching technology and using manganese-ceranin alloys. Among their other technical advantages are extremely low inductivity and good pulse loading capability. Foil technology is particularly suitable for resistors in the 2 mΩ to 150 kΩ range.

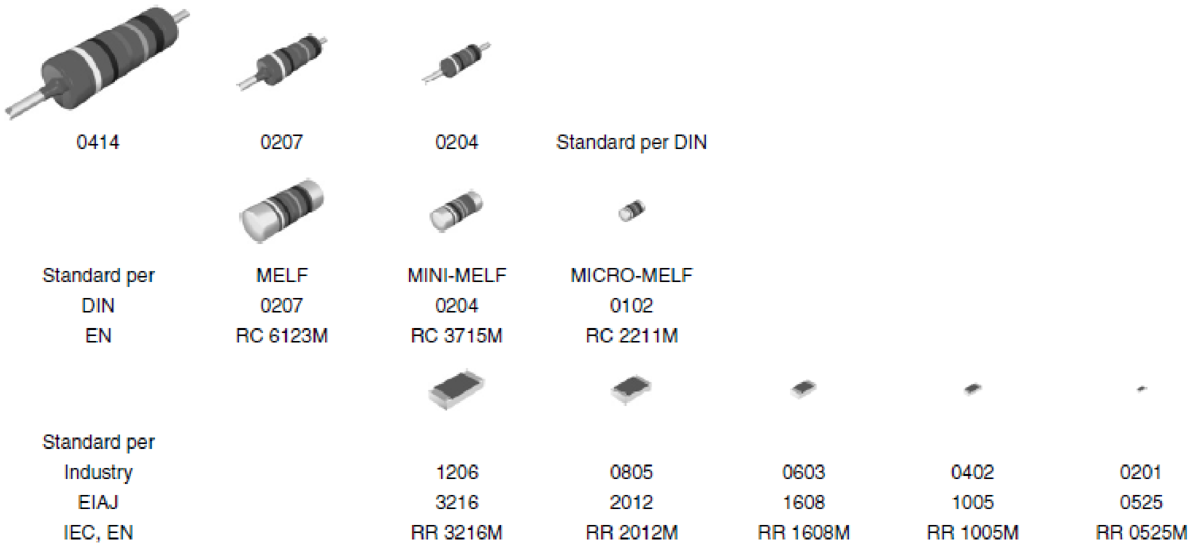


5.1.2 Classification

Linear fixed resistors are classified as film, foil, composition, Power Metal Strip®, and wirewound resistors, depending on the material used. Film resistors can be further subdivided into carbon, metal and thick film resistors.

COMPONENT	TECHNOLOGY	RESISTIVE MATERIAL
Resistors	Film	Carbon
		Metal
		Paste
	Power Metal Strip®	Metal
	Foil	Metal
	Wirewound	Metal
	Composition	Carbon

The most elementary distinction is between leaded and SMD. High-power resistors are also available with termination clamps. Surface-mounted resistors are further subdivided into cylindrical MELF and rectangular chip devices.



Common size and shape

DIN - German Standards Institute (Deutsches Institut für Normung)

EN - European Norm

EIAJ - Electronic Industries Association of Japan

5.1.3 Specific space constraint and requirements

Since resistors are dissipating components thermal management shall take into account space vacuum condition.

5.1.4 Main characteristics

Each technology has its strengths and weaknesses which are identified by defined electrical characteristics :

- Nominal Resistance Value
- Resistance Tolerance
- Temperature Coefficient of Resistance (TCR)
- Stability
- Rated dissipation (power)
- Limiting element voltage
- Non linearity
- Noise
- Temperature range
- Case size

The following table brings together some typical figures. It ignores specialities, such as ultra-precision metal film resistors (± 0.01 % tolerance, TCR = ± 2 ppm/K) or metal film resistors for temperature above 155 °C.

Resistor	Thin film	Metal film	Thick film	Metal foil	Carbon composition	Wire-wound	Power metal strip
Resistance value	Up to 76MΩ	0.22Ω to 22MΩ	1Ω to 100MΩ	2mΩ to 1MΩ	1Ω to 20MΩ	0.01Ω to 300kΩ	200μΩ to 1Ω
Tolerance (%)	As low as ±0.01%	+/- 0.1 to +/-2	+/- 1 to +/-5	+/- 0.005 to +/-5	+/- 5 to +/-20	+/- 0.1 to +/- 10	+/- 0.5 to +/-1
Temperature coefficient (ppm/K)	As low as ±5	+/- 5 to +/-50	+/- 50 to +/-200	+/- 0.6 to +/- 50	-200 to -1500	+/- 1 to +/-200	+/- 30 to +/-250
Maximum operating temperature (°C)	+155	+155	+155	+150	+150	+400	+275
Rated power dissipation P70 (W)	Up to 0.5	0.063 to 1	0.063 to 0.25	0.25 to 10	0.25 to 1	0.25 to 100	0.1 to 5
Stability at P70 (1000h) ΔR/R (%)	As low as ±0.1%	+/- 0.15 to +/-0.5	+/- 1 to +/-3	+/- 0.05	+4/-6 (typical -3)	+/- 1 to +/-10	+/- 1 to +/-2
Maximum operating voltage (V)	35 to 150	50 to 500	50 to 200	200 to 500	150 to 350	25 to 1000	(P70xR)-1/2
Current noise (μV/V)	<0.01	<0.1	<10	<0.025	2 to 6	negligible	negligible
Non linearity a3 (dB)	N.A.	>110	>50	negligible	~60	negligible	negligible
Strength/ application	Precision voltage dividers	General purpose	General purpose	Precision current sensing Precision voltage dividers		High power handling Pulse overload performance Performance in harsh environments	Current sensing Ultra low values Pulse overload performance

5.1.5 *Suppliers and available products*

Today in ESCC System there are 8 different QPL or QML qualified resistors components.

Sub-Section	Page No.	Cert.	Type Designation	Manufacturer
10-02			Fixed, Film, High Precision	
	10-02-001	116 L	Type RNC 90	Vishay S.A. Sfernice
10-07			Shunts	
	10-07-001	285 A	Types SM*-PW and SM*-PT	Isabellenhütte
10-08			Fixed, Film	
	10-08-006	256 F	Surface Mount, Type MS1	Vishay Electronic (Selb)
	10-08-007	289 A	Surface Mount, Type TNPS	Vishay Electronic (Selb)
10-09			Chip	
	10-09-002 A to D	287 B	Type PHR; PFRR; PRAHR/CNWHR	Vishay S.A. Sfernice
	10-09-003	314	Type CHP	Vishay S.A. Sfernice

Note: Chips Types PHR; PFRR; PRAHR/CNWHR are ESCCQML Qualified.

In addition to the QPL listed components, the EPPL include the high voltage resistor from Caddock Electronics (axial resistor), the RM2010 series from State of the Art (chip film resistor) and the VCS1625 series from VPG (chip foil resistor).

From the NASA Parts selection List, the following resistors are available.

Film MIL-PRF-39017 RLR MIL-PRF-55182 RNC/RNR MIL-PRF-55342 RM GSFC S-311-P-742 G311P742 GSFC S-311-P-813 G311P813	Network MIL-PRF-83401 RZ
Wirewound MIL-PRF-39005 RBR MIL-PRF-39007 RWR MIL-PRF-39009 RER MIL-PRF-39015 RTR	High Voltage GSFC S-311-P-672 G311P672 GSFC S-311-P-683 G311P683

Film resistors are available in chip form, or MELF form. Products used in space applications include :

- Chip, thin film, high precision, from size 0402 to 2010 (ESCC) or size 0505 to 2512 (MIL), with ESCC qualified parts from Vishay SA France, PHR 0603 to PHR 2010, PFRR 0402 to PFRR 2010, or Vishay Electronic Germany, TNPS 0603 to TNPS 1206, and MIL qualified parts from State of the Art, IRC or Mini-Systems,
- Chip, thin film, high precision networks with ESCC qualified parts from Vishay SA France, PRA HR or CNW HR,
- Chip, thick film, general purpose, from size 0603 to 2512 (ESCC) or size 0505 to 2512 (MIL), with ESCC qualified parts from Vishay SA France, CHP HR, and MIL qualified parts from Vishay US, Mini-Systems or State of the Art.
- Chip, thick film, high frequency variants, non qualified, are also used in space applications, often HCHP type from Vishay SA France,
- Chip, thick film, current sensing, MIL qualified RCZ types, sizes 0505, 0705 or 1206 are generally procured from State of the Art,
- Chip, thick film, high voltage, non-MIL qualified CRHV types, sizes 1206 to 2512, 1 500V to 3 000V,
- Chip, thick film, general purpose networks, rarely used in space applications, with some non qualified CRA types from Vishay US or BCN types from BI Technology.

Film resistors are also available in leaded versions, with some general purpose MIL RLR or precision MIL RNC types generally procured from Vishay US, a few Single in Line thick film networks from Vishay SA (no longer ESCC qualified), and mostly high voltage resistors such as :

- Caddock (US) MG types present in EPPL and procured with a GSFC specification,
- Ohmite – Victoreen (US) MOX types also procured with GSFC specification,
- IRC CMH types, Vishay Electronic VR types or Vishay SA HTS types based on commercial data sheet.

Metal foil resistors are available in chip or leaded form and are used for Low TCR and Very Low TCR resistors. These products are available from a single source, Vishay Precision Group and include :

- VSMP very low TCR chip, ±2 ppm/°C, procured with a manufacturer specification compliant with NASA EE-INST-002 requirements,
- VCS1625 current sensing SMD, available from EPPL,
- RNC90 style radial leaded types, Low, ± 5 ppm/°C, to Very Low, ± 0,2 ppm/°C, TCR available as MIL qualified and also ESCC qualified (RCK02HR, 5 ppm/°C) through an agreement between Vishay PG and Vishay SA in France. TCR and also packaging variants, such as the hermetic version VHZ555 may also be procured from Vishay PG.

Power metal strip resistors are mostly dedicated to current sensing, such as ESCC qualified parts from Isabellenhütte in Germany (types SMP, SMR, SMT, SMV), or non-qualified WSL Metal Strip® from Vishay US.

Wirewound leaded resistors types RWR (precision, inductive or non-inductive) or RER (power) are procured for space applications and as MIL qualified from Vishay (US),

Carbon composition resistors can still be found at a few US manufacturers, in particular RCD Components, and are procured according to obsolete MIL-R-39008 specification.

5.1.6 Activities

Miniaturization

Miniaturization will continue in the years to come. Size 0402 and even 0201 will increasingly be used for applications where space constraints are a prime requisite.

Another way for miniaturization already used in some industries are to embedded resistor in the substrate. It was already used in space for some project but there is a lack of reliability data. It implies a complete change of processes affecting: the board design, the procurement, potentially the resistor manufacturing, and all the assembly or rework processes used today in space.

High temperature

An increase of temperature based plate is envisaged for several equipment linked to GaN technology or to a simplification of thermal design. This increase of temperature base plate may impact the used of resistor usually rated up to 125C. The derating rules applies today implies the use of component with a max rating as high as 150C. High temperature resistors already exist and are used for automotive or drilling application but none are qualified for space application.

Other needs

Wirewound/carbon composition resistors are still used in space in a limited number of applications. There is no ESCC product in QPL and no European manufacturer are delivering this type of product at the requested quality level. It may be interesting to identify an European manufacturer able to support our project but for a very small market.

Few high power resistors are used today. This is usually leaded resistors from US manufacturer (mainly Caddock). An SMD version may be interesting as it will facilitate the assembly. However, no European manufacturer has been identified and the need stays relatively low but present for almost all space project.

5.2 Fuses

5.2.1 Overview

Fuses are used primarily to safely interrupt a circuit in the case of a short circuit or overload.

A fuse consists of a metal strip or wire fuse element, of small cross-section compared to the circuit conductors, mounted between a pair of electrical terminals, and (usually) enclosed by a non-conducting and non-combustible housing. The fuse is arranged in series to carry all the current passing through the protected circuit. The resistance of the element generates heat due to the current flow. The size and construction of the element is (empirically) determined so that the heat produced for a normal current does not cause the element to attain a high temperature. If too high a current flows, the element rises to a higher temperature and either directly melts, or else melts a soldered joint within the fuse, opening the circuit.

When the metal conductor parts melt, an electric arc is formed between the un-melted ends of the element. The arc grows in length until the voltage required to sustain the arc is higher than the available voltage in the circuit, terminating current flow. In alternating current circuits the current naturally reverses direction on each cycle, greatly enhancing the speed of fuse interruption. In the case of a current-limiting fuse, the voltage required to sustain the arc builds up quickly enough to essentially stop the fault current before the first peak of the AC waveform. This effect significantly limits damage to downstream protected devices.

The fuse element is made of zinc, copper, silver, aluminium, or alloys to provide stable and predictable characteristics. The fuse ideally would carry its rated current indefinitely, and melt quickly on a small excess. The element must not be damaged by minor harmless surges of current, and must not oxidize or change its behaviour after possibly years of service.

5.2.2 Classification

There are two basic types of over current protection, single use and resettable.

Single-use protection takes the form of fuses. Fuses are selected according to the operating current level, the operating voltage, and the ambient temperature of the application. The most common form factors include:

- Wire link: Cartridge fuses are the standard cylindrical body (glass or ceramic) with which most people are familiar. These fuses will not be discussed here as they are not widely used in space project. Wire link fuses are stiff used when the film fuses performances do not met the requirements.
- Film type fuse: chips fuses in which the fuse element is built onto a base substrate (organic or ceramic). Using fabrication techniques similar to chip resistors, capacitors, and inductors, these fuses allow for very space efficient devices. These types of fuses typically use thin or thick film metal elements.

Resettable devices provide another type of over current protection. The key benefit is that these devices are able to reset themselves after the over current condition is cleared. However, the key disadvantages are that they are limited as to the amount of current they can handle, as well as the voltage level that they can standoff after opening the circuit. These devices function by an increase in their resistance according to the amperage level that is applied to them. In other words, during normal circuit operation they are low resistance, and during an over current event, they transition to high resistance. The most common form factors include:

- Radial leaded fuse: Provide two leads for through-hole insertion processes
- Battery strap fuse: Provide thin straps that allow for welding to a battery pack
- Surface mount fuse: Provide terminations that allow for the use of surface mount processes

Single use fuses are the preferred choice for applications where personal safety and absolute electrical isolation is desired post an over current event. Resettable over current devices such as polymer PTCs aren't used today in space project due to lack of reliability data and understanding of the failure modes.

5.2.3 Specific space constraint and requirements

Vacuum condition will change the power dissipation inside the fuse then may change is characteristics like rated current or speed. Test shall be performed under vacuum to assess this potential variation.

5.2.4 Main characteristics

Mains characteristics of fuses consist of the following:

- Rated current

  There are generally 2 accepted methods of defining fuse current rating:

  - IEC specifications (IEC 60127 Part2) typically define fuse current rating as the current which can be carried indefinitely without causing fuse actuation. ESCC and MIL specification use this definition.
  - Underwriter Laboratory specifications (UL/CSA/ANCE 248-14 Standard) define the rated current as the minimum current at which operation may occur after several hours.

- I2t value

  A measure of energy required to blow the fuse element and so a measure of the damaging effect of overcurrent on protected devices; sometimes known as the let-through energy. Unique I2t parameters are provided by charts in manufacturer data sheets for each fuse family. The energy is mainly dependent on current and time for fuses.

- Breaking capacity

  The breaking capacity is the maximum current that can safely be interrupted by the fuse. Generally, this should be higher than the prospective short circuit current.

- Rated voltage

  Voltage rating of the fuse must be greater than or equal to what would become the open circuit voltage.

- Voltage drop

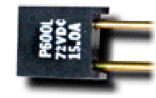
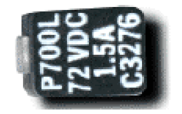
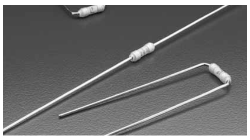
  A voltage drop across the fuse is usually provided by its manufacturer. Resistance may change when a fuse becomes hot due to energy dissipation while conducting higher currents. This resulting voltage drop should be taken into account, particularly when using a fuse in low-voltage applications. Voltage drop often is not significant in more traditional wire type fuses, but can be significant in other technologies such as resettable fuse (PPTC) type fuses.

- Temperature rating

  Ambient temperature will change a fuse's operational parameters. A fuse rated for 1 A at 25 °C may conduct up to 10% or 20% more current at −40 °C and may open at 80% of its rated value at 100 °C. Operating values will vary with each fuse family and are provided in manufacturer data sheets.

5.2.5 Suppliers and available products

Current space used fuses are summarised in table below.

Case	Type/manufacturer	Current rating	DC Voltage rating	specification	Comments
	P600/ AEM (US)	Up to 15A	135V max	MIL-PRF-23419 AEM specification	ITAR
	P700/AEM (US)	Up to 15A 20A	72V 50V	MIL-PRF-23419 AEM specification	ITAR
	MGAS/ Schurter (CH)	Up to 2.1A 2.8A 3.5A	125V 63V 32V	ESCC 4008/001	Small size
	FM01, FM08 and FM09 /Cooper Bussmann (US)	Up to 15A	Up to 125V	MIL-PRF-23419	Wire link
	FM8/ Little fuse (US)	Up to 10A 15A	125V 32V	MIL-PRF-23419/8	Wire link

AEM is the traditional supplier of fuse for the space market. However, ITAR statue of AEM fuses lead Schurter to enter the market. The main wire-link fuse used for space application is the FM08 according MIL-PRF-23419/8 (based on the PICOFUSE, commercial product)from Little fuse (US).

5.2.6 Activities

Due to ITAR restriction on AEM fuses, Schurter is developing a new SMD fuse, name HCSF, to serve space market.

No other needs identified for non resettable fuse, however a leaded version of HCSF may interest some users.

Resettable fuses are not yet used in space due to a lack of reliability data and knowledge of their capability to operate in space environment. The number of reset operation is also not well known.

5.3 Temperature sensors

5.3.1 *Overview*

The understanding of term “thermistor” is not defined. For some people it is each resistor which changed its resistance value versus temperature. On the other hand there is a common use to define the parts “resistance value versus temperature” as thermal sensor.

These thermal sensors are divided in three categories:

Thermistors

Thermistors can be divided into two groups.

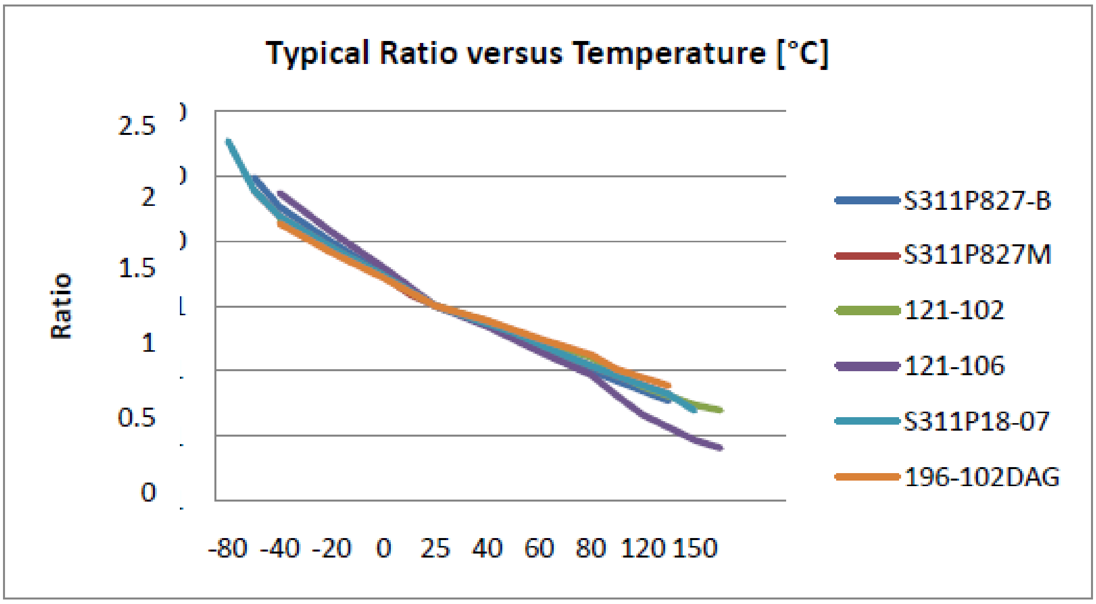
NTC (negative temperature coefficient) devices, which show a decreasing of the resistance value versus temperature. The resistance element is made from certain metal oxide (semiconductors). The metals can be manganese, nickel, cobalt, copper, iron. NTC are used for temperature measurements, monitoring, control and compensations. The temperature measurement is the most common application. All EPPL listed thermistors are NTC’s in the group temperature measurement,

For NTC exists a formula which provides a relation between temperature and resistors, the Seinhart-Hart-Equation

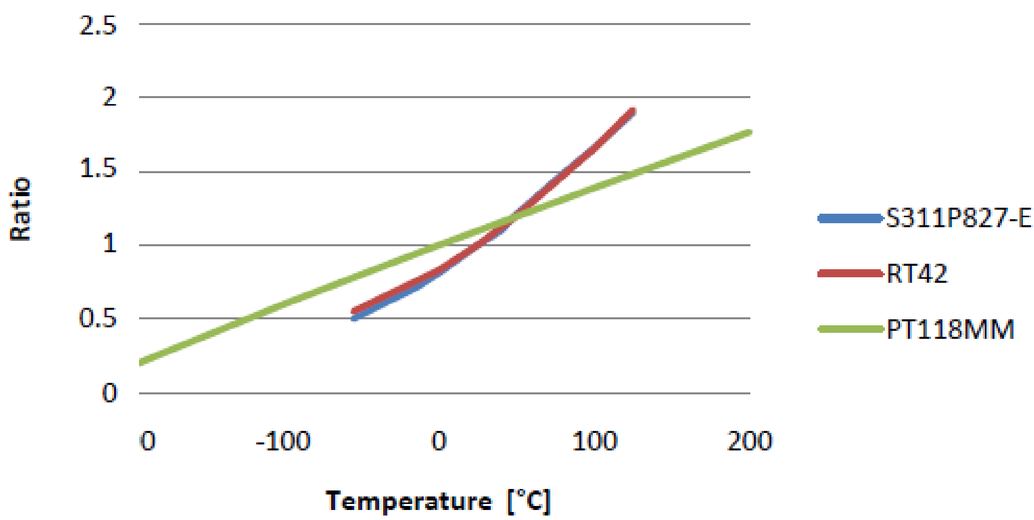
$$\frac{1}{T} = A + B(\ln(R)) + C\,(\ln(R))^3$$

(T=Temperature in Kelvin, R= Resistance in Ohm A, B, C constant material factors for a selected thermistor)

Typical Ratio Curves of NTC:



PTC (positive temperature coefficient) devices, which show an increasing of the resistance value versus temperature. The resistance elements are typical silicon semi-conductors. The applications are the same as for NTC but additional the PTC are used for current limitation.



The applicable temperature ranges are limited (typical between -90°C and +140°C), as the behaviour of resistance changing can be used only in a small temperature interval, which depends on the selected kind of material. It is possible that a PTC can show a negative temperature coefficient outside its defined temperature interval and therefore it is no longer unique.

Thermo-coupler

Thermo-coupler consists of two different metals, which generates a voltage, which increase with temperature. (thermoelectric effect / Seebeck effect). The advantage is the use at high temperatures up to over 1000°C.

Resistance Temperature Detectors (RTD)

The RTD consists of a pure metal, like Platinum. Only the metal resistance changing versus the temperature is used for such parts. The advantage is that a wide temperature range can be used. Platinum Sensors can typical cover temperature ranges from -200°C to 800°C.

Remark: Diode Temperature Sensors are not covered by this chapter, as DT670 or CX-1030 from Lakeshore

5.3.2 Classification

There are numerous kinds of thermal sensors depending on the market or the application. Thermal sensors may be classified according to :

- termination type : flexible wire, rigid lead or chip.
- electrical performance : NTC, PTC .
- internal construction: glass beads, epoxy probes, chip …
- applications: as proposed by EPPL : Temperature Compensating (11-01) , Temperature Measuring(11-02), Temperature Sensors(11-03), miscellaneous (11-0=99).

In the following, parts are classified according to their electrical performances (NTC, PTC) or their technology (chips, film, wire, …).

5.3.3 Specific space constraint and requirements

NTR

5.3.4 Main characteristics

The following is focused on the main thermistor types used in space applications.

The importance of the different parameters depends on the application. The key characteristics are:

Important for all application	Important for some applications
- Zero resistance (defined on 0°C or 25°C) - NTC, PTC - Delta resistance versus temperature - operating/storage temperature range - High accurancy	- Dissipation Constant - Thermal Time Constant - Time stability - Interchangability

5.3.5 Suppliers and available products

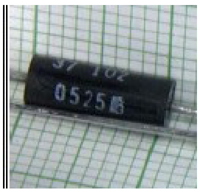
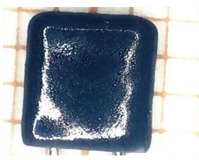
In the last years there is a concentration of the suppliers.

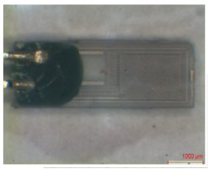
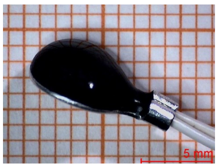
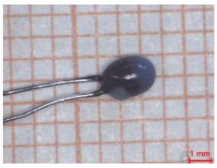
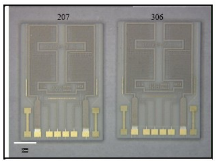
Measurement Specialties bought in the last years: Betatherm, Ireland, and Yellow Springs Incorporation, US (which was already merged with Victory US). They have now a high percentage of the space market.

There are some smaller suppliers which supplied thermistors for as niche market e.g. Rosemount, US; RTI US; Quality Thermistors US, Honeywell (bought Fenwal Electronics), US; Minco; US; IST, Switzerland.

Some US products (including some Betatherm products) are under export control (EAR, ITAR, etc.).

Available products are presented in the following table.

Mounting	Electrical performances	Type	Temperature range	Advantages	Drawbacks
Leaded	PTC	Epoxy moulded silicon chip 	-55 to 125C		Big size
		Winded platinum wire 	-269 to 400C	Temperature range Small size	Expensive

Mounting	Electrical performances	Type	Temperature range	Advantages	Drawbacks
		Platinum metal film 	-200 to 500C	Cheaper than winded platinum wire	
	NTC	Chip poured in glass bead 	-60 to 160C	Mounting plate for good thermal contact	Big sizes Difficult to mount on uneven surface
		Chip coated in epoxy 	-55 to 115C	Small size	Uneven mounting surface
Chip	PTC	Metal film with heater 	-60 to 150C	Small size, bondable, integrated heater	
		Chip gold termination	-40 to 100C	Small size, SMD	Limited value available
	NTC	Metalisation top/bottom or gold 	-40 to 125C	Small size, SMD	

5.3.6 *Activities*

Thermistors are expensive components and in some cases customers require a high number of verification points,. The assembly is generally performed manually and it should be interesting to have SMD chips for board application to simplify the assembly process. Chips like resistor (0805) exist on the market but they are not qualified and there are some solder restrictions due to the used materials (especially for the PTC).

Some external applications request a large temperature range that are today not fully covered for NTC type or only achievable with platinum sensors not available today in Europe at the requested quality level. Two activities are envisaged to answer to these needs:

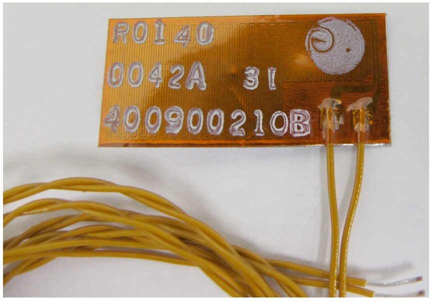
- NTC beads for higher temperature up to 200°C, with an acceptable price
- Platinum sensor might be procured to US source. Mainly wire technology is at the present used in space application. Pt sensor based on thin film deposition are nowadays available and could be interesting in term of reliability and size. This technology shall be evaluated to be considered in very stressing application such as solar panel temperature control (up to 60 000 cycles ΔT 200º).

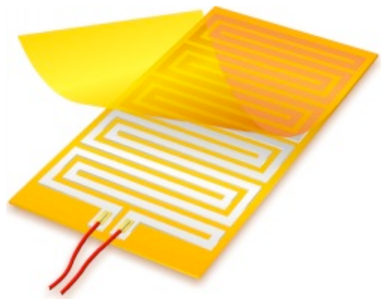
5.4 Flexible heaters

5.4.1 Overview

Flexible heaters provide accurate and rapid heat transfer.

Flexible heaters are thin and flexible consisting of an etched-foil resistive element laminated between layers of flexible insulation.





5.4.2 Classification

Different kinds of heaters are available on the market but are not always suitable for space application.

Materials for the cover include, silicone, kapton, polyester, and mylar constructions.

The flexible heater might be classified according different technologies:

- Silicone Rubber Heaters (foil)
- Silicone Rubber Heaters (wire-wound)
- Thermal-Clear Transparent Heaters
- Mica Heaters
- Standard Heater / Sensors
- PTFE (Teflon™) Heaters
- Polyimide (Kapton®) Heaters
- All-Polyimide Heaters

Pictures and information presented hereafter have been extracted form MINCO website (http://www.minco.com/).

Only Polyimide heaters and all polyimide heaters will be discussed hereafter as the others technologies are not suitable for space application (out-gassing issue, radiation concern, vibration withstanding capability, weight…).

5.4.3 *Specific space constraint and requirements*

Since heaters are dissipating components thermal management shall take into account space vacuum condition. The limiting element for the heater itself is the film temperature.

Different interpretations of derating exist in the space community:

- ECSS Q-ST-30-11 and ESCC 4009/002
  - ESCC 4009/002 defined the maximum rated power density equal to 0.54W/cm2 with the heater suspended in still air at 25C. Rated power density shall be derated against temperature.
  - ECSS Q-ST-30-11 requires a derating of 50% on the actual rated power which shall be specified in the applicable heater design drawing and which shall be determined from the specified heating area (s) taking into account the thermal properties of the mounted heater in the application
- EEE-INST-002 and GSFC S-311-P-079
  - According to GSFC S-311-P-079, heaters shall have a power rating of 0.54W/cm2 for effective element area, based on continuous full-load operation with the heater suspended in still air at 25C.
  - According to EEE-INST-002, the rated voltage and current voltage shall be as recommended by the manufacturer. The ambient temperature shall be 85 °C or 30 °C less than maximum rated temperature, whichever is less.

In practice, the mounting process and the surface on which the heater is mounted shall be taken into account in to determine the max power to be dissipated by the heater which really specific to each application.

5.4.4 *Main characteristics*

The main properties of heaters are:

- materials and shape
- backing plates
- Surface
- Ohmic density / resistance
- resistance tolerance
- temperature range
- power density
- insulation resistance
- dielectric strength
- connectivity
- flexibility
- radiation resistance
- out-gassing properties
- voltage / current / wattage
- temperature coefficient
- number of resistances
- number of layers single or double layer

Voltage and wattage values might be considered as reference only. Heaters shall be operated at other voltages if they do not exceed the maximum allowable watt density ratings.

The maximum power density depends on mounting method and environmental conditions (temperature/pressure).

Radiation resistance and out-gassing properties are not often provided when products is not intended to be used in space applications.

Backing plates are optional.

5.4.5 Suppliers and available products

5.4.5.1 Polyimide Heaters

Polyimide Thermofoil flexible heaters are suitable for applications with space and weight limitations, or where the heater will be exposed to vacuum, oil, or chemicals.

Typical applications are:

- Medical diagnostic instruments and analyzers
- Maintain warmth of satellite components
- Protect aircraft electronic and mechanical devices against cold at high altitudes
- Stabilize optoelectronic components
- Test or simulate integrated circuits
- Enable cold weather operation of outdoor electronics (card readers, LCDs or ruggedized laptops)

The insulation layer is Polyimide/FEP and the resistive layer is Ni/Cr/fe alloy (Inconel).

Those products are known to have good outgassing properties and radiation resistance (10^6 rads).

5.4.5.2 All-Polyimide Heaters

All-Polyimide heaters are a high performance alternative to standard polyimide flexible heaters, allowing higher temperatures and watt densities.

All-Polyimide heaters must be factory mounted or clamped to heat sinks and are only available as custom designs.

Those heaters are available in round, rectangular, and irregular shapes.

Typical applications are:

- Semiconductor wafer processing
- Satellites or other spacecraft
- Heating of electronic components
- Packaging, fusing, and splicing equipment

The insulation layer is Polyimide. Those products are known to have good outgassing properties (0.36% TML, 0.01%CVCM) and radiation resistance (10^6 rads).

5.4.5.3 Synthesis

The main characteristic of these 2 products are summarised in the table below.

Properties	Polyimide	All polyimide
Surface max Mm*mm	560 x 1065	560 x 1145
Ohmic density Ω/cm²	70	233
Resistance tolerance	±10% or ±0.5 Ω	±10% or ±0.5 Ω
Temperature range	-200 to 200°C (150°C with backfoil)	-200 to 240°C

Properties	Polyimide	All polyimide
power density (1)	3W/cm2 (2)	4W/cm2 (2)
Insulation resistance	NC	1000 Mohms
Dielectric strength	1000 VRMS	1000 VRMS
Connectivity	PTFE insulated, stranded, AWG20 to AWG30	
Flexibility Minimum bend radius	0.8 mm	NC
Material Insulation Resistive layer Backing plates	 Polyimide/FEP Inconel PSA adhesive (optional)	 Polyimide NC NC
Radiation resistance	10^6 rads	10^6 rads
Outgassing properties	OK	0.36% TML 0.01%CVCM
Shape	Rectangular, custom shape	

(1) Depends on mounting method and ambient temperature/pressure

(2) for heater mounted with acrylic PSA at 50C

Usually, space projects procure Polyimide heaters from 2 manufacturers RICA/IT (ESCC qualified) and MINCO.

MINCO produce parts in US (NASA QPL) and France (ESCC Qualified).

All polyimide heaters are not currently ESCC qualified.

5.4.6 Activities

The ESCC qualified range seems to be sufficient to cover most of the current and future needs concerning heaters however some improvements are envisaged

- In term of performance increase

The derating rules of heater might be detailed taking into account the mounting process and surface material. This might lead to a better understanding of heater physical limits and might induce a better definition of the products vs. user requirements.

- In term of miniaturisation

The evaluation of All polyimide heater might lead to the miniaturisation of heater due to higher rated power density.

- In term of application

The integration of temperature sensor within the heater element will provide accurate in-situ information about the temperature raise induced by the heater.

Cuttable heater are heater that could be cut during integration to the required length, This will provide users higher flexibility but might require deep evaluation of the mounting techniques.

5.5 Wires and cables

A wire or cable is a component providing an electrical link between two sub-assemblies, usually through connectors. It is a simple component, technologically stabilized, and well specified for each major applications area (IT, automotive industry, telecommunications, aeronautics, etc.).

RF cables are not included in this dossier and will be considered in a dossier dedicated to RF components

5.5.1 Overview

Wire is the basic component, made up of a conductor, usually in copper (conductor core), and an insulating layer (insulator) for protection (FEP, PTFE, polyimide, etc.). The conductor is usually made of silver-plated copper (only one cable variant is in nickel-plated copper in ESCC QPL) and can be single-strand or multi-strand, the latter being the most commonly used (in 2010, there are no ESCC-qualified single-strand cable). Insulation is essentially produced using either of two techniques, either hot extrusion of insulating powder evenly deposited through a die (extruded insulation), or by continuous taping of an insulating adhesive film (taped insulation).

Shielded wire is a basic wire to which is applied a conducting shield and an outer jacket for insulator protection. Shielding is done using silver-plated copper wires with a small diameter (» 0 .1 mm), either arranged in criss-crossing layers (braided shield), or wound in continuous closed coils (helical shield).

Cable is a set of associated wires twisted together, usually with an outer protective jacket. The cable may be shielded. If the cable includes identical wires, its designation will be akin to a "game of cards", with terms such as pair, tierce, quart and quinte, shielded or not.

5.5.2 Classification

The cable might be classified according to different criteria:

- Conductor: copper, aluminium …
- Insulating materials: PTFE, PFA (Teflon), ETFE (Tefzel), polyimide (Kapton)
- Application: power, voltage, high data rate, temperature
- Shielded or not

5.5.3 Specific space constraint and requirements

5.5.3.1 Insulation material

As mentioned at the start of this section, since space cables are derived from aeronautical cables, they require high-performance insulation materials, such as PTFE, PFA (Teflon), ETFE (Tefzel), polyimide (Kapton), meeting the vacuum resistance requirements in specification ECSS-Q-ST-70-02.

Space cables must also not be flammable, and have excellent resistance to radiation. Compared to others insulation materials, PTFE is the most sensitive to radiation and its use can be limited.

As far as use is concerned, not all these materials are interchangeable, due to their mechanical (flexibility, resistance to penetration, notch propagation, etc.) and environmental (temperature resistance) properties, which often differ widely. The selection of a cable family must be based on a precise analysis of the requirements. (See: "Wire Insulation Selection Guidelines" in the NASA NPSL, http://nepp.nasa.gov/npsl/Wire/insulation_guide.htm).

5.5.3.2 Conductor

The reliability and lifetime requirement mostly has an impact on the quality of the finish coating of conductor strands. For a long time now, the best compromise is the Silver finish:

- excellent electrical conductivity, both at low and microwave level,
- excellent solderability of strands, even after long-term storage of the cables,
- very good suitability to crimping or mini-wrapping, with no break in the layer,
- good behaviour for operation at high temperature (» 200°C).

The Silver thickness value specified is 2 µm min. This is necessary to guarantee the absence of any risk of galvanic corrosion between copper and silver in the presence of humidity and/or traces of flux ("red plague" phenomenon). At lower thicknesses (1 µm in the case of aeronautical/military cables for instance), there is a potential risk.

There is a specific test called the "Anthony and Brown test" which makes it possible to check the quality of a silver-plated wire and the absence of any risk of "red plague" during use (this test is defined in standard ECSS-Q-70-20).

It should be mentioned that the original Silver thickness criterion was 1.5 µm. It was specified at 2 µm minimum in 1987 upon request from ESA following their work concerning the red plague on silver-plated wires.

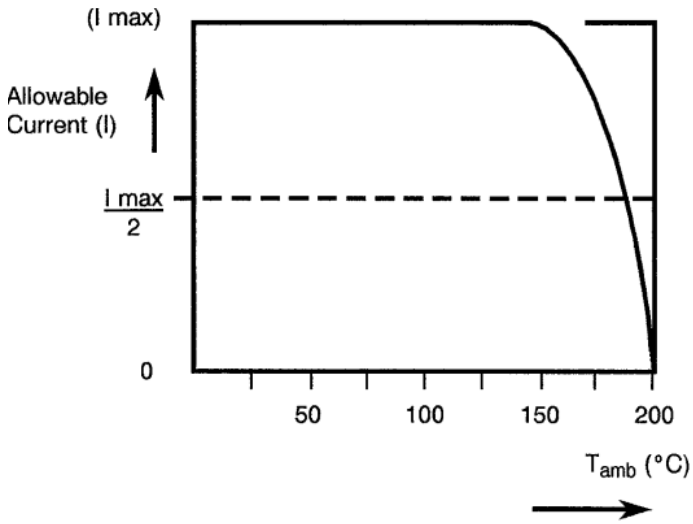
5.5.4 Main characteristics

Main electrical characteristics are:

- WITHSTAND VOLTAGE (SPARK TEST) : this is the maximum "instantaneous" voltage acceptable by a wire/cable without deterioration.
- WORKING VOLTAGE : This standard is that of the MIL standards corresponding to the creation of space wires. For main application the working voltage is set at 600V.
- MAXIMUM CURRENT : this is the maximum allowable current that can circulate in a wire (for a given gauge). It is defined in the table below, from ECSS-Q-ST-30-11.

Parameters	**Load ratio or limit**														
Wire size (AWG)	32	30	28	26	24	22	20	18	16	14	12	10	8	6	4
Maximum current Cu (I) (A)	1,2	1,3	1,5	2,5	3,5	5	7,5	10	13	17	25	32	45	60	81
Maximum current Al (I) (A)						4	6	8	10,4	13,6	18,4	25,6	36		

When the cable operating temperature is close to the maximum temperature defined in the corresponding specification, it is necessary to apply a temperature rating as showed in the figure below:



Allowable current according to temperature, from ESCC 3901/001

Other characteristic should be taken into account depending of the application like high-voltage cables, cables with matched impedance, flexibility (dynamic application), aluminium cables (low weight) or stainless steel cables with a high gauge (low thermal conductivity).

5.5.5 Suppliers and available products

There are several ESCC-qualified cable manufacturers, namely W.L. Gore & Co and Leoni Special Cables (based in Germany), Tyco Electronics (based in the UK), and Axon'Câble, Draka Fileca and Nexans (based in France). The three French manufacturers of space cables hold a total of 13 qualification certificates out of a European total of 26. These different cable types are covered as a whole by about 15 detail specifications based on 2 generic specifications:

- 3901, for low-frequency wires and cables, under the working voltage standard of 600 Volts

- 3902, for flexible coaxial cables

Independently of formatting elements imposed by the system, these different specifications have changed relatively little in terms of the content of technical requirements; this reflects the stability of the products and the initial motivation of the manufacturers to contribute to the relevance of the documents.

Basically same offer exist in US but often with a lower silver plating thickness.

The following tables present the current range of ESCC qualified cables. All these wires have a voltage rating of 600V and withstanding voltage of 3KV for primary insulation.

Elements/Characteristics	Polyimide Insulator 3901/001-002	3901/009	3901/019	3901/021
Conductor	Silver plated copper	Silver plated copper	Silver plated copper	Silver plated copper
Primary insulator	Double polyimide tape	Expanded PTFE tape	Expanded PTFE tape	Expanded PTFE tape
Isolator Protection	Polyimide coating	Double polyimide tape	Double polyimide tape	Double polyimide tape
Shielding	Silver-plated copper 2µm, Helical	Silver-plated copper 2,5µm, Braided	Silver-plated copper 2.5µm, Helical	Silver-plated copper 2.5µm, Helical
Jacket	Polyimide tape + FEP coating	Double polyimide tape	Double polyimide tape	Double polyimide tape
Operating temperature	-100°C to +200°C	-200°C to +200°C	-200°C to +200°C	-200°C to +200°C
Weight (1)	1.23g/m	1.49g/m	1.4g/m	4.4g/m
	3.05g/m	6.81g/m	3.3g/m	
Stiffness	High	High	Medium	Medium
Qualified AWG range	28 to 12 (18 for -002)	28 to 12	30 to 12	30 to 20

(1) Weight for a simple cable AWG 28 and simple shielded protected cable AWG 28

CABLES WITH POLYIMIDE INSULATION

Elements/Characteristics	PTFE-polyimide Insulator 3901/017	3901/013	3901/018
Conductor	Nickel plaeted copper	Silver plated copper	Silver plated copper
Primary insulator	Expanded PTFE tape	Extruded PTFE	Expanded PTFE tape
Isolator Protection	Double polyimide tape	Polyimide coating	Polyimide/PTFE tape
Shielding		Silver-plated copper 2µm, Braided	Silver-plated copper 2µm, Braided
Jacket	Extruded PFA	Polyimide tape	Extruded PTFE-PFA
Operating temperature	-200°C to +200°C	-100°C to +200°C	-200°C to +200°C
Weight (1)	542g/m (AWG 0)	1.8g/m	1.81g/m
	98g/m (AWG 8)	3.77g/m	6.52g/m
Stiffness	High	Medium	Medium
Qualified AWG range	8 to 0	28 to 16	32 to 12

(1) Weight for a simple cable AWG 28 and simple shielded protected cable AWG 28

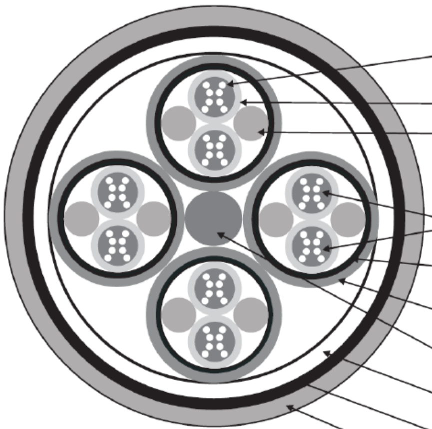
CABLES WITH PTFE-POLYIMIDE INSULATION

	Floropolymer Insulator			
Elements/Characteristics	**3901/024**	**3901/012**	**3901/020**	**3901/022**
Conductor	Silver plated copper	Silver plated copper	Silver plated copper	Silver plated copper
Primary insulator	PTFE tape (HST-F)	Extruded cross-linked ETFE	Extruded cross-linked ETFE	Extruded cross-linked ETFE
Isolator Protection	PTFE tape			
Shielding	Silver-plated copper 2µm, Helical	Silver-plated copper 2µm, Braided	Silver-plated copper 2µm, Braided	Silver-plated copper 2µm, Helical
Jacket	Expanded PTFE tape + extruded PFA	Extruded cross-linked ETFE	Extruded cross-linked ETFE	Extruded cross-linked ETFE
Operating temperature	-200°C to +200°C	-100°C to +200°C	-100°C to +200°C	-100°C to +200°C
Weight (1)	1.7g/m	1.35g/m	1.15g/m	
	5.0g/m	6.12g/m	4.78g/m	3.56g/m
Stiffness	Low	Low	Low	Low
Qualified AWG range	30 to 12	30 to 12	30 to 12	28 to 12

(1) Weight for a simple cable AWG 28 and simple shielded protected cable AWG 28

CABLES WITH FLUOROPOLYMER INSULATION

To be noted "space wire" is included in ESCC QPL. Two cable variants are defined in the ESCC specification, both of them qualified. The only difference between variants 1 and 2 is the basic wire gauge, AWG 28 and 26 respectively. Only one manufacturer is ESCC-qualified in 2010, namely Axon (Montmirail plant). Recent development activity has led to new variants definition allowing important mass saving. However, the new design might induce some difficulties during Cable Assembly manufacturing.



5.5.6 *Activities*

The range of ESCC products meets most of our current and near-future requirements, it being understood that in each product family, the range of existing variants can be broadened to include either high gauges (miniaturisation) or low gauges (power). However, a few possibilities for improvement are being considered.

5.5.6.1 Derating

Unlike other components and connectors, the demand for cost reduction is not very strong on the part of satellite manufacturers; it seems that the performance-quality-reliability-price results of space cables are satisfactory, as the manufacturers were able to improve their rates due to the increase in volumes manufactured. Obtaining substantial reductions would mean modifying the products through replacement with less noble elements, at the expense of quality. Nonetheless, one possible line of improvement would consist in reviewing the established harness derating rules by considering that all the cables making up a harness have as their intensity the maximum authorized derating. However, this "worst case scenario" configuration seldom reflects reality. For instance, cables conveying signal-type intensities should not be taken into consideration when calculating the harness derating. As a result, better suitability of the derating rules to the reality of the stresses to which the harness is subjected would make it possible to optimise the harness, and therefore to significantly reduce its weight.

5.5.6.2 High-Temperature, High-Power Cable

Electrical or electromagnetic propulsion of the "Ion thruster" type is an attractive solution, notably for satellite station-keeping operations or for planetary exploration missions. This propulsion equipment requires high powering, and locally generates high temperatures. In order to meet this requirement, it is necessary to develop and assess cables able to withstand such environmental stresses in order to point users towards one or more solution(s) with a proven space quality assurance, but also to draw up a generic specification for assessment or project validation of this type of cables.

Development of high temperature cable implies that more power may be used for a specified gauge. A diminution of the number of cable used for supplying a certain amount of power may be expected reducing the whole weight of harness.

5.5.6.3 Aluminium

Replacing the copper traditionally used in cables as an inner conductor or shield with aluminium allows for a significant decrease in weight. However, aluminium is not as suitable for crimping or soldering as copper, which leads to certain difficulties when it is used. The current solution consists in using aluminium cables jacketed with copper and protected by nickel, or aluminium cables protected by silver.

The gain in weight achieved through these solutions is on the order of 50 to 60%, and this solution is widely used today in aeronautics. A study on the spatialisation of these cables would be interesting, in particular for high-gauge cables or for multi-shielded cables for which the absolute gain in weight would be significant. The long-term objective of this assessment would be to introduce a reference to this type of cable in QPL.

5.5.6.4 High Data Rate

It seems increasingly necessary to adapt the ESCC specification system in order to introduce a new generic specification for high-rate cable assemblies.

The reason is that the performance of high-rate cable assembly (connector + cable) depends on the combined performances of three elements: the connectors, the cable and the assembly process. Therefore the performance of a connector and of a cable may lead to deteriorated assembly performance. The reason is that if the connector and the cable come from different manufacturers, the connection between these two components might not be optimised, and may therefore result in deteriorated performance.

Moreover, the users specify and stipulate by contract with the manufacturers the performance to be provided by the cable assemblies according to the requirements and constraints for the connected equipment items. It would appear therefore advantageous to have an ESCC specifications system which describes the performance of the cords according to these characteristics (length, cable and connector types).

It is then more rigorous to qualify the quality of a cord or family of cords rather than to qualify the quality of each component individually. This approach has the added benefit of reducing the qualification costs compared with a qualification of connectors and cables, and of increasing the quality assurance of the product, as the assembly would also be qualified.

5.5.6.5 High-Voltage

For certain specific applications, it is necessary to use high-voltage cables able to withstand several kV. Currently, there is no ESCC-qualified solution, as the space market for this type of cable is not extensive enough. It therefore would seem worthwhile to assess, for the space industry, one or more high-voltage cable references, in order to point users towards one or more solution(s) with a proven space quality assurance, but also to draw up a generic specification for assessment or project validation of this type of cables. Same as for high data rate, it should envisaged to qualified cable assembly.

5.5.6.6 Anti-ESD Cables For Solar Power Arrays

The cables used for the connection of a satellite solar array are subject to extremely high radiation constraints. As a result, there is a build-up of parasitic loads on the outer insulating layer of these cables which can, in the long term, lead to electrostatic discharges potentially harmful to the equipment. The current solution consists in using polyimide-insulated cables, because of their excellent resistance to radiation; however, their very high stiffness, and the fact that polyimide is prone to the phenomenon of localised dielectric breakdown, represent two major drawbacks.

The new insulating materials charged with carbon nanotubes might make it possible to manufacture cables with an insulation whose conductivity is controlled, so that surface charges can be adjusted.

The objective is to assess the compatibility of these new materials with the making of cables for space applications.

5.5.6.7 Cables With Low Thermal Conductivity

Cryogenic or low-temperature applications on board satellites must be servo-controlled in temperature by cooling systems. In order to minimise the size of these cooling systems, it is necessary to keep to a minimum the thermal losses of applications by thermal conduction through wiring components used for data exchange or for powering. As it happens, the wiring solutions applied in the space industry are based on the use of copper, which has excellent thermal conductivity.

There are therefore two ways of reducing the thermal conduction of cables: reducing the diameter of the inner conductor, and replacing it with a material with a low thermal conductivity. The solution selected for some satellites has consisted in using a cable with an AWG 38-size stainless steel single strand inner conductor. Although this solution has been validated by LAT-type tests, it only guarantees the quality of the cable. However, the use of such a high gauge and of stainless steel is problematic (crimping, soldering, implementation) and would need to be assessed before drawing up recommendations for use.

Screwlock device Shell

Insert Back-shell Socket Contact

5.6 Electrical Connectors

5.6.1 Overview

A connector is an electrical component which aims to make an electrical connection when there is no physical link. A connector is composed by a shell which protects an insert in which are placed the male (pin) or female (socket) contacts.

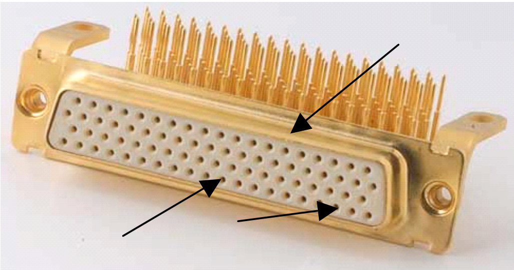


Illustration of Connectors piece parts through D-SUB PCB connectors from C&K components

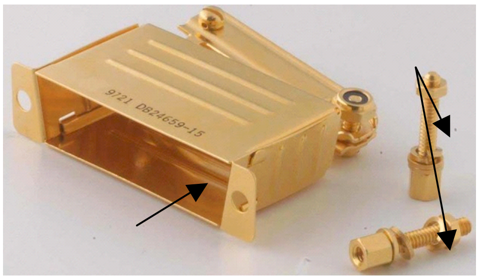


Illustration of connector accessories

To ensure electrical connection, a plug connector (moving parts of a harness or daughter card) is mated with a receptacle connector (non movable part of an equipment or mother board).

Some accessories might be used to achieve connector pair locking (screw-locks), mechanical protection (backshell) or electrical function (EMI backsell).

5.6.2 Classification

There are numerous kinds of connectors depending on the market or the application.

Connectors may be classified according to

- their form : rectangular, circular, …
- their size : sub-miniature, micro-minature, nano-miniature, …
- their electrical performance : high voltage, low frequency, radio frequency, power, filtered…
- their utilisation : pyrotechnic, hermetic, cryogenic, PCB, harness, …
- their contact technology : solder, crimping, solderless, PCB, twist-pin, flex-pin, wired …

For space application, more than 100 ESCC detail specifications describe connectors and contacts.

5.6.3 Specific space constraint and requirements

Connectors have to comply with the general requirements common to all components. In addition, specific requirements are to be considered:

- Residual magnetism
- Gold Plating (Au) 1.27µm for contacts
- Intermateability
- Lubricant forbidden
- Workmanship standard such as cleanliness

5.6.4 Main characteristics

The following is focused on the main connectors technologies used in space applications, i.e. :

- Rectangular and Circular Connectors
- Microminiature Connectors
- Printed Circuit Board Connectors
- Interposer
- BUS 1553
- RF Connectors

The key characteristics are:

- dimension /pitch
- number/density of contacts
- removable contacts
- mixed design (signal and power/coaxial contact in the same insert)
- operating/storage temperature range
- Maximum current and voltage
- contact resistance
- durability

The following table sums up the main characteristics of connectors to be used in space application. Values are extracted from ESCC specifications ESCC 3401/0XX. Exact values for an identified product shall be read in relevant detail specification.

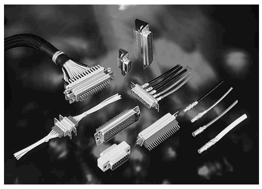
Connectors	Md	Ct Size	Nc	Pitch	RmC	OP T	Vmax	Imax	Rc	H	Mag	MP	ESCC spec.
SUB-D Rectangular subminiature Non filtered Solder, crimp, PCB filtered, power coax	Y	8-16 20-22	9/104	2.74-2.29	Y	-55/125	300/250	10-40 7.5-5	7	N	NMD	NA	3401/001 3401/002 3401/004 3401/005 3401/040
MICRO-D Rectangular microminiature Non filtered , PCB, wired, crimp,	N	26 28	9-51	1.27	Y	-55/125	150	2.5 1.5	6	N	ND	NA	3401/029 3401/031 3401/077 3401/078 3401/080 3401/081 3401/082 3401/083
DBAS-38999 CIRCULAR Non filtered Solder, crimp, PCB, power coax	Y	4-22	128	NA	Y	-65/200	575	5-80	8	Y	2Mu	NA	3401/008 3401/009 3401/012 3401/044 3401/045 3401/052 3401/056 3401/057 3401/058
PCB RECTANGULAR	N	22	17-400	2.69	Y	-55/125	200-300	2-5	12	N	NA	NA	3401/016 3401/017

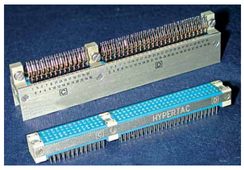
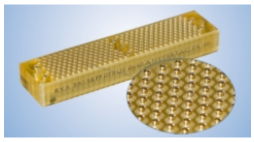
Connectors	Md	Ct Size	Nc	Pitch	RmC	OP T	Vmax	Imax	Rc	H	Mag	MP	ESCC spec.
Non filtered Solder, crimp, PCB,													
INTERPOSER RECTANGULAR Non filtered solderless,	N	1mm	660	2	NA	-55/125	160	1	25	N		2mm thick	3401/076
BUS1153 CIRCULAR Non filtered Wired, kit	NA	24	2	NA	NA	-55/150	200	1	8-20	N		1553 bus	3401/079
DJ Rectangular subminiature Filtered MF Solder,	NA		9-50	2.74	N	-55/125	200 300	5	5	N	NM	1-100 MHz	EPPLII 3405/001

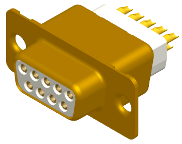
Item	Signification	**Unit**
Md	Mixed design : in same shell, coaxial or power contacts with signal contacts	**NA**
Nc	Number of contacts	**U**
Pitch	Distance between two contacts	**mm**
RmC	Removable contacts	**NA**
OP T	Maximum Operating Temperature	**C**
Vmax	Maximum Operating Voltage	**V**
Imax	Maximum Operating Current	**A**
Rc	Contact resistance	**mOhm**
H	Hermetic solution	**NA**
Mag	Magnetism sensibility	**NA**
Y,N, ND, NA	Yes, No, Not Defined, Not applicable	**NA**
MP	Main properties	NA

5.6.5 *Suppliers and available products*

Connectors range for space application is composed by:

connectors	Type	Advantages	Drawbacks	
Sub-D	D*M D*MA D*BMA	Large range of size and arrangement Crimp, solder, power and coaxial contacts Repairs allowed ESCC qualified	Size and weight No hermetic	

connectors	Type	Advantages	Drawbacks	
Micro-miniature	MDM MDMA	Large range of size and arrangement Crimp and wired Repairs allowed ESCC qualified	No power and coaxial contacts No hermetic variants	
MicroComp	Removable or non removable contact	Large range of size and arrangement Crimp and PCB Repairs allowed Size and weight ESCC qualified	Not compatible with MDM No power and coaxial contacts No hermetic variants	
Micro-miniature	MTB1	Size and weight Wired ESCC qualified	Repairs not allowed No power and coaxial contacts No hermetic variants	
Connector for PCB	KN KM	Low insertion force PCB, crimp contacts ESCC qualified	Weight and size	 
Connector for PCB	MHD	Low insertion force PCB, crimp contacts ESCC qualified	Weight and size	
Connector interposer	RX/IHD	Interposer type ESCC qualified	Height	
Circular	DBAS	Large range of size and arrangement Crimp, solder, power and coaxial contacts Repairs allowed ESCC qualified	Size and weight No hermetic Not compatible with 38999	
Circular	38999	Large range of size and arrangement Crimp, solder, power and coaxial contacts Repairs allowed ESCC qualified	Size and weight Hermetic only feedthrought Not compatible with DBAS	

connectors	Type	Advantages	Drawbacks	
Circular	ACB1 for bu 1553	Dedicated for 1553 bus Locking system ESCC qualified	Dedicated for 1553 bus	
Rectangular filtered	DxJ	D-SUB compatible	Limited for Medium frequency Not ESCC qualified EPPL II	

European space connectors used in space are presented in table below

Connectors	Manufacturer	type	Comments
DxM, DxMA, DxBMA	C&K (FR) SOURIAU (FR)	Rectangular BF	QPL ESCC
MDM-MDMA	C&K (FR)	Miniature BF	QPL ESCC
MDSA	AXON (FR)	Miniature BF	EPPL II
MICROCOMP	SOURIAU (FR)	Miniature BF	QPL ESCC
38999	SOURIAU (FR)	Circular BF	QPL ESCC
DBAS	DEUTSCH (FR)	Circular BF	QPL ESCC
38999 hermetic	SOURIAU (FR)	Circular BF	QPL ESCC
KM,KN,MHD	HYPERTAC (FR UK)	PCB BF	QPL ESCC
RX/IHD	HYPERTAC (FR)	INTERPOSER	QPL ESCC
ACB1	AXON (FR)	1553 DATA BUS	QPL ESCC
DJ	C&K (FR)	Rectangular BF	EPPL II

Available connectors for space application

NASA and JAXA recommended products

Type	Specification
Circular	NASA MSFC 40M3XXXX NASA SSQ 21635 MIL-DTL-38999 MIL-C-26482 MIL-DTL-5015
D Subminiature	NASA GSFC S-311-P-4, P-10 MIL-DTL-24308
Microminiature	MIL-DTL-83513

Type	Specification
Printed Circuit	MIL-DTL-55302
EMI Filter Contact	NASA GSFC S-311-P-626
Satellite Umbilical Interface	NASA GSFC-S-311-P-718 NASA SSQ 21637 SAE-AS81703
MIL-STD-1553 Databus	MIL-PRF-49142
Nanominiature	DSCC 94031

Connectors procurement specifications according to EEE-INST-002

Microminiature	JAXA-QTS-2060_F301A
SUB-D	JAXA-QTS-2060_C101C JAXA-QTS-2060_E102B JAXA-QTS-2060_D114A JAXA-QTS-2060_D114A JAXA-QTS-2060_D114A JAXA-QTS-2060_C201A JAXA-QTS-2060_D202A

JAXA QPL

5.6.6 Activities

Application of connectors are various and numerous. New needs are always coming and can be classified as follow:

<u>In term of performance increase</u>

- Maximum working voltage is limited to 500Vrms in the current available qualified range.Specific connector design are necessary for high voltage application.
- Maximum Temperature is limited to 125-160C. The need of higher temperature connectors shall be discussed (increase of temperature base plate for some application up to 150C).
- Low Rc connectors to carry High current are not available (bus bar, electrical propulsion, high power)
- High data rate connector are not ESCC qualified (up to 10Gbit/s)
- Improvement in material solution (weight, temperature resistance…)

In term of miniaturisation

- Microminiature connectors are not available with power and coaxial contacts to replace D-SUB or circular connector solutions.
- Microminiature connectors are the smallest ESCC qualified products whereas nanoD connectors are QPL MIL 32139 and some projects have expressed needs (science or earth observation).
- miniature interposer (2mm thick) might provide interesting solution when BGA/LGA packaging is under concern

In term of application

- Filter connectors are only available for Medium frequency (1-100MHz)
- No ESCC qualified connectors for pyro initiator devices are available to replace ITAR US products.
- Locking devices are composed by simple screw devices which does not allow easy and fast locking operation. Some fast locking system have been developed but the ESCC qualification shall still be performed.
- Only one ESCC qualified hermetic LF connector is available (38999 hermetic feed-through).
- No qualified or preferred connector is dedicated to solar panel.
- Modular connector with integrated smart locking solution might ease integration of equipment on satellites

5.7 Quartz/Oscillators

A crystal oscillator is an electronic oscillator circuit that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency. This frequency is commonly used to keep track of time, to provide a stable clock signal for digital integrated circuits, and to stabilize frequencies for radio transmitters and receivers. The most common type of piezoelectric resonator used is the quartz crystal.

5.7.1 Quartz

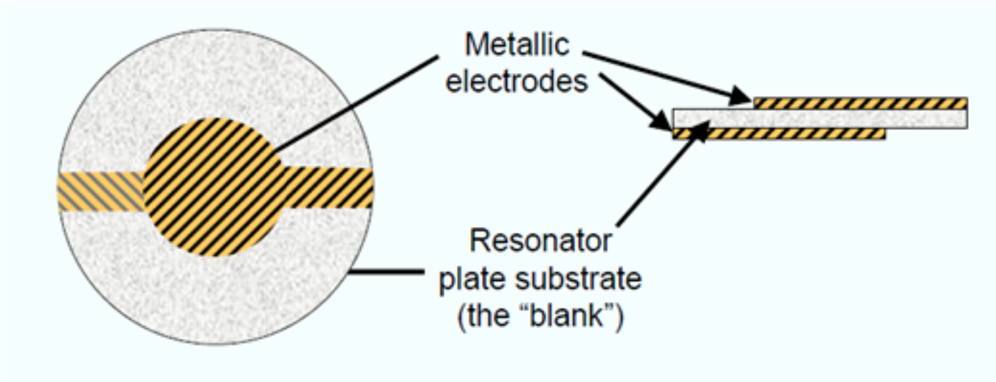
5.7.1.1 Overview

Quartz crystals are manufactured for frequencies from a few tens of kilohertz to tens of megahertz. More than two billion crystals are manufactured annually. Most are small devices for consumer devices such as wristwatches, clocks, radios, computers, and cell phones. Quartz crystals are also found inside test and measurement equipment, such as counters, signal generators, and oscilloscopes.

Quartz is the only material known that possesses the following combination of properties:

- Piezoelectric ("pressure-electric"; piezein = to press, in Greek)
- Zero temperature coefficient cuts exist
- Stress compensated cut exists
- Low loss (i.e., high Q)
- Easy to process;
- Abundant in nature; easy to grow in large quantities, at low cost, and with relatively high purity and perfection.

A quartz crystal can be described as a resonator plate substrate between 2 metallic electrodes as showed below:



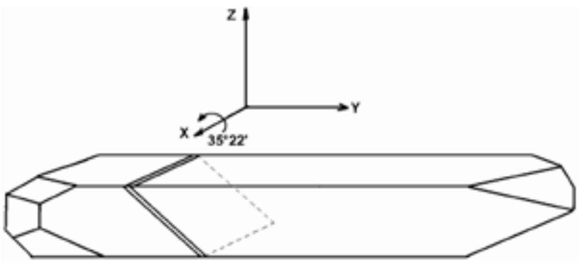
Different modes of vibration may be electrically excited by suitably placed and shaped electrodes.

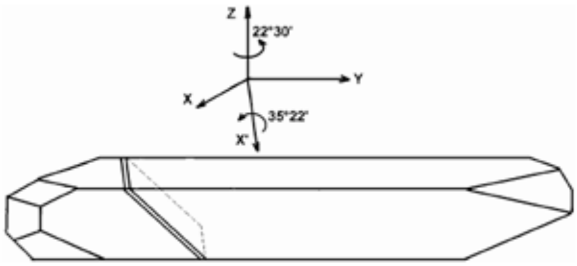
5.7.1.2 Classification

Different quartz crystal cuts can be made possessing different properties.

Cuts are defined by two rotation angles phi and theta around the crystallographic axes. Most common cuts are the single rotation AT- cut (phi = 0°) and the double rotation SC-cut (phi = 22°). The theta angle in both cases is around 34°. Other double rotated cuts like MSC-, IT-, FC-, LD- for special applications also exist.

2 types of cut are currently used in space application: the AT cut and the SC cut (double rotated).





The suitability of double rotated crystals for use in crystal oscillators is essentially restricted to those oven controlled applications (OCXO oscillators) where the improved aging, warm-up, and close-in phase noise characteristics justify a significant cost increase.

5.7.1.3 Specific space constraint and requirements

The assembly of the quartz crystal and its purity require special attention. In particular, for almost all space application, swept quartz are used for stability in radiation and 3 or 4 points are used for mounting the quartz in package to withstand mechanical constraint.

5.7.1.4 Main characteristics

The quality of a quartz crystal is measured by the factor Q. Q is proportional to the decay-time, and is inversely proportional to the line width of resonance. The higher the Q, the higher the frequency stability and accuracy capability of a resonator (high Q is a necessary but not a sufficient condition). Phase noise has an especially strong dependence on Q.

The maximum Q of a resonator can be expressed as:

$Q_{max} = 1/2\ \pi f\ \tau$,

where f is the frequency in Hz, and τ is an empirically determined "motional time constant" in seconds, which varies with the angles of cut and the mode of vibration of the crystal.

The properties of quartz crystal vary greatly with crystallographic direction (type of cut), purity of the crystal, geometry (crystal and electrode), surface finish, gas inside the package, drive level, temperature, radiation, mechanical stresses on crystal and overtone used. All the above points will affect the main characteristics of resonator which are:

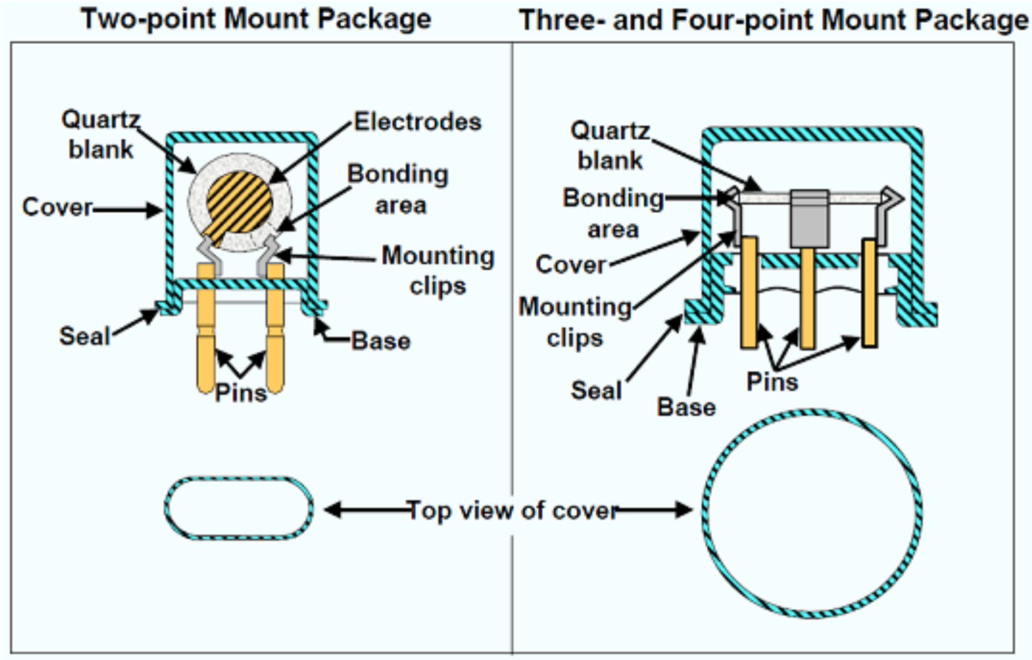
- The frequency
- The frequency stability
- The frequency variation due to temperature
- Drive level

Parameters that should be specified for procuring quartz resonator are presented in the table below.

N°	Characteristic	Symbol	Limit Min.	Limit Max.	Unit	Remarks
1	Holder type					
2	Resonance Frequency	f_1 or f_L			MHz	
3	Reference Temperature	To			°C	
4	Overtone Order	-				
5	Load Capacitance	C_L			pF	
6	Rated Drive Level	Po			mW	
7	Frequency Adjustment Tolerance	$\frac{\Delta F}{F}$			10^{-6}	At To °C
8	Resonance Resistance	R_1 or R_L			Ω	At To °C
9	Frequency Variation with temperature over T_{op}.	$\frac{\Delta F}{F}$				From frequency measured at To °C
10	Resistance Variation with temperature over T_{op}	$\frac{\Delta R}{R}$			% Ω	From resistance measured at To °C
11	Operating Temperature Range	T_{op}			°C	
12	Frequency variation with Drive Level	$\frac{\Delta F}{F}$			10^{-6}	From P_{s1}= .005mW to P_{s2} =.25mW
13	Resistance variation with Drive Level	$\frac{\Delta R}{R}$			%	From P_{s1}= .005mW to P_{s2} = .25mW
14	Motional Inductance	L_1			mH	
15	Motional Capacitance	C_1			pF	
16	Static Capacitance	C_0			pF	
17	Q Factor	Q			-	
18	Ration of unwanted : Response Resistance to Resonance Resistance or Response Impedance to Resonance Resistance	Rp/R or IZp/R				In the frequency range : f - KHz to f + KHz
18*	Ageing	Δf/f0			10^{-6}	To be specified : per year/ over lifetime
18b **	Ageing on test oscillators (if needed)					To be specified : per year/ over lifetime
19	Terminal length	L			mm	
20	Storage Temperature Range	T_{sto}			°C	
21	Intended Application					

5.7.1.5 Suppliers and available products

2 types of packaging are mainly used. For space application, due to mechanical constraint, 3 or 4 points mount package are preferred.



AT cut crystal quartz are available in the market. Rakon (France) is ESCC qualified since several years. KVG (Germany) is also ESCC qualified since 2011.

There are several North America manufacturers in MIL QPL according to MIL-PRF-3098. Among them Precision Devices hold a plant in UK able to produce quartz crystal according to MIL standard.

Nihon Dempa Koqyo is also proposing quartz crystal qualified according to JAXA standard.

Quartz crystal may also be procure from Vectron (US) or TDK (J) with customer specification.

Mode	Holder type	Frequency Range (MHz) ESCC-3501 qualified HC35CW T-805 / TO-5	HC37CW T-1507 / TO-8	Program qualified HC40CW T-2111
Fundamental	F	14 to 35	3 to 20	2 to 10
third Overtone	3rd. OT	25 to 100	10 to 30	10 to 30
fifth Overtone	5th. OT	50 to 140	15 to 50	10 to 50

Rakon range of space product (similar types are available at KVG)

SC cut quartz crystals are not directly available on the market at space level. They are used mainly for the manufacturing of OCXO oscillators. Several users like TAS or Astrium have expressed a short term needs for this type of component. Rakon is currently extending their range of ESCC qualified quartz to SC cut.

5.7.1.6 Activities

Quartz mainly used today in space project are based on bulk acoustic wave propagation. Some evolution of this technology may be envisaged to improve the performances. In addition, surface-acoustic wave type of resonator may allow an increase of the frequency range. Finally, SMD type and sensor type may be interesting for some application.

Bulk-acoustic wave resonator

Limitation due to AT cut of quartz crystal in term of frequency stability can be solved by using SC cut quartz with an increase of cost. Rakon is currently extending the QPL range to include SC cut quartz crystal.

Several satellite manufacturers express the needs to lower input voltage as digital applications are mowing to lower voltage.

These 2 types of limitation may be overcome by changing the electrode design and/or the materials used for the resonator blade.

Surface-acoustic wave resonators

For bulk-acoustic wave resonator (BAW), the plate thickness determines the fundamental-mode frequency. It is the ultimate reason for the limitation in term of frequency.

In Surface-acoustic wave resonators (SAW), wave motion is concentrated at the surface of the crystal. The inter-digital transducers' spacing determines the frequency. For quartz, a 300 MHz BAW resonator plate is 6 µm thick then too brittle. A 2.6 GHz SAW resonator has 0.3 µm IDT spacings, and can be produced by e-beam lithography.

Other needs

Several manufacturers proposed SMD package in their commercial range that may be adapted for space usage.

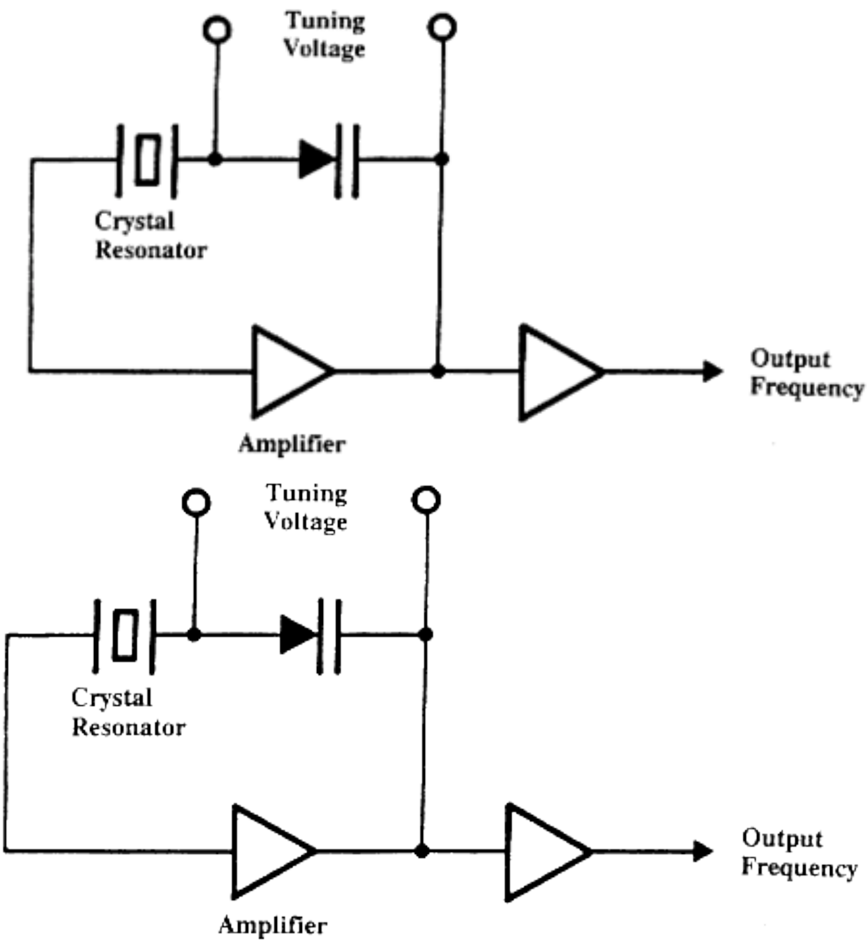
Quartz crystal may be also used as sensor for temperature and pressure.

5.7.2 *Oscillator*

5.7.2.1 Overview

This document will only cover the domain of crystal oscillator and will not discuss other type like atomic based resonator.

Figure 1 is a greatly simplified circuit diagram that shows the basic elements of a crystal oscillator. The amplifier of a crystal oscillator consists of at least one active device, the necessary biasing networks; and may include other elements for band limiting, impedance matching, and gain control. The feedback network consists of the crystal resonator, and may contain other elements, such as a variable capacitor for tuning.



Crystal Oscillator - simplified circuit diagram.

The frequency of oscillation is determined by the requirement that the closed loop phase shift = 2np, where n is an integer, usually 0 or 1. When the oscillator is initially energized, the only signal in the circuit is noise. That component of noise, the frequency of which satisfies the phase condition for oscillation, is propagated around the loop with increasing amplitude. The rate of increase depends on the excess loop gain and on the bandwidth of the crystal network. The amplitude continues to increase until the amplifier gain is reduced, either by the nonlinearities of the active elements (in which case it is self-limiting) or by an external level-control method.

At steady state, the closed-loop gain = 1. If a phase perturbation Δf occurs, the frequency of oscillation must shift by a Δf in order to maintain the 2np phase condition. It can be shown that for a series-resonance oscillator

$$\frac{\Delta f}{f} = -\frac{\Delta\phi}{2Q_L},$$

where Q_L is the loaded Q of the crystal in the network.

5.7.2.2 Classification

There are mainly 4 categories of crystal oscillator used in space application.

XO (type 1 according to MIL-PRF-55310)

Clocks are a subset of the general crystal oscillator (XO) type. Clocks are usually used to supply frequency timing to digital circuits and microprocessors. Clocks are typically available in the same technology as any other digital IC's such as TTL, CMOS, ECL, etc. The frequency range of these clocks is primarily limited by the technology being driven such as 75 MHz for STTL, 125 MHz for 10k ECL, etc. The frequency characteristics are basically that of the crystal being used (AT cut is mostly used). Clocks can obtain calibration frequency tolerances of below ±10ppm. The oscillator circuit could add to the crystal drift depending on the temperature change of critical resistors, capacitors, or inductors in the oscillator circuit.

Typically the circuit will be insignificant in the frequency variation. The clock is the simplest of all the oscillator types. Because of this, they are smaller, cheaper, and use less power to operate than other types. Start-up time (the time it takes to start the oscillator once power is applied) ranges from under 1 msec. to 20 msec. The clock oscillator generally requires only one power supply voltage for operation.

VCXO (type 2 according to MIL-PRF-55310)

VCXO, or voltage controlled oscillators, can have the output frequency change with a change in voltage at a control pin of the oscillator. VCXOs are used in many applications such as telecommunications, TCXO, or phase locked loops. The amount of frequency shift with a given voltage change (pullability) is highly dependent on the oscillator circuit. Pullabilities of 35 to 50 ppm/volt are common and higher pullabilities are obtained by adding an inductor to "de-Q" the crystal. Most, if not all, VCXOs use varactor diodes to vary the frequency. The varactor diode changes the capacitance across its terminals based on the DC (or low frequency AC) voltage across the same terminals. The frequency calibration and drift are basically that of the standard clock oscillator. Calibration may be degraded somewhat by the additional variable of setting the control voltage where this calibration is defined at. Since the crystal load capacitance is varied by the varactor diode, the drift over temperature varies from one end of the control voltage to the other. Thus, the drift cannot be optimized for all control voltages. Those circuits that require "de-Qing" the crystal will have worse drift than the crystal by itself.

TCXO (type 3 according to MIL-PRF-55310)

TCXO (temperature compensated crystal oscillator) adjusts the frequency for temperature variation. An integral part of a TCXO is a VCXO. Connected to the VCXO is generally a network of thermistor designed to bias the voltage control of the VCXO properly for each temperature. Recently, other compensation techniques have been used such as digital processing. TCXOs commonly have an outside adjustment for setting the calibration frequency periodically. This is to compensate for the aging of the crystal over time.

The period between calibration will depend on the accuracy required and may range from once a month to once a year. Frequency drift can be expected to be in the ±1 to 5ppm range. Some of this tolerance comes from frequency versus temperature hysteresis (i.e., the difference in frequency at a particular temperature depending on whether the temperature was increasing or decreasing. Power dissipation is typically two to three times that of a standard clock oscillator. The size and cost of these devices are also larger than a standard clock oscillator. After power-up it could take as much as 100 msec or more for the frequency to stabilize in a TCXO. The TCXO may also require multiple power supplies depending on the design.

OCXO (type 4 according to MIL-PRF-55310)

OCXO, oven controlled crystal oscillator, uses an oven to stabilize the frequency variation. The oven contains, at a minimum, the sealed crystal. The oven temperature, to maintain control, must be higher than the maximum ambient temperature expected in the application. The crystal is selected so that it has nearly zero frequency change in the range of temperatures expected in the oven (usually less than ±5EC). Frequency tolerances of much less than ±1ppm are realizable with an OXCO. Additional circuitry is required to control the oven and maintain the proper temperature inside. Customarily, similar to the TCXO, a calibration must be done periodically to compensate for crystal aging. A separate power supply is used for the heater in the oven. Isolation between this supply and others required by the oscillator must be established because of the noise generated when the heater is activated. The power required is considerably higher than a standard clock oscillator (as high as several watts of power). Again, cost and overall size is much more than that of a clock oscillator (as much as 40 times the cost and size). OCXOs are popular as timing standards in the instrumentation market in such measurement equipment as frequency counters, spectrum analyzers, network analyzers, etc.

According to MIL-PRF-55310, there are also 2 other types: Temperature Compensated/Voltage Controlled Crystal Oscillators (TCVCXO) (type 5) and Oven-Controlled/Voltage Controlled Crystal Oscillator (OCVCXO) (type 6). This specification classify also the different types of oscillator in classes according to the technology used:

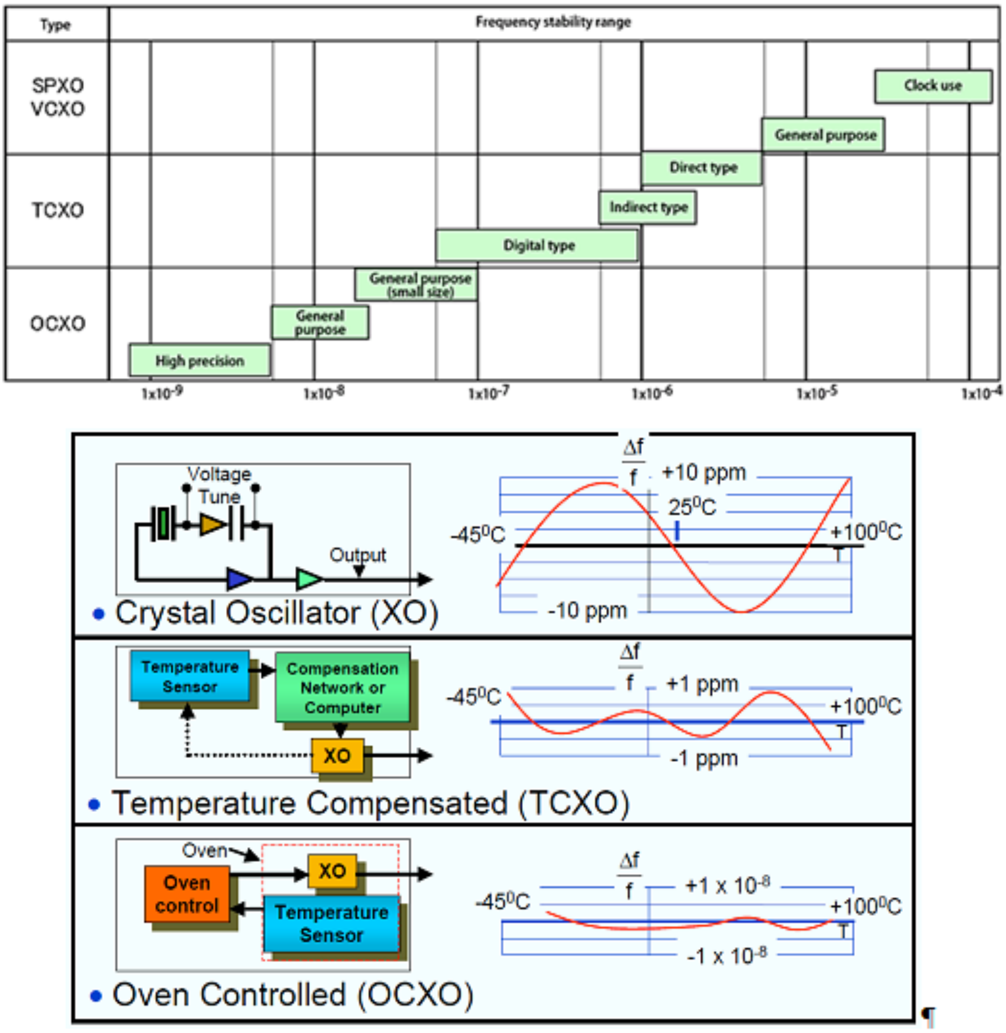
- Class 1 - Oscillators using discrete technology. This technology uses exclusively discrete type electronic parts (including surface mount devices) assembled and interconnected on a printed circuit board or an insulating substrate.
- Class 2 - Oscillators using microelectronic (hybrid) technology. This technology uses microelectronic circuit elements electrically and mechanically interconnected on an insulating substrate upon which resistors, capacitors, or conductors have been deposited, and used in a package that will be backfilled with an inert gas.
- Class 3 - Oscillators using mixed technology (i.e., a combination of discrete technology and microelectronic technology).

5.7.2.3 Specific space constraint and requirements

The assembly of the quartz crystal, its purity and the EEE components used in circuitry require special attention. In particular, for almost all space application, swept quartz are used for stability in radiation and 3 or 4 points are used for mounting the quartz in package. EEE parts used in circuitry (active devices) shall be resistant to a certain level of radiation.

5.7.2.4 Main characteristics

The frequency stability is the main characteristic of the different types of oscillator. It is summarised in the following table. Different parameter may influence the frequency like time, temperature, acceleration and radiation.



Type of crystal oscillator and frequency stability

Today, the logic used is mainly TTL, CMOS and AC MOS. Others, like HC MOS cannot be excluded. ECL is no longer used.

5.7.2.5 Suppliers and available products

All the different types of crystal oscillator are used in space.

Space needs by years: XO type around 1000 by years, TCXO and VCXO around 100 each and OCXO for several units.

The last 3 are relatively complex components and are usually treated as equipments. XO are either Hybrid or encapsulated PCB but are generally treated as a component.

No ESCC specification exist for this type of component, projects are using the MIL-PRF-55310.

RAKON and KVG (qualification on-going under DLR specification) are 2 European manufacturers of oscillators used in space application. TEMEX is part of RAKON group since 2010. QTECH is also used in space application with some parts in QPL MIL but space product are under ITAR like almost all US oscillator manufacturers sometimes used (VECTRON, …). These 3 manufacturers covers all the needs of space projects from simple XO to OCXO.

5.7.2.6 Activities

In term of performance increase

- Frequency range extension with SAW devices
- Power consumption for OCXO with work to be done on crystal but also on design
- Radiation on ASIC for OCXO potential to reduce the size of the device by integrating all the function in the ASIC

In term of miniaturisation

- SMD package to replace feed through or flat pack
- ASIC for OCXO (see above)

In term of procurement/use

- ESCC qualification
- XO programmable oscillator for telecom application 10 / 80Mhz with a potential to reduce the delay for production of oscillator with different but grouped resonance frequencies

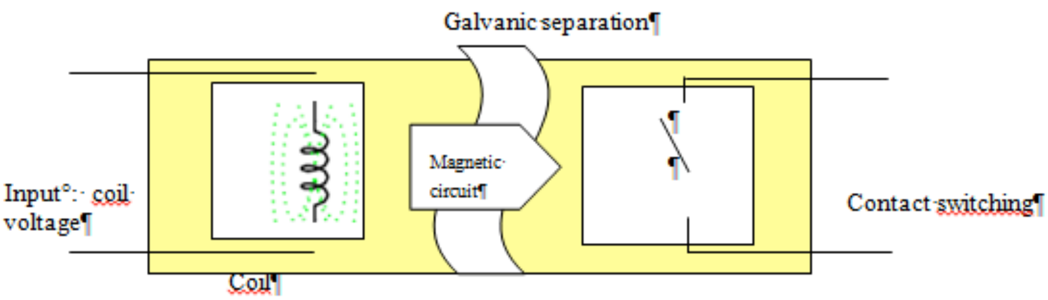
5.8 Relays

5.8.1 Overview

Electromechanical relays work on the principle of a mechanical force generated due to the current flow in a coil wound on a magnetic core. This force results in the operation of a contact arrangement which is used for relaying the operated condition to the desired circuit in order to achieve the required function. Since the mechanical force is generated due to an electric current flow, the term “electromechanical relay” is used.

Relay construction

All the relays are based on the same principle: a control circuit isolated from the contacts. This principle is declined on various configurations like latching or non-latching, the number of contacts, the switching capability ….



Control circuit (motor)

The circuit control is a magnetic circuit. An electric current through a coil will produce a magnetic field oriented along the length of the coil. The greater the current, the greater the strength of the magnetic field is. This magnetic field can be used to exert a mechanical force on a movable magnetic object (armature). This relay coil/armature assembly is used to actuate a set of movable contacts.

The "normal" state of relay's contacts is that state when the coil is de-energized, as not connected to any circuit. Those contacts may be normally-open or normally-closed.

Contact

The choice of the contact material depends on the switching capability of the relays. Relays can operate under a wide range of loads in terms of voltage and current. So far, no universal contact material is known, that can be used on all load types with optimum performance.

The main criteria to select the appropriate material are:

- Electrical conductivity
- Thermal conductivity
- Resistance to contact erosion (harness, Young's modulus)
- Resistance to material transfer
- Resistance to welding

It results that the main materials used are:

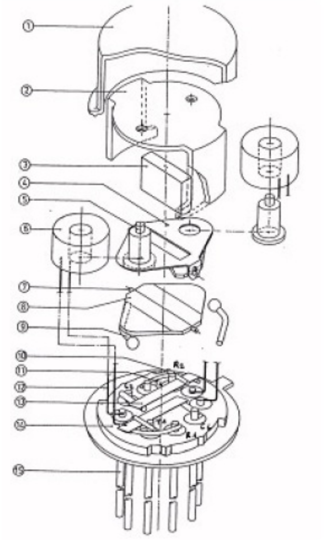
- For low current relays: Silver fine, with or not gold finish. Fine silver has the highest electrical and thermal properties of all metals. It is the best general purpose material available. The best advantage is the low contact resistance. The main inconvenient is quick deterioration in case of switching loads that produce a high energy arc.
- For high current: Silver Cadmium Oxide. Silver cadmium oxide contacts are less electrically conductive than fine silver contacts, but have superior resistance to material transfer and material loss due to arcing.

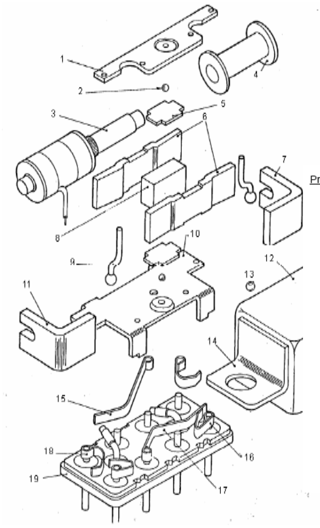
Setting

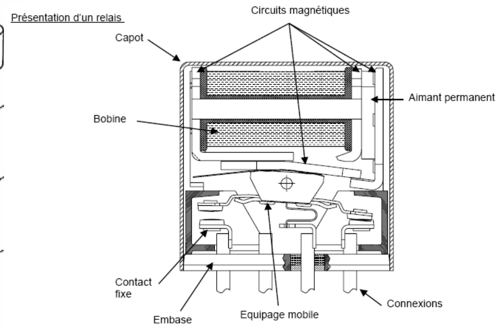
The settings of the relays are based on the Holm curves and take into account several elements like the contact materials, the contacts gap, the internal gas inside the cavity, the pressure, etc.

Cases

All the relays used for space activities are packaged in a hermetic case. First of all, the case protects the relay from all the external stresses like pollution and handing. But the main goal is to maintain a controlled internal atmosphere. The properties of the internal gas help to control the switching capability and the gas is a part of the setting of the relay. Generally, the nitrogen is used, pure or with a controlled percentage of other gas (helium for example). The hermeticity allows also maintaining a constant pressure inside the cavity. Consequently all the relays used glass/metal feed-through.







Several examples of relay construction

5.8.2 Classification

The various relays types are generally classified according the following criteria:

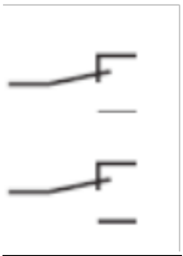
<u>Circuit control</u>

- Non latching relay: a relay is called “non-latching” or “monostable” when its contacts return automatically to the reset position (release state) after the coil is de-energized. A non-latching relay has an initial position of normally closed (NC) maintained by the force of a spring or permanent magnet while no current flows. The normally open (NO) contact is maintained by the force of the magnetic field while current flows through the coil. This kind of relays has only one coil.
- Latching relay: in a “latching” relay (also called “bistable”), the contacts remain in the last switching position once the coil input voltage is disconnected. Latching relays only require a short set or reset pulse and do not need any energization once the switching position changed. Unless otherwise stated the latching relays can endure a permanent energization. This kind of relays has 2 coils.

<u>Contact arrangement</u>

- <u>SPDT: Single pole double throw contact</u>. A single pole relay connects one common line (movable contact) to one load line (stationary contact). A double throw contact switches one common line between two stationary contacts, for example between a NO contact and a NC contact.

- DPDT: Double pole double throw contact. A double pole relay switches two, electrically not connected common lines with two electrically independent load lines. A double throw contact switches one common line between two stationary contacts, for example between a NO contact and a NC contact.



Switching capability

- Low current relays up to1A
- High current relay from to 2A to 25A
- High voltage (from 250V to more than 2KV)
- Very High current (>25A)

5.8.3 Specific space constraint and requirements

Relays are appreciated for having a physical insulation when switched off. (no parasitic diode like on MOSFET)

Most of the relays used in space applications are latching versions. Relays are currently used in power distribution, for instance: equipment reconfiguration, thermal control system, connecting /disconnecting of DC-DC converter, secondary voltage distribution. Additional TO5 relays can be used for status telemetry.

Relays are often used outside the qualified area, for example: few switching cycles but overload condition (failure suppression). Commutation aid circuits are often necessary for such application. This kind of use implies that the contacts are never switched during their mission.

Particular constraints shall be taken into account when considering relays for space applications.

- The high level of shocks and vibrations induced by the launch
- The vacuum environment is constraining. Special attention shall be paid to the hermeticity. A leakage would empty the cavity and modify the arc properties. Consequently the switching capability could be affected.
- Lot of applications is specific and need additional validations, even for qualified products, for instance the overload.

The other Space constraints common to all EEE components are also applicable: materials forbidden, etc. as mentioned in the ECSS Q ST 60.

5.8.4 Main characteristics

Relays are defined by 3 main characteristics; the circuit control, the switching capability and the contact arrangement. The temperature range is similar to most of the components (-55°C / +125°C)

The circuit control: 1 coil for non-latching relays and 2 coils for latching. Typically the coils are specified to work from 6 to 26V.

KEY parameters: coil voltage

coil resistor

The switching capability depends on the material, the shape, the atmosphere and the setting of the relay. The space range starts from 1A to 50A under 28V or 50V when used with resistive loads.

KEY parameters: pick up /drop out voltage for non-latching relay

latch / reset voltage for latching version

operate time

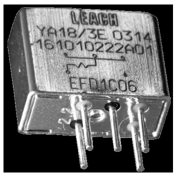
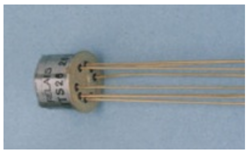
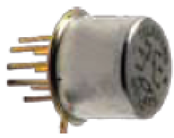
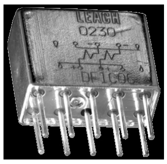
contact voltage drop

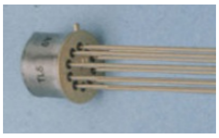
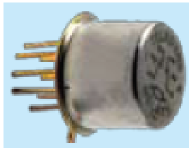
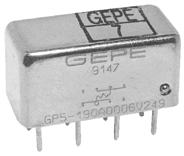
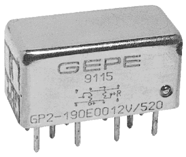
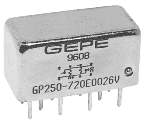
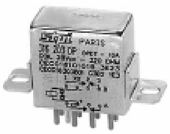
The contact arrangements allows various combinations in term of number of switches, single or double throw, or double break.

When used in standard conditions, rated current, rated voltage and resistive load, the electrical life expectancy is generally rated to be 100 000 operations. Special attention must be paid on other conditions (capacitive, inductive load, overload …)

5.8.5 *Suppliers and available products*

In Europe the manufacturers (Leach, REL, STPI) present a complete portfolio of relays that cover most of the needs. Recently Deutsch relays joined STPI group and change its name to REL. Teledyne (US) is also often used by project. Available products are presented in the following table.

Switching capability	Latching/non latching	Type/manufacturer	
1A/28V, 100 000 cycles	non latching	E/Leach	
		T/REL	
		J412/Teledyne	
	latching	D/Leach	

Switching capability	Latching/non latching	Type/manufacturer	
		TL/REL	
		J422/Teledyne	
2A/28V 100 000 cycles	non latching	GP5/Leach	
	latching	GP2/Leach	
2A/50V 100 000 cycles	latching	GP250/Leach	
15A/28V 100 000 cycles	non latching	E215/Leach	
	latching	EL215/Leach	
		317/STPI	
50A/50V 100 000 cycles	Latching 1PST + auxiliary contact (2A/28V)	PHL 50/REL	

High voltage and high current relays manufacturers are KILOVAC/US and HARTMANN/US (CII/US group).

5.8.6 Activities

The construction, which is quite old, leads to several limitations for the future needs.

Performance increase

- Maximum working voltage: the arc theory implies that voltage can't increase indefinitely. For these technologies, 120V seems to be a maximum. Higher voltage needs other technologies. Today, only Kilovac (US) propose component for high voltage application (which are under ITAR)
- Maximum temperature: due to the coil inside, the environment temperature is limited. If higher temperature usage was identified, other technologies should be used.
- Several new designs work under 100V. No relays able to switch 15A / 100V are available

Miniaturisation

- No more miniaturisation seems possible. Solid state relay may be a way forward but need deep evaluation.

Application

- Mechanical limitations: some relays are used in severe mechanical environment. The current specifications whatever the normative system is, are based on military specifications and don't cover the high level of shocks and vibrations induced by the launch phases.
- The switching capability of the relays is specified for one voltage. Most of the applications work at other voltages. A working area should be suitable.
- The common practices in term of coil supplying sometimes are different from the manufacturer recommendations.
- No best practice or hand-book available for relays used in space applications

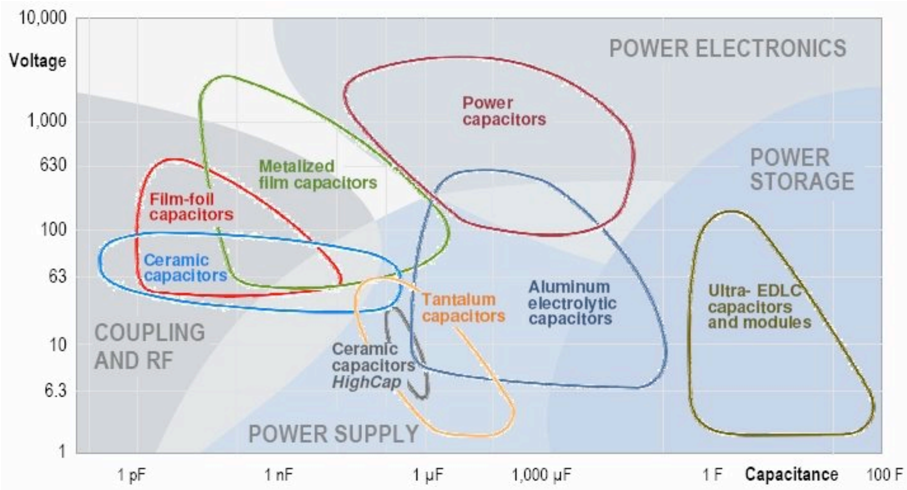
5.9 Capacitors

These pages focus on the main capacitor technologies used in space applications, i.e. :

- Ceramic capacitors
- Tantalum, Solid Electrolyte, Capacitors
- Tantalum, Gelled Electrolyte, Capacitors
- Metalized Film, plastic or Foil

Aluminium Electrolytic Capacitors, widely used in the industrial market, are not used in space applications due to their low reliability and propensity to expulse their electrolyte through a vent when temperature, and therefore pressure, increases.

The capacitance versus voltage repartition of the main capacitors technologies are shown in the picture below (KEMET 2008):



In the past, MLCC were essentially used in medium voltage (≥ 25V) and low capacitance (≤ 1µF) ranges. Higher capacitance and lower voltages applications were left to tantalum capacitors (or aluminium in industrial applications). Recently, MLCC experienced a growth in capacitance per volume, in particular with the introduction of class 2 X7R dielectrics, corresponding to a decrease of dielectric thickness, an increase of the numbers of active layers and the selection of dielectric materials showing an increase of dielectric constant. Still, solid tantalum capacitors have the highest volumetric efficiency. If voltages are limited, the recent improvements of tantalum polymer technology are expected to allow solid tantalum capacitors to compete with gelled electrolyte tantalum capacitors which offer high capacitance up to 100V – 125V. Significant limitations of gelled electrolyte tantalum capacitors are weight and capacitance loss under low temperature operation. If metalized film capacitors propose a lower volumetric efficiency, the voltage ranges peak above 1000 VDC and the manufacturing technology offers the possibility of flexible shapes.

Filters are not treated in these pages. For combined resistor and capacitor networks, no demand has been identified yet for space applications.

5.9.1 Ceramic

5.9.1.1 Overview

Ceramic, Multilayer, Chip

Multilayer ceramic capacitors (MLCC) are manufactured by mixing the ceramic powder in an organic or water based binder (slurry) and casting it into thin layers. In the dry process, metal electrodes, historically a mixture of silver and palladium (precious metal), are deposited onto the ceramic layers which are then stacked to form a laminated structure. In the alternate wet process, the dielectric (ceramic) ink and the metal electrode ink are sequentially printed onto a disposable substrate. The final element is then cut, released from the substrate in the wet process, and sintered to produce a single laminated block. The metal electrodes are arranged so that their terminations alternate from one edge of the capacitor to another. Upon sintering at high temperature the part becomes a monolithic block which can provide high capacitance values in small mechanical volumes.

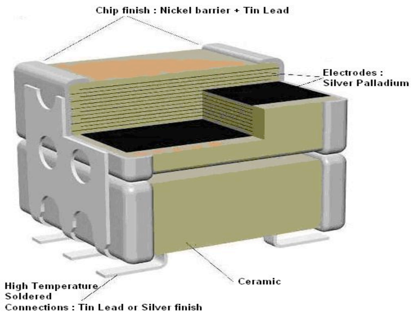
The development of thinner layers of metallic paste resulted in high quality thin metallic layers of greater smoothness and this led in turn to create thinner dielectric layers. Less metal is used and more layers, hence more capacity, can be achieved in the same volume. This has largely increased the ceramic range.

Products available in space QPLs (ESCC, MIL, JAXA) are compliant with the above description. MIL specifications require a 20µm minimum thickness when ESCC has no specific requirement since the Evaluation Phase allows to select adequate products for space applications.

Price pressure on palladium incited capacitors manufacturers to look for alternative inner electrode material. The alternatives are nickel and copper (base metal). Because of the oxidising properties of these two base metals, the firing process needs to be carried out under controlled inert atmospheres. Production of Base Metal Electrodes (BME) MLCC therefore requested large investments to achieve a low cost mass production. Most of the products use nickel electrodes. Although copper would offer the best solution in terms of cost, availability and electrical performance, its lower melting temperature and high oxidising rate make a successful production more difficult to achieve. Nickel electrodes BME MLCC are currently under space evaluation.

Ceramic Capacitors, Stacked

Some manufacturers propose stacked capacitor. Several (up to 5 in space qualified parts) MLCC capacitors are assembled in parallel. The quality of the soldering of chips on the lead frame, the nature and shape of the lead frame, play a great role in the thermo-mechanical behaviour of these assemblies. Mounting conditions have to be thoroughly defined by each user, including possible additional attachment such as gluing, clipping …



Ceramic Capacitors, Single Layer

The metallic plates that are the top and bottom of a single ceramic (dielectric) layer. In a Single Layer Capacitor (SLC), the outer metallized plates form the electrodes. Both Class 1 and Class 2 dielectrics may be used. Capacitance ranges from 0.05 pF to 2 000 pF. It is normally a low voltage device (25V to 100V). This technology is still used for high frequency products. Losses in the capacitors are identified with the Quality Factor $Q = 1 / 2\pi f C ESR$. The properties of the capacitor depends on the selection of the dielectric.

A US manufacturer, Dielectric Laboratories Inc. (A member of DOVER Group with NOVACAP, SYFER …) provides bondable chips generally used in high frequency hybrids.

Ceramic Capacitors, Multilayer, Porcelain

They are manufactured in a similar way as other MLCC and are dedicated to high frequency applications (RF / Microwave). The selection of the dielectric and the manufacturing process are tuned to guarantee the highest quality factor (low ESR / ESL) at the application frequency and minimize parasitic effects including the absence of piezoelectric effect and ageing.

These products are essentially procured from the US manufacturer American Technical Ceramics (ATC) , a subsidiary of AVX KYOCERA Group, with the following definitions :

Type	EIA Size	Q factor	TCC	WV DC	Range (pF)	Terminations
ATC100A	0505	>20 @ 1GHz	+90 ±20 ppm/°C	150V	0,1 to 100	Tin / Lead (W or P), Gold
ATC100B	1010	>10 @ 1GHz	+90 ±20 ppm/°C	500V 300V 200V 100V 50V	0,1 to 100 110 to 200 220 to 470 510 to 620 680 to 1 000	Tin / Lead (W or P), Gold
ATC700A	0505	> 2 @ 1GHz	0 ±30 ppm/°C	150V 50V	0,1 to 620 680 to 1 000	Tin / Lead (W or P), Gold
ATC700B	1010	>10 @ 1GHz	0 ±30 ppm/°C	500V 300V 200V 100V 50V	0,1 to 100 110 to 200 220 to 470 510 to 620 680 to 5 100	Tin / Lead (W or P), Gold

<u>Ceramic capacitors, leaded</u>

High voltage ceramic capacitors, with radial leads, Class 1 and Class 2, from 1.0 to 5.0 kV, are offered as ESCC qualified by AVX in Northern Ireland. The referenced specifications are ESCC 3001/033 (Class 1) and ESCC 3001/034 (Class 2). The related volumes remains quite low.

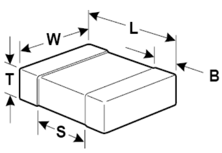
To complete this overview, some radial leaded ceramic capacitors type CKR06 (Class 2), are also procured from the US, either from KEMET or AVX, both qualified against MIL-PRF-39014. The most appreciated value in CKR06 range is the 50V – 1µF capacitor.

5.9.1.2 Classification

<u>Ceramic, Multilayer, Chip</u>

Chip ceramic capacitor are classified according to their size and dielectric type.

EIA SIZE CODE	Metric Size Code (Ref.)	LENGTH L (mm)	WIDTH W (mm)	BANDWIDTH B (mm)	SEPARATION S (mm) Minimum
0402	1005	1.0 ± 0.05	0.5 ± 0.05	0.2 – 0.4	0.3
0603	1608	1.6 ± 0.15	0.8 ± 0.15	0.35 ± 0.15	0.7
0805	2012	2.0 ± 0.2	1.25 ± 0.2	0.5 ± 0.25	0.75
1206	3216	3.2 ± 0.2	1.6 ± 0.2	0.5 ± 0.25	n/a
1210	3225	3.2 ± 0.2	2.5 ± 0.2	0.5 ± 0.25	n/a



1812	4532	4.5 ± 0.3	3.2 ± 0.3		0.6 ± 0.35	n/a
2220	5650	5.6 ± 0.4	5.0 ± 0.4		0.6 ± 0.35	n/a

The maximum height (T) allowed depends on the specification system used for reference :

EIA SIZE CODE	SPECIFICATION	HEIGHT T Max. (mm)	EIA SIZE CODE	SPECIFICATION	HEIGHT T Max. (mm)
0402	DSCC-DWG-03029	0,61			
0603	*ESCC 3009/0xx*	***1,00***	1210	ESCC 3009/004	2,30
	ESCC 3009/0xx	***1,00 (2C1)*** ***1,00 (X7R)***		ESCC 3009/009	2,30 (2C1) 1,80 (X7R)
	DSCC-DWG-03028	0,91		MIL-PRF-55681	1.50
	CECC 32101-801	0,80		CECC 32101-801	1,80
	QC 32100	0,80		QC 32100	2,00
0805	ESCC 3009/003	1,80	1812	ESCC 3009/005	2,30
	ESCC 3009/008	1,80 (2C1) 1,30 (X7R)		ESCC 3009/010	2,30 (2C1) 1,80 (X7R)
	MIL-PRF-55681	1.30		MIL-PRF-55681	1.50
	CECC 32101-801	1,30		CECC 32101-801	1,80
	QC 32100	1,30		QC 32100	2,50
1206	ESCC 3009/022	2,30	2220	ESCC 3009/006	2,30
	ESCC 3009/023	2,30 (2C1) 1,60 (X7R)		ESCC 3009/011	2,30 (2C1) 1,80 (X7R)
	MIL-PRF-55681	1.30			
	CECC 32101-801	1,60		CECC 32101-801	1,80
	QC 32100	1,60		QC 32100	2,50

EIA also defines the standard capacitance values available from manufacturers, identified as the E12 series :

10 12 15 18 22 27 33 39 47 56 68 82 to be used with $10^{\pm x}$ multipliers in pF, nF, µF.

Dielectric classification is defined in EIA, CECC and MIL as shown in the Table below (from SYFER) :

Dielectric Class	Class 1			Class 2		
Dielectric characteristics	Ultra stable			Stable		
IECQ-CECC	1B/CG			2C1	2R1	2X1
EIA		C0G/NP0			X7R	
MIL			CG(BP)	BZ		BX
Rated temperature range	-55ºC to +125ºC			-55ºC to +125ºC		
Maximum capacitance change over temperature range No DC voltage applied	0 ± 30 ppm/ºC			± 20%	± 15%	± 15%
Rated DC voltage applied	-			+20-30%	-	+15-25%

Ceramic Capacitors, Stacked

The temperature coefficients applicable to these products in the -55°C, +125°C range, vary from one specification to another as follows :

Specification	Dielectric Type	Voltage Range	Bias = 0 Volt	Bias = Rated Voltage
Mil-PRF-49470	BX	50/100V	±15%	+15, -25%
	BR	200V	±15%	+15, -40%
	B	500V	±15%	+15, -50%
ESCC 3001/030	-	50V to 500V	± 20%	+30, -50%
ESCC 3001/037		16V / 25V	± 20%	+30, -50%
ESCC 3001/038		50V to 500V	± 20%	+30, -50%

5.9.1.3 Specific space constraint and requirements

Ceramic, Multilayer, Chip

Ceramic chip capacitors are potentially fragile and are therefore sensitive to mounting conditions, thermal mismatch with the printed circuit boards and constraints applied to the boards (vibrations, shocks, flexions …). In order to overcome this problem, the automotive market requested more robust ceramic capacitors and manufacturers introduced flexible terminations, which consist in adding a polymer layer between the external electrode and the finishing layers. Flexible terminations have shown their capability to withstand an ESCC evaluation and are currently under ESCC qualification.

When available to space users, these new technologies will be defined in new ESCC detail specifications since they might apply to specific ceramic chip capacitors sizes and ranges.

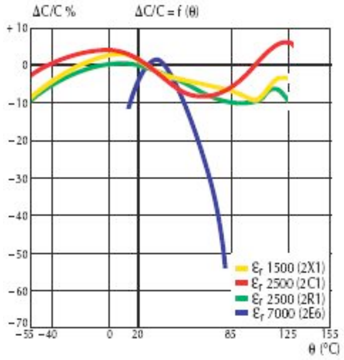
Ceramic chip capacitors sizes are compliant with EIA definition. Sizes used in space applications typically range from 0603 to 2220. Size 0402 starts being selected by some users. Sizes above 2220 are not recommended for surface mounting due to mechanical risk. Each user should validate the capability of selected ceramic chip capacitors to withstand its mounting conditions and its repairing methodology. The mechanical behaviour of ceramic capacitors depends on the ceramic / process used by the manufacturer, the size of the capacitor, the selected substrate, the pads design and the mounting conditions.

5.9.1.4 Main characteristics

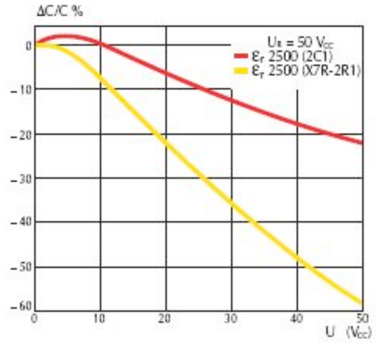
Tolerance typically ranges from 1% to 20%, Voltage rating ranges from 16V to 500V and the standard Operating Temperature range is -55°C / +125°C.

MLCC have an excellent Equivalent Series Resistance (ESR), very low with Class I dielectrics but to be taken into account with Class II dielectrics.

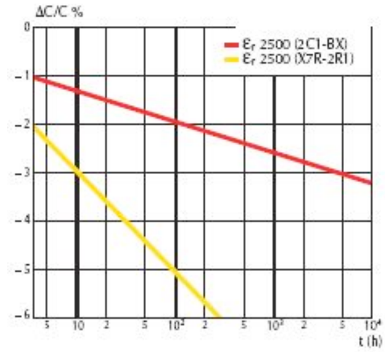
The electrical performance of MLCC depends on the characteristics of the selected ceramic material. Low dielectric constant (ε_r) Class 1 ceramics, known as C0G or NP0, are usually non-ferroelectric materials and show a linear response to voltage and temperature. C0G guarantees a capacitance variation from room temperature (+25°C) within 0 ± 30 ppm/°C (or $\Delta C_{Max}/C \leq 0.3\%$) over the -55°C to +125°C temperature range. They show no aging, no piezoelectric effect, as well as a low dielectric loss. High dielectric constant (ε_r) Class 2 ceramics are sensitive to external constraints and even in the absence of these the capacity has a tendency to decrease over the lifecycle of the component (ageing phenomenon).



Class 2 – Temperature (θ) effect



Class 2 – Applied Voltage (U) effect



Class 2 – Time (t) effect (Ageing)

(figures extracted from EUROFARAD data sheets)

5.9.1.5 Suppliers and available products

Ceramic, Multilayer, Chip

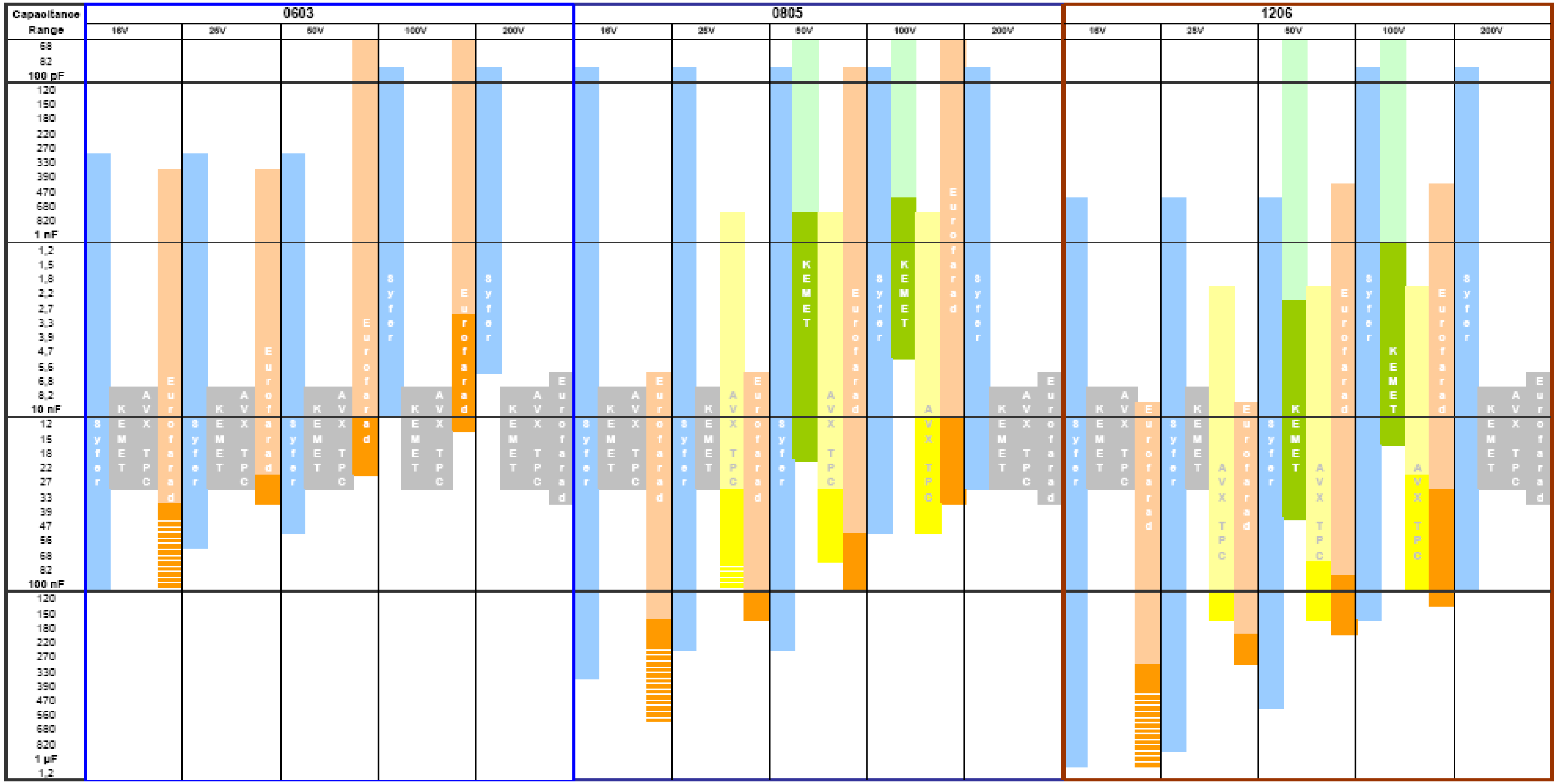
Manufacturers of Class 1 and 2 MLCC generally selected for space applications are AVX TPC (ESCC Qualified, 0805 to 2220, 25V to 100V), SYFER (EPPL Part 2, CECC 32101-801 Qualified, 0805 to 1812, 50V to 200V) and KEMET (MIL-QPL-55681, CDR31 to CDR34, 0805 to 1812, 50V and 100V). They all offer the possibility to have a tin-lead finish.

ESCC activities are currently on-going at EUROFARAD (ESCC Evaluation / Qualification in progress, 0603 to 2220, 16V to 100V), AVX Ireland (ESCC Evaluation of BME technology, 0603 to 2220, 25V to 100V) and AVX TPC (Extension of ESCC Qualification of class 2 25V range and extension to 200V range).

The Tables below show the actual Class 2 and Class 1 ranges for these manufacturers. For an accurate status, refer to the relevant QPL or EPPL.

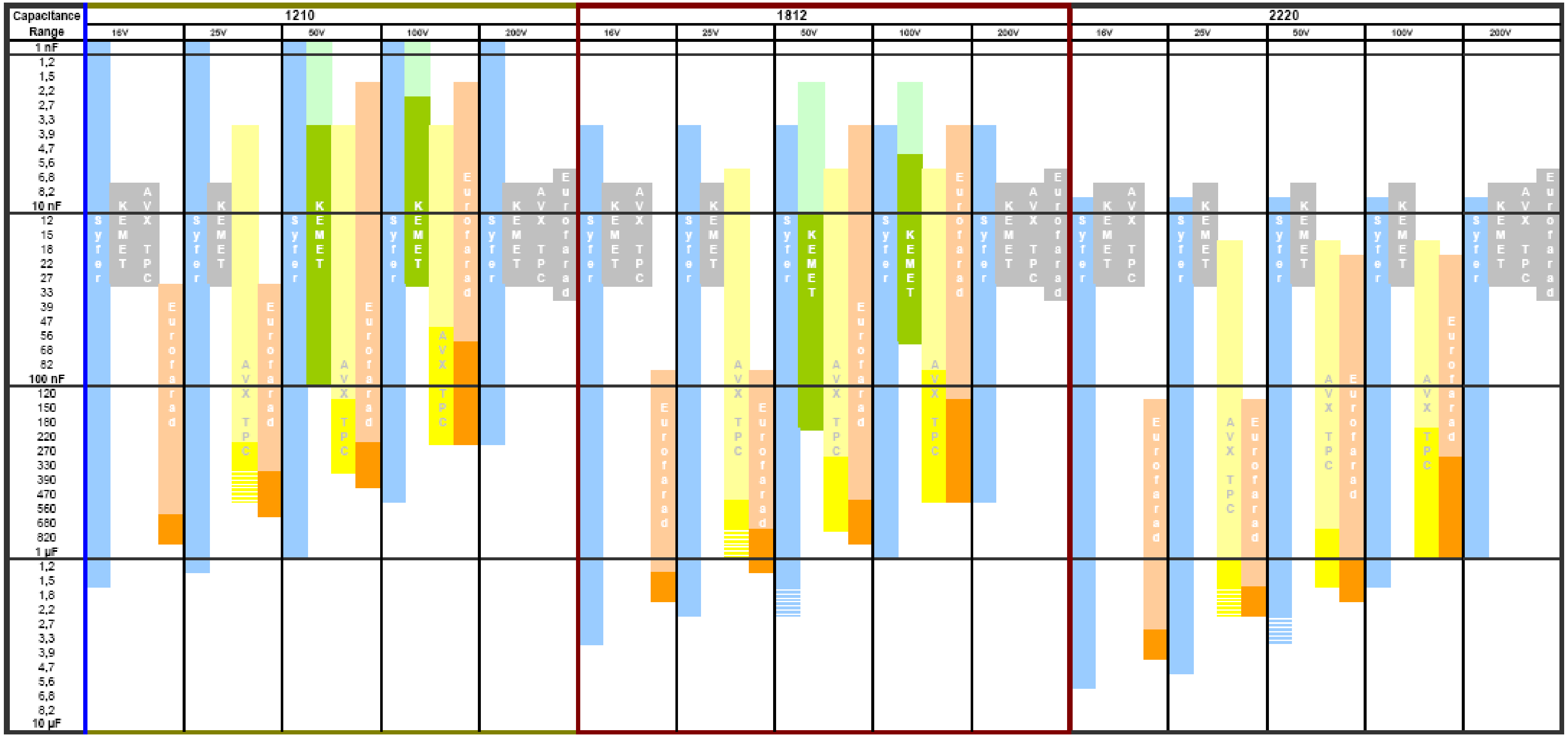
Ceramic chip, high voltage, class II are also available as ESCC qualified from AVX (UK). The available chip sizes are 1812 and 1825, available rated voltages are 1.0 to 3.0 kV. Although not ESCC qualified, high voltage chip are also available from EUROFARAD, France. Types C179S and C180S are class I chip, sizes 1812 and 2220, available according to ESCC with rated voltages from 200V to 4kV (1812) or 5kV (2220). Similarly, types C279S and C280S are class II chip, X7R, sizes 1812 and 2220, available according to ESCC with the same rated voltages.

Note also that, for high voltages, leaded versions were usually preferred and are still available as ESCC qualified from AVX (UK) with class II types VR, CV and CH offering rated voltages from 1.0 to 5.0 kV.



Cl

Class 2 ceramic chip capacitors, 0603, 0805, 1206



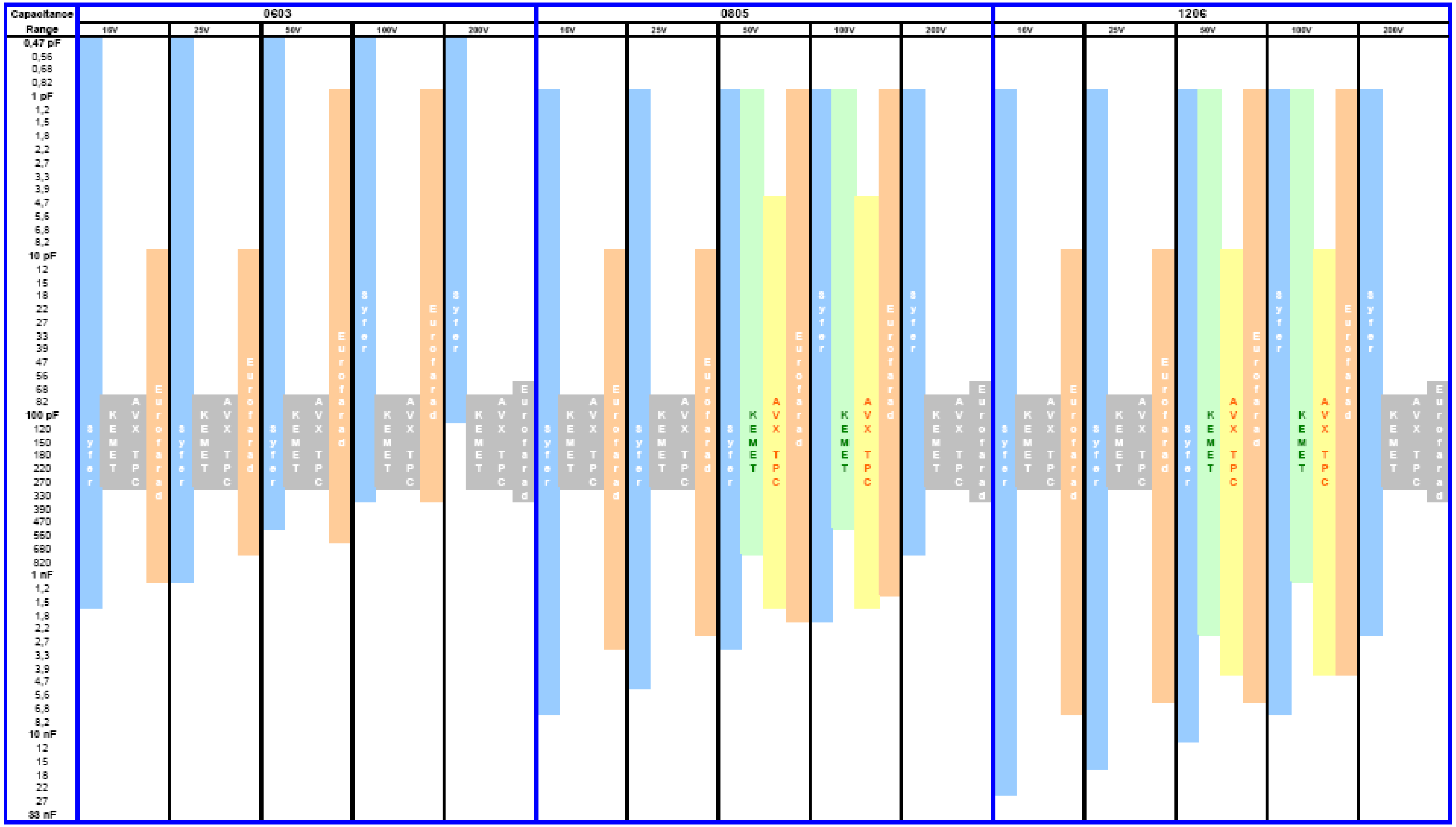
Class 2 ceramic chip capacitors, 1210, 1812, 2220

Class 1

Ceramic

Chip Capacitors

0603, 0805, 1206



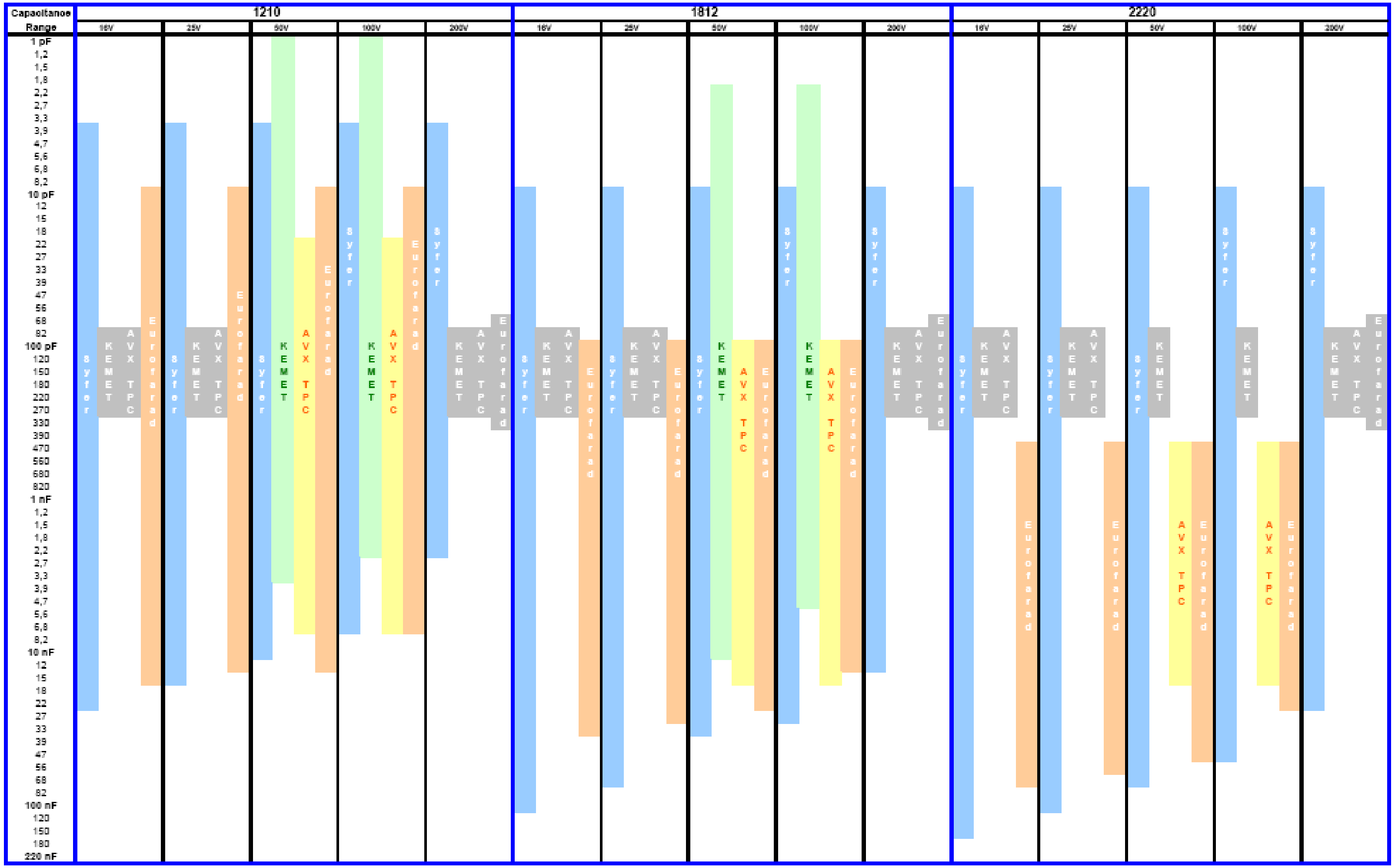
European Space Agency
Agence spatiale européenne

Class 1

Ceramic

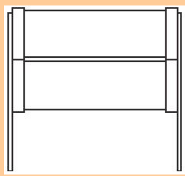
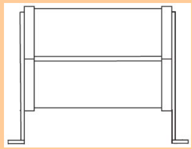
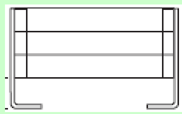
Chip Capacitors

1210, 1812, 2220



Ceramic Capacitors, Stacked

The main manufacturers used in space applications are AVX (ESCC Qualified), EUROFARAD (EPPL) and PRESIDIO (MIL) :

Supplier / Specification	Voltage Range						Leads Shape		
	16V	25V	50V	100V	200V	500V	Straight Leads	L shape Leads	J shape Leads
AVX ESCC 3001/030									
EUROFARAD ESCC 3001/037									
EUROFARAD ESCC 3001/038									
PRESIDIO MIL-PRF-49470									

5.9.1.6 Activities

Selected for their very low ESR, their stability in temperature (Class 1), the wide voltage ranges offered, ceramic capacitors have still to progress in terms of size and weight to better compete with other technologies. Their mechanical fragility has also to be taken into account.

The evolution of ceramic capacitors tends to answer to users' needs

- replacement of Silver Palladium inner electrodes with non-noble materials (BME) such as nickel or copper associated to high dielectric constant / low thickness ceramics thus resulting in increased capacitance ranges and lower voltages,
- miniaturisation up to 0201 and now 01005 although placement costs increase strongly below 0402,
- implementation of flexible terminations with polymer reduces mechanical fragility.

Space business is showing interest in these evolutions. The following activities have been initiated and should be pursued in the coming years :

- evaluation of BME technology which potentially offers higher volumetric capacitance (a first action initiated by CNES with AVX in 2007 on 0603 chip dedicated to the automotive market gave positive results and has been followed with an ESA evaluation of AVX BME chip manufactured with a more flexible process that have been introduced in EPPL II)
- evaluation/qualification in 2007 – 2011 of Sizes 0603 to 2220 and 16V to 100V ranges manufactured by EUROFARAD with a new process put in place in 2006 should be shortly followed with an extension of these activities to Size 0402 and 10V range

- evaluation / qualification in 2009 – 2011 of flexible terminations proposed by EUROFARAD on Sizes 0603 to 1206 should be followed shortly with the evaluation / qualification of full 0402 – 2220 ranges implementing flexible terminations

Have also to be taken into account :

- customer requests to beneficiate of 200Vand 500V ranges when chip are generally qualified up to 100V
- similar requests for higher voltages chip when current high voltage ceramic capacitors (1kV to 5kV) are only available in radial leads form as space qualified,
- market evolutions or constraints which make the availability of dielectric powders more volatile, including the potential impacts of RoHS and WEEE, the tension around rare earths (Neodymium is used in Class 1 dielectrics …)
- High temperature for new converter for GaN based application

5.9.2 Electrolytic, solid

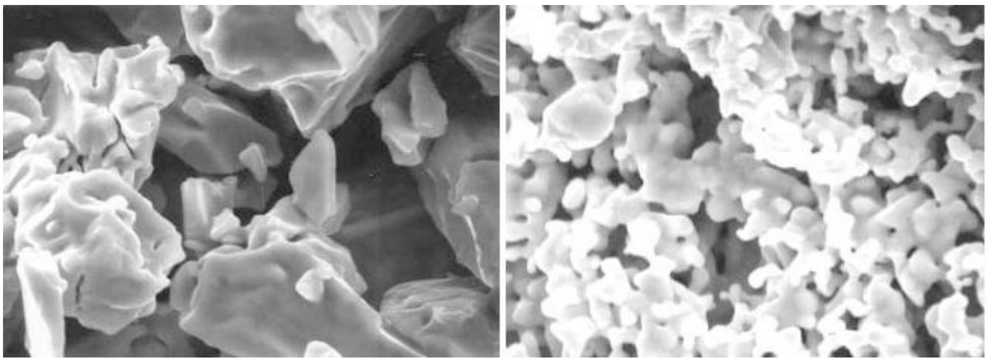
5.9.2.1 Overview

<u>Tantalum Sintered Anode, Manganese Dioxide (MnO2)</u>

The anode consists of tantalum powder mixed with an organic binder and pressed into a pellet form.

The binder ensures that the tantalum particles will adhere to each other when pressed to form the anode and flow easily into the press tool. The particles are generally pressed around the anode tantalum wire (in the picture beside, the tantalum wire will later be welded on the pellet). The binder is driven off by heating the pellet (or slug) under vacuum at temperature around 150°C for several minutes.

The pellets are then sintered at high temperature (typically 1500-2000°C) under vacuum. This causes the individual particles to join together to form a sponge-like structure. This structure is of high mechanical strength and density but is also highly porous giving a large internal surface area. The capacitance value will depend on the particle size distribution resulting from the selection by the manufacturer of the proper particle density (below two examples with a 4 400 CV/g and a 20 000 CV/g powder shown at the same x8600 magnification) The sintering process also helps to drive off the majority of the impurities within the powder by migration to the surface.



The anode tantalum wire is welded on the pellet.

The dielectric layer of tantalum pentoxide is produced by the electrochemical process of anodisation. The pellet is dipped into a very weak solution of acid (as example phosphoric acid) at elevated temperature (for example 85°C) and the voltage and current are controlled to form the pentoxide layer (Ta2O5).

The dielectric thickness is controlled by the voltage applied during the formation process (a pentoxide colour chart allows to identify the dielectric thickness corresponding to the voltage range and formation duration). The thickness of this layer is about 60 Angstroms (6nm) per capacitor rated volt. The formation voltage is about 4 times the expected nominal voltage.

The pellets are then impregnated with an aqueous solution of manganese salt, which is decomposed by pyrolysis to yield manganese dioxide (MnO2 cathode layer).

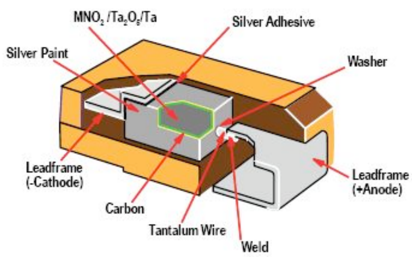
The manganese dioxide is the working electrolyte in the solid form.

A graphite layer is applied over the surface of the manganese dioxide to allow for application of a silver paint.

The graphite layer is used to prevent the silver layer coming into direct contact with the manganese dioxide. If this occur a chemical reaction would take place, and the silver would be oxidised to high resistivity silver oxide and the manganese dioxide reduced to manganese oxide which has a high resistivity. The part would therefore become high resistance and the capacitor cease to function adequately.

The surface mount tantalum solid capacitor is obtained by gluing with a conductive epoxy / silver paste the cathode to the cathode lead frame / terminal and soldering the tantalum wire to the anode lead frame / terminal, then moulding the whole with an epoxy resin.

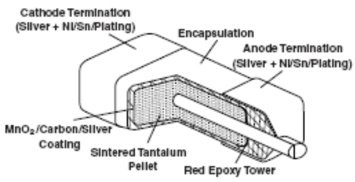
A new construction, with face down termination, has been recently proposed in order to lower the capacitor ESL. This design also allows a better volumetric efficiency, however the potentially negative impact of mounting conditions has to be assessed.

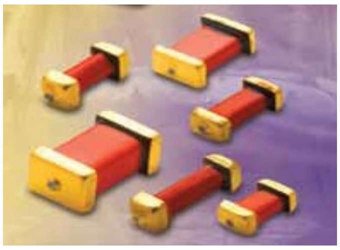


KEMET CWR11

A similar process is used to manufacture solid tantalum leaded capacitors in metal cases. The completed pellet is then inserted into a pool of molten solder inside the metal case which is then sealed. The solder is displaced up around the sides of the pellet to provide an electrical and mechanical bond to the case.

Alternative designs such as conformal coated capacitors, with or without end caps, have been showing greater limitations, in particular as a result of mounting constraints and are therefore **not recommended for space applications**.





VISHAY 595D **VISHAY CWR 06/16**

Tantalum, Sintered Anode, Conductive Polymer

This type of capacitor is a recent development and is in continuous evolution with the support of polymer material suppliers. A conductive polymer counter electrode replaces the classical manganese dioxide (MnO2) cathode electrode and allows very low ESR values. This type of capacitor combines the best high frequency performance characteristics of ceramic capacitors with the unmatched high volumetric efficiency/capacitance of tantalum capacitors. The primary applications for these parts are input/output filtering on power converters and power decoupling around microprocessors. The electrical characteristics have shown a slightly different current conductivity mechanism compared to standard tantalum capacitors. However, some self-healing of the cathode film has been reported. This can be attributed to film evaporation, carbonising or re-oxidation. Not all the breakdowns of conductive polymer capacitors will lead to self-healing or an open circuit state. Short circuits may also occur. MnO2 parts were found to be more capable of self-healing but some additional work on conductive polymer materials may be required in order to understand their physical properties and potentials for future applications.

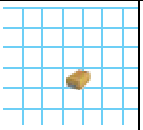
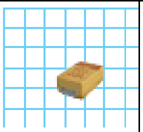
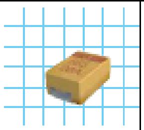
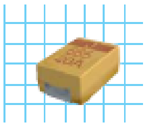
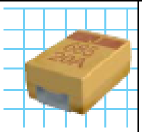
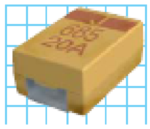
The available manufacturers data show limited temperature and voltage ranges, higher leakage current, some sensitivity to moisture and to the moulding constraints. Some manufacturers therefore envisaged sealed packages. This construction also implements face down termination. Preliminary evaluations have already been initiated under space contracts. Regarding the nominal voltage, manufacturers have announced that advanced studies show the possibility to increase voltage to 75V and above in the near future.

Niobium, Sintered Anode

Niobium is used as a replacement for tantalum to lower the production cost. If the volumetric efficiency is lower than tantalum-based capacitors, niobium-based configuration NbO / Nb2O5 / MnO2 is expected to offer a superior safety since it is more resistant to failure by ignition and also would rather fail in an open circuit state than in a short circuit state.

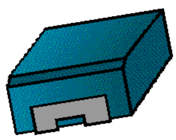
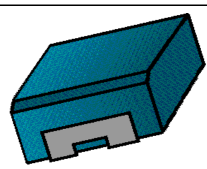
5.9.2.2 Classification

Surface Mount moulded tantalum capacitors sizes A to D have been initially defined in MIL specifications. Other sizes are available from manufacturers, without harmonization regarding their identification or the package height :

Packages (all dimensions in mm, mean values)						
AVX Identification	**A**	**B**	**C**	**D**	**E**	**V**
L(length) x W (width)	3.20 x 1.60	3.50 x 2.80	6.00 x 3.20	7.30 x 4.30	7.30 x 4.30	7.30 x 6.10
H (height)	1.60	1.90	2.50	2.80	4.10	3.45
KEMET Identification	**A**	**B**	**C**	**D**	**X**	**E**
L(length) x W (width)	3.20 x 1.60	3.50 x 2.80	6.00 x 3.20	7.30 x 4.30	7.30 x 4.30	7.30 x 6.00
H (height)	1.60	1.90	2.50	2.80	4.00	3.60

Both manufacturers AVX and KEMET provide matte pure tin and tin-lead finish options.

Are also used in space applications CTC21 and CTC21E from FIRADEC, available as ESCC evaluated and therefore present in EPPL up to 63V. The 100V range showed process related limitations and is not recommended for space applications. Two package sizes are available, C and D, significantly bigger than those offered by their competitors :

Packages (all dimensions in mm, maximum values)		
FIRADEC Identification	**C**	**D**
L(length) x W (width)	11.50 x 9.50	11.50 x 13.00
H (height)	5.00	6.00

The nominal finish is an electrolytic tin-lead. Pure tin can be obtained on request.

5.9.2.3 Specific space constraint and requirements

The main failure mode of tantalum manganese dioxide capacitors is high current leakage. When sufficient energy is available, a self-healing process allows the MnO_2 leaking sites to be transformed into highly resistive Mn_2O_3. When excessive energy is available, the leaking MnO_2 sites might not have enough time to become resistive and the capacitor may enter into thermal runaway conditions, therefore burning or exploding. These phenomena most of the time result in a short circuit condition and might be destructive for the surrounding electronics. Preventive actions include implementation of an efficient surge current screening of the capacitors, implementation of strict de-rating rules, and implementation of a high series resistance or a current limitation where possible. In addition, these capacitors, and in particular the highest values in the biggest packages, are sensitive to mounting conditions which must take into account manufacturer's recommendations.

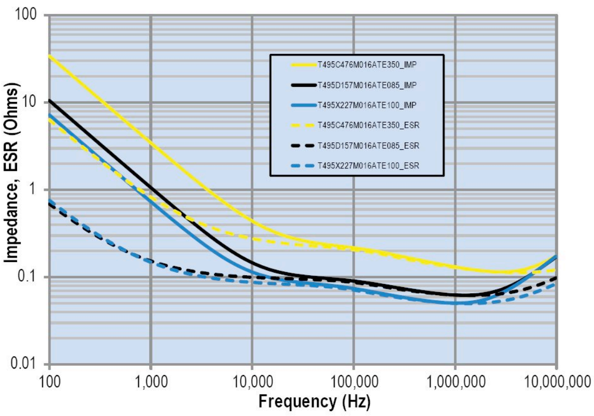
These polarized capacitors are very sensitive to reverse voltages. Among manufacturers' recommendations, AVX gives the most drastic ones.

Temperature	Maximum Reverse Voltage KEMET / FIRADEC	Maximum Reverse Voltage AVX
+20°C	15% Un	
+25°C		10% Un up to 1V max.
+85°C	5% Un	3% Un up to 0.3V max.
+125°C	1% Un	1% Un up to 0.1V max.

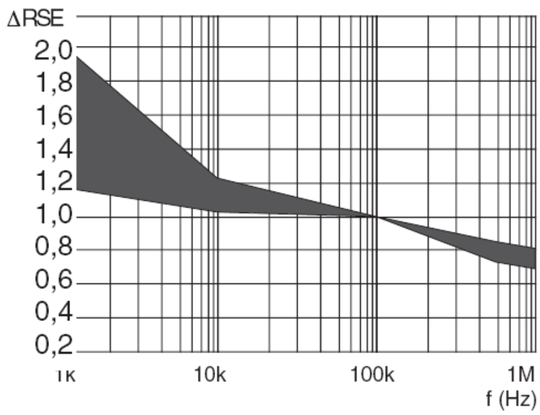
5.9.2.4 Main characteristics

The available standard capacitance values are defined by EIA as the E6 series ; **10 15 22 33 47 68** to be used with $10^{\pm x}$ multipliers in µF.

Tolerances typically ranges from 5% to 20%, Voltage rating ranges from 4V to 63V and the standard Operating Temperature range is -55°C / +125°C. Their main characteristics are high capacitance values, a good stability of the electrical characteristics over the temperature range and decreasing ESR values with the evolution of the capacitors technology. The lowest ESR values are obtained with multiple anodes in parallel. The ESR is the major contributing factor to the impedance at high frequencies (above 100 kHz) and is measured at 100 kHz (500 kHz on FIRADEC CTC21 and CTC21E).



KEMET T495



FIRADEC

5.9.2.5 Suppliers and available products

ESCC activity is currently on-going AVX Czech Republic, covering the ESCC Evaluation and Qualification of Low ESR TES series based on TPS (TRJ) and TPM (TRM) series.

The Tables below show the actual offer from the three manufacturers, AVX, KEMET and FIRADEC. For an accurate status, refer to the relevant QPL or EPPL.

Manufacturer	AVX				AVX			
Style	CWR 11	TAJ	TBx C+	TES	CWR 11	TAJ	TBx C+	TES
Voltage (V)	4	4	4	4	6.3	6.3	6	6.3
Values (µF)								
0.10								
0.16								
0.22								
0.33								
0.47								
0.68								
1.0								
1.6					A			
2.2	A				A	A		
3.3		A			A	A	A	
4.7	A	A			B	A	A	
6.8	B	A			B	A, B	A	
10.0	B	A, B			B	B	A	
16.0	B	B			C	B, C	A	
22.0		B, C			C	C	A, B	A
33.0	C	C	A			C	B	
47.0		C, D			D	C, D	C	B
68.0	D	C, D	A		D	D	B, C, D	
100.0	D	D	A, B			D	CL	
160.0		D				D	D, E	C
220.0		E				E	DL, E	
330.0							EL	D36
470.0							EL, VL E18	E30
680.0			E18				E18, V23	
1000.0			E18, V18					
1600.0			E15					

Manufacturer	AVX				AVX			
Style	CWR 11	TAJ	TBx C+	TES	CWR 11	TAJ	TBx C+	TES
Voltage (V)	10	10	10	10	16	16	16	16
Values (µF)								
0.10								
0.16								
0.22								
0.33								
0.47								
0.68					A			
1.0	A				A	A		
1.6	A	A			A	A		
2.2	A	A			B	A, B	A	
3.3	B	A			B	A, B	A	
4.7	B	A, B	A		B	B	A	A
6.8	B	B	A			B, C	A, B	
10.0		B, C	A	A	C	C	A, B	
16.0	C	C	A, B			C	B	
22.0		C	B, C		D	C, D	B, C	B
33.0	D	C, D	A, B, C	B	D	D	CL, D	
47.0	D	D	C, D			D	C, DL	C
68.0		D	CL, D, E			D	D	
100.0		D	CL, DL, E	C		E	DL, EL	D66
160.0		E	DL, E	D46			DL, VL E30	E40
220.0		E	DL, EL	D36			VL, E25	
330.0			DL, EL, VL E23	E36				
470.0			EL, VL E23					
680.0								
1000.0								
1600.0								

Manufacturer	AVX				AVX			
Style	CWR 11	TAJ	TBx C+	TES	CWR 11	TAJ	TBx C+	TES
Voltage (V)	20	20	20	20	25	25	25	25
Values (µF)								
0.10								
0.16								
0.22								
0.33					A			
0.47	A				A			
0.68	A				B	A	A	
1.0	A				B	A	A	A
1.6	B		A		B	A	A	
2.2	B		A		C	B	A, B	
3.3	B			A	C	B	B	
4.7	C		A, B		C	B, C	A, B	B
6.8	C		B		D	C	B, C	
10.0			B, C	B	D	C	C	C
16.0	D		B, C, D		D	C, D	D, EL	
22.0	D		B, C, D	C		D	C, DL, E	
33.0			C, DL	C		D	DL, EL	D86
47.0			DL, E	D66		E	D	E86
68.0			DL, E			E	VL, E46	
100.0			VL, E36	E46				
160.0								
220.0								
330.0								
470.0								
680.0								
1000.0								
1600.0								

Manufacturer	AVX				AVX			
Style	CWR 11	TAJ	TBx C+	TES	CWR 11	TAJ	TBJ C+	TES
Voltage (V)	35	35	35	35	50	50	50	50
Values (µF)								
0.10	A				A	A	A	
0.16	A				B	A	A	
0.22	A				B	A	A, B	
0.33	A				B	A		
0.47	B	A	A		C	A, B	A, B	
0.68	B	A	A		C	A, B	A	
1.0	B	A	A		C	B	A, B	B
1.6	C	B	A, B		D	B, C	C, D	
2.2	C	B	B		D	B, C	D	
3.3	C	B, C	B	B	D	C	D	C
4.7	D	C	B, C, D	C	D	C, D	D, E	D
6.8	D	C, D	C, D, E			D	D, E	
10.0		C, D	C, D, E	D		D	E	E
16.0		D	C, DL, E			D	E	
22.0		D	D, E80	D100		E		
33.0		E	D, E60	E86				
47.0			V, E66					
68.0								
100.0								
160.0								
220.0								
330.0								
470.0								
680.0								
1000.0								
1600.0								

L : low ESR version (≤ 100 mΩ) available
L : low ESR version (≤ 100 mΩ)
15 : ESR value
TBJ C+ values issued from DSCC Drawings 95158 and 07016

Manufacturer	KEMET				KEMET				KEMET				KEMET				KEMET			KEMET			KEMET			KEMET		
Style	CWR 11	T493	T495	T510	CWR 11	T493	T495	T510	CWR 11	T493	T495	T510	CWR 11	T493	T495	T510	CWR 11	T493	T495	CWR 11	T493	T495	CWR 11	T493	T495	CWR 11	T493	T495
Voltage (V)	4	4	4	4	6,3	6,3	6,3	6,3	10	10	10	10	15	16	16	16	20	20	20	25	25	25	35	35	35	50	50	50
Values (µF)																												
0.10																							A			A	A	
0.15																							A			B		
0.22																							A			B		
0.33																				A			A			B		
0.47																	A			A			B	A		C	B	
0.68													A				A			B	A		B	A		C		
1.0									A				A				A			B	A		B	A		C		
1.5					A				A				A				B	A		B	A		C	B		D	C, D	
2.2	A				A				A				B	A			B			C	B		C	B		D	D	
3.3					A	A			B				B	A			B			C	B		C			D	D	
4.7	A				B	A			B	A			B				C	A, B		C	B		D		C	D	D	X
6.8	B				B	A			B	A				B			C	B		D	C		D	D	X		X	
10.0	B				B	A				A			C	B				B, C		D	C			C	D, X			
15.0	B				C	A			C	A, B				B			D	C	D	D		D, X		D	X			
22.0					C	A, B				B, C			D	C			D	C	D		D	X		D	X			
33.0	C	A				B			D	B, C			D	C	D			D			D	X		X				
47.0					D	C			D	C	D			C	D			D	X		D							
68.0	D				D	C	D			C, D	X			D				D, X	X									
100.0	D	B				C					D, X			D	X													
150.0							X				D, X			D														
220.0						D	D, X			D, X	X																	
330.0						X				X		X35																
470.0																												
680.0								E23																				
1000.0				E18																								
1500.0																												

CWR11 = T492
T493 = Military COTS, Low ESR version available. Limited range available against DSCC drawing No. 07016
T495 = Low ESR, Surge Robust, available against DSCC drawing No. 95158 in C, D, X packages
T510 = Multianode, Ultra Low ESR, limited space range

Manufacturer	FIRADEC		FIRADEC		FIRADEC		FIRADEC		FIRADEC		FIRADEC		FIRADEC		FIRADEC		FIRADEC	
Style	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E	CTC21	CTC21E
Voltage (V)	6.3	6.3	10	10	16	16	20	20	25	25	40	40	50	50	63	63	100	100
Values (µF)																		
0.10																		
0.15																		
0.22																		
0.33																		
0.47																		
0.68																		
1.0																		
1.5																		
2.2																		
3.3																		
4.7																		
6.8															C			
10.0															C			C
15.0													C			C		
22.0											C		D	C	D			D
33.0									C			C				D		
47.0							C			C	D			D				
68.0					C				D			D						
100.0			C				D	C		D								
150.0	C				D	C												
220.0			D	C				D										
330.0	D	C				D												
470.0				D														
680.0		D																
1000.0																		
1500.0																		

C, D Preferred Values (refer to EPPL)
C, D Not Recommended for Space Applications

5.9.2.6 Activities

Tantalum electrolytic capacitors are mainly selected for their high volumetric efficiency and their reasonable size and weight. On the other hand, one might expect a better efficiency at high frequencies (lower ESR and ESL) and a least sensitivity to surge current, ignition risk resulting from high leakage current or sensitivity to mounting conditions.

The evolution of electrolytic solid capacitors tends to satisfy the users' needs

- replacement of MnO2 with polymer in tantalum capacitors in order to lower the ESR and improve their high frequency behaviour,
- replacement of tantalum with niobium to reduce production costs and minimize the risk of ignition,
- implementation of face down termination to reduce ESL and increase the volumetric efficiency,

But associated limitations such as increasing leakage current (polymer, niobium) or limiting the operating temperature (polymer) have still to be overcome.

Space business is showing interest in these evolutions. The following activities have been initiated and should be pursued in the coming years :

- evaluation of tantalum, polymer technology. An ESA / Czech Republic contract has been placed with AVX (CZ) and a GSTP tender is in progress with budgets coming from Portugal and France.
- evaluation of sealed packages for tantalum, polymer or tantalum, MnO2 capacitors in order to protect the anode from moisture (polymer) and reduce the moulding constraints which adversely affect the leakage current and thus reliability (polymer, MnO2). This is included in the ESA / Czech Republic contract with AVX on tantalum, polymer. A CNES contract has been placed with FIRADEC (F) as a follow-up of tantalum, polymer, capacitors developments 2003 – 2009 contracts.

Further to this continuous activities toward higher CVs, very low to ultra-low ESR and a greater safety, will have to be assessed the need for higher temperatures (above +125°C) for Tantalum, MnO2 and maybe Niobium as well as the potential introduction of chip technology based on CWR15 (for hybrids ?).

5.9.3 Electrolytic, non-solid

5.9.3.1 Overview

<u>Tantalum, Wet Slug</u>

The advantage of this type of capacitor is its high volumetric efficiency. For capacitance values in the µF range, it will generally provide the smallest case size available in a given voltage rating. The leakage current remains very low (lowest of all tantalum types) below +85°C.

However, it has disadvantages. This capacitor is usually polarised and its electrolyte which is a sulphuric acid solution in liquid or gel form is highly corrosive and can damage neighbouring circuitry if it leaks out (see below the best construction to avoid this leakage). Also capacitance value drop rapidly at low temperature. The nominal voltage is limited to 125V which is still much higher than solid tantalum capacitors voltages. The weight of these capacitors is also a disadvantage.

Their primary use is in low voltage power supply filtering circuits but also may be used in coupling and bypassing, circuit isolation, tuning, timing, power factor correction and phase shifting applications.

The construction of wet tantalum capacitor is similar to solid tantalum capacitor (slug, pellet manufacturing) except for the cathode structure.

The slug, with a tantalum wire lead extending, is assembled into a drawn case which serves as the cathode. The case is filled and the slug impregnated with a highly conductive electrolyte, usually a dilute sulphuric acid solution in gel from.

The case, of which the inner surface may be covered with anodised tantalum powder or some other material, becomes the cathode to prevent the loss of the liquid electrolyte, the case is normally grooved with a seal ring against a Teflon top gasket (double seal construction). The top of the case is then closed using a hermetic glass-to-metal seal.

The introduction of hermetic case eliminates the problem of external leakage but the capacitor is still subject to failure by leakage of electrolyte past the inner seal. Displacement of electrolyte past the Teflon seal into the area of the adjacent glass seal will result in a high leakage path between the positive lead and the case (connected to the cathode).

5.9.3.2 Classification

No classification exist for this type of components

5.9.3.3 Specific space constraint and requirements

The capacitor types with silver case shall be avoided. Short circuit can appear in reverse voltage due to silver electroplating (internal heat rises which liberate gases and generate catastrophic failure).

For these reasons tantalum hermetic with double sealing have to be used for this type of capacitor. If the capacitor is no longer hermetic, the predominant failure mode is a gradual loss of capacitance under operation and ultimately, an open circuit condition (resulting from the electrolyte vaporisation into the atmosphere).

5.9.3.4 Main characteristics

The maximum voltage can be applied up to 85°C and must be derated linearly up to 125°C (around 0.66 Un at 125°C). The ripple voltage and current are function of case size, working voltage and frequency. Their limitation is due to power dissipation of the case. The ripple current capability is given for non-polarised capacitor (value at 40 KHz and 85°C) and a ripple current factor versus frequency, temperature, and applied peak voltage (see MIL-PRF-39006/22 for CLR79). The internal temperature rise (generated by the current) is directly proportional to the ESR of the capacitor. As ESR increases with decreasing frequency, the percentage of the rated peak voltage decreases when frequency decreases. This percentage decreases when ambient temperature increases. The peak of the applied AC ripple plus the applied DC voltage must not exceed the DC voltage rating of the capacitor either forward or reverse. ESR is usually specified at 25°C and 120Hz. At low temperature, ESR increases rapidly. This effect in combination with a typical large decrease in capacitance at low temperature may require a capacitor of large nominal value to be selected for proper circuit operation over the temperature range. The ESR decreases when frequency increases. The impedance increases when temperature decreases.

The capacitance drop at low temperature varies from one manufacturer to another.

It depends on

1- the nominal voltage :

for example -35% @ -55°C for a 100V capacitor up to -80% @ -55°C for a 25V capacitor i.e, the residual capacitance at -55°C is higher for higher voltages,

2- the package size :

for example -17% @ -55°C for a 100V capacitor in the smallest package (T1 or A) up to -35% @ -55°C for a 100V capacitor in the biggest package (T4 or D) i.e, the residual capacitance et -55°C is higher for a smaller package.

5.9.3.5 Suppliers and available products

Styles CLR79, CLR81, CLR90 and CLR91 are for DC application only. However they will withstand up to 3V of reverse bias up to 85°C and 2V at 125°C according to MIL-PRF-39006. This information is not listed in ESCC specifications.

All the above references are with hermetic axial case. The case material is tantalum. They are available with double seal construction to avoid electrolyte leakage creating a short circuit at anode area. The double seal construction types of capacitor are the only recommended for space applications.

This type of capacitors is being progressively abandoned by commercial users and the number of available sources has been reduced. In addition to MIL-QPL-39006 sources, FIRADEC offers replacement parts for CLR 79/81 called CT79 which have been used in space applications and introduced in the EPPL. Extended ranges similar to those defined in DSCC drawing 93026, corresponding to FIRADEC ST 79 type, have also been introduced in EPPL. Up to now the voltage range has been limited to 100V.

5.9.3.6 Activities

The evolution of these electrolytic capacitors still rely on applications in harsh environments where higher CVs obtained with more efficient electrolytes, higher temperature (+150°C, +200°C) and higher voltages (150V) are required. Due to the diminishing space demand, no specific activity is expected to take place on this technology in the future.

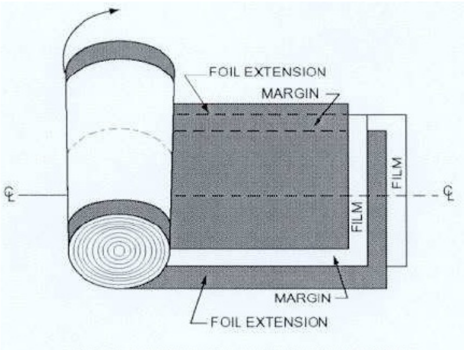
5.9.4 Film

5.9.4.1 Overview

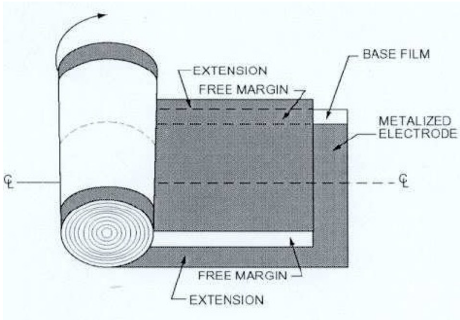
Plastic Film

This type of capacitor uses a plastic film as the insulator. The choice of insulator determines how much charge the capacitor can store. Dielectrics films commonly used in capacitors are polypropylene (PP), polyethylene terephthalate (PET) also known as polyester, polyethylene naphtalate (PEN) and polyphenylene sulphide (PPS). PPS replaces phased-out polycarbonate For specific capacitors, polystyrene and Teflon (PTFE) films may be used.

The dominant technology is the "Wound" construction. Film foil capacitors are constructed of layers (single or multiple) of plastic film dielectric wound alternately with metal foil electrodes. Metalized film capacitors are constructed of film dielectric on which the metal electrode has been previously vapour deposited. The metal foil electrode is typically a few µm thick and manufactured with aluminium or tin lead alloy. The metalized electrode (vacuum deposited directly on the plastic film) is normally 0,01 to 0,04 µm thick and manufactured with aluminium, zinc or zinc-aluminium alloys.



TYPICAL FILM/FOIL CAPACITOR CONSTRUCTION



TYPICAL METALIZED FILM CAPACITOR CONSTRUCTION

The layers are wound into a convoluted roll with the electrodes extending beyond the dielectric films. A low series inductance termination of lead wire to electrode is obtained by soldering or welding the lead wires to the metal electrodes. To connect to the thin metalized electrode layers, an intermediate layer of metal is applied to the extended end prior to attaching the lead wire. The quality of this termination is critical, particularly for AC and pulse applications. For special applications, such as high voltage AC, film capacitors may be impregnated with liquid or solid impregnants. These impregnants (which become part of the dielectric system) replace the air between the film and electrodes layers, resulting in increased AC voltage capabilities. The use of solid impregnants, such as epoxy resins, allow to obtain monolithic structures, suitable to withstand severe environments.

Another technology is the "Stacked" construction, where electrode / dielectric are built in a similar way as Multilayer Ceramic Capacitors and cut into individual parts. This construction is used in DC applications, not yet in space applications.

Film foil construction is slowly disappearing. The advantages of the metalized electrode design are decreased capacitor size, weight and self-healing properties offered by the thinner metalized electrodes. It is the dominant technology in space applications.

The two major failures are open and short circuit. A film capacitor may fail in other ways such as capacitance drift, high dissipation factor, instability with temperature and low insulation resistance. Failures can be the result of manufacturing defects or environmental overstress.

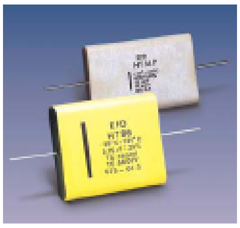
Open capacitors usually occur as a result of manufacturing defects (poorly solder or weld joint between the wire lead and the end of the roll) but occasionally result from overstress in application (high AC current level over DC rated voltage can cause localised heating at one of the internal terminations resulting oxidation of the joint).

Dielectric breakdown (and short circuit) can occur if a conducting particle is embedded among the electrode and the dielectric layers, if may cause an immediate short circuit. However, if it is sufficient small, it may only create a region of high electrical and mechanical stress. This particle will always be under pressure and will tend to slowly push through the adjacent materials. Many dielectrics become softer with increasing temperature, therefore increasing the internal pressure that produces the particle penetration. Thus, higher temperatures promote earlier failure. Dielectric breakdown can also occur as a result of switching transients or voltage surges induced by malfunction of associated circuitry. Transient exposure is of particular concern. The device may survive several applications of temporary over voltages without apparent degradation, but repeated overstress will eventually cause premature breakdown.

<u>Plastic Film, High Voltage</u>

High voltage capacitors use various composite dielectrics (plastic + paper or reconstituted mica) and are impregnated with solid thermo-setting resins such as epoxy, polyester or silicone.

The ESCC qualified product from EUROFARAD, HT86PS, is using a reconstituted mica composite impregnated with an epoxy resin which allow an operating temperature range from -55°C to +125°C and offers voltage ranges from 1.5kV to 20kV.



5.9.4.2 Classification

No classification exist for this type of components

5.9.4.3 Specific space constraint and requirements

Insulation resistance failures can occur due to moisture entrapped in the winding or case during manufacture (or if a non-hermetic capacitor is exposed to humidity).

5.9.4.4 Main characteristics

Self-healing allows avoiding the destruction of capacitor when a short circuit occurs at dielectric level. If a fault occurs in the metalized dielectric, energy stored in the capacitor will discharge through the fault. The high current density vaporises and the metal electrode in the immediate vicinity of the breakdown in the dielectric. The vaporisation of the electrode continues until the current path at the point of the breakdown becomes too great stopping the short circuit between electrodes. This phenomenon doesn't degrade the dielectric film (the film is made to guarantee that no damage or degradation of the film occurs during self-healing) except if the applied voltage is high (above 1KV). It should be pointed out that the circuit designer need not worry about the voltage drop during the "cleaning" of the fault. Only a very small portion of the stored energy is required for the self-healing process (250 µJ minimum) and the voltage drop is comparatively low. The self-healing is good in PP and in PET, weaker in PEN and not so good in PPS.

5.9.4.5 Suppliers and available products

Although hermetic metalized film capacitors are available from MIL-PRF-39022 (DC applications) and MIL-PRF-83421 (AC applications), most of the capacitors used in European space applications are non-hermetic and procured against ESCC 3006 at EUROFARAD in France, in SMD plastic package or radial leaded plastic packages. Due to potential difficulties with the mounting of these relatively big capacitors, a lot of them are still procured in the radial leaded version.

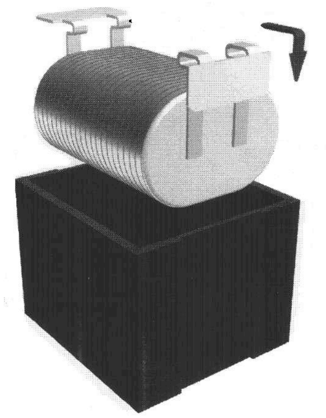
The main space application for metalized film capacitors is in high frequency switch mode power supplies.

Two types, PM90S and PM94S are being used, both made with PET (polyester), thus showing good self-healing properties. Both products are in an epoxy resin sealed plastic package.

Various packages and termination variants are offered, SMD terminals (picture on the right) or ribbons, radial four leads, DIL. All variants are available with tin lead finishes.

Both products operating temperature range is -55°C to +125°C and operating voltages start at 50V up to 400V (PM94S) or 630V (PM90S).

These two products will be replaced in the near future with two up-graded versions, PM907S and PM948S, which will allow a better volumetric efficiency and will offer a 170V range, optimized for 100V power supplies, and higher voltage (1250V for PM907S).



5.9.4.6 Activities

With the move of power supplies to 100V, space business has shown a lot of interest for an evolution of the classical PM90S and PM94S. An ESCC evaluation activity has therefore been initiated on PM907S and PM948S which offer :

- a better volumetric efficiency through the mastering of thinner dielectric films and metallization,
- an extended voltage range to 630V (PM948S) and 1.250V (PM 907S)
- an optimized 170V range suitable for use under 100V while respecting ECSS Q-ST-30-11 de-rating rules

Type PM 907S								
Size (mm x mm)	Capacitance Max. (µF)						Thickness Max. (mm)	Weight Max. (g)
	63V	100V	160V	250V	630V	1250V		
20 x 20	12	8,2	4,7	2,7	0,39		6,5	4,9
20 x 20	15	10	6,8	3,3	0,56	0,1	8	6
20 x 20	22	22	10	5,6	1	0,22	12,5	9,5
20 x 20	39	33	18	10	1,8	0,39	20	13,6
31 x 32	56	47	33	18	3,3	0,56	12,5	21,2
31 x 32	120	100	56	33	5,6	1,5	22	37,3
31 x 32	180	150	**100**	56	10	**2,2**	32	54,2

Type PM 948S								
Size (mm x mm)	Capacitance Max. (µF)						Thickness Max. (mm)	Weight Max. (g)
	63V	100V	160V	250V	500V	630V		
10,7 x 10,7	**5,6**	3,3	1,8	1	0,18	0,12	12	2
15,5 x 11,5	8,2	5,6	3,3	1,8	0,47	0,27	10	2,6
16,5 x 15,5	18	15	8,2	4,7	1,2	0,68	17	6,3
18,5 x 17	27	22	12	**6,8**	1,5	**1**	17	7,8

Some users also showed interest in chip film “Stacked” technology which should be evaluated in the next two years.

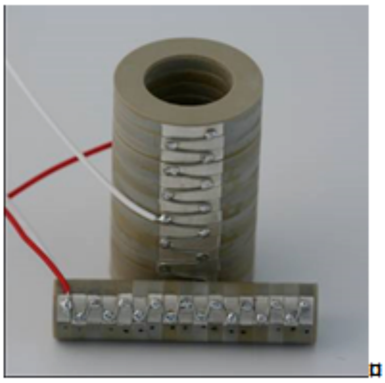
A great advantage of the film technology is its flexibility with regards to electrical performance and mechanical characteristics. This allow to design modules perfectly fitting with applications. This capability is widely used in military applications. With the extension of space volumes, this option could be further analysed in the future.

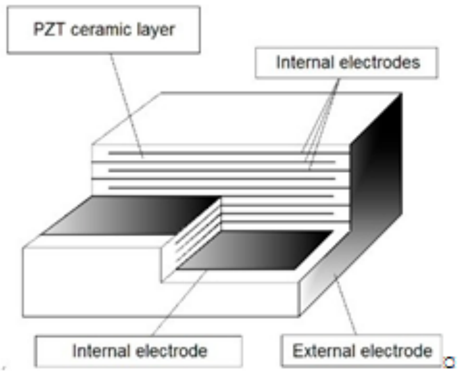
5.10 Miscellaneous

5.10.1 Piezzo ceramics element

5.10.1.1 Overview

Piezoelectric material comes in a variety of forms, ranging from rectangular patches, thin disks, and tubes to very complex shapes fabricated using solid freeform fabrication.

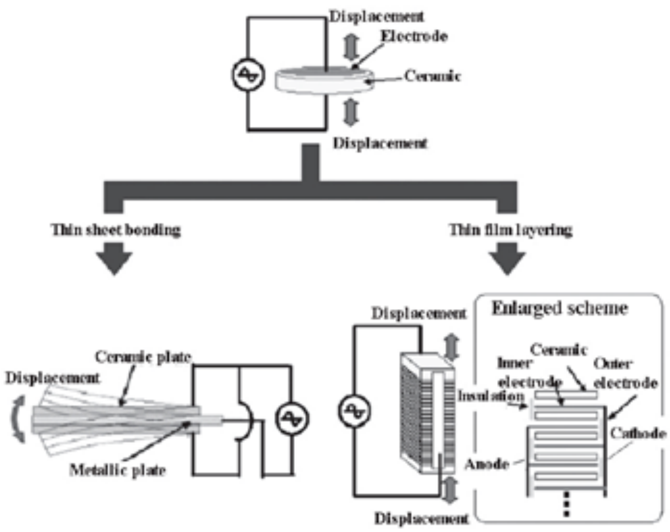




Multilayer Actuator with Internal Electrodes

The piezoelectric actuator is a device that makes use of the inverse piezoelectric effect. For example, when a voltage of about 1.000 V is applied to a piezoelectric ceramic plate with a thickness of 1mm (1.000V/mm electrical field), a displacement of about 1µm is obtained. However, as this in practise is insufficient, because only a small displacement can be obtained with a high drive voltage, the piezoelectric actuators are structurally processes in order to obtain a larger displacement from a lower drive voltage and the process has thus been put to practical use.

In order to reduce the drive voltage of a piezoelectric actuator, it is necessary to reduce the thickness of the ceramic plate. Reducing the plate thickness to 0.5mm makes it possible to apply a 1.000V/mm electrical field with a 500V drive voltage.



Typical example of piezoelectric actuators

The field of applications of piezoelectric actuators is comparable to that of electromagnetic actuators. Table 1 shows the comparison of electromagnetic and piezoelectric actuators based on their principles.

Comparison of actuator characteristics

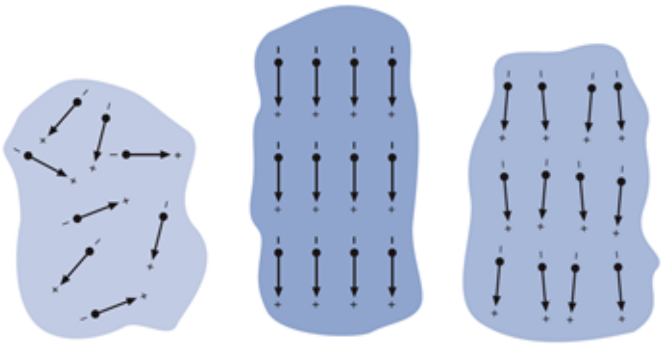
	Electromagnetic		Piezoelectric	
Drive system	Indirect drive by electromagnetic force		Solid deformation by inverse piezoelectric effect	
Displacement amount	⇗		⇘	1/10 to 1/100
Force generation	⇘		⇗	Utilization of solid rigidity
Displacement accuracy	⇘	> 0.1mm	⇗	0.01mm to 0.1mm
Response speed	⇘	1 msec.	⇗	0.1 to 1 msec.
Energy efficiency	⇘	Coil winding loss	⇗	No coil
Noise	⇘	Piston sliding reciprocation noise	⇗	No piston
Proportional control	⇘	ON/OFF control	⇗	Voltage-proportional
Drive voltage	⇗	Few volt	⇘	Hundreds of V/mm

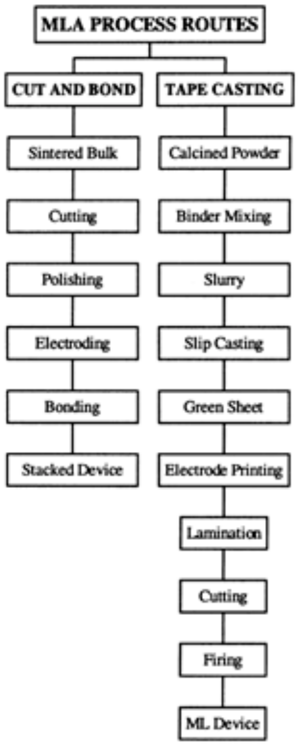
⇘ Disadvantage ⇗ Advantage

There are two main manufacturing routes for producing MLA's.

The "**cut and bond**" method is associated with low production numbers and basically involves cutting individual layers from pre-sintered bulk materials, depose electrode on each layer, and bonding the device together. The second process involves "**tape casting**" individual sheets, electrodes printing, laminated, and sintered. This latter method requires more expensive equipment and intricate techniques than "cut and bond". However, it is more suitable for mass production of MLA devices and for producing thinner piezoelectric layers

The last step is the poling process which takes place in a heated oil bath at electrical fields up to several kV/mm. Only here does the ceramic take on macroscopic piezoelectric properties.





The principal interest of the Piezo technology has made possible the alliance of strength and precision. Piezo-actuators based on ceramic material (manufactured by sintering ceramic powder) present the following characteristics:

- Elongation rate: 1000 ppm
- Precision in positioning: 10 nm in closed-loop
- Pressure control: 100 MPa
- High stiffness of the ceramics materials: E = 30-50 GPa
- Quasi-static mechanical modeling as a spring with an elongation proportional to the voltage applied to its terminals U_0
- Ability to perform non-magnetic actuators
- Operating under electric field of 1 kV/mm

In order to reduce the applied voltage, the piezo-actuators are manufactured by layers. Thus, the piezo components need only hundreds of volt to obtain the same electric field. Nevertheless, this configuration in layers does not permit application of a tensile stress. The component will suffer of delaminating. It is necessary to apply a pre-stress to the piezo component for its integration into the mechanical system.

5.10.1.2 Classification

Piezzo element may be classified by their geometry and mode of deformation. The main shape found are tube, ring, square and plate in multilayer or bulk construction. These elements may be stacked to increase the displacement. The deformation will depend of the application and of electrode design. Basically 2 types of deformation mode are used: compressive and shear.

5.10.1.3 Specific space constraint and requirements

This type of components is sensitive to humidity for DC application. Even if humidity is not a concern in space failure may occur during ground testing. Special care should be considered.

During operation, the components may heat. Validation in vacuum should be performed to evaluate the impact on heat dissipation.

5.10.1.4 Main characteristic

Operating voltage

Two types of piezoelectric actuators have become established. Multilayer, low voltage actuators (LVPZT) operate with potential differences up to about 100 V and are made from ceramic layers from 20 to 100 µm in thickness. Classical high-voltage actuators (HVPZT), on other hand, are made from ceramic layers of 0.5 to 1 mm thickness and operate with potential differences of up to 1000 V.

Stiffness, Load capacity, Force Generation

To a first approximation, a piezo actuator is spring-and-mass system. The stiffness of the actuator depends on the Young's modulus of the ceramic (approx. 25% that of steel), the cross-section and length of the active material and a number of the other non-linear parameters (e. g. temperature, humidity rate) Typical actuators have stiffness between 1 and 2.000 N/µm and compressive limits between 10 and 100.000 N. If the unit will be exposed to pulling (tensile) forces, a casing with integrated preloaded or an external preload spring is required. Adequate measures must be taken to protect the piezoceramic from shear and bending forces and from torque.

Travel range

Travel ranges of piezo actuators are typically between a few tens and a few hundreds of µm (linear actuators). Bender actuators and lever amplified systems can achieve a few mm. Ultrasonic piezomotors can be used for longer travel range.

Resolution

Piezoceramics are not subjected to the "stick slip" effect and therefore offer theoretically unlimited resolution. In practice, the resolution actually attainable is limited by electronic and mechanical factors.

Sensor and servo-control electronics (amplifiers): amplifier noise and sensitivity to electromagnetic interference (EMI) affect the position stability

Mechanical parameters: design and mounting precision issues concerning the sensor, actuator and preloaded can induce micro-friction which limits resolution and accuracy.

5.10.1.5 Suppliers and available products

Several manufacturers have delivered piezzo MLA to different space projects: Noliac (D), Ceramtec (G) and NEC/Tonkin (J).

5.10.1.6 Activities

Piezzo element for actuators application

In the frame of GSTP, an activity is on-going with the aim of qualifying a new source of piezoelectric multilayer components accounting for space project constrains.

The objectives of the activity are:

- to establish a process identification document for the fabrication of piezo components,
- to establish ESCC generic and detailed specifications,
- to qualify a European Source of piezo components through a Lot Acceptance Testing,
- to get functional characteristics for several sizes of Pre-stressed Piezo Actuators,
- to establish recommendations for further qualifications.

Piezzo for transformer application

Traditional electrical transformers convert voltage through the action of magnetic fields induced by an alternating current. They have several drawbacks: heat production, electromagnetic interference, humming noise, and low power density. Piezoelectric transformers, however, use piezoelectric ceramics vibrating in resonance to convert electrical energy into mechanical energy (primary side) and back to electrical energy (secondary side). This new application requires further maturation to be competitive with magnetic transformer and relative important effort have to be made for matching electronics to drive this component.

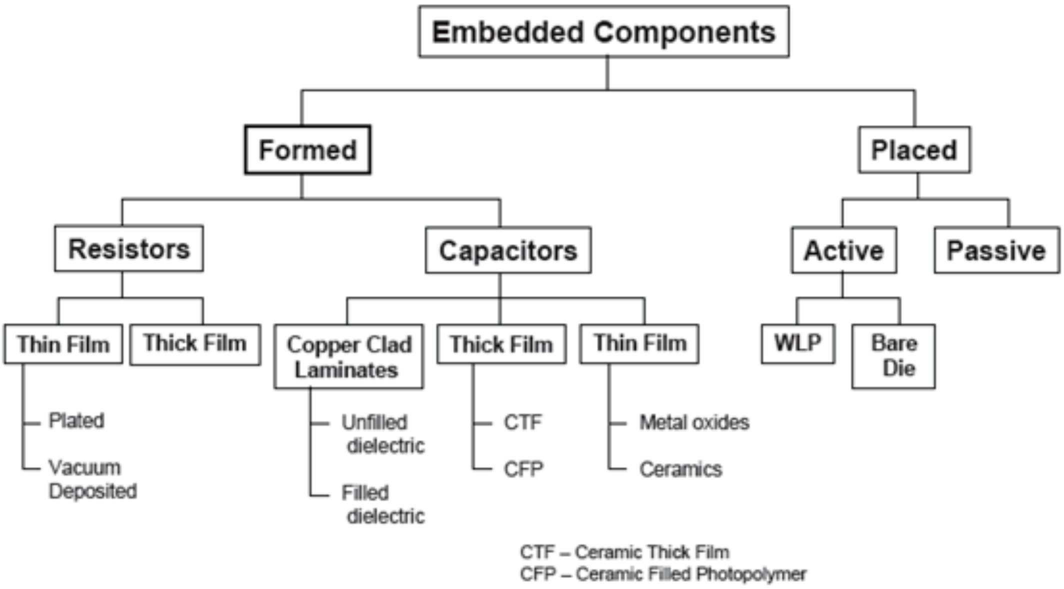
5.10.2 Embedded passive

An embedded component is defined as an active or passive device that is placed or formed on an inner layer of an organic circuit board, module or chip package such that it is buried inside the structure when completed as opposed to being on the top or bottom surface.

Passive devices being embedded are primarily resistors and capacitors however there is also some effort focused on inductors. Development in embedded passive technology began almost 20 years ago. The promised advantages of embedded passives are: reduced board size, the reduction of component parasitic, the elimination of handling issues with small discrete components and the reduction in the number of solder joints. Embedded passives can be buried in the volume of the board, thus the overall use of board surface area by passive components is decreased. The embedded components can be moved closer to the active component reducing parasitic losses—particularly inductive losses. Use of embedded components could eliminate problems with placement and attachment of very small size surface mount components, pick and place become a critical operation for chips of size below 0402.

The decision to embed components must be made early in the design process. Some components are easy candidates for integrating into the multilayer structure. Others are more difficult to rationalize as to the added performance value compared with the extra processing steps needed to achieve the desired results. There is no doubt that the technology of including resistive material or capacitive structures in the substrate will become a way of increasing the performance of the product being designed.

Embedding passive can be achieved by 2 different means. Forming layers of resistive or capacitive nature may be buried in the substrate or specifically designed (thin) discrete passive chips may be placed in cavities. These technics imply choice in the substrate design and risk that should be assessed early in the selection process.



Issues with Embedded Components

- For formed technology
  - Predictive modelling for buried capacitance
  - Resistor tolerance
  - ESD protection
  - Shift in value from assembly to raw substrate/board
- For placed technology
  - New requirements in substrate/board manufacturing (ESD, Component handling, Assembly techniques, Component testing and inspection)
  - Placement accuracy, thin core handling and large panel format drives new requirements for assembly equipment
  - Thinned components
  - Reliability of solder joints
  - Quality and liability concerns

An activity is starting in the frame of TRP project to assess this technology for space use. This activity will allow collecting reliability data on embedded components in PCB substrate.

5.10.3 Super-capacitor

Supercapacitors (also called ultracapacitors or electrochemical double layer capacitors) are suitable for high power applications (but requiring low energy). These devices are now available on terrestrial market and used in aeronautics (Airbus A380 emergency door opening), in automotive industry. Supercapacitors rely upon the capacity of the electrochemical double layer between an electrolyte and an electrode. As there is no electrochemical reactions (energy is stored physically and not chemically as for a battery), their cycle life is very high (> 1 million cycles). The energy stored (5 Wh/kg) is low compared to batteries, but can offer much greater specific power up to 20 kW/kg. To cope with applications requiring a very high number of cycles and also high specific energy, hybrid systems (coupling supercapacitors and Li ion batteries) could be a potential solution. In such hybrid system, the supercapacitors improve the power capability while the Li ion battery provides the energy density required. It is expected to improve the battery performances by filtering the power peaks by the supercapacitor. Hybrid systems (supercapacitor bank and Li battery) have been developed for electric vehicles (for power peak and regenerative breaking).

A TRP study on comparison of supercapacitors, high power battery and hybrids Lithium ion battery/supercapacitors, has shown the most interesting cells for space applications have a capacitance of 10F. Such cell is becoming a standard for industry. No European industry manufactures such devices today. However, Skeleton (Es). Montena (CH), producing small capacitance cells, has been bought by the American company Maxwell. Products form Hutchinson (FR) might present an interest for space application

6 ACTIVITIES AND ANNUAL QUALIFICATION PLAN

Based on limitation identified in the previous chapter for each type of EEE passive components, taking into account European manufacturer capabilities and needs expressed by the European industry, a relatively detailed list of activities has been defined with associated priority.

Based on this roadmap, the AQP objectives will be updated as necessary.

6.1 Activities

The activities are presented in the next table which provides for each activity the product under concerned the current and targeted TRL, the priority and the activity key drivers. During PCTBWG meeting, priority marking are discussed for each activity. The priority marking is the sum of the urgency marking (0 : not urgent ; 5 : very urgent) and interest marking (0: low interest ; 5 : high interest). Urgency is defined by the need of components under concern in space applications within short term. Interest is linked to the technological advantages that will bring the activity (new performances, improvements, problem resolution, etc.) whatever is the time required.

Activities that are on-going or being started are highlighted in green.

The activities are sorted by decreasing priority.

TRL are defined as follow :

Level	Definition	Explanation
TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven. At component level, this signifies that prototypes might have been produced
TRL 3	Analytical and experimental critical function and/or characteristic proof of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology. At component level this means that process is under control
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. At component level, this indicates that the product has been submitted to an evaluatation or to Lot Acceptance Testing. This means that the component might be presented for EPPL II introduction.
TRL 5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Equivalent data to qualification data are available.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment. Regarding EEE parts, this signifies that product is qualified according to recognised standard.

The key drivers are :

Cost, Lead Time	The activity shall aim to decrease manufacturing and/or procurement cost as well as the delivery time. One way to achieve such objectives is to reach ESCC qualifications
Miniaturisation	The activity is oriented toward mass and size reduction objectives.
Independence	The activity aims to reduce Technological dependence (exportation licence, ITAR, etc.)
Disruptive technology	During the activity, disruptive technology will be evaluated
Performances	New technologies and new design shall be developed
Use improvement	The activity shall provide recommendation and data to improve use of EEE passive parts

6.2 Annual Qualification Plan

The Annual Qualification Plan identifies the objectives or the achievements per year and refer to the activity references from the roadmap.

Activity	Priority = Interest + Urgency			TRL											Objectives						status / potential funding
	P	I	U	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Cost, LT	save mass/size	Non dependence	Disruptive techno	Performance	use improvement	
Temperature sensors Pt Film	10	5	5					2	3	4	6				X	X	X	X	X		running
Oscillators XO	10	5	5		2	3	4	6							X		X		X		running
Relays 100V/15A	10	5	5		1		2		3		6				X			X	X		CNES
Capacitors Film HV	10	5	5			4			6						X				X		running
Thermo-switches 100V/4A	10	5	5		1				3		6				X				X		CNES
Fuse 15A	10	5	5		4			6							X	X	X	X	X		running
Capacitors Tantalum Low ESR	10	5	5		3		6								X	X		X	X		done
Capacitors Ceramic BME II	10	5	5	2		3			6						X	X		X	X		self M
Passive test facilities	10	5	5																	X	done
Cables Assemblies High Data Rate	10	5	5					3		6									X		
Relays High vibration and shock	9	5	4					2	4	6									X		TRP
Cables/Connectors Derating study	9	5	4																	X	TRP
Derating study on Relays/Heaters	9	5	4																	X	
Cable Assembly High Voltage	9	5	4					2		4	6						X		X	X	ECI IV
Connectors Interposer Miniature	8	5	3		1	2		3	4	6						X					CNES/GSTP

Activity	Priority = Interest + Urgency			TRL											Objectives						status / potential funding
	P	I	U	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Cost, LT	save mass/size	Non dependence	Disruptive techno	Performance	use improvement	
Capacitors Polymer tantalum	8	5	3			3		4	6							X		X	X		CNES/GSTP
Cables High Temperature	8	5	3			3	4		6										X		ECI
ThermoElectric Cooler	8	5	3			2	3			4	6						X	X	X		
Connectors Impedance matched	8	4	4					2		4						X		X	X	X	TRP
Connectors High Temperature	8	4	4						2	3	4							X	X	X	
Transformers Coil	7	4	3			2	3			6					X				X		
Connectors Combo uD	7	4	3				2		3		6				X	X					TRP
Connectors Modular	7	4	3					2	3	4	6				X	X		X		X	ARTES
Crystal SMD	7	5	2				2			3	4	6				X		X			CNES
Fuses resettable	7	4	3			1	2											X			
Transformers Planar	7	4	3	1			3	4		6											
Cables SC layer insulation	7	4	3			2	3		4		6							X			CNES/TRP
Capacitors Ceramic BME I	7	4	3					2			6										
XO SMD	7	5	2							2	3	4	6			X				X	

Activity	Priority = Interest + Urgency			TRL											Objectives						status / potential funding
	P	I	U	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Cost, LT	save mass/size	Non dependence	Disruptive techno	Performance	use improvement	
Resistors Lower size (0402-0302)	6	4	2				3	6								X					CNES/MAN
Connectors nano D	6	4	2	2		4		6								X					
Capacitors Silicon	6	5	1				2	3							X	X		X	X		TRP
Capacitors Lower size chip	6	4	2				3		6							X					CNES/MAN
Cable Assemly High Power	6	4	2									2	3						X	X	
Capacitors, Low voltage, Low ESL/ESR tantalum	6	4	2						2	3	4	6							X		
Capacitors low voltage, high capa ceramic	6	4	2						2	3	4	6							X		
Crystal/oscillator up to 250MHz	6	4	2				1		2	3			6				X		X		CNES
SAW oscillator	6	4	2							2			6				X		X		
Crystal SAW (high frequency)	6	4	2			1			3							X		X			
Capacitors Ceramic 200V-500V	5	3	2					3								X			X		
Super-capacitors Ionic Liquid	5	4	1					1		3	4		6			X	X	X	X		ITI
Capacitors High Voltage	5	4	1						2							X			X		
Capacitors, resistors HT (>150°C)	5	4	1					3	6										X		ECI IV

Activity	Priority = Interest + Urgency			TRL											Objectives						status / potential funding
	P	I	U	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Cost, LT	save mass/size	Non dependence	Disruptive techno	Performance	use improvement	
Cables Self-regulated heating	5	5	0				2	3		4	6				X	X		X	X	X	TRP
Piezo ceramic	5	4	1		2		3	4							X	X			X		
Capacitors Tantalum hermetic very low ESR	5	3	2	1	2	3		6										X	X		done
Connectors for pyro devices	4	3	1						2						X		X			X	
Cable Aluminium	4	3	1					2	3						X						ARTES
Embedded Passives on PCB	4	4	0				2		3							X		X			TRP
Connectors SpaceWire Backplane	4	4	0					2								X			X		TRP/CNES
Relays High Voltage	4	3	1						2						X		X				
Capacitor filter Smaller feedthrough	4	3	1						2	3											
Relays user guide	3	3	0																	X	
Connectors Low Rc For High Current BusBarr	3	2	1						2						X					X	
Connectors for Solar Panel	3	2	1						2						X						
Heaters All polyimide	3	2	1						2										X		
Thermistors SMD NTC	3	3	0						2									X			

Activity	Priority = Interest + Urgency			TRL											Objectives						status / potential funding
	P	I	U	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Cost, LT	save mass/size	Non dependence	Disruptive techno	Performance	use improvement	
Transformers Piezo	3	3	0						2							X					
Connectors Hermetic	3	3	0						2						X		X				
Oscillators VCXO/TCXO	2	2	0						3								X				
Hand Book of good practice	2	2	0																	X	
Relays SMD	2	2	0								2					X				X	
relays/crystals, low mass hermetic package for	2	2	0								2				X	X					
Wires and cables CNT	2	2	0							2						X					
Connectors 38999 miniature	1	1	0					3								X					
Heaters Cuttable	1	1	0					2										X		X	
Heater with Embedded thermistor	1	1	0					2								X					
Connectors Filter	1	1	0					3							X						

done	running
no funding	funding approved

6.3 Annual Qualification Plan

Year	Manufacturer/Country	Products/Description	Funding	Comnments
2013.	EFD / F	Ceramic Chip II, 0402, 10-16V	MFR - CNES	
2013.	AXON / F	HDR uD connector	MFR - CNES	
2014	Schurter / CH	Fuses 15A	ECI II - ESA	
2014	Hypertac (F)	PCB LGA package devices interposer	MFR - CNES	.
2014.	AXON / F	carbon nanotubes for ESD protected cable	CNES	Started in September 2011
2014.	COMPEPA (F)	Thermostat 100V,	CNES	
2014.	KVG/G	Oscillators	MFR -DLR	.
2015.	AXON (G)	HT Cables	ECI III	Follow-up of GSTP activity
2015.	AVX / Ir	BME Ceramic Capacitor	TRP - ESA	
2015	EFD (F)	PM907S/PM948S	ECI III	
2015.	AXON / F	Comnbo uD	TRP	Target is EPPL II
2015.	AXON (UK)	NanoD connector	TBC	2013 : EPPL II
2015	KEMET/P	T483 Tantalum capacitor	MFR-P	
2015	RAKON	XO Oscillators	ECI	