Electric Propulsion Cables for milli-Newton Thrusters

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ABSTRACT

AXON' Kabel GmbH, is developing and manufacturing cables and connectors up to complete interconnect systems for all types of applications needed in Space. As a request from ESA, AXON has developed a new generation of cables suitable for current and future applications to feed electric propulsion thruster systems in spacecraft with electric power. Under this project the main objectives were to find and select materials for the composition to produce a cable withstanding quite strong requirements for operating temperature, radiation resistance, high voltage application and in variants to various current ratings (A); the cable construction will also include ESD immunisation. The paper will summarise the specification achieved and will give an overview on the test results with the prototype cables.

1. Initial Situation

As today's mN-thruster wiring is done with more than one wire, using a relay box which as a result is quite heavy, thus limiting the power, the objective of this development is to get a cable with high radiation resistance for high voltage and high temperature applications, suitable to feed electrical thrusters with power (including Hall Effect Thrusters , Gridded Ion Engines)

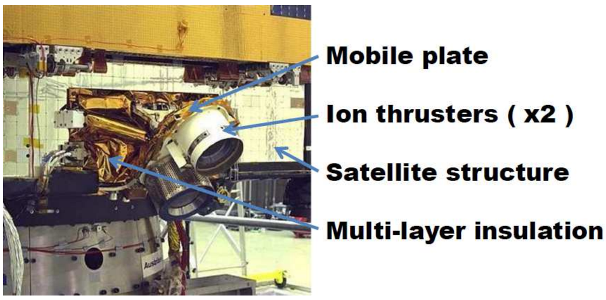

Figure 1. ION thruster example

Thrusters are mounted outside satellite, exposed to extreme temperatures (high and low), vacuum (no convective cooling), ionizing radiation, high energetic particles (heavy ions, protons).
In "Fig2" an application example from ASTRIUM is shown, identifying the stress of the existing thruster cables: As the thruster is mounted on a mobile plate for the pointing mechanism, the cable needs to be suitable for dynamic use under the above conditions. Currently stress of this solution is minimized through the use of "Multi layer insulation"(MLI). The today's cables are a sort of mineral rigid type of product which is quite heavy, too.

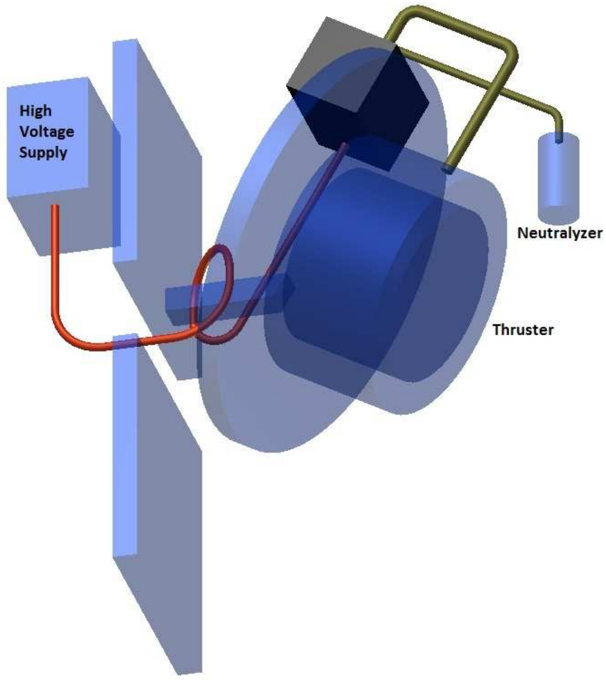

Figure 2. thruster schematic old

One of the critical technologies for further enhancement of Electric Propulsion technology in Europe is the availability of space qualified cable that can be used for Electric Propulsion (EP) applications requiring high temperature, high current and high voltage capabilities. In some applications the harness also has to cross the dynamic interface imposed by a pointing mechanism, which demands the additional feature of flexibility in the selected cable. Until today cable insulation has been limited to PTFE, polyimide etc. Although these insulation materials have excellent dielectric capabilities they are fundamentally limited to operate at temperatures below approximately 200 degrees Celsius. Qualified wires will greatly simplify EP thrusters' thermal and electrical design and are mandatory to ease thruster implementation on spacecraft.

2. Requirement Specification

During our study a research has been made by ASTRIUM to identify the specification needs of today's thruster technologies.

2.1 Electric Requirements

The cable will be designed to withstand a maximum continuous operating voltage of 5kV (derating included). The maximum operating current will be 12 A for a maximum nominal power of 5000W (also derating included). After successful achievement of this requirement, there will be more cables with lower current loads available. Therefor this requirement is the max. requirement.
The cable will be designed to withstand possible Corona effects that may occur into the cable for a range of pressure going from 0.1 to 13 Pa.
The overall shielding for EMI protection shall be effective in a range of 10 to 100kHz. The conductor gauge will be in a range of AWG 16 to AWG 4.

2.2 Temperature Requirements

The operation temperature's requirements are from min. -50°C to max.+280°C for static applications, and from min. -20°C to max +120°C for dynamic applications. Other values are targeted for non operating temperatures; see "Tab1".

Tabellary 1. Temperature requirements

		Static application	Dynamic application
Operating temperature	min °C	-50	-20
	max°C	280	120
Non operating temperature	min °C	-100	-50
	max °C	200	120

2.3 ESD

The cable will be designed to be immunized against ESD (electrical discharges).

2.4 UV Requirements

The cable will be designed to withstand an exposure to UV equivalent to 2555 equivalent sun hours (esh).

2.5 Radiation Requirements

As a result of discussion with ESA's radiation specialist, electron irradiation is used for testing because it is more representative of the radiation effects on cable exposed to the space environment.
The cable shall be designed to withstand radiation level of 200MRad.

2.6 Geometrical Requirements

The cable design will allow to withstand bending movement in 2 angular ranges: First range will be applied only once at the beginning of the cables lifecycle – in a non-operating modus – and is about 135° on a first axis and +180° on a second axis. Second range is for the daily operation and shall not exceed +/- 45deg within an overall +/- 6 deg range, on first and second axis.
The linear displacement of the cable, due to rotation movement, is typically of 40mm.
As a design goal the minimum bending radius shall be a ratio of 5 between bendradius and cable diameter.
The maximum resistive torque per wire shall be 200mN.m.

3. Proposed Technology

In "Fig.3" a concept including advantages such as

- Weight gain
- Less vibrations
- Simplified integration

are shown in a schematic.

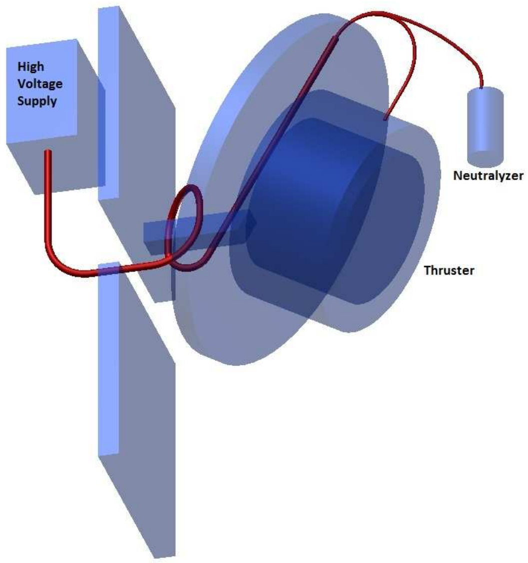

Figure 3. thruster schematic (new)

The loop is shown to demonstrate the bending possibilities of the cable. The loop is to absorb the stress on the cable for high amplitude bending.

4. Conductor Solutions

Axon worked on specific alloys and specific configuration of such conductor materials to fulfill all requirements. The following conditions have been taken into account:

- Risk of softness of the pure copper if exposed to high temperature for a long time
- After 2000h at 250°C, the copper suffers from creep.
- Risks with usual plating:
  Tin plating impossible (Cu/Sn intermetallic compounds creation after 1000 h at 125°C).
  Silver shown to be weakened if exposed for a long time to high temperature. After 100h, copper begins to oxidize in the interfacial area. After 2000h, the oxidation layer has grown and the remaining silver forms coalescence.
  Nickel plating is the only plating that is able to withstand high temperature while keeping good properties.
  Need to evaluate a material with good conductivity, good mechanical properties and higher temperature rating.
  Conductivity shall be high enough to maintain the conductor weight as low as possible.
  Aluminium is a low weight metal but when exposed to high temperature (e.g. at >260°C) the elongation rate is too high. Furthermore, this material has very poor conductivity (25-30% of the IACS) and shows difficulties to be connected.
- Flexibility can be provided by the nature of the conductor material but also by the configuration of the conductor. The construction configuration is characterized by the number of strands and the stranding type.
- The stranding may also have a significant impact on the electrical phenomenon involved in high voltage.

Axon can supply single strand for this requirements from size AWG 32 to size AWG 18, and assemblies of such single strands.

In “Fig.4” a solution of the selected conductor (19 x 0.511 unilay) is shown.

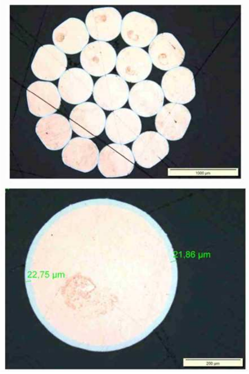

Figure 4. selected conductor

This conductor consists of specific alloy, specific construction and specific coating (type of material not released to be published at this time). With this material the tests proof for good mechanical stability when exposed to very high temperature (short exposition), good mechanical and electrical stability when exposed for long time to high temperature. The design is suitable for High voltage application, and a good flex life.

5. Solutions of adequate insulations

The polymeric materials are very sensitive to high temperature.
Some thermosetting materials like rubbers or silicone are able to withstand high temperature but they don’t meet all the requirements and more particularly for the out gassing and for the low temperature requirements.
Because of the need of flexibility and high voltage requirement, thermoplastics seem to be the more suitable solutions.
The polymers have excellent electrical and mechanical behavior but have temperature limitation of about 260°C. Radiation resistance is an intrinsic property of the material.
In general, high performance thermoplastics that are known for having elevated radiation resistance, also often show important rigidity with risk of fragility in cold temperature.
The study did focus on the higher performance

insulators of different nature and forms (thermosets, thermoplastics, coatings, tapes…) and on possible combinations of them in order to meet the requirements.

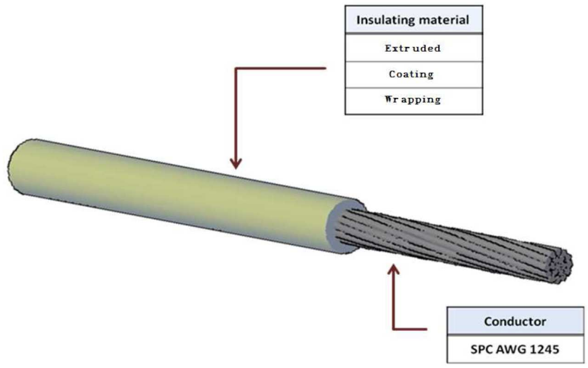

Figure 5. samples structure

In „Fig.5“ the setup of the sample structure is shown.

For the evaluation, many different kind of materials have been evaluated and tested: for extrusion e.g. Polyimide, Peek compounds. For coating e.g. Vicote, Polyimide, solvent base PBI etc have been tested.
The tests, which the materials had to pass were:
Standard mechanical tests, such as weight, dimensions, elongation and breaking load, stripping capability and shrinking at high temperature.
Specific mechanical tests included deployed modus characterization tests, bending test in deployment modus, alternate bending at various angles.
Then standard electrical tests such as spark test, voltage test, insulation resistance, followed by specific electrical tests such as partial discharge measurement (PD), breakdown test at high temperature and overload resistance.
Ageing tests were performed such as thermal cycling test, thermal shock test, thermal ageing test including long term thermal ageing test for 2000 hours.
Other tests were ESD measurements, radiation tests, out-gassing tests and wrapping tests.

Among the above mentioned tests the PD test is a rare and most interesting and important type of test:
The measurement of partial discharges consists in detecting and determining the level of the electrical discharges that occur in faults within the cable insulation. When the cable is energized, the micro-cavities in the insulation tend to load and unload or periodically depending on the type of tension. These discharges have the effect of damaging the insulation and may cause a dielectric failure of the cable.
Appropriate equipment (see “Fig.6”) can measure accurately the level of these discharges in the cable and determine if the insulation is healthy or if it contains defects.
Detect and measure the discharge is a delicate thing because we must be sure that what is measured is in the insulation. Therefore the measurement principle needs to use a partial discharge free HV-transformer [Tr].

During its operation, the air near the cable, subject to the electric field, can also generate partial discharges. These partial discharges "parasites" should be eliminated by using a proper mounting. The immersion of the assembly in an insulating (dielectric oil for example) can remove the sources of non-DP cables. The measurement is performed when applying a voltage between the conductor and medium [2]) at ground potential (or conductive liquid at ground potential). The values are measured in pC via the Discharge detector [AKV] and the Partial Discharge Meter [TEM]. [Ck] is a coupling capacitor. The specimen extremity [4] is insulated by immersion in insulation liquid.

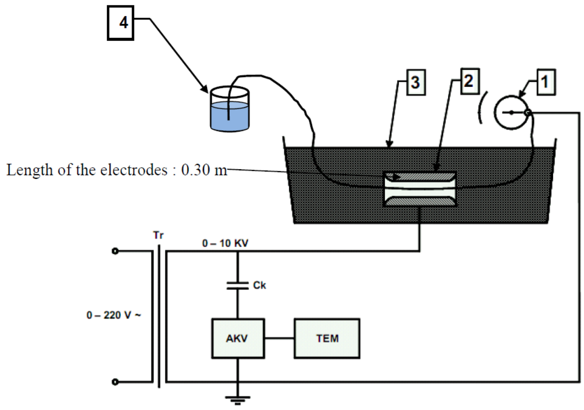

Figure 6. PD principle measurement system

Figure 7. high voltage test chamber

6. Semiconductive Layer

Due to the position of the semiconductive layer on the cable composition it will face the highest environmental stress:

High temperature up to 280°C

High radiation up to 200 MRad.

Semi-conductive layers are already used on very sensitive thin signal cables which operation can be disturbed by ESD that are produced by simple manipulation of the wire (triboelectric noise).

In power cable, the use of such technique is quite frequent, and more particularly in high voltage cables. Its purpose is to evacuate electrical discharges (electrostatic, partial discharges…) which may lead to failure of the cable.

The semi-conductive layer can be obtained in many ways: extrusion, coating, taping. The semi conductivity is often obtained by the adjunction of a conductive load in the mass.

Regarding space applications, semi-conductive layer may have an effect in protection against radiations.

This layer is submitted to the same requirements as the insulation in term of resistance to its environment.

The conductivity shall be homogenous throughout the whole layer.

Known charges :

- Carbon black
- Metallic charges
- Carbon nanotubes

For the study we have done the evaluation using an available semi-conductive tape, at ambient temperature.

For the final product a space grade semi-conductive tape will be used, which is currently under evaluation in a separate project as well.

7. Shielding

Wide range of designs and configurations possible, but will be limited because of some specific requirements and space oriented functions :

- Ability to filtrate radiation.
- Flexibility.
- Good shielding effectiveness.

Some shielding constructions have better shielding effectiveness but less ability to be bended and have shorter flex life. Braided shields have improved flex life, good shielding effectiveness.

Spiral shields have important flex life but lower shielding ability.

Tape shield have shorter flex life and make the whole cable more difficult to bend but it provides excellent shielding effectiveness.

The strands material shall withstand high temperature exposition and well protected against corrosion.

In order to use the shielding as a supplementary protection against radiation, it is important that the recovery shall be complete with no gaps that could let radiation pass and alter the insulation.

The material (alloy) selected will be the same as the selected conductor material.

Test targets for construction are aiming that flexibility performance of the cable will not be reduced.

The method of construction (Band wrapping or breading) has not yet been tested.

8. Summary

The final product is available since Nov. 2011