

Development of new high temperature wires and cables for space applications

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INTRODUCTION

With the need for reducing system size and weight while increasing performance, today and future aerospace systems require high-temperature electronics to run devices like electric motors (electric propulsion). This inevitable evolution of the technology leads to a concentration of the energy and push the limits of the amperage capacity of the current wires. The required performance level of wires and cables is growing higher and results in the necessity of upgrading properties of existing cables.

In fact, the need to increase the temperature rating reflects two aspects of technologies evolution: one comes from the desire to introduce new solutions to enable the transport of more power in wires and cables of smaller size, and the other from the need of more efficient solution to withstand harsh environments where the temperature exceeds usual limits.

The present document summarizes the advances in field of high temperature wires and cables and is focused on the development of a high power flexible cables that may be used for electric thrusters systems under the ESA EMITS ITT A0/1-5245/NL/SFe and on the current development of a high temperature continuous use wires range which is expected to become a new family among ESCC3901 standard wires and shall be rated at a significantly higher temperature than the existing wires.

HIGH TEMPERATURE ISSUES

Temperature is a critical influencing factor when it comes to polymeric materials. Thermoplastics are even more sensitive to temperature because of their nature, and their properties significantly depend on the temperature. For instance, the volume resistivity, which reflects the electrical insulating ability of the material, decreases as the temperature rises.

The intensity of the resistivity decrease is different from a polymer to another, and depends of the chemical nature and structure of the polymer. The dielectric strength is also highly influenced by the temperature. As it increases, the dielectric strength significantly decreases. The direct consequence is that the voltage that may be easily withstood at ambient temperature can become critical at higher temperature and lead to the failure of the wire.

Other physical properties are also directly impacted by the temperature elevation like mechanical characteristics such as tensile strength, compressive strength (less important), flexural and young modulus. Globally, we can observe a kind of "softening" of the material which is illustrated by a decrease of the flexural modulus (the material becomes more flexible) and tensile strength and an increase of the young modulus and of the elongation.

A continuous operating at temperature up to 250°C requires an insulation material that is able to keep an acceptable level of properties at such temperature. The purpose of the evaluation test sequence is to reproduce as far as possible the critical operating conditions in terms of temperature and to evaluate the risks of failure.

Long-term effects of heat are also destructive as they are mainly characterized by irreversible damages of the material due to thermo-oxidation mechanisms ultimately leading to scissions of macromolecular chains. Other kinds of stressful factors encountered in space environment, such as radiation or atomic oxygen, or due to operating conditions (e.g. voltage) will induce an accelerating ageing effect on the material.

This high temperature requirement was the main problematic for the development of a flexible cable solution for electric propulsion systems.

The following part summarizes the advances in field of high temperature wires and cables and focuses first on the development of a high power flexible cable technology for electric thruster applications.

HIGH TEMPERATURE FLEXIBLE CABLE SOLUTION FOR ELECTRIC PROPULSION DEVELOPMENT

Electric propulsion requires high voltage and operates in harsh environment characterized by both high levels of radiation and temperature in the area close to the thruster, as well as mechanical stress due to mobile plate motion. Depending on the thruster technology, temperatures up to 280°C are expected in critical areas.

The main objective of this project was to find and select materials to propose a new cable composition able to withstand these stringent requirements.

A specific test plan, close to these operating conditions was also defined and applied to characterize selected materials, followed by a final phase where the whole cable construction was evaluated.

Special tests were defined to simulate the operating conditions and to characterize materials in different states of thermal and radiation ageing and especially the combination of these factors.

Corona testing, highly significant for high voltage applications, was also performed through partial discharge measurement for each state of cable ageing.

Partial discharge measurement is an effective way to predict potential defects that may lead to the failure of the cable but also to characterize the degradation of the material at different ageing levels.

This project finally led to a cable technology suitable for powering a wide range of electric propulsion thruster technologies (Table1).

The advantages of a flexible solution for thruster powering lie in the weight gain provided by the use of polymeric materials that are lighter than mineral insulated rigid cables; it reduces the complexity of the system as it requires less components and facilitates the integration.

With the use of polymeric materials, ionizing radiation is a critical issue due to degradation it induces on some polymers.

Thruster	Technology	Nom. Power (W)	Nom. Voltage (V)
FEEP	Field emission electric propulsion	50	10000
T6	Gridded ion thruster	5000	1850
ROS 2000	Hall effect thruster	200	350
HET	Hall effect thruster	5000	550
HT100	Hall effect thruster	150	300
DS HET	Hall effect thruster	5000	550
			100
HEMP-T	Plasma thruster	1500	1000
PPS 1350	Stationary plasma thruster	1500	350

Table 1. Overview of the electric propulsion technologies.

The Total Ionizing Dose (TID) has been set up to 200 MRad (2 MGy) and has been tested on cable samples at different state of ageing. This test method allows to better understand the effects of radiation and degradation mechanisms on the polymeric insulation.

The dose-depth profile approach used is more realistic for cable insulating materials exposed to space environment than expressing radiation as a total dose only.

Figure 1 presents the radiation profile used in the study compared to theoretical dose-depth profile based on trapped electron and proton models fluxes (AE8/AP8) for Earth's radiation belt environment.

The tests were carried out under inert atmosphere (nitrogen) to minimize oxidation in order to be closer to actual real space conditions.

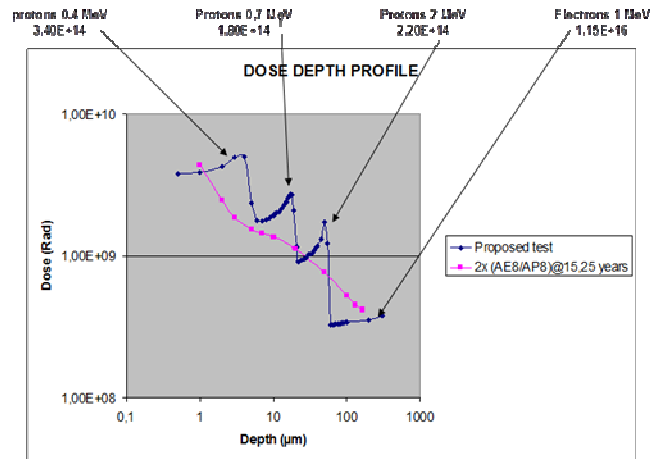


Figure 1. Radiation dose depth profile.

The final cable construction consists of a conductor specially designed to offer minimum resistance to bending, higher flexural life and high thermal resistance. The insulation consists of a multilayer combination of high performance polymeric materials (figure 2).

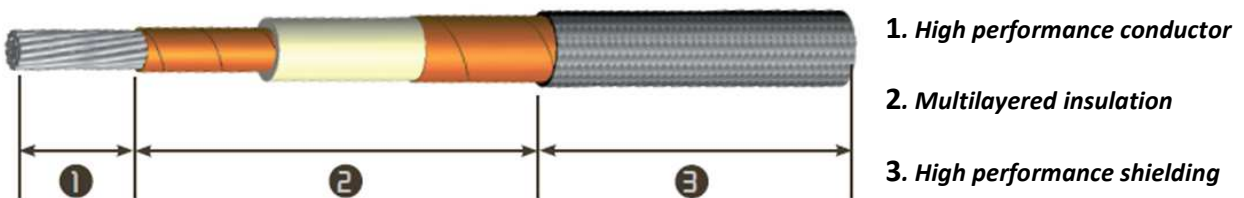


Figure 2. High temperature thruster cable construction

Most of the characterization was realized on the cable core structure (all components except the semiconductor layer and shielding). This approach allows adapting the construction to different requirements. Figure 3 shows a variant of this technology, designed for a lower temperature thruster but higher radiation resistance requirement.

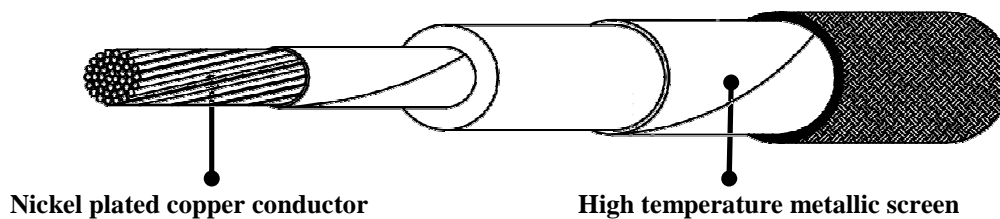


Figure 3. High radiation thruster cable construction

This study highlights that some recent engineering materials are able to meet the highest levels of requirements and are perfect candidates for a new range of high temperature wires. Their advantages should be multiple, like weight reduction or safe operation in a high temperature environment.

HIGH TEMPERATURE WIRES RANGE DEVELOPMENT

The development of a new range of wires which are able to withstand a significantly higher temperature than the current ESCC 3901 families is the main purpose of ESA EMITS A0/1-6839/11/EM EEE10. Current wires are rated for temperatures up to 200°C but the operating rules defined in ECSS Q-ST-30-11C and in the wires detailed specification impose strict limitation of the maximum current rating.

High temperature wires will allow transferring more current thus more power in an equivalent conductor section leading to many benefits like reduction of the weight and size of the harnesses.

The study approach is focused on the conductor behavior subjected to high currents and wire's insulation characterization mainly based on the thermal ageing.

Other important issues are included in the evaluation test plan, based on process issues such as stripping, crimping, flexibility, but also the behavior of the wire in the configurations commonly used in the field of space (bunches for instance) and thermal issues at the interface between wires and connectors. New derating rules shall, of course, also be defined in this study.

The objectives of this project is to qualify cable for continuous use at high temperature according to ESCC specifications, and to define the derating rules associated with these cables, in particular the determination of the current that may be used at different temperature.

The identification of adequate connectors and study of bundles or harnesses configuration are also part of the project.

The material that has been selected for the insulation of this wire and cable range has also extensively been assessed during the ESCC EMITS ITT A0/1-5245/07/NL/SFe (development of High Current, Voltage and Temperature Cable Suitable for Electric Propulsion) and gave satisfying results in terms of electrical and mechanical behaviour at high temperature (assessment up to 280°C).

PEKEKK (polyetherketoneetherketoneketone), a high performance polymer which belongs to polyaryletherketone (PAEK) group, is assessed as the main insulation material on the future high temperature wires range.

Concerning the conductor material, it is well known that silver coated copper (SPC) or copper alloy (SPCA) are rated up to 200°C and that a long exposure of this material at temperature above 200°C may results in severe degradations as showed in Figures 4 and 5.

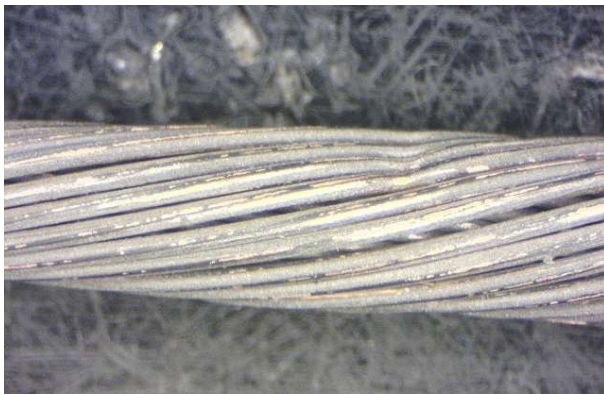


Figure 4. Silver plated copper conductor aspect after 2000 hours ageing at 250°C.



Figure 5. Nickel plated copper conductor aspect after 2000 hours ageing at 250°C.

Requirements

The definition of a higher temperature requirement makes this new wire range apart of the ESCC 3901 standards and influences several aspects of the wire specification. An update of the generic ESCC 3901 specification and the definition of an adapted detail specification are part of the tasks of this project.

The temperature capability is obviously one of the main requirement. The way the temperature is achieved is not a significant influencing factor so the wire shall be able to withstand high temperature from the environment (external) as well as the rise of temperature coming from a high current in the conductor (internal).

Another important requirement is the adaptability to existing connectors' technologies and that means that the new wire range shall be adapted to the components and the methods that are already in use by systems or satellites manufacturers. The gauges shall then be equivalent to the standard wires, and a validation of the cabling methods (crimping) shall be included in the evaluation test plan.

The flexibility is also an important criterion because the wires are often assembled in bundles of several lines. The flexibility of this new wires range shall allow an implementation close to that of existing components. As the selected material is known to be relatively stiff, then this aspect of flexibility shall be taken into account.

Material	Flexural Modulus (PSIx10³) @ 73°F (23°C)
PEKEKK	600
Polyimide	450
XL ETFE	200
FEP	95
PFA	95
PTFE	72

Table 2. Flexural modulus of the main insulation materials used for ESA qualified wires.

The radiation resistance is also an important requirement for space application and current specified values seem to need to be updated. The selected material is well known for its high radiation resistance (up to 1000 MRad) and discussion with satellite manufacturers highlighted the fact that total radiation doses encountered by components in some areas of the satellite are far more important than 1 MRad, which is the value required in ESCC 3901 standard. This development may also be an opportunity to review the radiation requirement for this new wire range.

The stripping ability is also one critical aspect that shall also be taken into account. The quality of the stripping (non barber or deformation of the insulation) and its ability to be realized with simple and compact tools (with the possibility to realize it onsite) were raised during by manufacturers.

Among the standard ESA wire families (ESCC 3091), the stripping ability is different from a construction to another. Fluoropolymers are soft materials that have high elongation and behave differently than Polyimide tapes that are stiffer, and multilayered.

The high temperature wires shall behave in a manner that no significant difficulties shall be noticed during stripping operation, either through manual stripping tools as well as semi-automatic or automatic systems.

Current capacity and derating rules definition

A direct consequence of the change of the temperature rating is the redefinition of the derating rules for this new wire range. Two aspects of the derating shall be taken into account:

- The derating for single wires and assemblies of wires from the same family is defined in the detail ESCC 3901 specification of the concerned wire.
- The derating for bundles are given by the ECSS-Q-ST-30-11 which defines a coefficient K that shall be applied to maximum rated amperage for each gauge and which depends on the number of wires that compose the bunch.

The amperage capacity depends of factors linked to the size and geometrical configuration of the wire or bundle but also to the maximum temperature rating of the wire. For safety operating, the standard specifications and space product assurance document defines the derating rules in function of temperature, conductor and number of wires in the bundle.

In the case of the bunch construction, the temperature will not be homogenous in the whole cross section of the bunch. The central area will be hotter than the external area and will result in the conductor resistivity increase in this area, thus leading to a lower amperage capacity. In order to avoid this scenario, the derating rules index the maximum allowable current on the number of strand composing the bundle.

The derating rules have been defined to prevent temperature rise that may locally exceeds the maximum temperature rating of the wire.

Increasing the temperature rating supposes that the conductor material shall also be adapted because silver plated copper (SPC) is rated up to 200°C. Nickel plated copper (NPC) is able to withstand higher temperature and is widely used for applications up to 250°C. However, the conductivity of NPC is lower than that of SPC; therefore the real benefit of amperage gain will be affected by the use of NPC.

Specific tests definition

The evaluation of this new family should be composed of specific tests focused on the main goal, operation in a high temperature environment. The operating modes of the wires predict that they may be exposed to high temperature in two different ways:

- The wire may be used in an environment of high temperature and in this case the carried current will be low
- The wire may be exposed to elevated temperature coming from “inside” and in this case; the high temperature is achieved because of the heat dissipation due to the amperage.

However in both cases, the material is subjected to the same thermal constraint, which is to withstand high temperature (the latter is generated by the conductor or by the external environment), and a long-term thermal test is expected to characterize the effect of aging.

Specific tests includes comparative amperage tests at room temperature that will help to define the difference of heat loss due to the lower conductivity of nickel plated conductor compared to silver plated conductor.

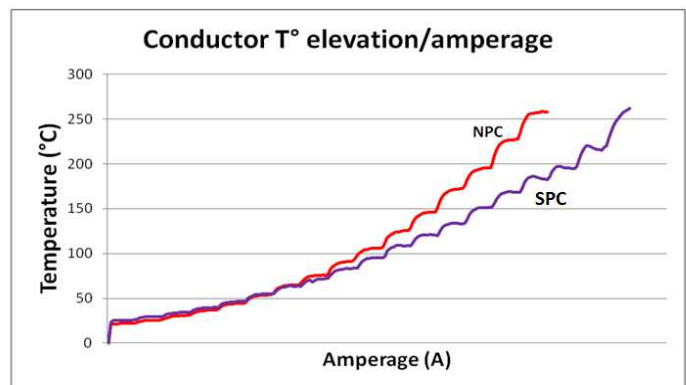


Figure 6. Typical graph showing temperature rise depending on the current in 2 different conductors.

Other specific tests will be defined according to the requirements and potential improvements (the radiation resistance for example could be significantly improved on this new wire family) to be included in the evaluation plan.

Connectors problematic

Another problematic of this project is the overheating that may occur near or in the connector because of the contact resistance induced at the male/female interface or the metallic junction at the crimping area. It clearly appears also that high temperature wires need adapted connectors with improved temperature capability.

Current solutions are qualified for use at maximum temperature of 125 °C and thus not suitable. These issues are studied in the following axis:

- by characterizing the temperature elevation in conventional connectors when the wires (bundle configurations) are in normal operating conditions.
- a survey of actual existing connector's solutions that may respond to the need (equivalent geometry, high temperature rating and compatible for space applications).

This survey will be based on an overview of connectors used in the space sector and more widely in the industry.

Perspectives

Whether for missions involving high temperatures or to transmit more power, the implementation of a range of high temperature wires shall provide many profits, mainly space and weight saving. The intrinsic properties, especially the radiation resistance, of the PEKEKK insulation material make this wire technology a good basis for special applications requiring higher level of performance provided that the construction is appropriate (for example, the use of adapted shielding techniques).

The development of adapted connectors with improved thermal performance will maximize the potential of this new range of wires and cables expected for 2014.