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Safety requirements for cables to be used in high-energy particle accelerators

Marc Tavlet

CERN, European Organization for Nuclear Research
CH - 1211 - Geneva 23

Abstract:

For the purpose of high-energy physics research, CERN operates several high-energy particle accelerators which are located in underground tunnels and which produce ionizing radiation. For safety reasons, in addition to the usual electrical, mechanical, thermal and environmental endurance properties, the requirements for all cables are that they be flame retardant, and in the event of a fire, that the resultant gases be non-corrosive, of low toxicity and provoke little smoke emission. Moreover, the organic materials have to be radiation resistant. This paper describes the safety qualification tests performed on materials to be used in the construction of the cables to be installed at CERN.

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1. Introduction

For the purpose of high-energy physics research, the European Organization for Nuclear Research, CERN, operates several high-energy particle accelerators. The largest one is the Large Electron-Positron (LEP) Collider, designed in the early eighties. The next one will be the Large Hadron Collider (LHC), which will be put into operation in the year 2005; it will be installed in the same underground tunnel of 27 km circumference as LEP.

The main components of these machines are the electro-magnets for bending, leading and focusing the particle beams. These magnets, as well as all other components, have to be powered, instrumented and controlled via electrical cables. In such large machines, this represents thousands of kilometres of cables, which have to be selected in accordance to electrical specifications and to severe safety requirements.

For safety reasons, in addition to the usual electrical, mechanical, thermal and environmental endurance properties, the requirements for all electrical installations at CERN are that the materials, including the cables, be flame retardant, and in the event of a fire, that the resultant gases be non-corrosive, of low toxicity and provoke little smoke emission.

Moreover, all of these machines produce ionizing radiation that degrades the components installed in the tunnels. Therefore, it is further required that the organic cable materials be radiation resistant. The distances are such that, for radiation reasons, it is impossible to use optical cables in the radiation environment of the tunnels.

2. General requirements for electrical installations

At CERN, a lot of high-technology equipment is used : ultra-high vacuum, superconducting magnets at the temperature of 1.2 K, superconducting radio-frequency cavities, fast-pulsed power supplies, high-rate data transmitters. The next generation of particle detectors will generate billions of data at each particle collision, at the rate of 40 MHz. The triggering of the acquisition of such a large amount of data, the handling and the storage of the data are a major aspect of the design of these experiments [1, 2, 3]. High-speed transmission, low cross-talk, low-mass cables, such as micro-coaxial, mini twisted-pairs (with half-pitch) or flat-twisted pair cables, will be needed; because of radiation levels as high as several kilograys per year, optical cables cannot be used, or only for some specific applications.

The safety requirements for electrical installations at CERN are based on the most recent IEC or CENELEC standards. The Electrical Safety Code C1 establishes the regulations for the construction, installation and use of electrical equipment [4]. It guarantees the protection of personnel and property.

3. Fire behaviour criteria and test methods

The requirements for fire safety at CERN are described in the Safety Code E [5], which sets out the fire prevention and protection rules and procedures to be followed in order to ensure primarily the safety and well-being of anyone and to protect property. Among its appendices, the Safety Instructions IS 23 and IS 41 define the selection criteria of cables and of any non-metallic parts, with respect to fire safety and radiation resistance [6, 7]. Table 1 is adapted from IS 23, summarizing the tests to be performed to check the fire behaviour of electrical cables.

In this table, it is to be noted that most of the tests apply to the constituent materials, while others apply to the complete cable. It should also be noted that other ISO, IEC and other international or national standards may be considered, in agreement with the safety department at CERN.

The limit of temperature index (required FT > 260^{0}C for the sheathing material) replaces the former limit of oxygen index (LOI > 28%).

The smoke density, the toxicity and the corrosiveness of fire gases can be measured on each individual material entering into the composition of the cable, but they can also be measured on a complete cable. The first option will be preferable if several types of cables are made from the same materials.

The choice of the type of vertical flame propagation tests (IEC 332) depends on the diameter (or the size) of the cable. Test type No 1 applies to all cables and wires with a section greater than 0.5 mm^2 ; the flame of a *bunzen* burner is applied for 60 s on a vertical cable which must not burn completely after the removal of the flame. Test type No 2 applies mainly to small single wires, the *bunzen* burner is of reduced power, the flame is applied for only 20 s. Test type No 3 is performed in a large fire cage (8 m^3) where the cables (3.5 m long) are attached to a vertical ladder. The flame of a powerful burner is applied for 20 min. In some cases, it can be required that bunches of small cables (diameter less than 10 mm) also pass the IEC 332-3 test if it is foreseen to use them in bunches.

The fire resistance test (IEC 331) only applies for cables with special safety functions such as emergency, lighting, alarms, lifts, etc. According to this test standard, the horizontal cable sample must remain operational after the continuous application of the voltage and of the flame for a period of 3 h.

The resistance to UV radiation will preferably be checked on a complete cable, which must not lose its colour, or become sticky after an exposure to UV light for a period of 10 days at the temperature of 40°C.

Table 1 : Required fire-behaviour properties for the selection of electrical cables and wires

Property	Standard	Requirements	Comments
Flame and fire propagation	IEC 332-1	Pass	Applies to all cables and single wires with section > 0.5 mm^2
	IEC 332-2	Pass	Applies to all single wires
	IEC 332-3	Pass Category CF	Applies to all cables with outer diameter > 10 mm
Fire resistance	IEC 331	Pass	For special safety cables
Smoke density	ASTM E 662	Ds < 250 in the flaming and non-flaming modes	For all cables
	IEC 1034-1 and -2	Pass	For major cable contracts
Toxicity of fire gases	ABD 0031	HF < 100 HCl < 150 HCN < 150 $SO_2 + H_2S$ < 100 CO < 3500 $NO + NO_2$ < 100	Mean values in ppm of at least 3 samples obtained within 4 minutes under flaming and non-flaming conditions
Corrosivity of fire gases	IEC 754-2	pH > 4 and conductivity < 100 µS/cm	All cables shall be halogen-free (less than 0.1% by weight)
UV resistance	IEC 68-2-5	No discoloration No stickiness	Procedure C, 10 days, 40°C

The full description of these standards can be found in the relevant publications. A compilation of most of the fire-behaviour tests can be found in the book by J. Troitzsch [8].

4. Radiation behaviour and lifetime assessment

As it has been shown by many authors that the electrical failure of an aged insulator usually results from the severe degradation of its mechanical properties, the radiation behaviour of an insulating material is assessed from mechanical tests.

At CERN, tensile tests are carried out on the cable insulations according to the publication 544 of the International Electrotechnical Commission (IEC) [9]. This standard is a "Guide for determining the effects of ionizing radiation on insulating materials", which defines the irradiation procedure and the mechanical tests to be performed: it recommends that flexible plastics (e.g. cable insulations) be submitted to tensile tests (according to ISO/R527 and ISO/R37). The standard recommends that the tensile tests are carried out to rupture of the material: the degradation is assessed from the reduction of the elongation at break. Since the type of rupture goes, with ageing, from ductile to fragile, this is an appropriate way of assessing the severe mechanical deterioration and the consequent possible electrical breakdown.

IEC 544 recommends that the limit of usability of a material be the absorbed dose at which the critical property (the most sensitive one being often the elongation at break) is reduced to 50% of its initial value. It defines a radiation index (RI) as the logarithm (base 10) of this dose. The use of the radiation index allows an easy ranking of the materials according to their radiation resistance.

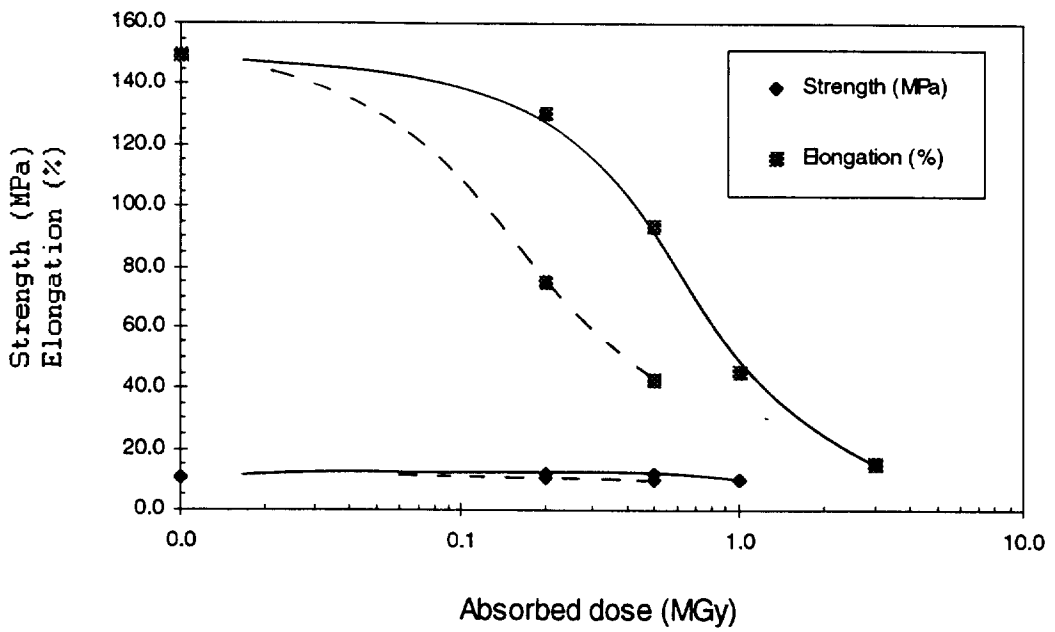
For the purpose of these tests, dumbbell samples are cut from the insulating polymeric materials. Tensile tests are performed on unaged samples and on irradiated samples. The irradiations are carried out either in a cobalt source (^{60}Co) at a dose rate of the order of 1 Gy/s, up to 1 MGy, or in a nuclear reactor at a dose rate of the order of 50 Gy/s up to 3 MGy. In both cases the irradiations take place in air, at temperatures between 15°C and 60°C, which are below the glass-transition temperatures of the thermoplastic materials.

For more than 20 years at CERN, hundreds of cable-insulating materials proposed by plastic producers or cable manufacturers have been systematically tested for their radiation resistance. Many results have been published in the form of catalogues [10, 11].

As it is known, organic materials are sensitive to oxidation, and the irradiation time influences the degradation of the material. A dose-rate effect is observed : for the same absorbed dose of radiation, the longer the irradiation time (lower dose-rate), the more severe the degradation [12, 13]. Figure 1 shows the reduction of the mechanical properties of a polyolefin-based cable- insulating material after irradiation at two different dose rates (full lines correspond to irradiations at dose rates of 4 kGy/h and 200 kGy/h, dotted lines correspond to irradiations at 100 Gy/h).

From several irradiations at different dose rates, and extrapolation down to the "life" dose rate, it is sometimes possible to assess the lifetime of cables in real environment of particle accelerators or of nuclear power plants [14, 15]. Sometimes it is not possible to extrapolate because of other ageing mechanisms taking place. The Engineering Safety Section of the International Atomic Energy Agency (IAEA) has set up a co-ordinate research programme to better define qualification procedures and the monitoring conditions that should allow a prediction of the lifetime of installed cables [16].

Fig. 1 : Radiation effect on polyolefin cable insulating material



5. Conclusion

From the design of the LEP collider in the early eighties, it was the policy at CERN to require the use of halogen-free cables. This requirement excludes the use of PVC, CSPE and other materials containing chlorine. Moreover, the toxicity tests exclude the use of materials containing too much sulphur, nitrogen and phosphorus.

In the beginning, this safety requirement led to cabling over-cost. However, with the years, more and more users, such as other national laboratories and underground public transports or public buildings, also require the use of this type of cables. As a consequence, more and more cable manufacturers started to produce halogen-free, flame-retardant cables that comply with our safety regulations. Nowadays, it has become possible to find most of the cable types in compliance with the safety requirements listed in Table 1, and this at no extra cost. Some cable types, such as "flat-twisted", flat "half-pitch" and micro coaxial are not yet easily available.

CERN, who had started with these severe requirements, has had a leading role in this safety aspect. We have now extended these requirements to any cable installation, be it underground or on the surface, as well as to the use of any non-metallic part.

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