Wiring Systems for Nuclear Power Stations

White Paper

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**Synopsis**

The fact is that almost everything will change over time and that rate of change is often highly dependent on the environment. Organic based electric cable insulations are particularly subject to change.

Electric cables with organic polymer insulations have a useful design life span under specific conditions but unlike many other components, electric cables remain the fundamental arteries or nerve connections that enable every other active component to work. Because electric cables are ‘embedded’ often it is difficult and expensive to replace them, as such electric cables should ideally provide a reliable service life equal to or better than the equipment connected and often aligned with the project design life.

- The genesis of polymeric cable insulations came in 1812 when Baron von Schilling took a copper wire covered it with India rubber, dried then varnished it.

- The next evolutionary step came in 1839 when it was found this India rubber could be vulcanized by treating it with Sulphur in the presence of heat to produce an insulation with a non-melting, more elastic property. Today for cables we call this process “crosslinking”.

Ever since we have been in the world of polymeric flexible cable insulations and with it, the inevitable effect of aging. The nemesis of most cable polymer aging is heat in the presence of air (more accurately oxygen) but chemicals, gases, water, light, radiation, mechanical (static and dynamic) stressors will all add to and multiply the speed of aging. These effects can be seen as both physical and electrical changes in the material properties and include reducing flexibility, deterioration of the materials elongation at break, hardening, cracking, surface chalking, discoloration and decreasing dielectric performance.

Many people think of electric cables as passive electrical components but nothing is further from the truth. With energisation, electric cables transmit voltage and current over a range of frequencies. Due to the fundamental limitations of conductors and insulations, secondary effects such as resistance, reactance, impedance, capacitance etc. all create unwanted conflicts which need to be both understood and designed out, or at least minimized as far as practicable. Connected equipment can also induce unfavorable influences in electrical cables but one very important conflict, be it inherent or induced, is the effect of conductor resistance on current flow because this creates heat.

Heat in the presence of air is a primary enemy of all polymer insulations. Thermal degradation is a molecular deterioration caused by the long chain molecules breaking (scission) and reactions within the polymer which change the properties over time. These changes typically cause the reduced flexibility, embrittlement (cracking) chalking, color changes and the reduced elongation as mentioned above. In addition to the physical changes caused by aging, operational properties may also be affected and these may include insulation resistance, flame retardance, oil / water resistance etc..

This paper explores the aging of polymer cable insulations as they relate to the Nuclear Industry and questions if the common useful life prediction standard of “Elongation at Break” (EAB) as used today for electric cable insulations in domestic, industrial and commercial applications is also appropriate for use in the Nuclear Power Industry, or if more stringent performance criteria should be adopted.
Aging

An internationally accepted test method to determine aging performance for electrical insulations is defined by IEC60216 which employs accelerated heat aging of test samples, comparing the aged elongation at break (EAB) performance against un-aged samples, tabulating the results on an Arrhenius plot and extrapolating to predict extended life performance.

This standard is adopted widely around the world and specifies the calculation and test procedures to be used for deriving thermal endurance characteristics from experimental data obtained in accordance with the instructions of IEC 60216-1 and IEC 60216-2, using fixed ageing temperatures and variable ageing times.

NASA report CR 1787 (Radiation Effects Design Handbook Sect 3. Electrical Insulating Materials) considers the useful lifespan of polymers for aerospace / space applications is when one original property of the material (tensile strength, elongation etc.) has changed by 25%. For electrical cables in non-aerospace applications, like commercial, domestic or industrial applications, we adopt the calculation of predicted lifespan by measuring the materials reduction in EAB (Elongation At Break) to 50% residual (IEC60216). EPRI (Technical Report 1008211, “Initial Acceptance Criteria Concepts and Data for Assessing Longevity of Low-Voltage Cable Insulations and Jackets” EPRI 2005) also describes 50% EAB as a conservative practical end-of-life threshold for cables that may be subjected to a loss-of-coolant accident (LOCA) exposure. What is not often realized is that a 50% residual EAB often corresponds to a change in the material properties from new of 80% or even more. This is significantly different to NASA’s criteria for aerospace/space applications.

Given the critical importance of system integrity, reliability and performance in the Nuclear Power Industry and the potential devastating consequences of failure, it is appropriate to question if the “50% residual” threshold as used today for all general industrial, commercial and domestic polymer wiring is also an acceptable performance criteria for critical Nuclear applications, or if adoption of a “change in property” in Elongation at Break (like NASA) for would be a safer ‘end of life’ threshold.
Today cable manufacturers blend polymers with fillers like plasticizers to improve flexibility, flame retardants to improve the fire performance, stabilizers & anti-oxidants to extend lifespan (by mopping up free radicals), pigments for colour and even calcined clays, zinc oxide, paraffinic waxes and oils. These additives can improve insulation and jacket material performance and slow the aging process but they cannot stop it. Unfortunately all the stressors to aging and polymer degradation are additive so if we factor the normal combinations of cyclic heating and cooling, the occasional overload or short circuit, presence of ozone (which is often greater in coastal areas) occasional exposure to cleaning agents, oils, water, light and humidity (or even the lack of it), polymer aging can be accelerated both considerably and unexpectedly.

Degradation occurs faster where air/oxygen is present so it is common that cable jackets may age faster than cable insulations. This is fortunate because many of the fillers used to improve physical performance and aging cannot so easily be added to insulating compounds as they would reduce the dielectric properties. It is therefore interesting to note the tested and published observation that cables meeting flame retardance tests, where subjected to open and external flame (IEC 60332 pts. 1, 3 etc.), may in fact not be flame retardant at all if subjected to internal and un-interrupted overcurrent or short circuit conditions. (8th International Conference on Insulated Power Cables - Jicable’11 – 19 – 23 June 2011, Versailles, France: “Fire Performance cables under current overload conditions”).

Perhaps one major cause of polymer degradation occurs due to polymer chain scission. This is caused when free radicals within or from outside the cable insulation cause breakages in the polymer backbone chain over time and even create additional crosslinks. This natural process is accelerated by heat, moisture, light and mechanical stressors. Not only does this degrade mechanical performance but the multiple processes combine to increase the number of carriers in the polymer insulation material, thereby increasing the conduction and will ultimately lead to dielectric breakdown.

Pic. Aged cables in power station showing cracking.
These effects are only accelerated again if exposed to radiation, so if a radiation exposure such as LOCA was to occur in the presence of old cables the effect may just be enough to push the insulation over the edge to failure, exactly when you might need the cables to operate reliably.

**Crosslinking**

Today most common insulations for electric cables can be categorized into two groups: Elastomeric or Thermoplastic. Generally Elastomeric cables are made from natural rubber based compounds (because they tend to be more “elastic” and “bounce”) whereas Thermoplastics are made from various man made polymer compounds and are generally harder with less elasticity.

The definition of what is Thermoplastic or Elastomeric depends on the materials so called “Glass Transition” (Tg) temperature. If this is above room temperature we call the material “Thermoplastic” if it is below room temperature we call it Elastomeric. Because Elastomeric materials have Glass Transition temperatures below room temperature and tend to melt at lower temperatures (Tm) than Thermoplastics they are mostly cross-linked when used as cable insulations. Thermoplastic materials can also be cross-linked but in many cases are not (such as with common PVC cables) because they often have higher than room Tg and Tm temperatures.

One fundamental for electric cable insulations is if the material will melt with heat. Both Elastomeric and Thermoplastic materials will melt with heat which is useful because we generally need to change the shape depending on the product we wish to make. A rubber band, a rubber ball, a plastic toy or a cable insulation. With many Thermoplastics the melt temperature is relatively high so after melting (extruding or molding) the material into the required shape or product we then cool it down. On cooling it hardens and retains its new shape. Many PVC cables we use are made like this but with Elastomeric materials the softening and melt temperatures are often rather low so with these materials we frequently treat them with an additional a process called crosslinking to stop them softening so much or melting in the presence of heat.

To understand better what this is means we need to understand a little more about the structure of the materials. Most common insulations are made up from long chain hydrocarbon based polymers. At room temperature these polymers have both crystalline structures and amorphous structures.

**Example of a partially crystalline polymer:**

![Crystalline regions with high density](image1)

![Amorphous regions with lower density](image2)
If we heat the material the crystalline sections will start to melt and the long chain polymers can start to slip and slide past each other. At first the material softens but with higher heat eventually melts into a liquid much like oil. This is good because we can then mold, shape or extrude the material into any shape (by extrusion for the insulation on electric cables). When we cool the material again the crystalline structures reform and the material becomes more solid again retaining the new shape. In fact this process could be repeated many times.

Conversely the opposite is also true. If you take a partially crystalline polymer and cool it down the crystalline regions will multiply and grow and correspondingly the amorphous regions will shrink. In this case the material hardens and becomes brittle. You will notice this effect when your plastic containers in the fridge become hard when cold or your garden hose becomes very stiff in the winter months. It’s the same for cable insulations.

It becomes clear that with fewer crystalline regions the polymer is softer, more flexible but perhaps weaker and with more crystalline regions the material hardens, becomes less flexible but stronger.

With this in mind we now turn to the processing of polymeric materials for electric cables. Electric cables have to transmit current and voltage through metallic conductors. Unfortunately even copper is not a perfect conductor so has a resistance to the flow of electrons. This resistance results in a heating of the conductor when we draw current, which in turn softens the polymer insulation. Certainly we don’t want our cables to melt or change shape due to this ohmic heating or from any external heating. It is often not possible to stop the crystalline regions from melting with heat so one way to prevent the polymer from actually changing shape and even melting is to create links (bonds) between the long polymer chains which will not melt with heat. This process is called “crosslinking”.

Crosslinking of polymers can be achieved in many ways. Adding chemical reagents to the compound like Sulphur with heat and pressure is a common method as is peroxide crosslinking but other methods are also used in the wire and cable industry such as saline bath or irradiation. All of these methods have some advantages and disadvantages but all create covalent bonds between the long polymer chains.

Example of a partially crystalline polymer with crosslinks:

It is perhaps worth noting that the crosslinks are only formed in the amorphous regions (represented by dots in this picture).

On heating the polymer the crystalline regions will still melt and the material will soften but the covalent (chemical) bonds will not break down with heat and therefore will stop the polymer from melting.

As can be expected the number of crosslinks will have an effect on the materials flexibility, hardness and elasticity and that these properties will constantly change with temperature.
Sophisticated cable manufactures will modify polymers to optimize operational performances. Depending on the application, crosslink densities can be manipulated to give optimum properties:

All this polymer manipulation is very clever and provides polymeric electrical cable insulations with specific and optimized properties for many applications, be it continuous flexion, tensile strength, abrasion resistance, best fatigue strength or a low coefficient of friction. What these processes cannot do is optimize cable insulations for every application because in favoring one property a compromise needs to be accepted in another property. Another thing they cannot do is stop the degradation or “aging” process.

So how long can I expect my cables to last?

Life Span as defined by reduction in EAB (Elongation at Break):

IEC 60216 defines that the temperature rating given to an insulation material is: “That temperature which degrades / reduces the material’s elongation at break (EB) to 50% absolute (residual) in a period of 20,000 hours exposure” (20,000 hours = 2.3 years).

Common cable insulating materials operating temperature defined by IEC 60216:

- PVC = 75°C
- XLPE = 90°C
- EPR / CPE / CSP rubber = 90°C
- Silicon Rubber = 180°C
- Teflon PTFE = 260°C
Understanding why PVC is rated at 75°C and why XLPE or EPR is rated at 90°C we can now better understand why the current rating standards we use calculate current ratings for PVC based on a 75°C conductor temperature and for XLPE or EPR insulations based on a 90°C conductor temperature:

- UK IEE wiring regulations 17th Edition,
- IEC 60364-5-52
- AS/NZS 3008-1
Perhaps what is not highlighted by these standards is that the elongation at break reduction to 50% absolute (residual) is calculated on 20,000 hours exposure time at this temperature - which is only 2.3 years. In fact these standards do not really expect engineers to use the cables at (PVC) 75°C or (XLPE) 90°C continuously or the cable lifespan will be exceptionally short. They assume usage will be on a basis of discontinuous loading where it is not anticipated the cables will be fully loaded or heated 100% of the time. This pragmatic approach is the only way polymeric cable insulations can be economically viable.

A common ‘rule of thumb’ for cable polymer insulation aging is that a reduction of 10°C in the average cable operating temperature across its life span will double the insulation life time to the 50% EAB (Elongation at Break) point: i.e.:

- PVC: operated continuously at 75°C will degrade to 50% EAB in 20,000 hours (2.3 yrs)
  - operated continuously at 65°C will degrade to 50% EAB in 40,000 hours (4.6 yrs)
  - operated continuously at 55°C will degrade to 50% EAB in 80,000 hours (9.2 yrs)
  - operated continuously at 45°C will degrade to 50% EAB in 160,000 hours (18.4 yrs)

- XLPE: operated continuously at 90°C will degrade to 50% EAB in 20,000 hours (2.3 yrs)

- EPR: operated continuously at 80°C will degrade to 50% EAB in 40,000 hours (4.6 yrs)
  - operated continuously at 70°C will degrade to 50% EAB in 80,000 hours (9.2 yrs)
  - operated continuously at 60°C will degrade to 50% EAB in 160,000 hours (18.4 yrs)

Conversely increasing the continuous exposure temperature by 10°C will half the time to 50% EAB.

In reviewing the above it must be remembered that any additional chemical, ozone, light radiation exposure, overload or short circuit events will serve to shorten the anticipated cable lifespan.

Of course where polymers have been formulated to have this degradation to EAB to 50% residual at higher temperatures, then the predicted lifespan at an anticipated mean temperature might be longer i.e: Where a polymeric insulation qualifies for a 110°C temperature rating but is operated at a mean temperature of only 60°C as per examples above, the 50% EAB will extrapolate out to 73.6 years (perhaps aligning with a 40 or even 60 year useful lifespan as often required for Nuclear Power station applications and as claimed by some suppliers of polymeric cables). This however, may not fully be accurate in practice because of the additive and cumulative effects over that time of all the other stressors like humidity, ozone, over temperature events like short circuit/overload, exposure to chemicals, light, mechanical stresses on fixings and supports, flexion and possibly even radiation events.

It is not commonly realized just how quickly common polymeric cable insulations will degrade with time and temperature when operated continuously in air at their rated temperatures:

<table>
<thead>
<tr>
<th>Insulation Material</th>
<th>Temperature Rating</th>
<th>Continuous exposure for 20,000 hours (2.3 yrs) at rated temp.</th>
<th>Expected percentage reduction in elongation at break from new</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>75°C</td>
<td>75°C</td>
<td>80%</td>
</tr>
<tr>
<td>PE and XLPE</td>
<td>90°C</td>
<td>90°C</td>
<td>85%</td>
</tr>
<tr>
<td>EPR, CSP,</td>
<td>90°C</td>
<td>90°C</td>
<td>85%</td>
</tr>
</tbody>
</table>

This differs wildly from the 25% change in original material properties as recommended by NASA for aerospace / space applications and lends weight to the argument for a review within the critical Nuclear Power Industry.
In normal practice, the use of IEC60216 for determining polymeric insulation temperature ratings by heat aging and elongation at break measurements with the subsequent calculations for determining cable current ratings is pragmatic only because circuits are not often sized exactly to maximum current demand. Full load current loading of cables circuits can be infrequent and the “averaged” operating temperature of cables over their lifetime may well be rather less than the maximum conductor temperature ratings quoted in the standards thus extending the useful cable life span to a reasonable time.

In defense of the mentioned standards for common industrial, commercial and domestic applications, to calculate polymeric cable current ratings based on any more conservative usage may require significantly larger conductor sizes having significant economic impact (although for power circuits corresponding reduction in Watt losses might well compensate for the additional cost over the cable installation life time).

The question for owners, designers and Authorities within Nuclear Power industry is:

“Is the protocol for determining temperature rating and useful lifespan of electrical cable insulations by aged Elongation at Break at “50% residual” appropriate (which as demonstrated above allows degradation in this property of 80% or more) or should temperature ratings and life span calculations for cable insulations for Nuclear Power applications demand, like NASA, a maximum change in the materials original EAB properties be less than 25% or perhaps more conservatively 50% (and not the 50% residual EAB as used today)?”

It is critical that electrical design engineers understand the ageing characteristics of polymeric insulations when selecting cables for use in applications where long reliable life is needed in essential applications. Examples today include aerospace/space but arguably should also include the Nuclear Industry.

It is also critical that where high continuous or ‘near continuous’ loading is expected, especially in high ambient temperatures, in sunlight or where higher than normal levels of humidity or ozone is expected. (Conventional or Nuclear Power Stations, generators, high temperature industrial facilities, transformers, continuous ventilation fans, continuous pumps etc.) that in these applications “continuous use” de-rating factors should be applied or the use of cables with a correspondingly higher continuous temperature rating.

For the Nuclear Industry, electrical cable performances over long periods of time are absolutely essential. Applying the same methodology for determining polymeric cable material temperature ratings and extrapolating expected life span as we do for non-critical domestic, commercial and industrial installations is at best questionable and could lead to potentially devastating, virtually permanent consequences for societies or even countries.

Conclusion

It is correct to sometimes stand back and question not just what we do, but why we are doing it and what is the basis for the actions and decisions we take. Often momentum leads us to assume the reasons we do things one way or another is because it is proven or normal, but as shown in this paper if the basis for our decisions is flawed then every step we take beyond this is equally flawed. The Nuclear Industry is not a normal industry so just like aerospace, it is not always appropriate or correct to simply apply the standards and protocols as used for everyday commercial, industrial or domestic environments. Certainly the consequences in the risk matrix justify a rethink.

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There is one cable technology that has been available and widely used for over 80 years and which is effectively non-aging. MICC cable with its copper outer jacket, inorganic magnesium oxide insulation and copper conductors will not age like polymers do with heat. They will withstand repeated overload and short circuit events without degradation. They are unaffected by sunlight, UV, Ozone and resist many chemicals. The copper jacket and Magnesium Oxide insulation are particularly resistant to radiation.

For this reason MICC cables are often used in critical applications, for high or continuous loading and for essential safety circuits in the Nuclear, Biological and Chemical hazard industries. MICC cables are frequently used in projects with long design lives of 60 years or more and are used regularly in many historic buildings as they are non-aging, never need replacing and are architecturally compatible in visible locations. The cable is also approved for use in all Hazardous locations.

Being inorganic, MICC cables are totally flame retardant. As they have no fuel element to propagate a fire they simply cannot spread flame. For the same reason, MICC cannot generate any smoke, corrosive halogen or toxic gases when subjected to high heating or fire, including the non-halogen toxic gases like CO and CO2.

MICC cables are also mechanically stronger than any other cable design and in all operating or emergency conditions. They do not soften when exposed to high temperatures, are crush, impact and cut through resistant. They require no conduit for mechanical protection and termites or rodents cannot eat through the outer sheath of bare MICC cables as they do for served Steel Wire Armored cables.

Another important feature of MICC cables is the compacted Magnesium Oxide insulation fully internally seals the cable eliminating any migration of toxic radioactive gasses, bio-hazard or chemical hazards along the inside the cable. For this reason MICC cables are also ideal for pressurized environments.

No other cable design today can guarantee the same electrical, mechanical and environmental performance of MICC cable or provide the same level of overall fire safety, integrity and security throughout the full design life of the project. MICC cables are both water and oil proof, have greater current ratings with smaller diameters and need fewer fittings compared to other cable designs. They are radiation resistant and are ideal for use in Nuclear, Bio-hazard, Chem-hazard and in cryogenic environments.

Mineral Insulated Cables with copper or special metal alloys are capable of meeting all known Fire Propagation, Flame and Oven circuit integrity tests. The cable technology provides a guaranteed Fire Proof wiring system which is not only 100% flame retardant but 100% Halogen free, 100% smoke free, 100% toxic emission free with zero organic content. Because MICC has no fuel element it contributes no heat of combustion, causes no oxygen depletion and no contribution to temperature rise. They are also inherently non-aging so will work reliably when you need them, whether this is on the 1st day or the last day of the project life cycle.