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Patrick M. Madden
Senior Fire Protection Engineer
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
White Flint, 8D1
Washington, DC 20555

Subject: Ultimate failure temperatures for electric cables

Following your request, we have reviewed the available information on this subject.

Old data

In our letter of August 5, 1992, we summarized the findings of Rosch [1] pertinent to natural rubber-insulated wires. He conducted tensile tests on furnace-aged rubber insulation. The data showed that, if aged at 60°C, rubber insulation lost, in some cases, all tensile strength. The same cable aged at 50°C, however, retained enough tensile strength to be considered adequate. Based on this data, Rosch established that rubber-insulated cables could be rated at 50°C. This implies a 10°C margin between the service temperature and the failure temperature.

ERA Studies

In 1964 the Electrical Research Association (England) sponsored a 'pilot' study to determine the temperature limits of PVC-insulated cables. Their study [2] involved applying mechanical load to power cables exposed to varied temperatures. The primary criterion was excessive deformation. The conclusions were that 70°C rated PVC cables could be exposed for up to 4 hours to 130°C temperatures without excessive deformation. Deformation became significant at 140°C, and at 150°C insulation cracking was seen upon cooling.

ERA have intended subsequently to expand upon this study and to examine other materials, but funding was never made available.

FMRC study

In 1981 FMRC conducted a study on this topic under the sponsorship of EPRI [3]. The methodology used by FMRC was unusual. Instead of exposing cables to uniform elevated temperatures, cable samples were exposed to a one-sided radiant heat flux. The cable sample was, essentially, at room temperature on its unexposed face, while seeing an elevated heat flux and a rapidly rising surface temperature on its exposed face. The test specimens were monitored for visual degradation, for the occurrence of short circuits and for specimen ignition. Results were reported in terms of the lowest radiant flux for the specimen at which each of the three events occurred. For a variety of cable types, the minimum flux for degradation was reported to range

from 6 to 24 $kW \cdot m^{-2}$. For piloted ignition to take place, the minimum flux ranged from 18 to 40 $kW \cdot m^{-2}$. For electrical shorting to take place, the minimum flux was 9 $kW \cdot m^{-2}$, ranging up to no failure having been observed for some specimens at the maximum test flux of 70 $kW \cdot m^{-2}$.

In terms of data analysis, FMRC present a table wherein surface temperatures at failure are **calculated** on the basis of some simplified (unexplained) heat transfer model. These calculations were in no case supported by any temperature measurements.

The FMRC results are impossible to relate to actual failure temperatures in the context of the cables located in cable trays and protected by a barrier. The experimental situation that FMRC created could represent a scenario where it is enquired whether unprotected cables can withstand a very brief, direct fire exposure. In the case of interest to NRC, however, the cables are (1) heated internally by I^2R heating; and (2) are exposed from the surface by heating which occurs at a low rate but over a long time period (1 to 3 hours). There is no simple relationship between the response of a real polymer under brief, high radiant flux surface heating versus being heated slowly by conduction, convection and radiation. In the former case the cable will see steep temperature gradients throughout its depth; in the latter case, it will tend to equilibrate throughout its thickness.

The FMRC study was analyzed by Nicolette and Nowlen at Sandia Laboratories [4]. They held in abeyance the question of whether a critical flux-based testing methodology was appropriate and, rather, examined the more narrow question of whether the FMRC results were consistent and plausible. By examining both the FMRC data and their analysis methods, the Sandia researchers concluded that "damage thresholds that are based on the critical flux methodology appear to be based on an incorrect and nonconservative extrapolation."

Proprietary European data

We asked the laboratories of a major European cable maker if they had any data on the ultimate failure temperatures of their cables. They were able to provide the following information.

Insulation	Rated temperature (°C)	Max. temperature for a 5 s short circuit condition (°C)
PVC	70	160
PE	70 - 75	130 - 150
XLPE	90	250
EPR	90	250

We were not able to find out the testing details used to determine these temperatures. Compared to the ERA data, the results quoted appear plausible. That is, if 150° C causes damage after several hours, it is consistent that 160° C could be sustained for 5 s with no damage.

Sandia National Laboratories tests

During the last decade, Sandia National Laboratories examined the damageability issue in connection with several of their experimental programs [5]. In one series of tests, they tested a non-IEEE-383-rated cable using PE wire insulation and jacketing and an XLPE cable which did pass the IEEE 383 test. For a 60 min exposure test, the thermal damage temperature was stated to be 130°C for the PE cable and 250°C for the XLPE cable, based on electrical shorting post-test. The test exposure itself was an elevated temperature oven where the sample were subjected to several different conditions of bending and mechanical stress while heating.

Later, Sandia concluded that post-test monitoring was not necessarily conservative, since shorting may occur during heating, but 'heal' afterwards. In a second series of tests, a non-rated cable using a PE/PVC wire insulation and a PVC jacket was tested, along with a rated XLPE cable. The tests were intended to identify only short-term failure behavior. The non-rated cable showed electrical failure at 10 min in a 250°C environment; the rated cable endured approximately 40 min at 270°C. Additional data were obtained for higher temperatures and short times, but not for longer times.

In the next program [6], two cables were subjected to testing. Both were IEEE-rated, but using different polymers for their insulation and jacketing. The tests comprised laying cable specimens flat on oven shelves and monitoring electrical shorting for up to 80 min. Electrical shorting was defined as current which causes the failure of a 2 ampere fuse. Tests were run on both aged and unaged specimens. For the unaged specimens, damage thresholds were concluded to be 325—330°C for one cable type and 365—370°C for the other.

The most recent Sandia effort has been a correlation [7] of the above results obtained from the direct oven tests to those obtained in the course of an aging study. In the latter study [8], the variable being monitored was the insulation resistance, taken as cables were progressively being heated in a steam chamber. The primary test results pertinent here was a listing of the temperatures at which various insulation resistance values occurred. These failure criteria examined were 100, 10, 1, and 0.1 kΩ per 100 m cable length. A total of 13 different cable types were examined with this protocol. For those two cables which were also tested in the previous program, a direct comparison of results could be made. It was found that using the 0.1kΩ criterion, the closest match could be made, i.e., 320—322°C and 375°C for the two types; this corresponded closely to the values of 325—330°C and 365—370°C obtained from the oven test program. Based on this comparison, the performance of the remaining cables was tallied at the 0.1kΩ failure point. The tabulation showed a range from 278°C to approximately 399°C. The 13 cables were considered to represent the major commercial types in common use in nuclear power plants.

Conclusions

The old data of Rosch and the somewhat less old ERA data are not relevant to NRC's concerns since the cables tested certainly would not represent IEEE-383-qualified products.

The FMRC study was based on more current cable types; however, the methodology used was incapable of producing useful numerical values for the ultimate failure temperatures.

The proprietary data we have been able to obtain from one manufacturer does not describe the details of the test protocol. Values of 250° C for failure temperatures of XLPE and of EPR would seem to be plausible. The data presumably reflect that the values are for 'still passing' rather than 'just failing,' but they are for short exposure times.

The Sandia Laboratories' tests represent the only significant data gathering effort which is well-documented, which examined IEEE-qualified products, and where quantitative values were successfully obtained. Despite this, the issue is not solved. The following considerations remain:

- The tests reflect exposure times only slightly over one hour. Issues associated with a 3 h endurance requirement are still unknown.

- A consensus on what constitutes the appropriate test conditions is lacking. It would appear reasonable to presume that the earliest failure will occur if the cables are kinked and under mechanical tension. This concern is important: If cables are laid straight and without stress, it is entirely possible to completely burn away all of the insulation from a length of such cable without causing shorting. Yet, of course, if there are mechanical forces tending to pull one conductor against another, even burning away is not required—melt flow or lowered indentation force requirement can suffice to cause circuit failure.

- The Sandia conclusions are based on a correlation which has only two data points. Furthermore, these two points are close together. Such a correlation may be entirely suitable as a basis for helping formulate future experimental directions, but certainly it is not a robust correlation in itself.

- In the earlier Sandia tests, the single IEEE-rated cable that was tested endured only 60 min at 250° C. Thus, it is not clear how to interpret the latest correlation from Sandia which indicates the lowest failure temperature of 278° C, especially in view of the statements accompanying the earlier study that the methodology used was possibly not conservative enough [5, p.96].

We note, in conclusion, that there does not appear to be much margin available, even based on the data known so far. For example, taking a 250° C failure temperature, minus a 90° C rated temperature, gives a temperature difference of only 160° C. This is in the same general vicinity as the ASTM E 119 failure criterion. Given all of the uncertainties discussed above, it is not prudent to assume that the ASTM E 119 temperature failure criterion is necessarily proven adequate for application to nuclear power plant cable protection.

References

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Sincerely yours,

Vytenis Babrauskas

APPROVED:

Andrew J. Fowell
Chief, Fire Science and Engineering Division