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THE CABLE RESPONSE TO LIVE FIRE (CAROLFIRE) PROJECT: ADVANCING THE CABLE FIRE RESPONSE KNOWLEDGE BASE

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ABSTRACT

This paper summarizes a recently completed project sponsored by the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES) including collaborative efforts conducted by both Sandia National Laboratories (SNL) and the National Institute of Standards and Technology (NIST). The project is known as the Cable Response to Live Fire (CAROLFIRE) project. A total of 78 small-scale tests and 18 intermediate-scale open burn tests were performed by SNL to investigate cable thermal response and electrical failure behaviors. The tests were designed to complement previous testing and to address two needs; namely, to provide data supporting (1) resolution of the 'Bin 2' issues as identified in Regulatory Issue Summary 2004-03 Revision 1 - Risk informed Approach for Post Fire Safe Shutdown Circuit Inspections and (2) improvements to fire modeling in the area of predicting cable response to fires. This paper will focus on the second of these two need areas. Included are descriptions of the test configurations and examples of the type of test data gathered. Also included is a discussion of efforts at NIST to develop a simple cable thermal response and electrical failure modeling algorithm called the thermally-induced electrical failure (THIEF) model to predict the behavior of power, instrument, and control cables in a fire. The THIEF model is intended to be incorporated as a subroutine for deterministic fire models, and it is of comparable accuracy and simplicity to the activation algorithms for various other fire protection devices (e.g., sprinklers, heat and smoke detectors). THIEF model predictions will be compared to experimental measurements of instrumented cables in a variety of configurations.

Key Words: electrical cables, fire testing, cable fires, fire PRA, fire PSA, fire modeling

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1 INTRODUCTION

This paper summarizes a recently completed project sponsored by the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research (RES) including collaborative efforts conducted by both Sandia National Laboratories (SNL) and the National Institute of Standards and Technology (NIST). The tests were designed to complement previous testing and to address two needs; namely, to provide data supporting (1) resolution of the 'Bin 2' issues as identified in Regulatory Issue Summary 2004-03 Revision 1 - Risk informed Approach for Post Fire Safe Shutdown Circuit Inspections [1] and (2) improvements to fire modeling in the area of cable response to fires. This paper will focus on the second of these two need areas.

The project is known as the Cable Response to Live Fire (CAROLFIRE) project. A total of 78 small-scale tests and 18 intermediate-scale open burn tests were performed by SNL to investigate cable thermal response and electrical failure behaviors. In collaboration with the testing efforts, staff at the National Institute of Standard and Technology (NIST) utilized the test data to support development of a simple cable thermal response model with the intent that the developed cable response model be used to supplement existing room fire modeling capabilities.

This paper provides a summary of the CAROLFIRE efforts with a particular focus on the test conditions, test data, and the fire modeling activities. For additional detail, the reader can refer to the three-volume main project report [2-4]. This report is available though the U.S. NRC, and the publication does include full release of all of the test data files. Volume 1 of the main report focuses on the Bin 2 circuit issues and Volume 2 focuses on presentation of the test data associated with the cable thermal response monitoring and correlation of those results to cable electrical failure. Volume 3 focuses on the development of the cable thermal response model.

2 GENERAL TEST CONDITIONS AND DIAGNOSTICS

2.1 Cable Selection

CAROLFIRE Testing included a broad range of both thermoset (TS) and thermoplastic (TP) insulated cables as well as one mixed TS-insulated and TP-jacketed cable. The tested cables are representative of those currently in use at most U.S. commercial nuclear power plants (NPPs). The tested cables also span a range from those cables that are most vulnerable to fire-induced electrical failure to those that are most resistant to fire-induced electrical failure.

The primary factor in cable specification that was considered by CAROLFIRE was the materials that make up the primary insulation (the insulation over each individual conductor) and the cable jacket (a physical protection layer applied over the grouped and individually insulated conductors). The materials are identified here in the format 'insulation/jacket.' CAROLFIRE tested 15 different cable types. This included nine different cable insulation and jacket material configurations as listed in Table I.

In order to focus the applicability of these tests on generic utilization, the emphasis for testing relative to resolution of the Bin 2 Items was on 7-conductor 12 AWG[1] cables. A limited number of tests on 3-conductor 8 AWG light power cables, 12-conductor 18 AWG instrument cables, and 2-conductor 16 AWG instrument cables were also performed. These secondary cable configurations were included primarily to support the fire model improvement need area by varying the relative content of plastics and copper in the target cables. The thermal response data for the various cables helps calibrate the model and assess the sensitivity of thermal response to this variable.

[1] AWG refers to the American Wire Gauge system of cable sizing.

Figure I shows an end-view photograph of the various cables used in the CAROLFIRE project. As a general scale reference, the outer diameter of the 15 cables shown varies from 7.6 mm (item #4) to 19.6 mm (item #11). The full CAROLFIRE report [1-3] provides extensive details regarding the cables tested. Tables are provided that identify the insulation and jacket material type, the manufacturer, the conductor count, and conductor size for each of the 15 cables used. The physical characteristics and dimensions of each cable are also provided including the insulation and jacket thickness, overall cable diameter, conductor diameter, total cable mass (pound per foot of cable), and volume and weight fractions for the copper conductors (i.e., as apposed to the various polymers used for insulation, jacket, and filler).

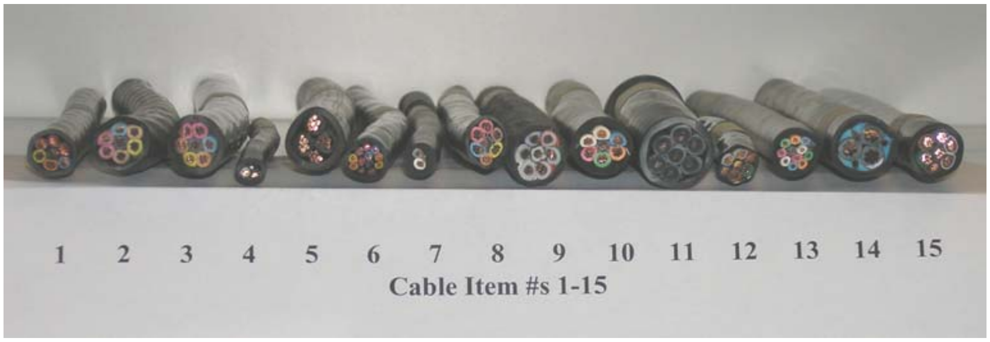

Figure I: End-view photograph of the 15 different cables tested in CAROLFIRE.

2.2 Test Conditions

To meet the CAROLFIRE objectives, two scales of testing were pursued. The tests exposed cables to either simulated or actual fire conditions. The small-scale tests involved exposure of from one to six lengths of cable to grey-body radiant heating in a cylindrical fire simulation exposure chamber called Penlight. The small-scale exposures are radiative in nature. Radiant lamps heat a cylindrical steel shell which in turn heats the target cables located at the nominal center of the cylinder. The ends of the cylinder shell were generally closed during testing to minimize air flow. Penlight is illustrated in Figure II.

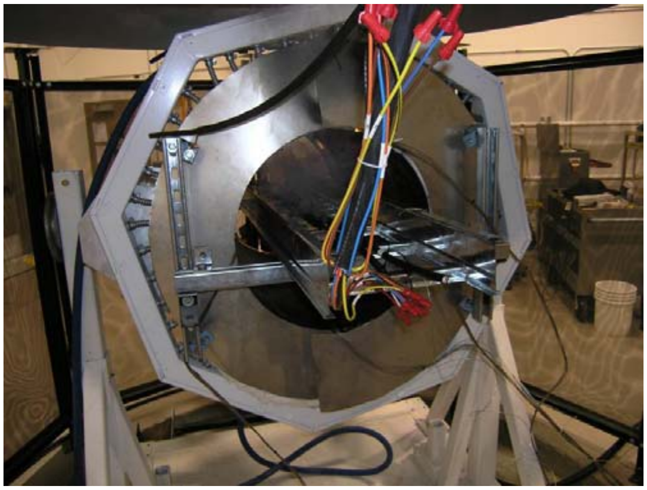

Figure II: General view of the Penlight Facility with the cable tray in place and a test in progress. Note that this view shows Penlight in an 'open-ends' configuration used in many of the Penlight preliminary tests. For most tests in the main matrix, the ends were covered.

The larger or intermediate-scale tests involved actual fire conditions in a larger test enclosure and involved more extensive and more complex arrays of cables. For the intermediate-scale tests, the source fire was created by a propene (propylene) gas diffusion burner running at roughly 200kW.

The exposure conditions used in testing represent a range of credible fire conditions. The exposure heat fluxes used in the small-scale radiant heating tests were set so as to induce cable failure times of on the order of several minutes consistent with cable damage times typically associated with fire probabilistic risk assessment (PRA) fire scenarios. The intermediate-scale tests used gas burner fire intensities between 200 and 350 kW (190 and 332 BTU/s). The intermediate-scale test structure allowed for the creation of hot gas layer conditions sufficient to induce cable failure. At the same time, the test structure was quite open allowing for open burning conditions (i.e., no oxygen starvation) consistent with expectations for cable fires in the relatively large spaces common in a typical nuclear power plant (NPP). The gas burner fuel, propene (also known as propylene), was chosen because is produces a luminous yellow flame and generates considerable visible smoke, again consistent with the anticipated behavior of actual NPP fires. The test structure was housed in a larger test facility so that the smoke layer development and other general fire conditions are also typical of those expected in actual applications. The intermediate-scale test structure is illustrated in Figure III.

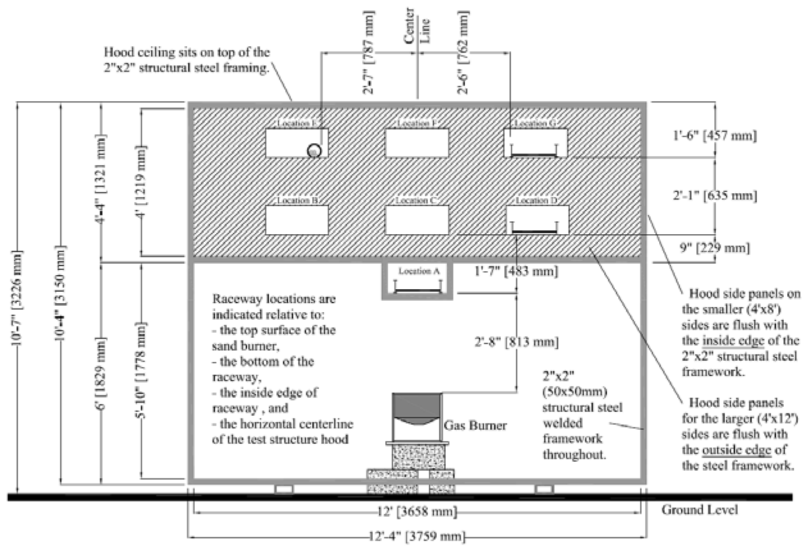

Figure III: Schematic representation of the CAROLFIRE Intermediate-Scale Test Structure.

In both the small- and large-scale test series, cables were tested as individual lengths of cable and cable bundles (ranging from 3 to 12 cables). A limited number of the intermediate-scale tests involved fully loaded random-fill cable trays. The small-scale tests involved relatively simple cable configurations whereas the intermediate-scale tests involved more extensive and more complex cable arrays. Cables were tested in cable trays, in conduits, and in air drop configurations. The intermediate-scale tests included exposure of cables both in the fire plume and under hot gas layer exposure conditions.

2.3 Test Diagnostics

The tests involved a range of diagnostics for the monitoring of the thermal exposure conditions, cable thermal response, and cable electrical performance. All tests measured the cable thermal response using thermocouples (TCs) placed both on the surface and embedded within the target cables. Cable electrical performance was monitored based on two different electrical monitoring systems. For a full description of the test instrumentation please refer to Volume 2 of the project report [3].

Cables were generally tested in matched pairs; that is, testing generally involved placing pairs of nominally identical cables or cable bundles side-by-side in a common raceway. One of the pair would be monitored for electrical performance while the second would be monitored for thermal response. This ensured that the installation of thermocouples for thermal response measurement would not interfere with electrical performance.

Cable electrical functionality (electrical failure) was measured using two different electrical monitoring systems. One system, the Sandia National Laboratories (SNL) Insulation Resistance Measurement System (IRMS) [5], measured the insulation resistance of individual cable conductors (or groups of conductors) providing a direct measure of cable electrical integrity. The IRMS is able to detect the onset of cable degradation and determine the specific pattern and timing of shorts occurring among the conductors of one or more cables. The second system, the Surrogate Circuit Diagnostic Units (SCDUs), involved control circuit simulators where a hot short (i.e., a short circuit between an energized 'source' conductor and a normally non-energized 'target' conductor) could lead to spurious actuation of a motor contactor. The SCDUs were typically configured to simulate a common Motor Operated Valve (MOV) control circuit in a similar manner as was employed in the NEI/EPRI test program [6].

3 THE THERMALLY-INDICUED ELECTRICAL FAILURE MODEL (THIEF)

3.1 Background

As noted above, one objective of CAROLFIRE was to improve the state of fire modeling for nuclear power plant applications. One particular need for such applications is the ability to predict if and when a postulated fire might lead to fire-induced failure of an electrical cable. To meet this objective, in parallel with the testing efforts, researchers at NIST worked to develop a simple thermally-induced electrical failure (THIEF) model to predict the behavior of power, instrument, and control cables in a fire. The THIEF model is intended to be incorporated as a subroutine for deterministic fire models, and is of comparable accuracy and simplicity to the activation algorithms for various other fire protection devices (e.g., sprinklers, heat and smoke detectors).

The description and validation of the THIEF model are summarized here. Comparisons between the experimental data and THIEF predictions are presented. For additional detail beyond this summary discussion please refer to Volume 3 of the CAROLFIRE project report [4].

3.2 A Brief History of Cable Modeling

The thermal decomposition and electrical failure of multi-conductor cables in a fire have been of interest to the nuclear power industry dating back to the Browns Ferry fire of 1975 (US NRC 1975). However, the development of a predictive model of cable failure has been elusive for a number of reasons. First, cables are a fairly complex combination of insulating polymers, metal conductors, protective armors, and a variety of filler materials. The availability of comprehensive thermo-physical properties of these materials is limited. Even when the material properties for a particular cable are available, it is still a challenge to calculate the heat penetration through a bundle of the cables lying in a tray or run through a conduit.

Rather than try to develop detailed models, engineers have looked for a practical correspondence between electrical failure and the compartment temperature in a fire. A simple approach is to develop an empirical relationship between the time to electrical failure and the "exposing" temperature; that is, the temperature of the hot gases in the vicinity of the cable. NUREG-1805 [7] has a set of engineering calculation methods specifically designed for nuclear power plant applications, suggests that the time to electrical failure is inversely proportional to the exposing temperature. For the two major classes of cables, thermosets and thermoplastics, it provides an estimated failure time (in seconds) for a given exposing temperature (in °C) as follows:

$$\frac{1}{t} = 3.343\times10^{-5}\,T - 0.01044 \qquad \text{for thermoset cables} \qquad (1)$$

$$\frac{1}{t} = 3.488\times10^{-5}\,T - 0.007467 \qquad \text{for thermoplastic cables} \qquad (2)$$

These expressions were originally developed for the fire protection Significance Determination Process (SDP) [8] and were derived from cable failure data gathered during NRC-sponsored fire tests in the 1980's and early 1990's [9]. These relationships are based on linear regressions performed on the then available cable failure test data. The resulting curves with the original test data are shown in Figure IV.

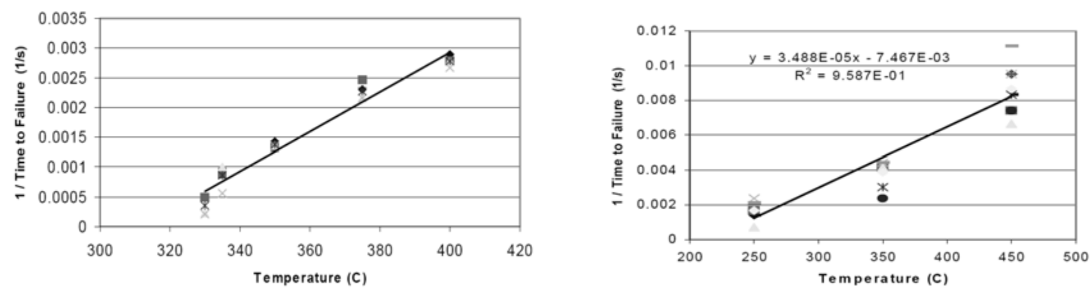

Figure IV: Cable failure linear regression curves for thermoset (left) and thermoplastic (right) cables from the SDP basis document [8].

While Eqs. (1) and (2) are useful screening methods, they are somewhat limited in application. First, they are based on constant temperature exposures that, while characteristic of the air-oven tests the data were drawn from, are unrealistic in actual fires. For example, the larger-scale test results from CAROLFIRE cannot accurately be characterized in terms of a single exposing temperature or heat flux. Second, Eqs. (1) and (2) do not account for different cable installations or configurations. For example, suppose the cable is routed through a conduit, or has a protective armor jacket. What if the cable is considerably different in size and composition to those that were tested? The formulae only distinguish between a thermoset and thermoplastic cable, based on the fact that the latter have been shown to fail at lower temperatures than the former. The formulae do not take into account size, mass, protective barriers, or site-specific conditions. For several of the CAROLFIRE test configurations, neither Eqs. (1) nor (2) could be applied directly.

Because of these limitations, a more flexible predictive model must have some consideration for the thermal mass of the cable, and it must infer electrical failure from the attainment of a given "failure" temperature somewhere within the cable. Over the past 30 years, a number of studies on electrical cable performance in fires have suggested various "failure" temperatures for different classes of cables. A review of these studies is included in NUREG-1805 [7]. The intent of the THIEF work is to demonstrate that a simple heat conduction calculation, along with an empirically-based "failure" temperature, is sufficient to predict cable failure times to an accuracy that is consistent with that of current generation fire models [10]. The calculation is described in the next section.

3.3 Model Development

Petra Andersson and Patrick Van Hees of the Swedish National Testing and Research Institute (SP) have proposed that a cable's thermally-induced electrical failure (THIEF) can be predicted via a simple one-dimensional heat transfer calculation, under the assumption that the cable can be treated as a homogenous cylinder [11]. Their results for PVC cables were encouraging and suggested that the simplification of the analysis is reasonable and that it should extend to other types of cables. In the section, the model is described.

The assumptions underlying the THIEF model are as follows:

- The heat penetration into a cable of circular cross section is largely in the radial direction. This greatly simplifies the analysis, and it is also conservative because it is assumed that the cable is completely surrounded by the heat source.
- The cable is homogenous in composition. In reality, a cable is constructed of several different types of polymeric materials, cellulosic fillers, and a conducting metal, most often copper.
- The thermal properties – conductivity, specific heat, and density – of the assumed homogenous cable are independent of temperature. In reality, both the thermal conductivity and specific heat of polymers are temperature-dependent, but this information is very difficult to obtain from manufacturers. More discussion of this assumption is found below.
- It is assumed that no decomposition reactions occur within the cable during its heating, and ignition and burning are not considered in the model. In fact, thermoplastic cables melt, thermosets form a char layer, and both off-gas volatiles up to and beyond the point of electrical failure.
- Electrical failure occurs when the temperature just inside the cable jacket reaches an experimentally determined value.

Given these assumptions, the governing equation for the cable temperature, $T(r,t)$, is given by:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} k \, r \frac{\partial T}{\partial r} \qquad (3)$$

where ρ, c, and k are the effective density, specific heat, and conductivity of the solid, all assumed constant. The boundary condition at the exterior boundary, $r = R$, is given by:

$$k \frac{\partial T}{\partial r}(R,t) = \dot{q}'' \qquad (4)$$

where $\dot{q}''$ is the assumed axially-symmetric heat flux to the exterior surface of the cable. The heat flux is provided by the fire model or fire analysis that is being used to assess the overall thermal environment of the compartment where the cable is located. In most realistic fire scenarios, the heat flux to the cable is not axially-symmetric. For the purpose of modeling cable failure, it is recommended that the maximum value of the heat flux be used.

Obviously, there are considerable assumptions inherent in the Andersson and Van Hees THIEF model, but their results for various polyvinyl chloride (PVC) cables suggest that it may be sufficient for engineering analyses of a wider variety of cables. In this study, the model was applied to fifteen different cable samples exposed to a variety of thermal exposures. The only difference in the application of the model here is that the 1-D heat transfer equation (3) is solved numerically rather than analytically. The analytical solution derived by the SP researchers, while perfectly correct, is fairly complicated and a simple numerical solution is easier to implement in a large-scale fire model. Indeed, most fire models already employ a 1-D heat transfer algorithm to compute heat losses to walls. The accuracy of either the analytical solution or the numerical solution is not of concern, given the much greater uncertainty in the material properties of the plastic and the underlying assumption of homogeneity. Moreover, the numerical solution is less restricted, which is important if it is found that a particular type of cable cannot be described as a homogenous cylinder.

The THIEF model can only predict the temperature profile within the cable as a function of time, given a time-dependent exposing temperature or heat flux. The model does not predict at what temperature the cable fails electrically. This information is gathered from the experiments. The CAROLFIRE experimental program included bench-scale, single cable experiments in which temperature measurements were made on the surface of, and at various points within, cables subjected to a uniform heat flux. These experiments provided the link between internal cable temperature and electrical failure. The model can only predict the interior temperature and infer electrical failure when a given “failure” temperature is reached. It is presumed that the temperature of the centermost point in the cable is not necessarily the indicator of electrical failure. This analysis method uses the temperature just inside the cable jacket rather than the centermost temperature, as that is where the first electrical shorts in a multi-conductor cable are most likely to occur.

3.4 Cable Properties

As noted above, fifteen types of cable construction were tested in the CAROLFIRE project. Each cable is typically composed of an outer jacket, insulated conductors, and, for certain types, a light weight filler material. Various polymers are used for the jacket and insulation, typically classified as either thermoset or thermoplastic. The THIEF model does not distinguish between thermosets and thermoplastics, but the behavior of each at elevated temperatures is distinctly different, and consequently the experimental test parameters depended on the cable type.

The only information required by the THIEF model for a particular cable is its overall diameter, its mass per unit length, its outer jacket thickness, and an experimentally determined “failure” temperature. The first two pieces of information are needed to describe the geometry and bulk thermal inertia of the cable; the jacket thickness is needed because it is assumed that cables fail electrically when the temperature of the insulation material surrounding the first layer of conductors just inside the jacket of a multi-conductor cable reaches a particular value which is determined experimentally (the last piece of information required as input). The cable diameter, mass per unit length and jacket thickness are all easily obtained either from the manufacturer or by direct measurement. The insulation thickness itself is not used by the model. Generally speaking, the insulation is relatively thin, and its thermal penetration time is relatively short, compared to the jacket. The copper volume and mass fractions also varied among the CAROLFIRE cables as detailed in the project reports. It will be shown below that the results of the THIEF model are insensitive to the relative amounts of copper and plastic, at least for the 15 cable types tested.

One of the challenges in developing a more detailed model of the cable is the difficulty in obtaining material properties. The insulation and jacket materials are often complex polymers that undergo a number of reactions as they heat. Given the complexity of these processes and the expense of obtaining various thermo-physical properties, the THIEF model employs a single value for the specific heat and the thermal conductivity, 1.5 kJ/kg/K and 0.2 W/m/K, respectively, for both thermoset and thermoplastic cables. The bulk density of the cable, ρ, can be calculated by dividing the cables mass per unit length by the cross sectional area. The emissivity of the cable jacket is assumed to be 0.95. These values are typical of several types of commonly used cable jacket and insulation materials [10]. Of course, each type of polymer is different; the properties are temperature-dependent, other decomposition reactions occur, etc. The calculations presented in this report could easily be repeated using other values, but it is hardly worthwhile because the predicted “failure” times are, to a first approximation, linearly proportional to the jacket thickness, the specific heat, and the density, and inversely proportional to the thermal conductivity.

A numerical solution of the heat conduction equation (3) can be incorporated into any fire model that predicts the thermal environment surrounding the cable(s). This can be as simple as a gas temperature predicted by an empirical correlation, or as detailed as a spatially-resolved flow field in a computational fluid dynamics model. Whatever model is chosen, it must produce an estimate, as a function of time, of the heat flux to the cable surface, even if the cable itself is not explicitly included in the fire model. The details of the implementation exercised in the CAROLFIRE project are detailed in Volume 3 of the project report [4]. The implementations completed covered both open raceway (e.g., cable tray) and conduits.

3.5 Examples of the Simulation Results

The results of 35 Penlight experiments involving single (non-bundled) cables were used as the initial basis for calibration of the THIEF model. From the measurements of the temperatures just below the jacket, it is fairly evident that the tested thermoplastic cables failed electrically when their inner (under the jacket) temperatures reached somewhere between 200 °C and 250 °C (392 °F and 482 °F). For thermosets, the range was about 400 °C to 450 °C (752 °F to 842 °F) depending on the specific cable type. It is not possible to be more precise for several reasons. First, there were a limited number of replicate tests for most of the cable samples. Second, the electrical monitoring and thermal measurements were never made on the same cable, but rather on identical cables separated by a few centimeters in the tray or conduit. This was done to prevent interference between the thermocouple wire and the energized cable conductors as noted above. Finally, the measured inner cable temperatures often increased dramatically just before the first electrical short because typically these types of cables ignite and fail electrically at about the same temperature (Nowlen and Wyant 2007b).

The THIEF model predictions of each of the 35 Penlight single cable experiments are presented in detail in Volume 3 of the full project report [4]. Each experiment is summarized by a single graph. Figure V provides an annotated illustration of the typical graphs highlighting the elements each graph contains.

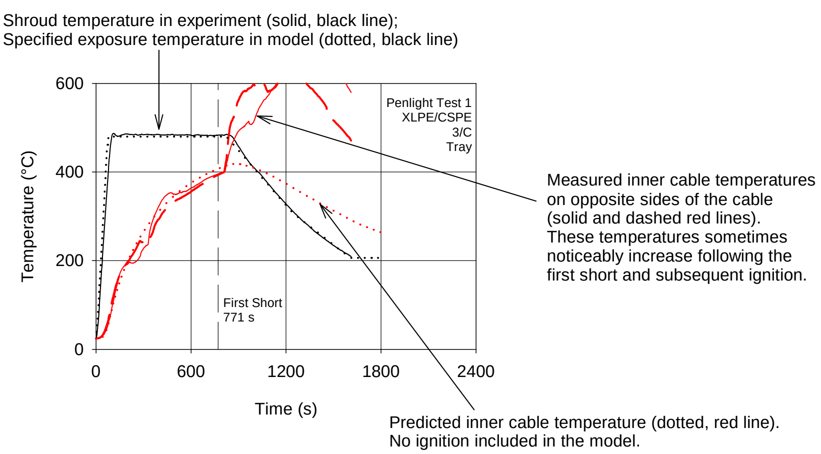

Figure V. Key to graphs showing results of penlight tests. Note that the term "First Short" indicates the first electrical failure, regardless of the specific type. In the experiments, subsequent shorts were observed, but are not relevant here.

For purposes of illustration, this paper presents only sample results from these tests focusing on certain of the thermoset-insulated cables. Thermoset cables, in general, have been observed to short at higher temperatures than thermoplastics [7]. For this reason, the thermoset cables included in the CAROLFIRE program were exposed to higher temperatures in the Penlight Test Series. Even though the THIEF model does not distinguish between thermosets and thermoplastics, it is convenient to present the results according to this classification scheme.

Figure VI illustrates four of the typical THIEF model predictions of the temperatures for the XLPE-insulated thermoset cables when tested within the Penlight apparatus. The plots include cables in both the 7-conductor 12AWG and 3-condutor, 8AWG configurations. Also illustrated are cables routed in an open cable tray and cables routed in conduit.

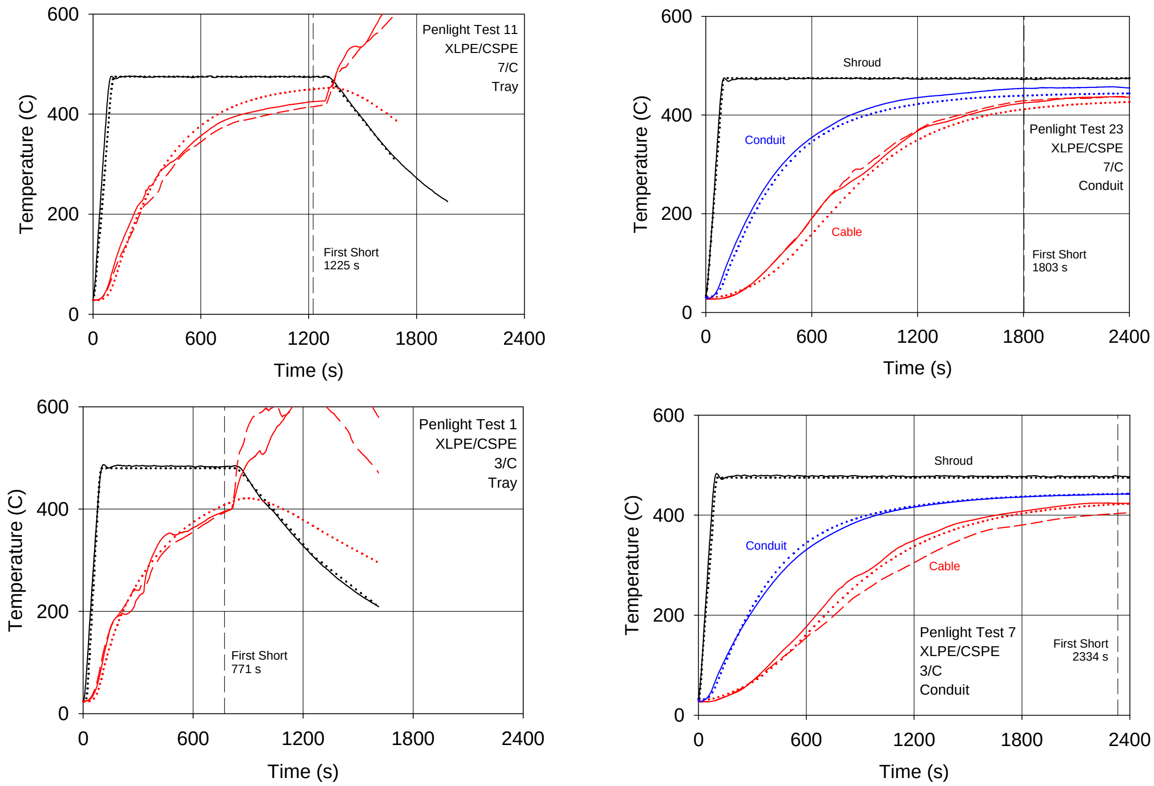

Figure VI: Illustration of thief model predictions for XLPE-insulated cables in the following configurations: 7/C-12AWG in an open tray (upper left); 7/C-12AWG in conduit (upper right); 3/C-8AWG in open tray (lower left); and 3/C-8AWG in conduit (lower right).

The shroud temperature for the single cable thermoplastic penlight tests was set to just over 300 °C (572 °F). For the THIEF model predictions, the same thermal conductivity and specific heats that are used for the thermosets are also used for the thermoplastics. Thus, no distinction is made in the THIEF model between thermosets and thermoplastics. Similar results to those illustrated above were obtained for the thermoplastic cables as documented in the full project report.

For the purpose of evaluating the THIEF model against the Penlight tests, it is sufficient to simply choose a “threshold temperature” for each class of cable to serve as a surrogate for a true failure temperature that would have to be determined from a more extensive set of measurements. For this exercise, 400 °C (752 °F) was chosen for all thermosets; 200 °C (392 °F) for the thermoplastics. Figure VII compares the predicted time to the threshold temperature versus the measured times for the 35 single cable tests chosen from the Penlight series. There are two inner-cable measurements considered, made on opposite sides of the cable, just beneath the jacket. In all, 66 THIEF model predictions of time to "threshold" temperature were compared to the measured counterparts (in 4 tests, the Point B measurement was not made). The THIEF model under-predicted the times by 3 %, on average, and the standard deviation was 20 %.

Overall, there is only a slight bias in the THIEF model towards under-predicting the time to reach the threshold temperature in the ideal environment of the Penlight apparatus. To assess potential model bias, the relative differences[2] between the predicted and measured "failure" times were assessed as functions of the various cable properties. The full results are provided in the project report, and show that the accuracy of the model does not appear to be related to the various bulk properties of the cable. If, for example, the model were to over-predict the "failure" time for thin cables, one would expect to see that reflected in the graph.

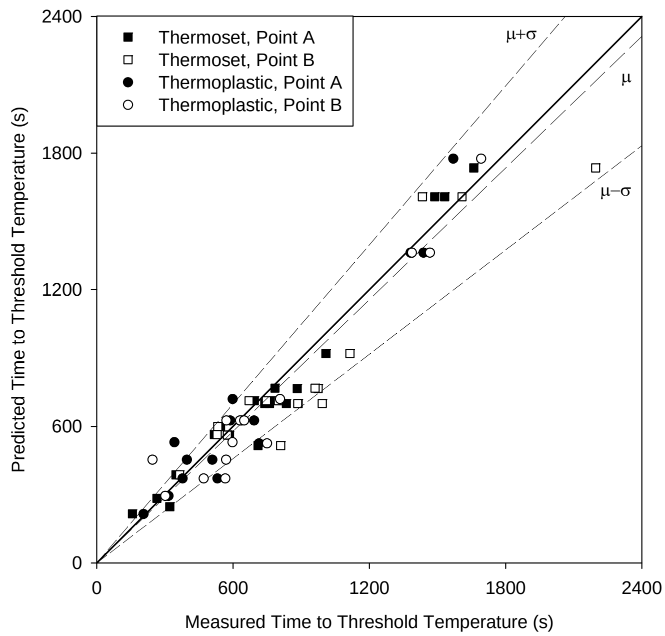

Figure VII. Comparison of THIEF model predictions to the experiments for the Penlight series. Point A and B refer to the thermocouple measurements made on opposite sides of the cable, just under the jacket. The "Threshold Temperature" is 400 °C (752 °F) for thermoset cables and 200 °C (392 °F) for thermoplastics. The dashed lines represent the average (-3 %) and standard deviation (20 %) of the data.

In addition to the small-scale tests, simulations of various configurations in the intermediate-scale tests were also undertaken. In general, the intermediate-scale tests are more complex and less well characterized, but also are representative of real fire conditions. The THIEF model's performance in these simulations illustrated a number of expected trends. In all, 65 temperature predictions were compared to 65 measurements during the Intermediate Scale Test Series. The results are essentially 65 time histories of the predicted and measured inner cable temperatures. These graphs are provided in the full project report, but are far too extensive to reproduce here.

[2] The relative difference was calculated as the difference between the predicted and the measured time divided by the measured time. A positive value of the relative difference means that the model over-predicted that particular threshold time.

To quantify the accuracy of the THIEF model, the same procedure that was developed for the Penlight results was followed. Instead of using the observed electrical failure times from the experiments, appropriate “threshold” values were used. The reason for this is that in the intermediate-scale tests, some cables were monitored only for thermal response, some only for electrical response, and some were monitored for both using identical bundles. Consequently, it was not possible to draw conclusions about the THIEF model based on the measured failure times. A more appropriate test of the model is to compare its predictions of inner cable temperature directly with that which was measured for the time period between ignition of the fire and the point where the inner cable temperature measurements passed beyond a specified “threshold” value. As noted above, based on the Penlight series, the thermoset cables tested failed at temperatures between 400 °C and 450 °C (752 °F and 842 °F); the thermoplastics failed between 200 °C and 300 °C (392 °F and 482 °F). The exact failure temperatures are not particularly important for this exercise, rather the time to reach some threshold temperature consistent with the particular type of cable under consideration. For the Intermediate Scale Tests involving thermoset cables, 400 °C (752 °F) was chosen as the “threshold” temperature. For thermoplastics, 200 °C (392 °F) was chosen.

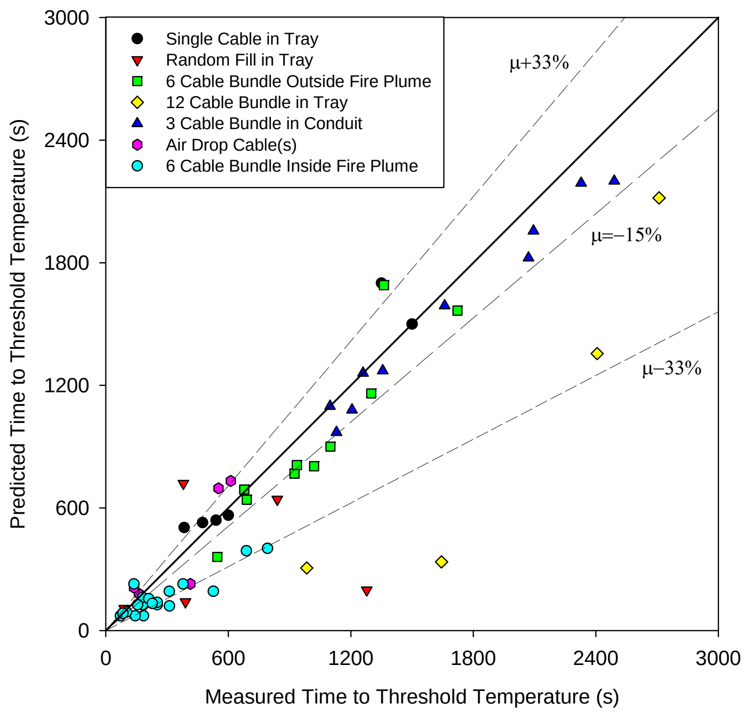

Figure VIII. Summary of the intermediate-scale test predictions. The dashed lines indicate the average (-15 %) and standard deviation (33 %) of the data. Also note that the description “Inside Fire Plume” refers to locations A and C, which were within the flaming region of the fire.

The results are shown in Figure VIII. For the 65 point to point comparisons, the THIEF model under-predicted the times to reach the “threshold” temperature by 15 %, on average, and the standard deviation was 33 %. That is, the model predicts a failure time that is generally shorter than the time measured in the test. The model predictions in this case are noticeably less accurate than the Penlight predictions. This is by design. The THIEF model was designed to under-predict cable failure times because it assumes that a given cable is completely exposed to the elevated temperatures of the surrounding hot gases. In reality, a cable is almost always shielded in some way by other cables, the tray, the conduit, and so on. Often cables are buried deep within a loaded tray of other cables and do not respond nearly as quickly to hot gases as the THIEF model would predict. Indeed, the most under-predicted failure times for the intermediate-scale tests are those of the 12-cable bundles.

In predicting the outcomes of the intermediate-scale tests, no attempt was made to modify or adjust the THIEF model to account for the relative position of the target cable within the bundle. Rather, the model was applied as it had been for the Penlight series, because that is the way the model is intended to be applied in practice. That is, it was assumed that the cable was not within a bundle, as there is no way to account for a bundle in the model. The reason for this assumption is that it is unlikely that a given cable randomly installed in a given tray will always be protected by its neighbors from hot gases of a fire. Thus, it is prudent to apply the THIEF model under the assumption that the cable will at some point along its length be directly exposed to the hot gases, and even if it is not, the prediction will err on the realistically conservative side by predicting an early failure.

4 CONCLUSIONS

The CAROLFIRE tests have produced a unique set of fire test data characterizing the response of cables exposed to a broad range of fire conditions. This data set also advances the state of knowledge to better understand cable functionality during a fire. The main focus of this paper has been on that data that is of most interest to the development of improved fire modeling tools capable of predicting if and when a cable might fail in a fire environment. The small-scale tests provide very well-controlled and well-characterized tests that are appropriate to the calibration of fire modeling tools. The intermediate-scale tests provide less controlled but more complex and more realistic exposure conditions and are especially useful in assessing model performance under more challenging modeling conditions.

In parallel with the experiments, a thermally-induced electrical failure (THIEF) model for cables has been shown to work effectively in realistic fire environments. The THIEF model is essentially nothing more than the numerical solution of the one-dimensional heat conduction equation within a homogenous cylinder with fixed, temperature-independent properties. The model was used to predict the inner cable temperature of approximately 100 instrumented cables from the CAROLFIRE small-scale Penlight (35 single cable experiments; 66 point to point comparisons) and intermediate-scale tests (14 experiments; 65 point to point comparisons). Because the Penlight experiments tested single cables that were heated uniformly on all sides, the one-dimensional THIEF model accurately predicted the times for the temperature inside the cable jacket to reach “threshold” values that are typically observed when the cable fails electrically. For 66 measurements, the model under-predicted the time to reach threshold temperature by 3 %, on average. In the intermediate-scale experiments, where the cable configurations were more typical of actual installations, the model under-predicted the times to reach threshold temperature by 15 %, on average. This latter result is realistically conservative and results from the fact that the THIEF model does not account for the shielding effects of cable bundles, and thus over-predicts cable temperatures and under-predicts “failure” times.

The cables included in the study ranged from 7 mm (0.25 in) to 19 mm (0.75 in) in diameter, a common size for control cables, plus some instrument and low power cables. The copper content by volume ranged from 0.07 to 0.36 and the content by mass ranged from 0.31 to 0.89. The volume and mass fractions are not direct model inputs, but rather the average density of the cable as a whole. Nevertheless, the range in cable properties demonstrates that the THIEF model is applicable to a wide variety of cables with no need for additional information beyond the cable diameter, mass per length, and an empirical “failure” temperature. In addition, there was no indication from the model results that indicated a bias related to the number of conductors, plastic composition, or copper content.

While there are various ways to refine the THIEF model – multiple layers of materials, two or three spatial dimensions, temperature dependent thermal properties, polymeric decomposition, and so on – it is unlikely that any of these enhancements would dramatically improve its overall accuracy, especially in light of the uncertainty associated with the fire simulation of the entire compartment. According to a recent NRC/EPRI verification and validation (V&V) study of five different fire models [10], the error in the predicted net convective and radiative heat transfer to various "targets" is on the order of 20 % or higher, depending on the type of model. Given an uncertainty of 20 % in the exposing heat flux for the simple cable failure calculation, it is unclear how additional complexity would generate better results than those presented in this report.

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