CAROLFIRE—Cable Response to Live Fire Project[1]

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ABSTRACT

Fires in a nuclear power plant (NPP) are a significant safety concern. The Browns Ferry NPP cable spreading room fire of March 22, 1975, demonstrated that a moderately sized fire would not only disable important safety systems, but would also cause systems to malfunction. The malfunction could be as innocuous as providing incorrect instrument readings or as lethal as starting plant equipment and diverting reactor coolant flow paths. Immediately after the Browns Ferry fire and continuing to the present, the U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry have performed research to better understand the phenomenon of electrical cable shorting that result in spurious actuation of equipment and its impact on safe NPP operation. This research has taken on additional importance with the NRC's evolution to a risk-informed, performance-based regulatory environment. The Cable Response to Live Fire (CAROLFIRE) test program is the latest NRC phase of this research. The CAROLFIRE test program included a combination of bench-scale and intermediate-scale experiments. The CAROLFIRE program built upon previous research and provides the latest insights to spurious actuation of NPP equipment when a plant's electrical cables are exposed to fire conditions. CAROLFIRE also developed methods to reduce the uncertainty of predicting electrical cable damage with fire models. This feature of the test program (i.e., monitoring actual electrical cable performance and thermal degradation during fire exposure to gather relevant thermal measurements for fire modeling) makes the CAROLFIRE program unique. The NRC Office of Nuclear Regulatory Research sponsored the testing program, and Sandia National Laboratories, in partnership with the National Institute of Standards and Technology and the University of Maryland, performed the work. This paper discusses the CAROLFIRE test program, experimental results, and the fire model subroutine development for predicting cable damage.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research initiated the Cable Response to Live Fire (CAROLFIRE) project to further explore the fire-induced thermal response and functional failure modes of electrical cables.[2] The project is a collaborative effort. Sandia National Laboratories (SNL) is the primary testing laboratory, and both the University of Maryland and the National Institute of Standards and Technology are general collaborative partners working to develop a better predictive model for cable thermal response and failure in deterministic fire models.

The primary objective of CAROLFIRE is to characterize the various modes of electrical failure within bundles of power, control, and instrument cables. A secondary objective is to

[1] This paper was prepared in part by a member of the NRC staff. The views presented do not represent an official staff position. The NRC has neither approved nor disapproved its technical content.
[2] The CAROLFIRE report, entitled "CAROLFIRE Test Report," is available at http://www.nrc.gov/reading-rm/doc-collection/nuregs/contract/cr6931.

develop a simple thermal model of a single cable that predicts electrical failure when a given interior region of the cable reaches an empirically determined threshold temperature [1].

CAROLFIRE

The CAROLFIRE project was designed to complement previous industry testing conducted by the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI)[3] which aimed to provide data supporting two needs areas—(1) resolution of the "Bin 2" items identified in Regulatory Issue Summary (RIS) 2004-03, Revision 1, "Risk-Informed Approach for Post-Fire Safe-Shutdown Circuit Inspections," [2] and (2) improvements to fire modeling to reduce uncertainty in predicting cable response to fires.[4] Volume 1 focuses on the first needs area—resolution of the Bin 2 items, while Volume 2 focuses on the second needs area—fire modeling improvement.

CAROLFIRE testing included a series of 78 small-scale radiant heating tests and 18 intermediate-scale open burn tests. The small-scale tests were performed in an SNL facility called "Penlight" and involved exposure of two to seven lengths of cable to grey-body radiant heating. These tests were aimed primarily at the fire model improvement needs area, but they also provided data pertinent to the resolution of two of the five Bin 2 items addressed by the project (i.e., Bin 2, Items A and B, which both explore inter-cable shorting configurations).

The intermediate-scale tests involved exposing cables, generally in bundles of 6 to 12 cables each, under various routing configurations and at various locations within a relatively open test structure. The fires were initiated by a propene (also known as propylene) gas diffusion burner. The fire typically spread, at a minimum, to those cables located directly above the fire source. The intermediate-scale tests exposure included cables just above the upper extent of the gas burner's flame zone, in the fire plume above the flame zone, and outside the plume but within a hot gas layer. The results of the intermediate-scale tests contribute to both needs areas.

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 U.S. commercial nuclear power plants (NPPs). The tested cables also range from those cables that are most vulnerable to fire-induced electrical failure to those that are most resistant to fire-induced electrical failure.

Project staff measured cable electrical functionality (electrical failure) using two different electrical monitoring systems. The first system, the SNL Insulation Resistance Measurement System (IRMS), measured the insulation resistance of individual cable conductors (or groups of conductors), thereby providing a direct measure of cable electrical integrity. The IRMS can 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 in which 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 the same manner used by the NEI/EPRI test program.

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 to induce cable

[3] The main report provides specific references to the NEI/EPRI tests.

[4] Note that with respect to the Bin 2 items, CAROLFIRE addresses five of the six identified items. The sixth Bin 2 item (Item F) deals with safe-shutdown systems and is not amenable to resolution through testing. Therefore, Item F is outside the scope of CAROLFIRE and has not been evaluated in this report.

failure times on the order of several minutes, which is consistent with cable damage times typically predicted in risk-relevant fire scenarios (e.g., in fire risk analyses). The intermediate-scale tests used gas burner fire intensities between 200 and 350 kilowatts, a range that represents the fire intensities expected from many credible fire ignition sources (e.g., moderate-size oil spills and electrical control panel fires). 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 NPP. The gas burner fuel, propene, was chosen because it 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 would also be typical of those expected in actual NPP environments.

The results of a facilitated workshop conducted by the NRC in February 2003 [3] defined, in large part, the Bin 2 items investigated by CAROLFIRE. The Bin 2 items were those cable and circuit faulting configurations for which the experimental evidence was inconclusive or nonexistent. At the time of the workshop, the NEI/EPRI tests were the most recent source of experimental data considered, although the results of other prior cable research programs were also taken into account.

This paper summarizes the conclusions based on the CAROLFIRE project with respect to the Bin 2 items. For each of the five items addressed by CAROLFIRE, the discussion opens with a statement of the Bin 2 item quoted directly from the RIS. The discussion then provides background information associated with each item focusing on the preexisting data and discussions that took place during the February 2003 workshop. The test data relevant to each item are summarized and the project's conclusions relative to each item are presented.

CAROLFIRE SPURIOUS ACTUATION TEST RESULTS

<u>RIS 2004-03 Bin 2 Item A</u>: *Intercable shorting for thermoset cables, since the failure mode is considered to be substantially less likely than intracable shorting.*

One spurious actuation attributed to inter-cable interactions between two TS-insulated cables was experienced during the NEI/EPRI tests. This failure mode was placed in Bin 2 because the test in which this particular fault was observed had used a rather contrived bundling arrangement intended to maximize the potential for inter-cable interactions. Hence, the one observed spurious actuation was considered to be weak evidence of potential TS-to-TS hot short interactions. Furthermore, the fact that inter-cable interactions among the TS cables were not observed more frequently during these tests was taken as evidence of, at most, a low probability of such interactions.

CAROLFIRE sought to explore the plausibility of inter-cable hot shorts between TS and TP cables by providing many more opportunities for the detection of inter-cable shorting than were present in the NEI/EPRI tests. CAROLFIRE also used more realistic cable bundling configurations involving collocated multiconductor control cables in cable trays and conduits.

With respect to the SCDUs, the project staff did not observe in any of the CAROLFIRE tests a case in which inter-cable shorts led to spurious operation. However, staff did observe cases in which inter-cable shorting between TS cables led to momentary hot shorts on collocated SCDUs (e.g., intermediate-scale test IT-1). These results demonstrate a potential for some level of TS-to-TS interactions.

With respect to the IRMS, project staff evaluated these results on the basis of an assessment of if and when (relative to other modes of faulting) inter-cable interactions were detected between collocated TS-insulated cables. For inter-cable interactions to be risk relevant, one cable must remain energized and the second cable must remain sufficiently intact

so that a hot short can actuate the target circuit. As cable failures progress through primary, secondary, and tertiary fault modes, the likelihood of meeting these conditions decreases until spurious actuations are no longer plausible.

The IRMS observed a number of relevant inter-cable faults. The most significant case occurred during Test IT-1, the first intermediate-scale test in the primary matrix. In this test, a clear-cut and sustained conductor-to-conductor inter-cable short circuit occurred between two TS-insulated and TS-jacketed seven-conductor control cables. Inter-cable shorting was the primary failure mode for both cables (i.e., the first detected faults for either cable). The inter-cable short was sustained for over 3 minutes (194 seconds) before the cables cascaded through secondary and tertiary fault modes.

The second most significant inter-cable faults were observed in Tests PT-60, one of the later Penlight tests, and IT-7, one of the intermediate-scale tests. In both cases, TS-to-TS inter-cable shorting was observed as a secondary fault mode for one cable (i.e., after intra-cable faulting of this first cable had been detected) and as the primary fault mode in the second cable (the fire-detected fault for the second cable). In practice, these faults could have led to spurious operation if the proper combination of conductors were involved, a matter that appears to be essentially random.

The IRMS observed other potentially relevant inter-cable interactions between TS cables during at least two other tests (IT-6 and IT-7). In these two cases, the interactions were the tertiary fault mode for one of the two cables involved, but the primary fault mode for the second cable. These faults are less likely to lead to spurious actuation, but the potential cannot be dismissed entirely.

Overall, the collective data demonstrate that TS-to-TS inter-cable hot shorts are plausible. However, the data also show that risk-relevant interactions between TS cables are generally of low likelihood and, in particular, are substantially less likely to cause spurious operation in comparison to intra-cable hot shorts. In cases in which either intra- or inter-cable faults might lead to the same effect on plant equipment (e.g., spurious actuation of the same component), the intra-cable shorting will be the predominant effect in terms of the likelihood of spurious actuation.

Based on the available data with respect to Bin 2, Item A, the CAROLFIRE project reached the following conclusions:

> Inter-cable shorting between two TS-insulated cables that could cause hot shorts and the spurious actuation of plant equipment was found to be a plausible failure mode, although the likelihood of this failure mode is low in comparison to intra-cable short circuits leading to spurious operation. While no detailed statistical analysis has been performed, it appears that the conditional probability (given cable failure) of spurious actuations arising from this specific failure mode is small in comparison to that previously estimated for spurious actuations from intra-cable shorting.

<u>RIS 2004-03 Bin 2 Item B</u>: *Intercable shorting between thermoplastic and thermoset cables, since this failure mode is considered less likely than intracable shorting of either cable type or intercable shorting of thermoplastic cables.*

In this case, no direct relevant experimental evidence was available at the time of the February 2003 facilitated workshop. This item was included among the Bin 2 items on the basis of expert judgment expressed at the workshop. The prevailing opinion was that such interactions were unlikely to cause risk-relevant circuit effects because the TP cables will generally fail more quickly in a fire than the TS cables when the cables are collocated and exposed to the same fire conditions. As noted above in the discussion of Item A, for inter-cable interactions to be risk relevant, one cable must remain energized and the second cable must

remain sufficiently intact that a hot short can actuate the target circuit. This scenario becomes less and less likely as one or both cables cascade through progressively more severe faulting modes. If the TP cables cascade through all relevant fault modes to the point that all of the conductors are shorted both to each other and to ground prior to faulting of the TS cable, then risk-relevant inter-cable interactions would not be at all plausible. The general approach to analysis for Item B parallels that of Item A in all respects.

As with Item A, CAROLFIRE offered many opportunities for inter-cable interactions to occur between TS and TP cables. In all of the tests conducted, no TS to TP spurious actuations attributable to inter-cable shorting were observed among the SCDU circuits. However, cases of inter-cable shorting were observed between collocated TS and TP cables.

The most notable case occurred during Test IT-8 between a TP cable (polyethylene (PE)) and a TS cable (cross-linked polyethylene (XLPE)). The PE cable failed initially causing a fuse blow failure for that SCDU. Subsequently, a hot short from the XLPE cable impacted the PE cable as evidenced by a current increase on one of the PE cable conductors which lasted for about 10 seconds. In this case, the hot short impacted the grounded conductor in the PE cable rather than a target conductor. It is not clear whether a hot short to a target conductor could have caused a spurious operation in this case because the exact extent of faulting in the PE cable is not known (only a fuse blow was known to have occurred).

In other tests, inter-cable interactions on the SCDUs were seen, but these were manifested as momentary voltage and/or current spikes on one cable concurrent with the failure of the second cable. As noted, none of these cases actually led to a spurious actuation. Such faults could, however, be relevant to circuits that possess a “latching” feature such that a momentary hot short could lock in a circuit actuation signal.

With respect to the IRMS data, the project staff did not observe a case in which inter-cable shorting between a TS and a TP cable was the primary fault mode for both cables. However, in Test IT-9, an inter-cable short was the secondary fault mode for one cable and the primary fault mode for the second cable. Somewhat surprisingly, the TS cable had experienced internal faulting first and then shorted to a TP cable as the primary fault mode for the TP cable. The fact that the TS cable experienced failures first was unexpected. During this test, the same TS cable experienced a second inter-cable short to another collocated TP cable. This became the tertiary fault mode for the TS cable, but was again the primary fault mode for the TP cable.

The IRMS observed other interactions. However, in all other cases, the inter-cable faulting occurred only after the TP cable had displayed extensive faulting both internally and to the external ground. These interactions are not considered risk relevant.

The data demonstrate that risk-relevant TS-to-TP inter-cable interactions are plausible. However, the data also indicate that such interactions are of low likelihood. Based on the available data with respect to Bin 2, Item B, the CAROLFIRE project has reached the following conclusions:

> Inter-cable shorting between a TP-insulated cable and a TS-insulated cable that could cause hot shorts and the spurious actuation of plant equipment was found to be a plausible failure mode, although the likelihood of this failure mode is low in comparison to intra-cable short circuits leading to spurious operation. While no detailed statistical analysis has been performed, it appears that the conditional probability (given cable failure) of spurious actuations arising from this specific failure mode is very small in comparison to that previously estimated for spurious actuations from intra-cable shorting.

<u>RIS 2004-03 Bin 2 Item C</u>: *Configurations requiring failures of three or more cables, since the failure time and duration of three or more cables require more research to determine the number of failures that should be assumed to be ‘likely.”*

In terms of the number of concurrent spurious operations to be considered, the consensus opinion expressed during the February 2003 workshop was that, if inspections began by looking at failures impacting two cables at a time, they would likely capture the risk-dominant scenarios. No particular basis for limiting the consideration to two cables was put forth; rather, the recommendation was simply cited as a reasonable starting point pending a clearer understanding of the issues and relevant behaviors.

Both the NEI/EPRI tests and CAROLFIRE involved the testing of no more than four simulated control circuits per test (four SCDUs in the case of CAROLFIRE). Even with just four circuits present, both programs included tests in which spurious operations occurred in all circuits. Hence, there is little reason to limit the number of spurious operations that might ultimately occur based only on the general likelihood of spurious operation given cable failure. In fact, CAROLFIRE has broadly confirmed that, given the failure of electrical cables, one or more spurious actuations are a relatively high-likelihood outcome. For the CAROLFIRE results with the SCDUs in an MOV configuration, approximately 70 percent of the total failures led to a spurious operation of the control circuit.

The key question then becomes one of timing. That is, how likely is it that the <u>effects</u> of multiple spurious operations might overlap in time? CAROLFIRE has explored one aspect of this problem that the NEI/EPRI tests did not evaluate. In particular, CAROLFIRE confirmed that both cable location relative to the fire and the routing configuration can have a substantive impact on cable failure times. If the failures are separated in time by a substantial margin, then the effects of spurious operations will be less likely to overlap.

The question of how long the effects of a spurious actuation might persist is tied strongly to the nature of the circuit. For certain circuits, once the hot short itself is mitigated (i.e., when the cable cascades to higher failure modes and circuit power is ultimately lost) the component will return to its non-energized (often fail-safe) position. This applies to devices such as solenoid operated valves (SOVs).

However, for a range of other typical components, such as MOVs, the device will be left in whatever state it was in when the hot short itself is mitigated. For an MOV, this might be closed, open, or partially open. Furthermore, the normal control functions for such devices will generally be lost, given that the control circuit power is also likely to trip. Hence, for many circuits an operator manual action will be needed to overcome the effects of the spurious actuation. The action may be a remote shutdown action (e.g., manual closure or opening of a valve) or an action within the main control room (e.g., closing or opening other valves to mitigate the effects of a spurious operation), but some action would be needed. Unfortunately, in these cases, the only basis for establishing how long the effects of any given spurious operation might persist will often be human factors analysis.

Given the available data relevant to Bin 2, Item C, the CAROLFIRE project has reached the following conclusions:

> The currently available data do not provide a basis for establishing an a priori limit to the number of spurious operations that might occur during a given fire. The project further finds that the timing of spurious actuation is a strong function of various case-specific factors including, in particular, the relative location of various cables relative to the fire source, the routing configuration (e.g., open cable trays or air drops versus conduits), the thermal robustness of the cable insulation material, and the characteristics of the fire source.

<u>RIS 2004-03 Bin 2 Item D</u>: *Multiple spurious operations in control circuits with properly sized control power transformers (CPTs) on the source conductors, since CPTs in a circuit can substantially reduce the likelihood of spurious operation. Specifically, where multiple (i.e., two or more) concurrent spurious operations due to control cable damage are postulated, and it can*

be verified that the power to each impacted control circuit is supplied via a CPT with a power capacity of no more than 150 percent of the power required to supply the control circuit in its normal mode of operation (e.g., required to power one actuating device and any circuit monitoring or indication features).

This item derived from one aspect of the NEI/EPRI testing where a substantial reduction in the spurious actuation likelihood was observed given the use of CPTs compared to the case with effectively unlimited power available to the control circuit. The CPTs used by NEI/EPRI were sized at 150 VA which represented 150 percent of the nominal power required to actually operate the simulated MOV control circuit in its normal mode of operation.

The CAROLFIRE tests evaluated a variety of relatively larger CPTs ranging from 166 percent to 333 percent of the nominal design load required to operate the circuit. In these tests, no effect on spurious actuation likelihood was observed, and, as noted previously, nearly 80 percent of the cable failures led to spurious actuation signals of at least momentary duration. The CAROLFIRE tests did experience some cases of voltage decay prior to fuse blow, but in most of these cases a prior spurious operation had been observed. No cases were explicitly noted in which voltage decay appeared to have prevented a spurious operation from occurring. The differences between these two programs cannot be fully explained, and this may be an area that is worthy of further investigation.

Given the available data relevant to Bin 2, Item D, the CAROLFIRE project has reached the following conclusions:

> The currently available data do not provide a basis for establishing an a priori limit to the number of spurious operations that might occur during a given fire, even given that the circuit is powered by a "properly sized" CPT. The project further finds that, as with non-CPT cases, the timing of spurious actuations depends on the timing of cable electrical failure which is in turn a strong function of various case-specific factors, including the relative location of different cables relative to the fire source, the routing configuration (e.g., open cable trays or air drops versus conduits), the thermal robustness of the cable insulation material, and the characteristics of the fire source.

RIS 2004-03 Bin 2 Item E: *Fire-induced hot shorts that must last more than 20 minutes to impair the ability of the plant to achieve hot shutdown, since recent testing strongly suggests that fire-induced hot shorts will likely self-mitigate (e.g., short to ground) in less than 20 minutes. This is of particular importance for devices such as air-operated valves (AOVs) or power-operated relief valves (PORVs) which return to their de-energize position upon abatement of the fire-induced hot short.*

During the original NEI/EPRI tests, the spurious actuation signals observed lasted for a maximum of 11.3 minutes. Hence, 20 minutes was recommended as an upper bound on the duration of a hot-short signal. CAROLFIRE has confirmed that hot shorts will generally be of relatively short duration, and, in fact, the longest spurious actuation signal observed in the CAROLFIRE tests was 7.6 minutes.

Given the available data relevant to Bin 2, Item E, the CAROLFIRE project has reached the following conclusions:

> While the available data cannot definitively support the conclusion that no hot short would ever persist for greater than 20 minutes, they do provide a strong basis for concluding that hot shorts lasting greater than 20 minutes are of at most very low probability. Hence, the project concludes that, with high probability, hot-short-induced spurious actuation signals will clear within less than 20 minutes. The project further concludes that, upon clearing of the hot-short signal, the

effects of the spurious actuation on plant equipment could persist for a longer time depending on the nature of the impacted equipment. For example, a normally closed MOV might well remain open or partially open even after the hot-short-induced spurious actuation signal is mitigated, whereas an SOV would return to its fail safe condition upon mitigation of the hot-short-initiated spurious operation signal.

METHODOLOGY FOR DEVELOPING A THERMAL DAMAGE CABLE MODEL

Current NPP fire probabilistic risk assessment methods employ simple linear regression techniques for different classes of cables, most often TS and TP. These methods take into account the general makeup of the cable, but no other information, such as its mass or diameter. The simple cable failure model described here makes use of the general bulk properties of the cable, but does not require more detailed thermo-physical properties. For example, the mass per unit length and diameter are needed, but the thermal conductivity, specific heat, and emissivity of the polymers used in the cable insulation and jacket are assumed based on the current generation of cables in existing NPPs. This latter information is often impossible to obtain because the material properties of commercial cables are usually proprietary.

Numerous models of cable failure have been developed over the years, ranging from empirical correlations of experimental data to detailed thermo-physical models [4]. Most of these models relate electrical failure to a particular degree of thermal degradation, usually an elevated temperature at some specified location within the cable. In 2005, Petra Andersson and Patrick Van Hees of the Swedish National Testing and Research Institute proposed that cable failure can be modeled by means of a simple one-dimensional heat transfer calculation through the cylindrical cable, based on the assumption that the cable can be treated as a homogenous plastic cylinder [5]. Obviously, this is a considerable assumption, but their results for various polyvinyl chloride cables suggest that it may be sufficient for engineering analyses of a wider variety of cables.

The Andersson and Van Hees model is purely thermal; it does not directly predict electrical failure. It can only infer failure based on a predicted inner cable temperature. Experimental data must be used to determine the radial location at which failure has occurred and the temperature at that location. It is presumed that the temperature of the centermost point in the cable is not necessarily the indicator of electrical failure. Rather, the temperature near the outer layer of conductors, where electrical failure is likely to occur first, should be used as the “failure” temperature.

The input data needed by the model include the diameter of the cable and its mass per unit length. The specific heat and thermal conductivity are assumed constant at 1.5 kJ/kg/K and 0.2 W/m/K, respectively. The emissivity of the cable jacket is assumed to be 0.95. The average density of the cable is derived from the specified diameter and mass per unit length. In a sense, these two parameters characterize the thermal inertia of the cable, a concept not unlike that used to predict the activation of the thermal element in an automatic sprinkler or thermal detector.

The following equation is the numerical solution of the one-dimensional heat equation written in cylindrical coordinates:

$$\rho c \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} r \frac{\partial T}{\partial r} \tag{1}$$

Where k , ρ , and *c* are the thermal conductivity, density, and specific heat, respectively. Most

fire models perform this type of calculation to predict the temperature of walls and various targets within the computational domain; thus, it is not a difficult task to incorporate the simple cable failure algorithm into any fire model.

THERMAL DAMAGE MODEL RESULTS

The simple model of cable failure outlined above was applied to 15 different cable samples in a variety of configurations—within a horizontal tray, within a conduit, and free-hanging air drops.

Figures 1 and 2 display the results of the model for two of the cables tested, a TS and TP, both with seven conductors. Note that the model only uses the cable diameter and mass per unit length as input, which in the case of the two cables selected were fairly comparable. The distinction between TS and TP is only because of the experimentally determined link between inner cable temperature and electrical failure. The model merely predicts the temperature as a function of time and has no means to assess electrical failure.

Note from the figures that the model tends to slightly overpredict the cable temperature, especially as it approaches the point at which failure occurs. This is because the model does not account for endothermic processes like melting and off-gassing that tend to slow the increase in the cable temperature leading up to electrical failure.

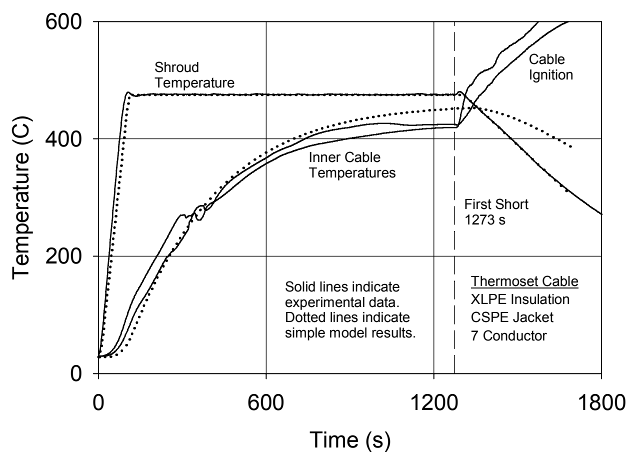

Fig. 1 Predicted inner cable temperature of a seven-conductor TS cable compared to experimental measurement

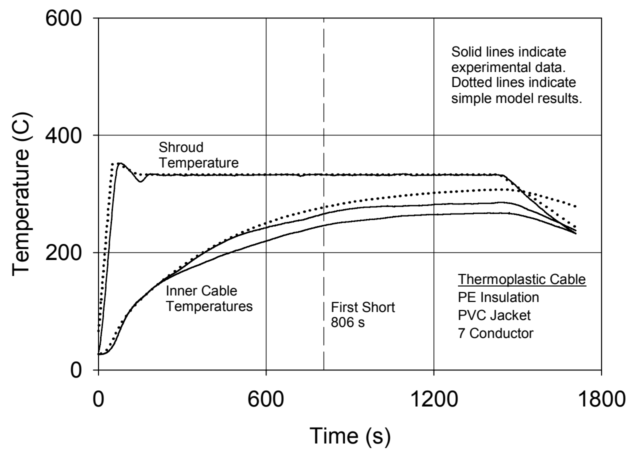

Fig. 2 Predicted inner cable temperature of a seven-conductor TP cable compared to experimental measurement

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