Project Plan for CAROLFIRE: Fire Testing to Address RIS 2004-03 Bin 2 Circuit Issues and Fire Modeling Cable Damage Threshold Needs

Revision B.2
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1.0 Background

1.1 Introduction

RES has initiated a combined test effort to address two specific need areas; namely, (1) those items identified as "Bin 2" circuit configurations in Regulatory Issue Summary (RIS) 2004-03, Rev. 1, 12/29/04, and (2) ongoing needs related to the verification and validation of fire modeling tools. The combined testing project will be known as Cable Response to Live Fire (CAROLFIRE).

An initial test project planning meeting was held August 16-17, 2005 to discuss the needs and objectives of the test project. At this meeting a set of nominal strawman test configurations was identified. In attendance at the meeting were representatives of the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES), Sandia National Laboratories (SNL), the National Institute for Standards and Technology (NIST), and the University of Maryland (UMd) (see Appendix A for a list of meeting participants, hereafter referred to as the "CAROLFIRE team"). One staff member from the NRC Office of Nuclear Reactor Regulation (NRR) also sat in briefly to discuss one specific RIS 2004-03 Bin 2 item[1]. The original project plan was developed based on the outcome of that meeting and several follow-up discussions among the CAROLFIRE team.

1.2 Changes in this Revision

This revision (B.2) reflects changes in the project plan that have been implemented since November 2005. The primary changes reflected in this revision (as compared to Revision A) are summarized as follows:

- Two changes were made relative to the 'copper content variation' cable configurations to be tested in CAROLFIRE. That is, the test matrix includes 'matched set' cable

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[1] It should be noted that RIS 2004-03 Bin 2 item F, cold shutdown systems, cannot be addressed through the planned experimental program. That is, data/testing needs are not the unique aspect of the issue. Rather, this item hinges on an understanding of the risk implications of failures in cold shutdown systems. The data gathered on the other Bin 2 items, and that available for the Bin 1 items, is directly applicable to cold shutdown systems, but new and better data will not resolve the item in the context of the RIS. A tailored risk-informed analytical effort that is outside the scope of the planned test program will be needed to resolve this particular item.

configurations that vary the relative content of plastic (insulation and jacket) versus copper (the actual conductors) for the same insulation/jacket material configurations (one matched set in thermoset (XLPE/Hypalon) and one matched set in thermoplastic). The objective of this variable is aimed primarily at the fire modeling activities where it is desired that testing include cables with a relatively high copper content (a smaller number of larger conductors) and cables with a relatively low copper content (a larger number of smaller conductors). The original test plan called for the following:

- The 'core' cable configuration is a 12AWG, 7-conductor (7/C) cable typical of the control cables used in U.S. NPPs.
- The 'high copper - low plastic' cable was a 00AWG, 1/C cable.
- The 'low copper - high plastic' cable was a 18AWG, 12/C cable.
- The variation would be provided for XLPE/Hypalon thermoset cables and for PE/PVC thermoplastic cables.

The two changes are as follows:

- The 'high copper - low plastic' configuration will be a 8AWG, 3/C cable.
    - Basis: The originally desired 00AWG, 1/C cable is not available in a material configuration to match the 'core' thermoset XLPE/Hypalon material configuration (i.e., without placing a high cost special order).
- PVC/PVC cables will be used for the matched set thermoplastic cable.
    - Basis: The originally planned PE/PVC cables are not readily available (i.e., without placing a high cost special order) in either of the two 'high copper - low plastic' matching configurations considered (i.e., either the 00AWG, 1/C or 8AWG, 3/C configurations).

The test matrices have been updated to reflect these changes.

- After discussions with representatives of the Rockbestos Surprenant Cable Corporation (suppliers of the core XLPE insulated thermoset cables for CAROLFIRE) *Vita-Link*® fire-rated cables have been added to the test matrix (see Section 3.3 for further discussion of this product line).

- Various sections of the plan incorporate new details relative to test configurations and instrumentation.

- An additional appendix (PENDING INPUT FROM NIST/UMD) has been added to further describe the companion fire modeling activities anticipated for each of these two partner organizations.

1.3 Roles and Responsibilities

In addition to the NRC staff, CAROLFIRE will involve a continued collaboration partnership between SNL, NIST and UMd. The roles and responsibilities of each organization are summarized below. Appendix F provides additional discussion specific to the efforts being planned by NIST and UMd to support the overall CAROLFIRE objectives. (The balance of the body of this test plan focuses on the cable tests to be performed.)

Sandia National Laboratories:

SNL will act as the primary test contractor. Hence, SNL is responsible for development and maintenance of this Project Test Plan, including the incorporation of comments and suggestions from collaboration partners (NIST and UMd). SNL will also be responsible for conduct of the planned experiments, gathering of test data, and communication of test results and data to the collaboration partners. SNL will also be responsible for the preparation of NUREG/CR reports documenting the experimental aspects of the CAROLFIRE project. SNL is also responsible for all contractual obligations under the terms of the DOE/NRC memorandum of understanding (e.g., all responsibility for tracking and reporting project milestones and expenditures associated with the NRC research project (JCN N6125)).

National Institute for Standards and Technology:

The role of NIST is threefold. First, NIST is acting as a member of the overall collaborative team. As such they have provided comments and suggestions relative to the development of this program plan, and will continue to play a similar role throughout the project. Second, NIST will assist in the review and interpretation of test data. Finally, NIST intends to develop a simple model of cable failure that can be incorporated into a large scale fire model (FDS or CFAST for example). Their intent is to develop a thermal response / cable failure model that requires, as input, only the basic physical/electrical cable characteristics (e.g., cable diameter and bulk material properties). Various studies on the thermal degradation of cables suggest that this simple approach will work. That is, prior efforts seem to indicate that reasonable results can be obtained by treating a cable as a homogenous cylinder of plastic. This simple cable model will be combined with a heat transfer calculation using the gas phase temperatures predicted by the fire model as the thermal driving force. The experiments will provide a basis for defining a representative temperature condition that coincides with electrical failure. That is, what is the relevant location on or within the cable whose temperature should be used as a predictor of failure behavior (e.g., the cable surface, the cable center, or perhaps the conductor nearest the surface) and what is the appropriate failure threshold for the cables tested. These insights will be factored into the cable response / failure model.

University of Maryland:

Similar to NIST, UMd has a threefold role in the project. The first two roles parallel those of NIST; namely, (1) to act as collaborative partners providing comments and suggestions during program planning and execution, and (2) to help in the interpretation of test results. UMd's third role also parallels NIST's model development activities, but UMd is interested in a complementary part of the cable failure problem. UMd intends to extend the cable damage model to more fully explain the phenomena of cable electrical failure by taking into account the detailed physical and thermal properties of the cable's various materials. They intend to develop a model that inputs transient cable temperature versus time data and outputs predictions of failure time. The intent is to treat the failure behavior as a statistical uncertainty problem, so the model's output would not be a single failure time, but rather, a probability distribution of the likelihood of damage versus time. This type of uncertainty treatment will allow for a direct method of incorporating failure time uncertainty into some risk analysis estimates (e.g., core damage frequency and large early release frequency).

2.0 Overview of Testing Needs

The two primary need areas, resolution of RIS 2004-03 Bin 2 and reducing fire model uncertainty, have distinct but complementary needs. Based on the consensus of those participating in the August 16-17, 2005 meeting, the specific needs are summarized as follows:

- Circuit analysis and the RIS 2004-03 Bin 2 items:
    - Primary need: RIS 2004-03 identifies six circuit configurations under the heading "Items To Be Deferred at This Time, Pending Additional Research - Bin 2" (see Appendix B for a list of the specific Bin 2 items). The primary need is to investigate each of the Bin 2 issues and to provide a recommendation as to the ultimate resolution of each item - should the item move up to Bin 1, or should the item be moved down to Bin 3[2].
    - Secondary needs: It would be desirable, to the extent feasible, to provide additional supporting cable failure modes and effects data in two areas: (1) additional data to support estimations of the likelihood for the circuit configuration identified as the Bin 1 items in the RIS; and (2) validation results for the spurious actuation likelihood empirical model for cables presented in NUREG/CR-6850.[3]

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[2] RIS 2004-03 defines three separate categories of circuit configurations based on the potential to prevent operation or cause maloperation of equipment necessary to achieve and maintain hot shutdown in the event of a fire:

Bin 1 - Circuit configurations most likely to cause failure (to be considered during inspections),

Bin 2 - Circuit configurations that need more research (to be deferred from inspection pending additional research), and

Bin 3 - Circuit configurations unlikely or least likely to cause failure (not included in the inspection procedure).

[3] EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Volume 2: Detailed Methodology, Electric Power Research Institute (EPRI), Palo Alto, CA, and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD:

- Improving Fire Model Cable Damage Predictions:
    - Primary need: The primary need is for data to support the development and validation of predictive thermal/damage target response models. Data is first needed to help calibrate the fire models; that is, fundamental target exposure and response data under simplistic conditions to support initial model development. Data are also needed to support model validation; that is, separate tests under more realistic and representative testing configurations against which model predictions can be compared. The response models of interest include both basic thermal response models and models to predict the onset of target functional failure. The primary target of interest is electrical cable. It is highly desirable that the tests explore a range of credible exposure conditions (e.g., direct radiant heating, flame zone, plume exposure, ceiling jet, and hot gas layers).
    - Secondary need: Given that the testing will involve the burning of cables in electrical raceways, it would be desirable to gather data on the ignition, flame spread, and burning behavior of cables in electrical raceways, especially cable trays.

3.0 Approach

It was the consensus of all participants in the August 16-17, 2005 meeting that both the RIS 2004-03 Bin 2 and Fire Model Improvement need areas can be addressed through a single combined fire testing effort. While the specific needs in the two need areas are unique, they are also complementary. Hence the concept of the combined CAROLFIRE test project was found to be viable, and indeed desirable. The planned approach therefore involves a series of tests designed to meet the needs of both the Bin 2 issues resolution and Fire Model Improvement. There are some tests in the proposed test matrices that address only the needs of the Fire Model Improvement area (in particular, those identified as “fire model calibration tests”). Others are aimed primarily at resolution of the Bin 2 items. However, the majority of the proposed tests will provide data useful to both need areas.

To meet the goals of CAROLFIRE the team will need to perform a fairly large number of tests involving varied arrays of cable types, cable bundling arrangements, heating conditions, and cable raceways. The test matrices (described below) include over 60 small scale tests and over 50 intermediate scale tests for a total of more than 110 individual tests. The test design has been optimized to allow for considerable flexibility as the testing proceeds. In particular, both the small and intermediate test facilities are designed such that cable and instrumentation configuration changes can be made with little effort and little or no impact on schedule should insights gained as the tests proceed suggest that changes are in order. Hence, both matrices should be viewed as ‘nominal’ test sets that will remain subject to change throughout the project.

2004. EPRI TR-1008239 and NUREG/CR-6850.

The test matrices are also designed to ensure some level of statistical confidence in the final results for both need areas. For example, the Fire Model Improvement effort requires that some tests be repeated with virtually identical test conditions in order to provide some understanding of the inherent (or aleatory) uncertainty. For the Bin 2 Resolution effort, one goal is to provide statistical estimates of failure mode likelihoods of sufficient fidelity to provide confidence in the recommended resolution for each of the identified Bin 2 items. Under these conditions the time and level of effort involved in test facility turnover becomes a significant cost factor.

Given both the identified needs and the discussion above, two scales of testing are being pursued for CAROLFIRE. In general, testing will follow a progression of increasingly more complex test conditions and configurations. The intent is to take maximum advantage of low-cost, smaller scale and less complex testing configurations and to then move up in scale and complexity toward more representative cable raceway and cable loading configurations. The two test scales proposed are:

- Small-scale radiant heating tests in an existing SNL facility called *Penlight*, and
- Intermediate-scale cable burn cell in a larger test facility allowing for both direct radiant heating and open burn tests.

Additional detail on the proposed testing at each scale is provided immediately below.

3.1 Small-Scale Radiant Heating Tests

The small-scale test configuration will utilize the SNL facility *Penlight*. *Penlight* was originally designed and constructed to support the USNRC Fire Protection Research Program in the late 1980's and was know at that time as SCETCh (the Severe Combined Environments Test Chamber). The facility was used in a range of component exposure tests including cables, pressure transmitters, and relays (examples include NUREG/CR-5546 and NUREG/CR-6220)[4, 5]. After a period of idleness, the facility was turned over to the SNL Fire Safety Science Group and reconfigured for use in a somewhat more flexible format. It was in this transition that SCETCh was renamed *Penlight*.

The *Penlight* cell itself consists of a cylindrical ring of 0.61 m (24") long water-cooled quartz lamps. A stainless steel cylindrical shroud (or shell) 0.46 m (18") in diameter and 0.61 m (24") long is installed within the array of heating lamps. The quartz lamps are used to heat the shroud

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[4] Nowlen, S.P., "An Investigation of the Effects of Thermal Aging on the Fire Damageability of Electric Cables," NUREG/CR-5546, Sandia National Laboratories, Albuquerque, NM, 1991.

[5] Vigil, R. A. and Nowlen, S. P., "An Assessment of Fire Vulnerability for Aged Electrical Relays," NUREG/CR-6220, Sandia National Laboratories, Albuquerque, NM, 1995.

to a desired (and fully controlled) temperature. The shroud in turn acts as a gray-body radiator heating any target object located within the shroud at a known (and controlled) radiant heat flux. *Penlight* is quite similar in its conceptual approach to the Cone Calorimeter originally developed at NIST and now used widely in standardized material characterization tests. However, *Penlight* is physically much larger, and is able to accommodate small bundles of energized cables in a representative raceway configuration. (By comparison, the cone calorimeter is designed to accept much smaller material samples on the order of 100mm (4") square, and generally no more than 25 mm (1") thick.)

Penlight allows for the exposure of as few as a single cable up to small bundles of on the order of 6-8 cables. The quantity of cables that can be tested is limited only in that the facility is not designed to endure large-scale burning. Hence, the total mass of combustible material is limited. Cables can be run in a range of configurations. Routing can be either vertical or horizontal, and cables can be run in cable trays, conduits, or as an air drop (with no supporting raceway). For CAROLFIRE, individual cables and small cable bundles passing through the *Penlight* shroud (with or without a supporting raceway) will be heated using a predefined exposure heat flux and monitored for temperature response and for electrical failure.[6] Figures 1 - 3 show the planned *Penlight* test setups with cable tray, conduit and cable drop, respectively.

Penlight provides significant cost advantages in that tests can be performed quickly and facility turnover between tests requires minimal effort. The very fast turnaround allows for the conduct of up to three tests per day (less as the test configurations become more complex). The small scale tests provide a unique opportunity to gather target response calibration results for a range of cable configurations up to and including small bundles of cables (nominally up to six cables per test). *Penlight* will be used in CAROLFIRE to (1) test the more simplistic configurations including fire model "calibration" configurations, and (2) gain preliminary insights into the RIS 2004-03 Bin 2 circuit behaviors of interest prior to testing in a larger scale. A matrix of proposed *Penlight* tests is provided in Section 5.0 below.

3.2 Intermediate-Scale Cable Burn Tests

As noted above, the small-scale radiant heating tests in *Penlight* will provide valuable insights, but the small-scale tests cannot address all of the needs identified for CAROLFIRE. This is largely due to the limitations on open burning in *Penlight*. To meet CAROLFIRE goals, tests will also be run at a more representative scale and involving the open burning of larger arrays of cable. There are four primary driving factors for the proposed intermediate-scale approach namely:

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[6] Note that no single cable sample is monitored for both temperature and electrical performance because attachment of thermocouples might impact electrical performance. Rather, two identical samples (individual cables or cable bundles) are run concurrently and in symmetric exposure locations, one with thermocouples, and one electrically monitored.

- the limited number of cables that can be bundled and concurrently tested in *Penlight* and the contradictory need to test larger cable bundles up to and including "random fill" cable trays,
- the need to demonstrate that the overall test results are applicable to real installations (i.e., confirmation of *Penlight* results),
- the Fire Modeling Improvement areas need for cable response data under more representative exposure conditions, preferably including real fires, plume exposures, and hot gas layer exposures, and
- the need to optimize the efficiency of testing so as to minimize costs while maximizing the number of tests performed.

Given these factors, a second set of tests will be performed at a scale more representative of actual installations and fires. The intermediate-scale tests will involve three exposure modes; namely, radiant heating panels (at a scale larger than *Penlight*), gas burner fires, and liquid fuel pool fires. The test matrix also includes several tests where cables located near the fire source will also burn (further exposing more remote raceways). As noted above, no standard fire test method or protocol currently exists that would meet the CAROLFIRE needs. Hence, a new test cell has been constructed for the conduct of the intermediate scale tests.

The intermediate-scale test cell is illustrated in Figure 4. The test cell consists of a steel framework of which only the upper portions are enclosed. That is, the framework has an overall height of 3 m (~10 feet) but remains open up to a height of 1.8 meters (6 feet). Each of the four sides from a height of 1.8 m (6 ft) up, and the top of the structure itself are covered (enclosed) using gypsum wall board. During testing smoke and hot gasses will fill the enclosed upper portion of the test cell, eventually spilling out around the sides.[7] In this way we can create the desired hot gas layer exposure conditions under actual fire conditions.

This test cell is positioned within a larger fire test facility so that the air flow conditions can be controlled, and so that outlet stack measurements (such as Oxygen depletion) can be made. An existing SNL facility (Building 9830) will serve as the outer test structure. Figures 5 and 6 show the planned Test Cell setups in the Sandia facility for conducting the radiant panel heating tests (Fig. 5) and the open burn tests (Fig. 6).

Overall, the framework is similar in size to the recommended dimensions of an ASTM E603 fire

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[7] An option is being maintained to raise the level of the enclosing panel on one end higher than those on the other sides and/or to fully enclose one end panel of the framework. This alternate approach would have two effects. First, raising the level of the enclosing panels on one end would create a "preferred" direction for the flow of hot gasses (flow would tend to spill out at the highest point along the perimeter of the framework). Second, if the fire is placed adjacent to the closed end panel, the upper layer temperature would increase somewhat due the restricted entrainment flow of fresh cooler air into the plume (e.g., based on the wall-plume effect).

test room. An ASTM room is typically 2.4 m x 3.7 m x 2.4 m (8'W x 12'L x 8'H). The proposed test cell is slightly taller (2.4 m x 3.7 m x 3.0 m [8'W x 12'L x 10'H]) allowing for some additional capacity for the upper region while maintaining accessibility. The open nature of the facility is considered key to optimizing test turnaround times. Testing in a standard room facility is rather cumbersome especially when that testing involves rigid raceways (trays and conduits) which must be re-loaded and or re-positioned between tests. The standard room has only a single 0.9 m (36") wide door. All equipment (and technicians) must enter and leave through this door. The standard room will have no interior lighting, and quickly becomes cramped by instrumentation and in our case, by cable raceways.[8]

In contrast, the open configuration of the CAROLFIRE test cell means technicians can work from all sides and can easily access the raceways, cables, and supporting instrumentation. The open framework also simplifies the cable and instrumentation routing (compared to a small room with just a single doorway). Burned cables and even entire raceways can much more easily and quickly be removed and replaced in preparation for the next test. The open configuration also means that after any given test, the test cell will return to ambient conditions more quickly than a typical standard room facility. These factors are expected to substantially increase the efficiency of facility turnarounds and thereby optimize the cost per test while meeting all of the identified CAROLFIRE project test needs.

Consideration was given to potential criticisms of the proposed test cell. It is acknowledged that the use of a standard test is desirable whenever feasible. In this case, no standard test method or protocol directly meet the identified needs. In the same spirit, minor modifications or adaptations of a standard test would also be desirable if that approach offers specific advantages. In this case, the ASTM E603 room fire facility was the obvious choice. However, given that we are not seeking room response data, the standard room offers few if any technical advantages. The E603 room is considerably smaller than any compartment typically found in a nuclear power plant, so it cannot be argued that the exposure conditions would be more representative of in-plant configurations. In fact, the proposed test cell is arguably a good analog for a very common in-plant configuration; namely, a beam pocket within a larger room. In-plant installations often involve areas where the floor above is supported by massive steel and/or concrete beams creating isolated ceiling level beam pockets. For fires in most rooms, damaging hot gas layer conditions are likely to be found only when the fire occurs below such a beam pocket, not in the larger open room configuration. For these reasons, the proposed test configuration is considered acceptable, and indeed, offers several unique advantages.

Given the CAROLFIRE test cell, conduits and trays can be routed in any manner desired. Cable

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[8] Note also that the design allows for installation of additional outer enclosure panels should this prove desirable or even necessary to create the desired exposure conditions (e.g., we could easily enclose one end wall all the way to the floor if wall-effect fire conditions are desired).

raceways can be run at any desired location through the structure either above or below the 1.8 m (6') level. Vertical raceways may also be installed with little difficulty. Through-wall penetration holes in the side or top panels will be used to simplify raceway routing (any such holes will be filled with non-combustible insulation during testing). Figure 4 illustrates the proposed nominal set of raceway locations. Note that not all raceway locations will be involved in every test. Rather, raceway loadings will be varied. For example, in the initial radiant panel tests, only one or two raceways will be loaded. In later tests, several raceways will be loaded with cables, some simply as fire sources, some as thermal damage targets. As in the small-scale tests, the intent is to start with simple configurations and build up to the more complex configurations allowing for maximum flexibility as the tests progress.

As noted above, three exposure conditions will be used: radiant heating panels, gas burners, and liquid fuel pools. (Note that the test matrix has been divided into two parts; namely, the “radiant panel tests” and the “open burn tests.” The latter set encompasses both the gas burner and pool fire tests. The specific source desired for a given test will be determined in consultation with the collaborative partners.) The fire source can be positioned anywhere within the test cell framework and can be elevated above floor level when desired. This simple structure should easily withstand fire up to on the order of 1 MW in size (including the burning of cables). In effect, the test cell represents a capture hood that will contain the hot fire gasses allowing us to create the desired hot gas layer conditions without the need for a full room fire test facility. The matrix of tests to be performed in the intermediate-scale test cell is discussed in Section 5.0.

3.3 Cable Selection Criteria and Results

The goal of resolving the RIS 2004-03 Bin 2 issues requires the testing of both thermoset and thermoplastic types of cable insulations. There is also potential interest in mixed cable construction (i.e., thermoset insulation with a thermoplastic jacket). There is a clear need to make these tests as broadly applicable as possible. This, unfortunately, is a substantially complicating factor for the test program given the variety of cable materials, conductor sizes, physical configurations (e.g., number of conductors, shielded versus unshielded, etc.), and cable manufacturers represented within industry.

It was critical that CAROLFIRE explore a reasonable range of materials and configurations, and yet also establish reasonable limits on the range of cables to be used in testing. The addition of any variations on cable type (material type, manufacturer, or physical (conductor count and size) configuration) implies an expansion of test matrices and overall work scope (hence cost). The final results of the cable selection process are detailed in Appendix E which provides a detailed table listing each selected cable configuration and the basis for its selection. The primary considerations that went into the selection of cable configurations are summarized as follows:

- Each addition cable type tested introduces significant ‘entry level’ material costs. Manufacturers typically require a minimum purchase of 300-1500 m (1000'-5000') of each specific type of cable purchased. For CAROLFIRE, the desired minimums were typically 300-900 m (1000'-3000'), and for the two core configuration 3000-4500 m (10,000'-15,000') of cable were required. The cost per 0.3 meters of cable ($/ft) ranged from as little as $1 to as high as $12 for the cable products actually procured for CAROLFIRE. For some specialty configurations that were considered (e.g., a fully nuclear qualified Tefzel 280 or silicone insulated cable), costs ranged as high as $18/ft making them prohibitively expensive.

- One of the most important factors considered was the relative popularity of different cable insulation materials. For CAROLFIRE, material selection considered surveys done under various Equipment Qualification Research Programs[9] conducted during the 1980's and 1990's. CAROLFIRE is exploring a broad range of insulation materials including all of the following:
  - the materials most used in the U.S. nuclear power industry is the thermoset material cross-linked polyethylene (XLPE). XLPE is the ‘core’ thermoset insulation material for the CAROLFIRE program.
  - Ethylene-propylene rubber (EPR) is the second most popular insulation material (another thermoset).
  - Of the thermoplastic materials, which are used by a smaller number of plants, polyethylene (PE) is the most common. PE is nominally the ‘core’ thermoplastic insulation material for the CAROLFIRE program
  - PVC is a second thermoplastic material popular in general industrial applications, Canada, and Europe. PVC plays an important role in the CAROLFIRE matrices, especially in the context of the plastic-to-copper relative content issue (as discussed below).
  - Other *common* insulation materials used by U.S. nuclear plants include the thermoset materials cross-linked polyolefin (XLPO) and Silicone, and the thermoplastic Tefzel.

  Other minority materials are used by industry, but will not be included in the CAROLFIRE program.

- Another factor that was considered desirable was traceability of the CAROLFIRE cables to materials and products supplied to the U.S. NPP industry during the 1970's and 80's. This proved difficult to achieve, and in some cases, it proved to be impossible. Appendix E provides detailed discussion relative to each material configuration, but to

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[9] There were a number of USNRC-sponsored cable aging research efforts at Sandia National Laboratories in the 1980's associated with the Nuclear Plant Aging Research (NPAR) programs, and at EPRI and the U.S. Department of Energy relative to Plant Life Extension (PLEX) programs. During the 1990's most of the USNRC-sponsored efforts shifted to Brookhaven National Laboratory. The insights cited here are based on information gathered from all of these resources. Specific references are available on request.

summarize:

- While nuclear grade (i.e., fully qualified) cable lines maintain a traceable history to early qualification testing, many of the historically popular product lines have simply not survived as viable products in the current marketplace and can no longer be obtained. This is in part due to the limited market for nuclear grade cables, and in part due to the consolidation of manufacturers in the cable industry.
- One particular success in this regard is a decision to procure the core thermoset material configuration (XLPE insulated cables) from the Rockbestos Firewall III line of cable products. This is arguably the single most popular line of cable products for the U.S. NPP industry, and the line continues in production today.
- For silicone insulated cables, the manufacturers known for production of such cables in the 1960's and 1970's either no longer exist, or no longer market silicone-insulated cables.
- There was an explicit interest in including XLPO cables given evidence that these cables may be more vulnerable to thermal damage than other thermoset materials. In particular, the Kerite FR line of XLPO cables was sought for testing. No manufacturer of an XLPO insulated cable with a history traceable back more than 15 years could be identified. The Kerite FR line of materials is no longer manufactured at all and Kerite no longer manufacturers control cables.
- Many plants used general industrial grade cables in areas outside of containment where nuclear qualification is not required. In particular, this includes all of those plants using cables insulated with either PE or PVC because, in effect, no PE or PVC cable is advertised as nuclear grade. However, this also potentially includes virtually all cable materials for the simple reason that nuclear certification adds substantially to the per linear foot cost of cables (a nuclear grade cable may easily cost four times as much as a corresponding industrial grade cable). For industrial grade cables there is no real impetus to maintain historical traceability because there is no nuclear grade qualification basis to be maintained. Hence, formulations for industrial grade cables are routinely updated to enhance performance and/or to reduce production costs.

- There was a strong desire to, in some sense, bound the range of materials relative to their robustness (i.e., their resistance to thermal damage). For example, in the context of the Bin 2 cable-to-cable interactions issues, the relative timing of cable failures is likely to be critically to the likelihood of inter-cable hot shorts. Timing of failure is directly correlated to the insulation material’s robustness against thermal damage. The materials for CAROLFIRE are as follows:
    - The one material generally found to be the most robust of all the polymeric insulation materials is silicone-based insulations (another thermoset).
    - XLPE and EPR are both expected to perform at a mid-range of the thermoset materials.
    - Of the thermoset materials, the one material thought to be the least robust is a

    generic grade of cross-linked polyolefin (XLPO). Given formulation changes and the marketing of entirely new lines of XLPO cables, this presumption may prove false, but an XLPO cable has been included in the test program.
  - In terms of thermoplastic materials, the relative robustness is not well understood. However, in the interest of diversity, three material will be tested: polyethylene (PE, non-cross-linked), polyvinyl chloride (PVC), and the Teflon-based material Tefzel 280.

- Another consideration was the issue of cable conductor physical configurations; that is, the size and number of conductors in each multi-conductor cable:
  - The most common configurations used by industry include 1, 2, 3, 7, 9, and 12-conductor cables.
  - Some applications also involve so called “trunk cables” which can have 20 or more conductors.
  - Typical conductor sizes range from and upper bound of 350 kcm through AWG #8 for power applications, AWG 12 - 14 for control cables and AWG 16 - 22 for instrument circuits.

  Again, in order to focus the applicability of these tests on generic utilization, the focus has been placed on 7-conductor cables which are representative of the predominant control cable configuration. A limited number of tests on 2, 3, and 12-conductor cables have also been included. Note that the focus has been placed on#12 AWG size conductors, again based on the predominance of this cable size in control circuits. A few tests of #8, #16 and #18 AWG cables have been included to assess their impact on cable failure mode and thermal response. Table 1 provides a listing of the specific cable types selected for inclusion in this test project. To summarize:
  - The focus of the test protocols for the resolution of the RIS 2004-03 Bin 2 issues will be on the 12AWG, 7-conductor control cables as the ‘core’ physical configuration. All of the cable materials will be tested in this configuration.
  - As discussed briefly in Section 1.2, in the context of fire modeling there was also a desire to test cables of nominally the same overall size (e.g., outside diameter) but with variations in the relative content of copper to plastic. For this reason, testing of the XLPE and PVC materials will include the 8AWG, 3/C (high copper - low plastic content) and 18AWG, 12/C (low copper - high plastic content) configurations.

- To address the RIS 2004-03 Bin 2 issues related to cable-to-cable interactions, the cables must be tested in bundles. There is interest in both bundles of like cables, and bundles of mixed cable types. The test plan calls for bundles of 3-, 6- and 12-cables. A small number of the earliest tests in each matrix involve just one cable. These are what have been referred to as fire model calibration tests and are designed primarily to provide thermal response data under the most simplistic of all possible test conditions. At the opposite end of the spectrum, a number of the intermediate-scale tests will involve trays with up to a 40% load of cables. In these tests, only select cables within the overall fill will be monitored.

As noted here, and as discussed further in Appendix E, the core XLPE-insulated thermoset cable for CAROLFIRE was ultimately procured from the Rockbestos Firewall III® line of nuclear qualified cables. The SNL/NRC order for a considerable quantity of cables attracted the attention of the western regional manager for Rockbestos Surprenant Cable Corp., Mr. Mark Valaitis. SNL subsequently had a series of discussions with Mr. Valaitis to explain the intent and objectives of the CAROLFIRE project. The culmination of these discussions was a proposal by Mr. Valaitis to include one additional Rockbestos cable product in the test matrix; namely, the Vita-Link® line of fire-rated cables. As cited on the corporation web site, Vita-Link® "is a unique silicone rubber insulation material that ceramifies and maintains physical & electrical integrity when exposed to flame conditions." Mr. Valaitis offered to supply, free of charge, a sufficient length of the Vita-Link® cables in a control cable configuration from off-the-shelf stocks of material to allow for inclusion in the CAROLFIRE test matrix. This offer was discussed with the NRC/RES Staff. Staff determined that inclusion of this new line of cable products offered substantial benefits to the NRC program, and directed SNL to accept Mr. Valaitis' offer. The NRC staff concluded that addition of the Vita-Link® cables enhanced the CAROLFIRE test matrix by incorporating a "look towards the future" with one cable product that might be highly useful and improve safety in the design and construction of the next generation of nuclear power plants. As a result, the Vita-Link® cable has been incorporated in the CAROLFIRE test matrices and will be subjected to the same testing and evaluation criteria as the other selected cables.

Table 1 provides a listing of the specific cables to be used in the CAROLFIRE project. (Note that orders have been placed for all of the cables identified in Table 1.) The information summary in Table 1 provide the material types for the insulation and jacket (ins./jacket), the manufacturer, and the conductor count and size physical configuration. More specific information relative to the selection of individual material configurations is provided in Appendix E.

4.0 Primary Measurements and Performance Diagnostics

There are a number of variables that need to be investigated in this test program. These variables can be divided up into several general categories: cable characteristics, exposure conditions, and fire behavior. In addition, cable thermal response measurements and electrical response/failure determinations must be made for each configuration tested.

4.1 Thermal Exposure Conditions

The conditions under which the cables will be subjected to thermal insults will be varied in order to meet the overall project objectives. The primary variables here are the energy source, source intensity (heat flux or heat release rate depending on the source type), and raceway types. The small-scale tests will limit thermal exposures to radiant heat conditions (see Section 3.1 for discussion). The intermediate-scale tests will also involve some radiant heating tests, but also will involve open burning of liquid fuel pool fires or gas burners. Note that the intermediate-scale radiant heating tests will provide an intermediate link between the small-scale tests and the open burn tests. The open burn tests allow us to investigate exposures to fire plumes and hot gas layers.

The *Penlight* radiant heat apparatus allows heat flux exposures at virtually any exposure level up to 97 kW/m^2. This is a heating level well above that typically experienced in real fires anywhere other than within the flame zone itself, or under wind-driven conditions. Given the nature of typical NPP fires, it is desirable to monitor the degradation of cable integrity and behavior over relatively long times (nominally on the order of 10-40 minutes), thus the *Penlight* test matrix uses two heating levels. The predominant condition is *nominally* 40 kW/m^2, and as a variation parameter, some tests will be performed at a lower heat flux, *nominally* 20 kW/m^2. (NOTE: Both flux values are cited as *nominal* because they remain subject to peer review input and can be easily modified to suit program needs.)

The intermediate scale tests will initially utilize radiant heating panels. The plan calls for testing in the intermediate scale radiant panel tests at the higher of the two levels used for the small-scale testing; that is, the tests will be run *nominally* at 40 kW/m^2. Again, one objective of this particular test set is to provide a basis for comparison between the small- and intermediate-scale tests.

In the balance of the intermediate scale tests, fire exposures will generally be limited to heat release rates of 100 or 250 kW. These values may be adjusted once initial calibration runs have been made and we can predict how the test cell will respond to these fire sizes. The purpose here will be to induce the burning of at least one of the test specimens to generate the thermal environment within the room, especially the hot gas layer, to which other test specimens will be exposed. Should the 100 and 250 kW fires prove to be insufficient to create the desired conditions, the fire size will be increased. The intent here is to induce the failure of the cables being tested. Cables that do not fail during testing provide no data relevant to resolution of the RIS 2004-03 Bin 2 issues.

The raceways to be employed during these tests will be 300 mm (12-inch) wide standard ladder-back cable trays and 63 mm (2 ½ inches) diameter rigid metal conduits. We expect to use the *B-Line* style cable trays as representative of industry practices. For the purposes of providing data for the fire model effort, a limited number of tests will be conducted on unsupported cables (“air drops”). Note that only single cable or three-cable bundles (for RIS 2004-03 Bin 2 needs), along with a single cable instrumented with thermocouples, will be run through the conduits for these tests. This two or four cable loading in the conduits is intended to represent an average utilization at power plants. Air drops will be simulated by a pair of single cables—one instrumented with thermocouples and the other monitored for electrical failure.

In the case of the intermediate scale tests, the cables will generally extend across the 2.4 m (8') width of the test cell. However, in order to match the locations of cable thermal monitoring (see additional discussion in section 4.4) to the likely locations of actual electrical failure, we anticipate using a thermal blanketing material to provide some nominal protection to portions of each raceway. That is, rather than exposing the entire tray length uniformly, only the center 1m section (3') would be exposed fully, and the balance of the tray would be provided with nominal thermal protection in the form of top and bottom thermal blanketing. The blanket protection will *not* be fire-rated in any sense, but will simply slow the thermal response of the peripheral raceway areas, and focus the exposure on the central portion of each raceway. This will maximize the correlation between the measurements of temperature and electrical response.

4.2 Fire Behavior

These tests are not designed explicitly as fire characterization tests. That is, the focus of this project is not on fire behavior. The intent is, however, to take an “opportunistic” view of fire behavior data gathering. That is, as opportunities and budgets allow, fire characterization data will be gathered, but not as a project priority

Some key fire parameters will be monitored during testing. Evaluation of fire behavior will involve the monitoring of fire spread along the length of cables routed in open cable trays as well as the propagation of fire from one tray to another, especially for stacked trays. This will involve a combination of video recording and observations, as well as analysis of the temperature data. Temperature measurements will be provided not only for the cables, but also for the surrounding air in key locations, and the raceways themselves. During the intermediate scale tests, measurements of the fire heat release rate will be made through exhaust stack gas monitoring (i.e., oxygen consumption calorimetry).

4.3 Thermal Response

All the measurements required to satisfy the RIS 2004-03 Bin 2 and fire modeling goals are electrical in nature. Hence, measurements of the cable thermal response is primarily of interest to the fire modeling activities. It is not appropriate to instrument any single cable for both thermal and electrical response. This is because installation of a thermocouple on, or within, a cable could impact the electrical failure behavior. Instead, for essentially each cable monitored for electrical performance, a ‘mirror’ cable (in an adjacent or symmetric location) will be monitored for thermal response. Thermocouples will measure the thermal behavior of cable upon heating and the more significant surrounding air temperatures.

The principal mechanism for determining this response will be by instrumenting cables with Type K thermocouples placed just below the outer cable jacket. The spacing between adjacent thermocouples will be ~25 cm (10-inches) along the length of the cable exposed to the thermal environment. For these embedded thermocouples, a small slit will be cut in the jacket to allow insertion of the thermocouple (~2.5-5 cm [1-2 inches] long) in the outer cover and sliding the tip of the thermocouple in under the jacket to a pre-marked position along the cable's length. The opening will then be closed and secured with a single layer of fiberglass tape.

In addition to these sub-jacket temperature probes, a number of cables will be instrumented with a larger number of thermocouples to determine the thermal response across the cable's radial cross-section (i.e., outer surface, sub-jacket, and as deep into the core of the cable as practical). The insertion of thermocouples into the cable core is a relatively difficult process and will be reserved for use in certain key tests and locations as suggested by the CAROLFIRE partner team members (i.e., NIST and UMd). Figure 7 provides a nominal depiction of these thermocouple placements in a 8AWG, 3/C cable versus the 12AWG, 7/C cable. As noted above, the intent is to employ cables of about the same overall diameter but with different proportions of copper to plastic. Figure 8 depicts the nominal spread along the length of the exposed cable that will be necessary to accommodate these thermocouple placements. Within bundles of cables, some thermocouples will be included to measure the temperatures at the interfaces between individual cables (i.e., a bare-bead thermocouple within the bundle but not attached to any individual cable).

Where it is practical to do so, the configurations of the thermocouple-instrumented cables/bundles will mimic exactly the configurations employed by the electrically monitored cables/bundles. The principal exceptions to this approach will be those cases where three-cable bundles are run through a conduit. Here only a single thermocouple-instrumented cable will be included with the conduit bundle due to space constraints within the conduit.

Additional diagnostics will be made of the environment to which the cables are exposed. These will include thermocouples measuring the air temperature near the cables, the conduit or tray temperature (where used). For a limited number of tests, calorimeters may be used to measure cable surface heat flux (e.g., to verify calibration of the radiant heating arrays).

In the selection of the variables to be measured, particular care will be taken to provide an effective scan rate of the more significant variables, such as those related to the thermal degradation of the polymeric insulation and the magnitude and characterization of the thermal insult. Surrogate variables, such as the ceiling temperature, wall temperature, heat flux, etc, will also be measured in the intermediate-scale tests.

4.4 Electrical Response

As indicated above, the Bin 2 issues hinge on monitoring the electrical failure behavior of the cables. Some of the cables included in each test run will be monitored for their electrical behavior as the fire-induced damage progresses. The principal method of electrical response monitoring will be by employing use of the Sandia Insulation Resistance Measurement System (IRMS). A secondary electrical response measurement system will also be employed to mimic the behavior of various control circuits and components more directly (the 'black box' approach). A complete description of the hardware associated with these two approaches are provided in Appendix C and D respectively.

Cable failure will be defined as the case where any one of the monitored conductors shorts to ground (e.g., the cable tray or conduit) or to another conductor. A short will be defined as that point when the insulation resistance of a conductor becomes less than or equal to 1000 ohms for control cables and 10,000 ohms for instrument cables. These particular insulation resistance limits were selected by the CAROLFIRE team as representative of expected failure onset conditions for control and instrument circuits. When bundles of cables are being tested, particular attention will be paid to the condition where conductors of different cables short together. This is an important measurement necessary to address two of the RIS 2004-03 Bin 2 issues under investigation (i.e., items 'A' and 'B' as shown in Appendix B).

Additional electrical response behaviors will be monitored using surrogate control/instrument circuits connected to some of the cables under test. These "Black Box" circuits will be designed to simulate the control circuits representative of motor operated valves (MOV), solenoid operated valves (SOV) and instrument loops. A number of circuit conditions will also be implemented to assess the effects of control power transformers (CPT), voltage/current form (AC or DC) and circuit grounding (grounded and ungrounded) on the cable failure modes and likelihoods. Also, these surrogate circuits will provide the electrical circuit response data needed to resolve additional RIS 2004-03 Bin 2 issues (i.e., C, D and E). Electrical parameters to be varied using these black box circuits will include the numbers of target, source and ground conductors that make up the surrogate control/instrument circuits. Different sizes of CPTs will also be included in some of the circuit tests. Refer to Appendix D for additional information.

A CPT is a device commonly installed in certain types of control circuits (e.g., MOVs). The CPT taps into the motive power supply source for the device being controlled (e.g., the power supply to the motor of the MOV), steps down the voltage, and thereby feeds power to the control side of the device's circuit. As an artifact of this design, the total power available to the control circuit is limited to the maximum power output of the CPT.

If the power demand (e.g., current flow) exceeds the power output limits, then the CPT output voltage will begin to degrade (it will be lower than the design voltage). If the voltage is degraded far enough, then the actuation circuit will not function. For example, a typical 120 VAC actuation relay may have a minimum pick-up voltage of 85-90 VAC. If the CPT output voltage drops below this minimum pick-up voltage, the relay cannot actuate. As a multiconductor cable degrades, each conductor experiences current leakage, not just to a second single conductor, but rather to various conductors. Each conductor also leaks power, to a lesser extent, to ground. In order to initiate a spurious operation, a source conductor must feed power to the specific target conductor associated with the postulated spurious operation. If the source conductor is leaking power to various conductors, the power available from a CPT powered circuit may not be sufficient to maintain the circuit voltage above the pick-up voltage of the relay coil. Hence, a subsequent hot short to the target conductor may not cause the relay to close. By similar arguments, even if an actuation does occur, subsequent increases in the leakage current (to other conductors or ground) might degrade the voltage below the dropout voltage causing the spurious operation signal to self-mitigate more quickly.

A critical factor in this behavior that is not well understood is the relative magnitude of the CPT power output compared to the power required to actuation the circuit. The choice of CPT output power is made during the circuit design. The CPT must be large enough to supply all of the normally anticipated control power circuit demands. However, in practice, some margin is provided above the nominal control circuit power demand. Hence, the CPT will typically be sized to provide 150% or more of the anticipated normal circuit load.

5.0 Test Matrix

Tables 2, 3 and 4 provide the test matrices for the separate small and intermediate-scale tests discussed above. Table 2 is the *Penlight* test matrix, Table 3 is the intermediate scale radiant panel test matrix, and Table 4 is the intermediate scale open burn test matrix. Note that all three matrices are intended to allow for flexibility. That is, each matrix defines the overall scope and general test conditions and configurations anticipated. However, it is intended that the program will maintain the option to adjust the test matrices based on insights gained as the program progresses. Any such adjustments would be based on discussions with the NRC staff and collaborative partners NIST and UMd.

Each table indicates the test number ("Test #") for the runs conducted in the particular facility, for each test run an "X" in a given column indicates the active choice for each experimental variable. The primary test variables are:

> Cable Insulation Material - specifies the cable insulation material for the cables being tested, the type of cable
> Number of Conductors - specifies the number of conductors contained within the cable
> Conductor Size - identifies the American Wire Gage (AWG) size of the copper conductors within the cable
> Cable Bundle Size - indicates the number of cables in each bundle of cables to be included in the test (note that some tests involve more than one cable bundle)
> Thermal Exposure - specified the thermal exposure conditions which vary somewhat depending on the test facility. For *Penlight* and the Intermediate-Scale Radiant Heat tests, the thermal exposure is defined by the incident heat flux. For the Intermediate-Scale open burn tests, the thermal exposure is defined by the fire intensity. The type (pool or burner) of the flame source will be determined at a later time

Raceway Type - indicates how the cable bundles will be supported and may involve either no raceway, cable trays, or conduits.

These matrices also indicate the primary application to be made of the temperature and electrical failure data in the column following the test number. For example, “FMI” denotes that the data will principally apply to the fire model improvement need area, while “2-A, C” means the data will be used to address RIS 2004-03 Bin 2 items A and C, etc. Note that data use for other need areas, where applicable, are not precluded by the notations in this column.

Tables 3 and 4 each have one additional column (third from left):

Location - indicates the raceway locations in the Intermediate-Scale Test Cell. Note that these tests all involve cables located in more than one of the available locations. These locations are identified by letter (A-G) and are shown schematically in Figure 4.

Penlight, Small-Scale Test Matrix:

Table 2 provides a test matrix for the small-scale tests to be conducted in the *Penlight* radiant heat chamber. The tests have been organized into several groups. Each test group represents a set of tests that are aimed at a particular aspect of the overall problem. The general nature of each test group is described in the following paragraphs.

The tests identified as Group 1 are Fire model calibration tests. The need for this test group was discussed during the meeting held at NRC HQ August 16-17, 2005. The primary objective of the Group 1 tests is to provide temperature response data to support the development of the cable thermal response models. The Group 1 tests represent the most simplistic of all possible cable exposure configurations. Each test in Group 1 involves a single length of cable either in open air, in a cable tray, or in a conduit. The Group 1 tests do provide some cable failure data for all tests. The failure data is not, however, relevant to the RIS 2004-03 Bin 2 issues. The main purpose in monitoring for electrical failure is so that we can correlate the exposure and temperature response conditions to electrical failure. The Group 1 tests do not support the Bin 2 resolution effort because the Bin 2 issues are not associated with the failure of individual cables.

The remaining test groups are designed to progressively attack the RIS 2004-03 Bin 2 circuit issues with increasing degrees of complexity and through variations in test parameters. In general, Group 2 represents the Bin 2 baseline test runs. These tests represent a core set of failure mode tests providing initial results against which we can begin to assess key RIS 2004-03 Bin 2 behaviors. The remaining *Penlight* tests represent variations on the Group 2 tests. Each subsequent test varies one or more of the testing parameters (e.g., exposure heat flux, cable type, mixing of cable types, bundle size, etc.).

Test Cell, Intermediate-Scale Test Matrix:

Tables 3 and 4 provide a test matrix for the intermediate-scale tests. Table 3 represents those tests to be conducted using radiant heating panels as the exposure source. Table 4 represents the intermediate-scale open burn tests involving either liquid fuel pool fires or a gas burner. Note that in the case of the open burn tests, the matrix specifies the nominal fire size, but does not indicate whether a pool fire or gas burner will be used. This decision remains pending, and will likely hinge on input provided by peer reviewers.

Here again, a number of fire model calibration tests are included. These are the tests identified as Group 1 (in Table 3) and the first six tests in Group 5 (Tests 34 through 39 in Table 4). The intent of these tests is to provide test results for the most simplistic configuration that will allow for a direct comparison between test scales and exposure conditions. That is, these tests provide data for cable configurations that are nominally identical for each of the three test sets; namely, *Penlight*, radiant panel tests in the intermediate-scale test cell, and the open burn tests.

The remaining tests in Table 3 provide data directly relevant to the RIS 2004-03 Bin 2 issues. They again involve increasing levels of configuration complexity, and the variation of test parameters. Note that the radiant panel tests all involve target locations essentially directly above the heating source. While we do anticipate ignition of the target cables, we do not expect wholesale burning of significant quantities of cable. This is deferred to the open burn tests.

The final set of open burn also involving increasingly complex and diverse test configurations. These tests are expected to result in significant cable burning in addition to the pool or gas burner source fire. Those cable raceways highlighted in RED are expected to ignite and burn during the tests. Especially in the tests of Groups 7 and 8, significant cable burning is anticipated. While the highlighting nominally indicates the burning of three trays for these later tests, it is possible that all of the cables will ultimately burn in these tests. These tests will likely, and intentionally, test the limits of the test cell.

6.0 Data Analysis and Reporting

The data from the tests will be analyzed, and two test reports will be written. Data analysis will assess the test results for each tested configuration. The reports will establish (as appropriate to the test results) estimates of the failure time for the test cables. The analysis will also explore the potential for generalizing the test results to other untested configurations. The limits of data applicability will be clearly defined.

6.1 Cable Electrical Response

The cable electrical response will be analyzed primarily by comparing conductor IRs versus time and versus cable temperature in order to determine the impact of the thermal exposure conditions on the time and temperature at which electrical failures occur. The large number of cable IR measurements taken will allow the determination of the likelihood of intercable shorting before other failure modes are manifest (e.g., shorts to ground or intracable shorts). The analysts will be looking for intercable conductor-to-conductor shorting that occurs prior to total cable failure. This focus is intended to provide the data necessary to make a determination on the final disposition of RIS 2004-03 Bin 2 items A and B, depending on the material composition of the cables tested.

Electrical data collected during the tests will be evaluated regarding the number of separate cable failures likely to occur from the same exposure conditions. The data will be evaluated to account for all cable failures–intracable as well as intercable. Again, the timing, concurrence and modes of failure will be correlated to cable temperature in order to support the determination of Bin 2 item C.

Surrogate circuit diagnostic units, setup to mimic MOV control circuits–both with and without CPTs of various rating sizes–will be used to assess the roll CPTs play in reducing the number of spurious actuations. Analysis will be done to assess the prevalence of multiple spurious operations for each of the CPT rating sizes tested. Then, if applicable, a recommendation will be made regarding an adjustment in the percent of nominal power factor for circuits employing CPTs as stated in the description of Bin 2 item D.

For addressing Bin 2 item E, additional diagnostic units, set up to simulate SOV control circuits, will be employed during the tests to provide electrical data concerning the times of onset and duration of fire-induced spurious operation failures. This data, coupled with that obtained from the MOV circuit responses (see above) would then be used to propose new guidelines in the expected mean duration of spurious operations and to provide information on the range of spurious operation failure durations observed (e.g., histograms of numbers of spurious actuations vs. duration time bins).

It should be noted that RIS 2004-03 Bin 2 item F, cold shutdown systems, cannot be addressed through a planned experimental program. That is, data/testing needs are not the unique aspect of the issue. Rather, this item hinges on an understanding of the risk implications of failures in cold shutdown systems. The data gathered on the other Bin 2 items, and that available for the Bin 1 items, is directly applicable to cold shutdown systems, but new and better data will not resolve the item in the context of the RIS. A tailored risk-informed analytical effort that is outside the scope of the planned test program will be needed to resolve this particular item.

6.2 Cable Thermal Response

Thermal response of the test cables will be analyzed and discussed in a separate report. The analysis will primarily consist of presenting plots of cable temperature versus time for those cables instrumented with thermocouples. Selected cables will also be instrumented to obtain temperatures across their diameter. This data will be presented as a family of curves (temperature vs. time) illustrating the delay in thermal response as the thermocouples are located deeper in the cable's core. Finally, correlations to the time of observed electrical failures in separate, collocated, cables will also be provided.

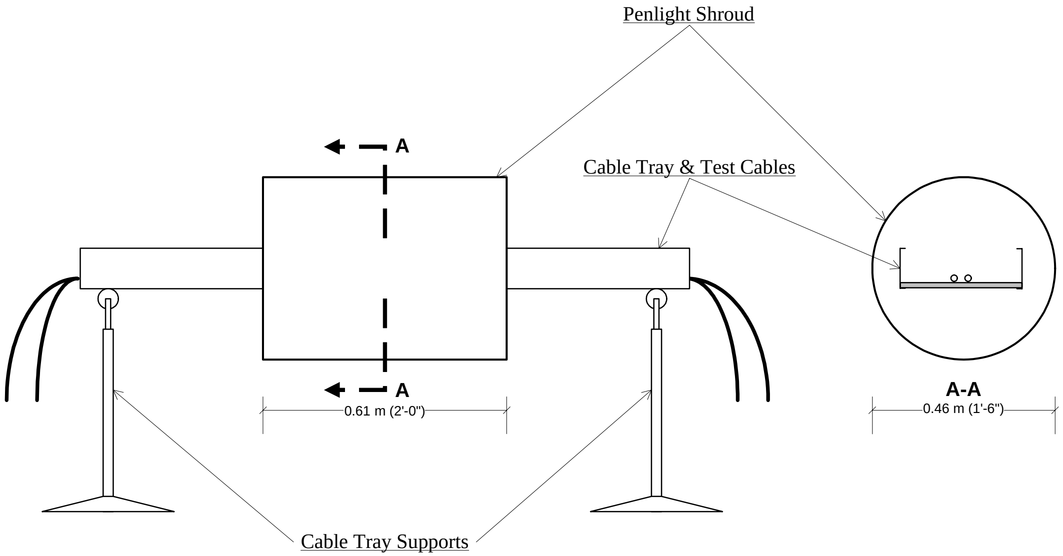

Figure 1: *Penlight* test setup with cable tray.

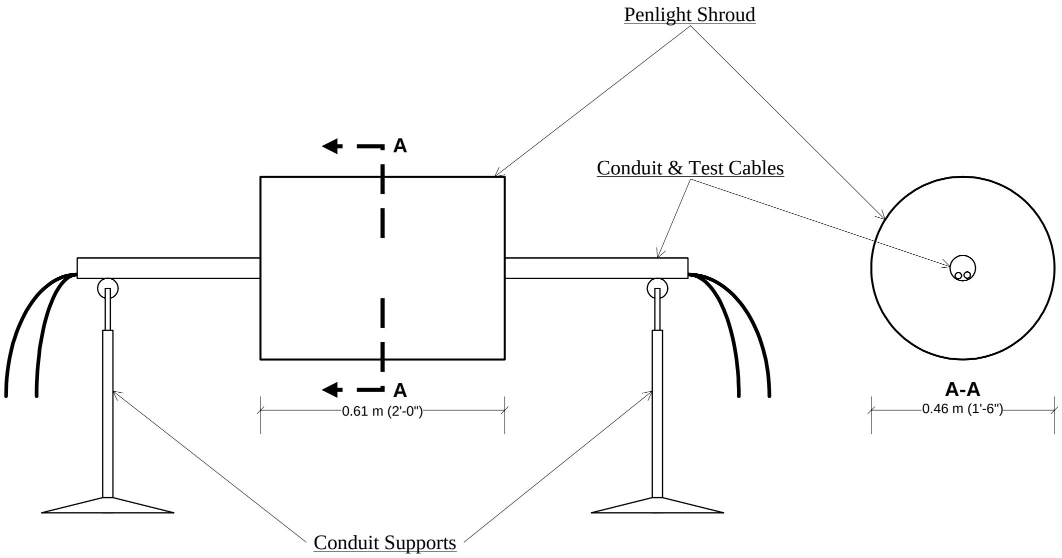

Figure 2: *Penlight* test setup with conduit.

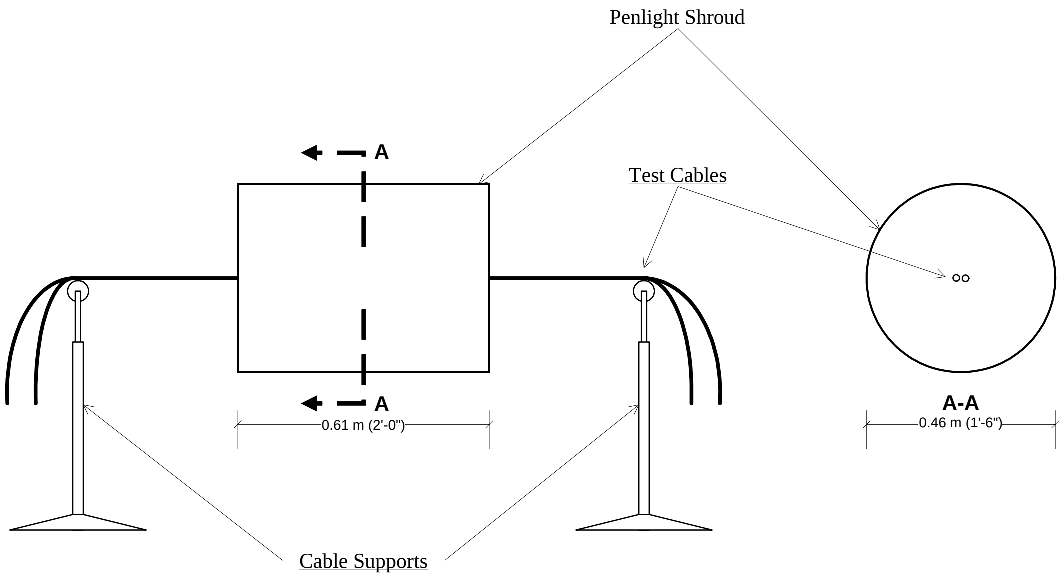

Figure 3: *Penlight* test setup with cable drop.

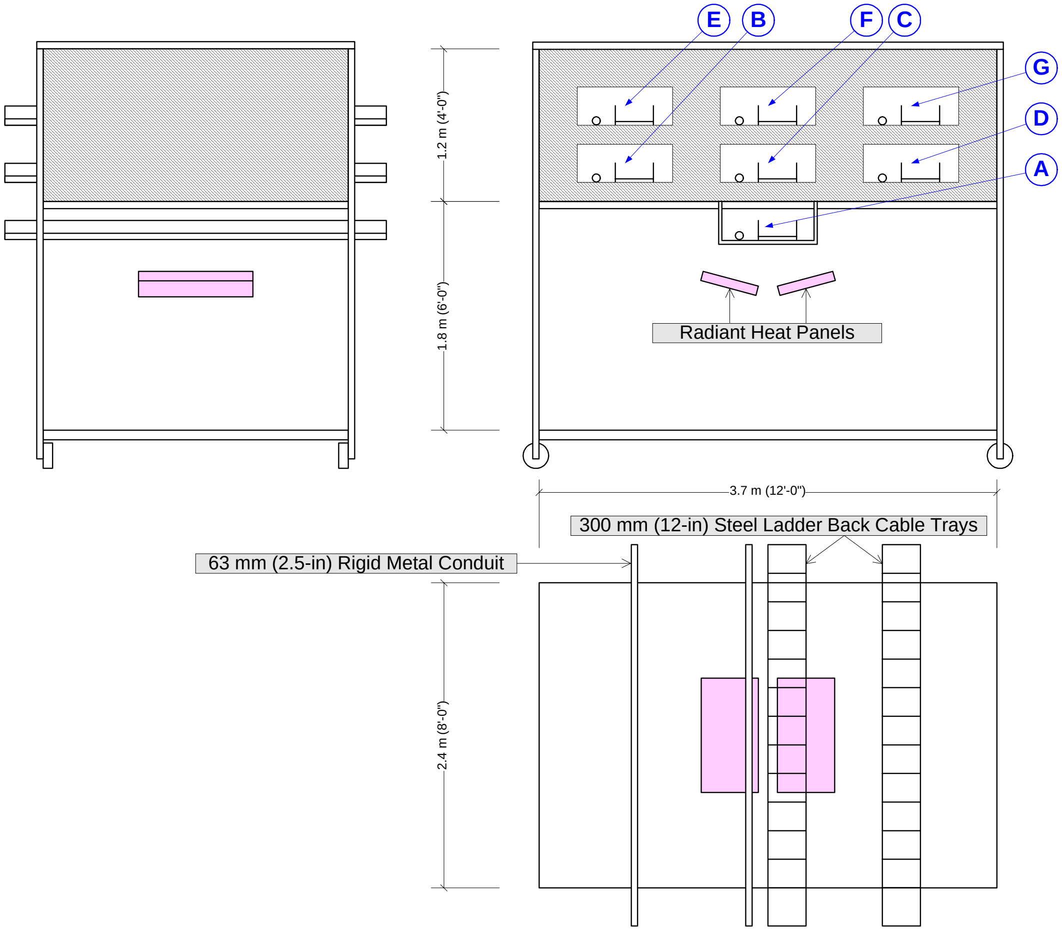

Figure 4a: Schematic illustration of the Intermediate-Scale Test Cell (part 1 - radiant panel heating configuration). Note that the raceway locations are those used in the corresponding test matrix (Table 3).

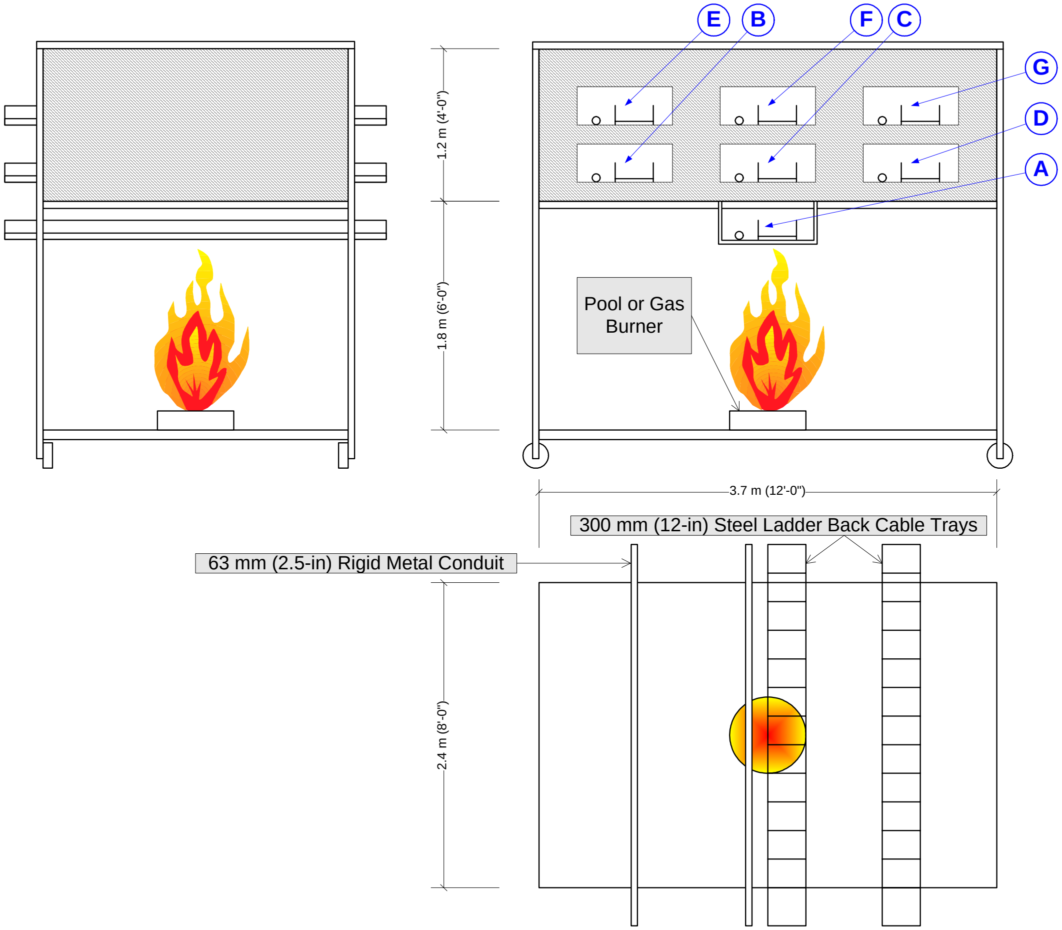

Figure 4b: Schematic illustration of the Intermediate-Scale Test Cell (part 2 - open burn configuration). Note that the raceway locations are those used in the corresponding test matrix (Table 4).

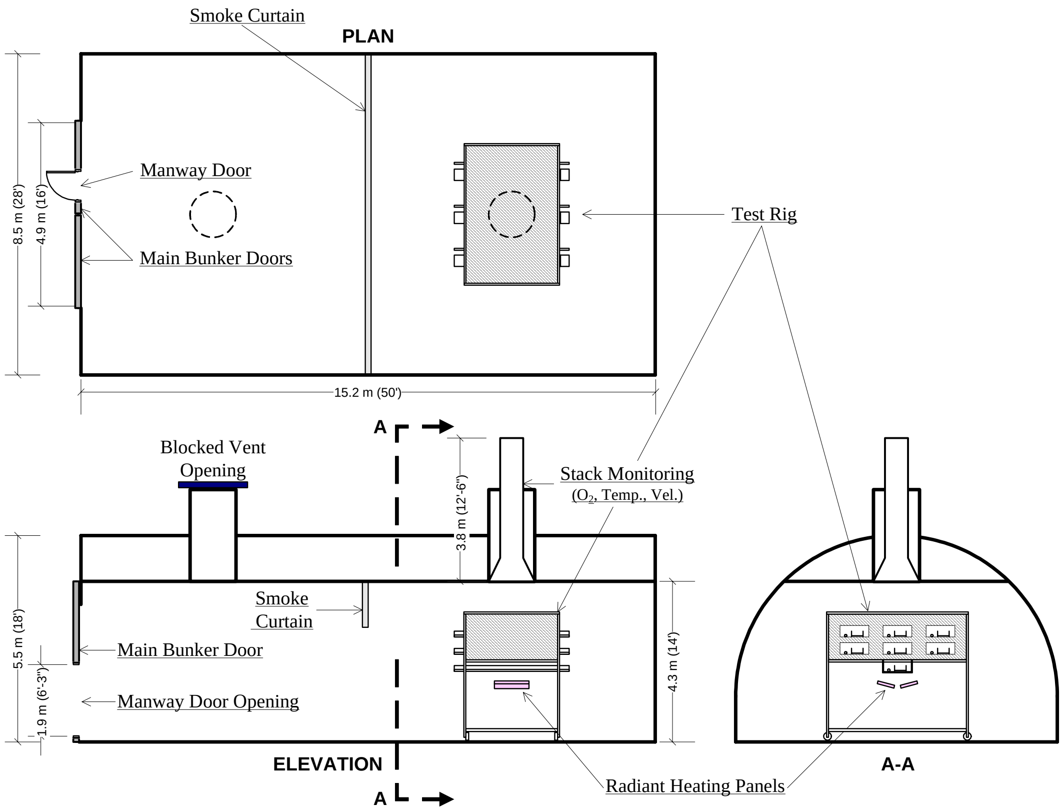

Figure 5: Intermediate-Scale Test Cell with radiant heating panel test setup in test facility.

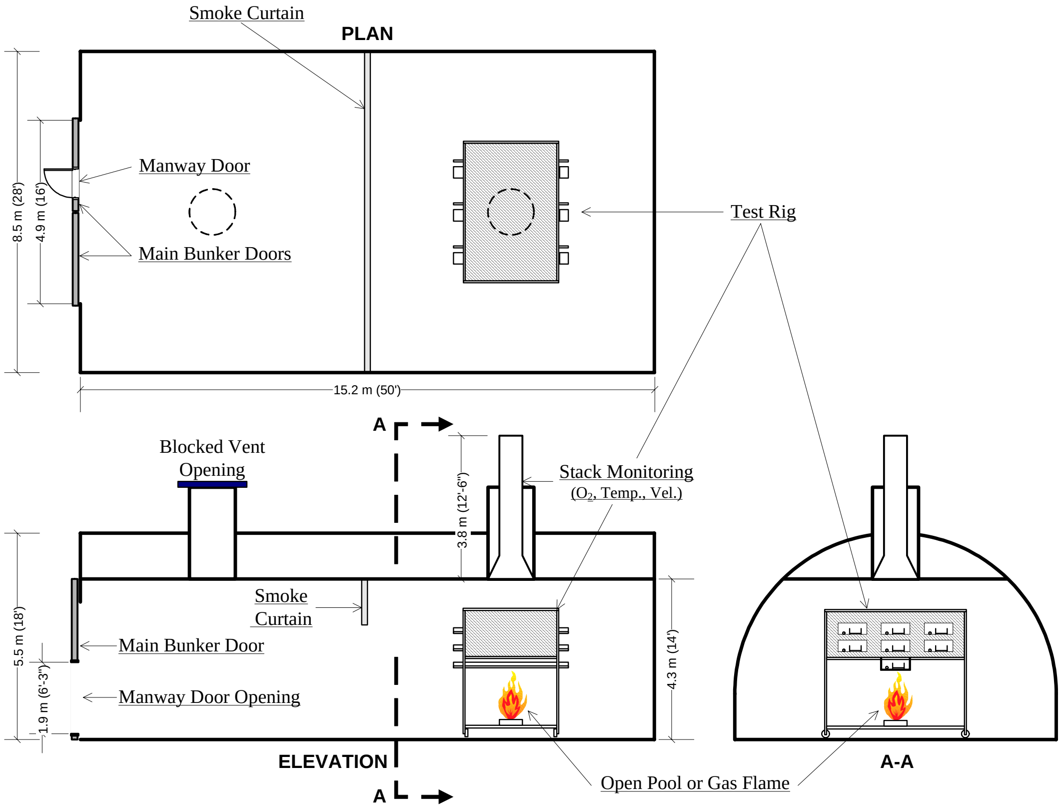

Figure 6: Intermediate-Scale Test Cell with open burn configuration test setup in test facility.

Figure 7: Example thermocouple arrangements for cross sectional temperature mapping of 3- and 7-conductor cables.

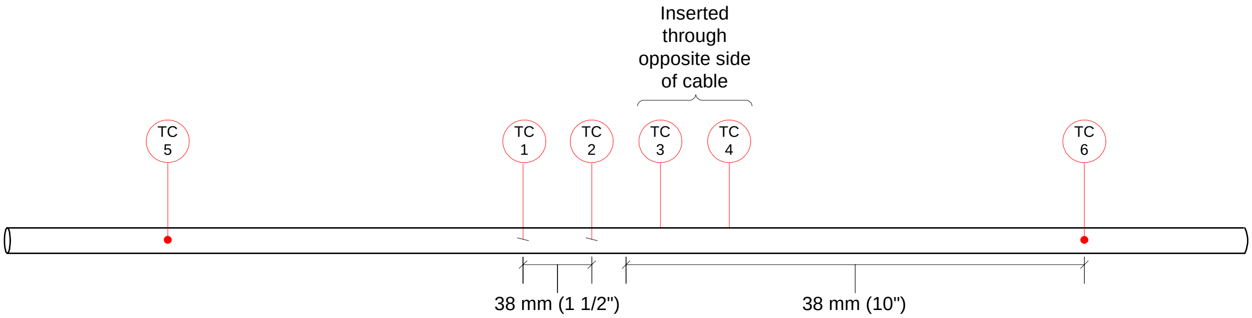

Figure 8: Thermocouple arrangement along cable length for 7-conductor cable example. Note that Thermocouples #1-4 are embedded inside the cable as indicated in Fig. 7, while Thermocouples #5 and 6 are attached to the outside of the cable jacket.

Table 1: Test Cable List.

Cable Function/Service	**Insulation & Jacket Materials (I/J)**	**Material Type (2)**	**Cond. Size (AWG)**	**No. Cond.**	**Manufacturer**	**Notes(3)**
Power	XLPE/CSPE	TS/TS	8	3	Rockbestos Surprenant	All XLPE cables were selected from the *Firewall III*® product line. All are nuclear qualified. The 16AWG, 2/C cable is shielded, others are un-shielded.
Control	XLPE/CSPE		12	7		
Instrumentation	XLPE/CSPE		16	2		
Instrumentation	XLPE/CSPE		18	12		
Control	*Vita-Link*®	TS/TS	14	7		A "fire-rated" cable based on silicone insulation that ceramifies when exposed to flames.
Control	XLPO/XLPO	TS/TS	12	7		Newer style 'low-smoke, zero halogen' formulation, IEEE-383 qualified.
Control	SR/Aramid Braid	TS/TS	12	7	First Capitol	Industrial grade cable from "sister company" to Rockbestos Surprenant
Control	Tefzel/Tefzel	TP/TP	12	7	Cable USA	Based on Tefzel-280 compound
Control	EPR/CSPE	TS/TS	12	7	General Cable	Industrial grade cable
Control	XLPE/PVC	TS/TP	12	7		Mixed type - thermoset insulated, thermoplastic jacketed
Control	PE/PVC	TP/TP	12	7		Industrial grade cables.
Power	PVC/PVC	TP/TP	8	3		
Control	PVC/PVC		12	7		
Instrumentation	PVC/PVC		16	2		Industrial Grade cable, Shielded
Instrumentation	PVC/PVC		18	12		Industrial Grade cable, Unshielded

Additional Notes:

(1) - XLPE = Cross-linked polyethylene; CSPE = Chloro-sulfanated polyethylene (also known as Hypalon); XLPO = Cross-linked polyolefin; SR = Silicone rubber; EPR = Ethylene-propylene rubber; PVC = Poly-vinyl chloride; PE = Polyethylene (non cross-linked).

(2) - TS = Thermoset; TP = Thermoplastic; shown as: (insulation type)/(jacket type).

(3) - All power and control cables are un-shielded.

Table 2: *Penlight* Small-Scale Test Matrix (1 of 4).

Test #	**Group #**	**Primary Application**	**Cable Insulation Material**									**Number of Conductors**			
			Thermoset						**Thermoplastic**						
			XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
1	1	FMI	**X**									**X**			
2		FMI	**X**									**X**			
3		FMI	**X**									**X**			
4		FMI								**X**		**X**			
5		FMI								**X**		**X**			
6		FMI								**X**		**X**			
7		FMI	**X**									**X**			
8		FMI								**X**		**X**			
9		FMI	**X**									**X**			
10		FMI								**X**		**X**			
11		FMI	**X**											**X**	
12		FMI	**X**											**X**	
13		FMI	**X**											**X**	
14		FMI							**X**					**X**	
15		FMI							**X**					**X**	
16		FMI							**X**					**X**	
17		FMI		**X**										**X**	
18		FMI			**X**									**X**	
19		FMI				**X**								**X**	
20		FMI					**X**							**X**	
21		FMI								**X**				**X**	
22		FMI									**X**			**X**	
23		FMI	**X**											**X**	
24		FMI	**X**											**X**	
25		FMI							**X**					**X**	
26		FMI							**X**					**X**	
27		FMI	**X**											**X**	
28		FMI	**X**											**X**	
29		FMI							**X**					**X**	
30		FMI							**X**					**X**	
31		FMI						**X**						**X**	
32		FMI						**X**						**X**	
33		FMI						**X**						**X**	

Table 2: *Penlight* Small-Scale Test Matrix (2 of 4).

Test #	Group #	Primary Application	Conductor Size (AWG)					Cable Bundle Size			Thermal Exposure (KW/m2)		Raceway Type		
			8	12	14	16	18	1	3	6	20	40	12" Tray	2.5" Cnd	Air Drop
1	1	FMI	X					X				X	X		
2		FMI	X					X				X	X		
3		FMI	X					X				X	X		
4		FMI	X					X				X	X		
5		FMI	X					X				X	X		
6		FMI	X					X				X	X		
7		FMI	X					X				X		X	
8		FMI	X					X				X		X	
9		FMI	X					X				X			X
10		FMI	X					X				X			X
11		FMI		X				X				X	X		
12		FMI		X				X				X	X		
13		FMI		X				X				X	X		
14		FMI		X				X				X	X		
15		FMI		X				X				X	X		
16		FMI		X				X				X	X		
17		FMI		X				X				X	X		
18		FMI		X				X				X	X		
19		FMI		X				X				X	X		
20		FMI		X				X				X	X		
21		FMI		X				X				X	X		
22		FMI		X				X				X	X		
23		FMI		X				X				X		X	
24		FMI		X				X				X		X	
25		FMI		X				X				X		X	
26		FMI		X				X				X		X	
27		FMI		X				X				X			X
28		FMI		X				X				X			X
29		FMI		X				X				X			X
30		FMI		X				X				X			X
31		FMI			X			X				X	X		
32		FMI			X			X				X		X	
33		FMI			X			X				X			X

Table 2: *Penlight* Small-Scale Test Matrix (3 of 4).

Test #	Group #	Primary Application	Cable Insulation Material									Number of Conductors			
			Thermoset						Thermoplastic						
			XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
34	2	2-A, C	X											X	
35		2-B, C	X						X					X	
36		2-A, C	X											X	
37		2-B, C	X						X					X	
38	3	2-A, C	X											X	
39		2-B, C	X						X					X	
40		2-A, C	X											X	
41		2-B, C	X						X					X	
42	4	2-A, C	X	X										X	
43		2-B, C		X					X					X	
44		2-A, B, C	X	X	X	X			X		X			X	
45		2-A, B, C	X	X	X	X			X		X			X	
46		2-A, B, C	X	X			X		X	X	X			X	
47		2-A, C	X	X										X	
48		2-B, C		X					X					X	
49		2-A, B, C	X	X					X					X	
50		2-A, B, C	X	X					X					X	
51	5	2-A, C	X	X										X	
52		2-B, C		X					X					X	
53		2-A, B, C	X	X	X	X			X		X			X	
54		2-A, B, C	X	X	X	X			X		X			X	
55		2-A, B, C	X	X			X		X	X	X			X	
56		2-A, C	X	X										X	
57		2-B, C		X					X					X	
58		2-A, B, C	X	X					X					X	
59		2-A, B, C	X	X					X					X	
60	6	2-A, C					X							X	
61		2-A, C					X							X	
62	7	2-A, C	X												X
63		2-B, C	X							X					X
64	8	2-A, C	X										X		
65		2-B, C	X							X			X		
66	9		X					X						X	
67								X	X	X				X	
68			X	X		X	X	X	X					X	

Table 2: *Penlight* Small-Scale Test Matrix (4 of 4).

Test #	**Group #**	**Primary Application**	**Conductor Size (AWG)**					**Cable Bundle Size**			**Thermal Exposure (KW/m2)**		**Raceway Type**		
			8	12	14	16	18	1	3	6	20	40	12" Tray	2.5" Cnd	Air Drop
34	2	2-A, C		X						X		X	X		
35		2-B, C		X						X		X	X		
36		2-A, C		X					X			X		X	
37		2-B, C		X					X			X		X	
38	3	2-A, C		X						X	X		X		
39		2-B, C		X						X	X		X		
40		2-A, C		X					X		X			X	
41		2-B, C		X					X		X			X	
42	4	2-A, C		X						X		X	X		
43		2-B, C		X						X		X	X		
44		2-A, B, C		X						X		X	X		
45		2-A, B, C		X						X		X	X		
46		2-A, B, C		X						X		X	X		
47		2-A, C		X					X			X		X	
48		2-B, C		X					X			X		X	
49		2-A, B, C		X					X			X		X	
50		2-A, B, C		X					X			X		X	
51	5	2-A, C		X						X	X		X		
52		2-B, C		X						X	X		X		
53		2-A, B, C		X						X	X		X		
54		2-A, B, C		X						X	X		X		
55		2-A, B, C		X						X	X		X		
56		2-A, C		X					X		X			X	
57		2-B, C		X					X		X			X	
58		2-A, B, C		X					X		X			X	
59		2-A, B, C		X					X		X			X	
60	6	2-A, C		X						X		X	X		
61		2-A, C		X					X			X		X	
62	7	2-A, C					X			X		X	X		
63		2-B, C					X			X		X	X		
64	8	2-A, C				X				X		X	X		
65		2-B, C				X				X		X	X		
66	9			X	X					X		X	X		
67				X	X					X		X	X		
68				X	X					X		X	X		

Table 3: Intermediate-Scale Test Cell, Part 1 - Radiant Heating Panel, Test Matrix (1 of 4).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**	
				Thermoset						**Thermoplastic**				
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	7
1	1	FMI	A	**X**									**X**	
2		FMI	A	**X**									**X**	
3		FMI	A	**X**									**X**	
4		FMI	A	**X**										**X**
5		FMI	A	**X**										**X**
6		FMI	A	**X**										**X**
7		FMI	A	**X**									**X**	
8		FMI	A	**X**									**X**	
9		FMI	A	**X**									**X**	
10		FMI	A	**X**										**X**
11		FMI	A	**X**										**X**
12		FMI	A	**X**										**X**
13		FMI	A								**X**		**X**	
14		FMI	A								**X**		**X**	
15		FMI	A								**X**		**X**	
16		FMI	A							**X**				**X**
17		FMI	A							**X**				**X**
18		FMI	A							**X**				**X**
19		FMI	A								**X**		**X**	
20		FMI	A								**X**		**X**	
21		FMI	A								**X**		**X**	
22		FMI	A							**X**				**X**
23		FMI	A							**X**				**X**
24		FMI	A							**X**				**X**
25		FMI	A								**X**			**X**
26		FMI	A								**X**			**X**
27		FMI	A						**X**					**X**
28		FMI	A						**X**					**X**

Table 3: Intermediate-Scale Test Cell, Part 1 - Radiant Heating Panel, Test Matrix (2 of 4).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**			**Cable Bundle Size**				**Thermal Exposure (KW/m2)**	**Raceway Type**		
				8	12	14	1	3	6	12	40	12" Tray	2.5" Cnd	Air Drop
1	1	FMI	A	X			X				X	X		
2		FMI	A	X			X				X	X		
3		FMI	A	X			X				X	X		
4		FMI	A		X		X				X	X		
5		FMI	A		X		X				X	X		
6		FMI	A		X		X				X	X		
7		FMI	A	X			X				X		X	X
8		FMI	A	X			X				X		X	X
9		FMI	A	X			X				X		X	X
10		FMI	A		X		X				X		X	X
11		FMI	A		X		X				X		X	X
12		FMI	A		X		X				X		X	X
13		FMI	A	X			X				X	X		
14		FMI	A	X			X				X	X		
15		FMI	A	X			X				X	X		
16		FMI	A		X		X				X	X		
17		FMI	A		X		X				X	X		
18		FMI	A		X		X				X	X		
19		FMI	A	X			X				X		X	X
20		FMI	A	X			X				X		X	X
21		FMI	A	X			X				X		X	X
22		FMI	A		X		X				X		X	X
23		FMI	A		X		X				X		X	X
24		FMI	A		X		X				X		X	X
25		FMI	A		X		X				X	X		
26		FMI	A		X		X				X		X	X
27		FMI	A			X	X				X	X		
28		FMI	A			X	X				X		X	X

Table 3: Intermediate-Scale Test Cell, Part 1 - Radiant Heating Panel, Test Matrix (3 of 4).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**	
				Thermoset						**Thermoplastic**				
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	7
29	2	2-A, C, D, E	A	X										X
			C	X										X
30		2-B, C, D, E	A	X						X				X
			C	X						X				X
31	3	2-A, C, D, E	A	X	X									X
			C	X	X									X
32		2-B, C, D, E	A		X					X				X
			C		X					X				X
33	4	2-A, B, C, D, E	A	X	X	X	X			X		X		X
			C	X	X	X	X			X		X		X
34		2-A, B, C, D, E	A	X	X		X	X		X		X		X
			C	X	X		X	X		X		X		X
35		2-A, B, C, D, E	A	X	X			X		X	X	X		X
			C	X	X			X		X	X	X		X
36	5		A	X	X		X		X	X		X		X
			C	X	X		X		X	X		X		X

Table 3: Intermediate-Scale Test Cell, Part 1 - Radiant Heating Panel, Test Matrix (4 of 4).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**			**Cable Bundle Size**				**Thermal Exposure (KW/m2)**	**Raceway Type**		
				8	12	14	1	3	6	12	40	12" Tray	2.5" Cnd	Air Drop
29	2	2-A, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
30		2-B, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
31	3	2-A, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
32		2-B, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
33	4	2-A, B, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
34		2-A, B, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
35		2-A, B, C, D, E	A		**X**					**X**	**X**	**X**		
			C		**X**				**X**		**X**	**X**		
36	5		A		**X**	**X**				**X**	**X**	**X**		
			C		**X**	**X**			**X**		**X**	**X**		

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (1 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**			
				Thermoset						**Thermoplastic**						
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
37	6	FMI	A	X											X	
			B	X									X			
			D	X									X			
			E	X											X	
			G	X											X	
38		FMI	A							X					X	
			B								X		X			
			D								X		X			
			E							X					X	
			G							X					X	
39		FMI	A								X				X	
			B								X				X	
			D								X				X	
			E								X				X	
			G								X				X	
40		FMI	A						X						X	
			B						X						X	
			D						X						X	
			E						X						X	
			G						X						X	
41		FMI & 2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X			X		X			X	
			D	X	X		X								X	
			E	X						X		X			X	
			G	X	X		X	X		X		X			X	
42		FMI & 2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B		X	X	X	X		X		X			X	
			D		X		X			X					X	
			E					X		X		X			X	
			G		X	X	X	X		X		X			X	
43		FMI & 2-A, B, C, D, E	A	X	X		X	X		X	X	X			X	
			B		X		X	X		X	X	X			X	
			D		X					X	X				X	
			E	X						X	X				X	
			G		X		X	X		X	X	X			X	

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (2 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**					**Cable Bundle Size**					**Thermal Exposure (KW)**		**Raceway Type**		
				8	12	14	16	18	1	3	6	12	Load Tr	100	250	12" Tray	2.5" Cnd	Air Drop
37	6	FMI	A		X							X			X	X		
			B	X					X						X	X		
			D	X					X						X		X	X
			E		X				X						X		X	X
			G		X				X						X	X		
38		FMI	A		X							X			X	X		
			B	X					X						X	X		
			D	X					X						X		X	X
			E		X				X						X		X	X
			G		X				X						X	X		
39		FMI	A		X							X			X	X		
			B		X				X						X	X		
			D		X				X						X		X	X
			E		X				X						X		X	X
			G		X				X						X	X		
40		FMI	A			X						X			X	X		
			B			X			X						X	X		
			D			X			X						X		X	X
			E			X			X						X		X	X
			G			X			X						X	X		
41		FMI & 2-A, B, C, D, E	A		X							X			X	X		
			B		X						X				X	X		
			D		X					X					X		X	X
			E		X					X					X		X	X
			G		X						X				X	X		
42		FMI & 2-A, B, C, D, E	A		X							X			X	X		
			B		X						X				X	X		
			D		X					X					X		X	X
			E		X					X					X		X	X
			G		X						X				X	X		
43		FMI & 2-A, B, C, D, E	A		X							X			X	X		
			B		X						X				X	X		
			D		X					X					X		X	X
			E		X					X					X		X	X
			G		X						X				X	X		

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (3 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**			
				Thermoset						**Thermoplastic**						
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
44	7	2-A, C, D, E	A	X										X	X	X
			B	X											X	
			D	X											X	
			E	X											X	
			G	X											X	
45		2-B, C, D, E	A	X						X	X			X	X	X
			B	X						X					X	
			D	X						X					X	
			E	X						X					X	
			G	X						X					X	
46		2-A, C, D, E	A	X										X	X	X
			B	X											X	
			D	X											X	
			E	X											X	
			G	X											X	
47		2-B, C, D, E	A	X						X	X			X	X	X
			B	X						X					X	
			D	X						X					X	
			E	X						X					X	
			G	X						X					X	

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (4 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**					**Cable Bundle Size**					**Thermal Exposure (KW)**		**Raceway Type**		
				8	12	14	16	18	1	3	6	12	Load Tr	100	250	12" Tray	2.5" Cnd	Air Drop
44	7	2-A, C, D, E	A		**X**		**X**	**X**					**X**		**X**	**X**		
			B		**X**							**X**			**X**	**X**		
			D		**X**					**X**					**X**		**X**	
			E		**X**					**X**					**X**		**X**	
			G		**X**							**X**			**X**	**X**		
45		2-B, C, D, E	A		**X**		**X**	**X**					**X**		**X**	**X**		
			B		**X**							**X**			**X**	**X**		
			D		**X**					**X**					**X**		**X**	
			E		**X**					**X**					**X**		**X**	
			G		**X**							**X**			**X**	**X**		
46		2-A, C, D, E	A		**X**		**X**	**X**					**X**	**X**		**X**		
			B		**X**							**X**		**X**		**X**		
			D		**X**					**X**				**X**			**X**	
			E		**X**					**X**				**X**			**X**	
			G		**X**							**X**		**X**		**X**		
47		2-B, C, D, E	A		**X**		**X**	**X**					**X**	**X**		**X**		
			B		**X**							**X**		**X**		**X**		
			D		**X**					**X**				**X**			**X**	
			E		**X**					**X**				**X**			**X**	
			G		**X**							**X**		**X**		**X**		

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (4 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**			
				Thermoset						**Thermoplastic**						
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
48	8	2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X	X	X			X	X
			D	X	X		X								X	
			E	X						X		X			X	
			G	X	X	X	X	X		X	X	X		X	X	
49		2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X	X	X			X	X
			D		X		X			X					X	
			E					X		X		X			X	
			G	X	X	X	X	X		X	X	X		X	X	
50		2-A, B, C, D, E	A	X	X		X	X		X	X	X			X	
			B	X	X		X	X			X	X			X	X
			D		X					X	X				X	
			E					X		X	X				X	
			G	X	X		X	X			X	X		X	X	
51		2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X	X	X			X	X
			D	X	X		X								X	
			E	X						X		X			X	
			G	X	X	X	X	X		X	X	X		X	X	
52		2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X	X	X			X	X
			D		X		X			X					X	
			E					X		X		X			X	
			G	X	X	X	X	X		X	X	X		X	X	
53		2-A, B, C, D, E	A	X	X		X	X		X	X	X			X	
			B	X	X		X	X			X	X			X	X
			D		X					X	X				X	
			E					X		X	X				X	
			G	X	X		X	X			X	X		X	X	

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (6 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**					**Cable Bundle Size**					**Thermal Exposure (KW)**		**Raceway Type**		
				8	12	14	16	18	1	3	6	12	Load Tr	100	250	12" Tray	2.5" Cnd	Air Drop
48	8	2-A, B, C, D, E	A		X								X		X	X		
			B		X			X				X			X	X		
			D		X					X					X		X	
			E		X					X					X		X	
			G		X		X					X			X	X		
49		2-A, B, C, D, E	A		X								X		X	X		
			B		X			X				X			X	X		
			D		X					X					X		X	
			E		X					X					X		X	
			G		X		X					X			X	X		
50		2-A, B, C, D, E	A		X								X		X	X		
			B		X			X				X			X	X		
			D		X					X					X		X	
			E		X					X					X		X	
			G		X		X					X			X	X		
51		2-A, B, C, D, E	A		X								X	X		X		
			B		X			X				X		X		X		
			D		X					X				X			X	
			E		X					X				X			X	
			G		X		X					X		X		X		
52		2-A, B, C, D, E	A		X								X	X		X		
			B		X			X				X		X		X		
			D		X					X				X			X	
			E		X					X				X			X	
			G		X		X					X		X		X		
53		2-A, B, C, D, E	A		X								X	X		X		
			B		X			X				X		X		X		
			D		X					X				X			X	
			E		X					X				X			X	
			G		X		X					X		X		X		

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (7 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Cable Insulation Material**									**Number of Conductors**			
				Thermoset						**Thermoplastic**						
				XLPE	EPR	Silicone	XLPO	TS/TP	Vita-Link	PE	PVC	Tefzel	3	2	7	12
54	9	2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X		X			X	
			C	X	X	X	X	X		X		X			X	
			D	X						X		X			X	
			E	X	X		X								X	
			F	X	X	X	X			X		X			X	
			G	X	X	X	X	X		X		X			X	
55		2-A, B, C, D, E	A	X	X	X	X	X		X		X			X	
			B	X	X	X	X	X		X		X			X	
			C	X	X	X	X	X		X		X			X	
			D		X		X			X					X	
			E					X		X		X			X	
			F	X	X		X	X		X		X			X	
			G	X	X	X	X	X		X		X			X	
56		2-A, B, C, D, E	A	X	X		X	X		X	X	X			X	
			B	X	X		X	X		X	X	X			X	
			C	X	X		X	X		X	X	X			X	
			D		X					X	X				X	
			E					X		X	X				X	
			F	X	X			X		X	X	X			X	
			G	X	X		X	X		X	X	X			X	
57	10		A	X	X		X	X	X	X	X	X			X	
			B	X			X	X	X	X	X				X	
			C	X	X		X	X	X	X	X	X			X	
			D	X					X	X					X	
			E	X					X	X					X	
			F	X			X	X	X	X	X				X	
			G	X			X	X	X	X	X				X	

Table 4: Intermediate-Scale Test Cell, Part 2 - Open Burn Configuration, Test Matrix (8 of 8).

Test #	**Group #**	**Primary Application**	**Loc.**	**Conductor Size (AWG)**					**Cable Bundle Size**					**Thermal Exposure (KW)**		**Raceway Type**		
				8	12	14	16	18	1	3	6	12	Load Tr	100	250	12" Tray	2.5" Cnd	Air Drop
54	9	2-A, B, C, D, E	A		**X**								**X**		**X**	**X**		
			B		**X**							**X**			**X**	**X**		
			C		**X**								**X**		**X**	**X**		
			D		**X**					**X**					**X**		**X**	
			E		**X**					**X**					**X**		**X**	
			F		**X**						**X**				**X**	**X**		
			G		**X**							**X**			**X**	**X**		
55		2-A, B, C, D, E	A		**X**								**X**		**X**	**X**		
			B		**X**							**X**			**X**	**X**		
			C		**X**								**X**		**X**	**X**		
			D		**X**					**X**					**X**		**X**	
			E		**X**					**X**					**X**		**X**	
			F		**X**						**X**				**X**	**X**		
			G		**X**							**X**			**X**	**X**		
56		2-A, B, C, D, E	A		**X**								**X**		**X**	**X**		
			B		**X**							**X**			**X**	**X**		
			C		**X**								**X**		**X**	**X**		
			D		**X**					**X**					**X**		**X**	
			E		**X**					**X**					**X**		**X**	
			F		**X**						**X**				**X**	**X**		
			G		**X**							**X**			**X**	**X**		
57	10		A		**X**	**X**							**X**		**X**	**X**		
			B		**X**	**X**						**X**			**X**	**X**		
			C		**X**	**X**							**X**		**X**	**X**		
			D		**X**	**X**				**X**					**X**		**X**	
			E		**X**	**X**				**X**					**X**		**X**	
			F		**X**	**X**					**X**				**X**	**X**		
			G		**X**	**X**						**X**			**X**	**X**		

Appendix A: List of Participants in the August 16-17, 2005 Test Planning Meeting: The CAROLFIRE Collaborative Team

RES:
- H. W. ‘Roy’ Woods
- Mark Salley
- Kendra Hill
- Nathan Siu

NRR:
- Gabe Taylor (Intern)
- Dan Frumkin (briefly)

SNL:
- Steve Nowlen
- Frank Wyant
- Liyang ‘Leon’ Chen
- Vern Nicolette

NIST:
- Kevin McGrattan

UMd:
- Genebelin ‘Gene’ Valbuena,
- Elie Avidor

Appendix B:
Listing of the Bin 2 items identified in RIS 2004-03 Rev. 1, Attachment page 3, 12/29/2004

(ADAMS ML042440791)

2. Items To Be Deferred at This Time, Pending Additional Research–Bin 2

The following items are deferred pending additional research:

A. Intercable shorting for thermoset cables, since the failure mode is considered to be substantially less likely than intracable shorting.

(This item will be evaluated based on the electrical insulation resistance measurements made on separate thermoset cables during test runs 31, 33, 35, 37, 39, 41 - 44, 46 - 48, 50 - 53, 55 - 59 and 61 using the Penlight radiant heat facility. Additional insulation resistance data will be collected during test runs 27, 29, and 31 - 33 using the Intermediate-Scale Test Cell with radiant heaters. Test runs 37 - 40, 42, and 44 - 52 using the Intermediate-Scale Test Cell in the open burn configuration will provide electrical insulation resistance data that will be used to verify and supplement the radiant heating results.

The cable conductor IRs will be analyzed primarily by comparing IR versus time and IR versus cable temperature in order to determine the impact of the thermal exposure conditions on the timing and temperature at which intercable failures occur. The large number of thermoset cable IR measurements taken will allow the determination of the likelihood of intercable shorting before other failure modes are manifest (e.g., shorts to ground or intracable shorts).)

B. 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.

(Intercable shorting between thermoplastic and thermoset cables will be evaluated, also by insulation resistance measurements made, during test runs 32, 34, 36, 38, 40 - 43, 45 - 47, 49 - 52, 54 - 56, 60 and 62 in Penlight. Test runs 28 and 30 - 33 in the Intermediate-Scale Test Cell using radiant heaters and test runs 37 - 39, 41 and 43 - 52 in the Intermediate-Scale Test Cell using flame sources will provide additional insulation resistance measurement data relevant to this item. The data analyses to be performed for evaluating this item will apply the same methods as for item A.)

C. 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.”

(Electrical data collected during Penlight tests 31 - 62, Intermediate-Scale Test Cell radiant heating tests 27 - 33 and Intermediate-Scale Test Cell flame tests 37 - 52 will provide the data that will be evaluated regarding the number of separate cable failures likely to occur from the same exposure conditions. In this case, the data will be evaluated to account for all cable failures–intracable as well as intercable. Again, the timing, concurrence and modes of failure will be correlated to cable temperature.)

D. 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).

(Multiple surrogate circuits, both with and without CPTs, will be used as part of the electrical performance diagnostics during tests 27 - 33 in the Intermediate-Scale Test Cell using radiant panels and during tests 37 - 52 in the Intermediate-Scale Test Cell in the open burn configuration. The CPTs used will bound standard sizes (VA ratings) in order to evaluate the 150% of normal circuit power requirement assumption.

The focus of the data analysis here will be on assessing the prevalence of spurious operations for each CPT rating size. Then, if applicable, a recommendation will be made regarding an adjustment in the percent of nominal power factor for circuits employing CPTs.)

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.

(Additional diagnostic units, set up to simulate SOV control circuits, will be employed during tests 27 - 33 in the Intermediate-Scale Test Cell with radiant heaters and tests 37 - 52 in the Intermediate-Scale Test Cell with flame sources to provide electrical data concerning the times of onset and duration of fire-induced spurious operation failures. This data would then be used to propose new guidelines in the expected mean duration of spurious operations and to provide bounds on the range of spurious operation failure durations observed.)

F. Consideration of cold shutdown circuits, since hot shutdown can be maintained and the loss of cold shutdown circuits is not generally a significant contributor to risk.

(It should be noted that RIS 2004-03 Bin 2 item F, cold shutdown systems, cannot be addressed through a planned experimental program. That is, data/testing needs are not the unique aspect of the issue. Rather, this item hinges on an understanding of the risk implications of failures in cold shutdown systems. The data gathered on the other Bin 2 items, and that available for the Bin 1 items, is directly applicable to cold shutdown systems, but new and better data will not resolve the item in the context of the RIS. A tailored risk-informed analytical effort that is outside the scope of the planned test program will be needed to resolve this particular item.)

Appendix C
Sandia Insulation Resistance Measuring System

What is it? What does it do?

The concept of the SNL IR Measurement System is based on the assumption that if one were to impress a unique signature voltage on each conductor in a cable (or cable bundle) then by systematically allowing for and monitoring known current leakage paths it should be possible to determine if leakage from one conductor to another, or to ground, is in fact occurring. That is, part of or the entire voltage signature may be detected on any of the other conductors in the cable (or in an adjacent cable) or may leak to ground directly.

To illustrate, consider a three-conductor (3/C) cable as shown in Figure C-1 (for now we will neglect leakage directly to ground). If 100 volts is applied to conductor 1, then the degree of isolation of conductors 2 and 3 from conductor 1 can be determined by systematically opening a potential conductor-to-conductor current leakage path and then reading the voltages of each conductor in turn while conductor 1 is energized. Determining the insulation resistance between conductors 1 and 2 at the time of voltage measurement on conductor 2 is a simple calculation employing Ohm's law:

$$I_{1-2} = V_2 / R$$

and

$$R_{1-2} = (V_1 / I_{1-2}) - R$$

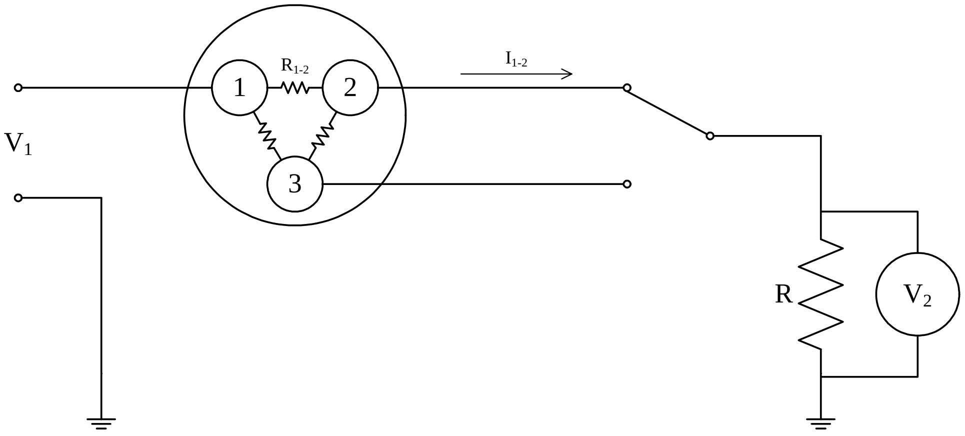

Figure C-1 Simple insulation resistance measuring circuit.

In the same way, the insulation resistance existing between conductors 1 and 3 at the time V_3 is measured can be determined. Continuously switching between the two conductors and recording the voltage drop across R at each switch position can obtain a time-dependent history of R_{1-2} and R_{1-3}. (Of course an alternate method would be to connect a resistor/voltmeter assembly to both conductors 2 and 3 simultaneously and keep a continuous record of the two voltages. This approach quickly becomes unwieldy as the number of conductors increases.)

The above method alone does not describe the isolation existing between conductors 2 and 3 (because conductor 1 is always the energized conductor). However, by sequentially energizing each conductor and reading the impressed voltages on the remaining conductors one can determine the relative resistance existing between any conductor pair (see Figure C-2).

This concept evolved to include the two sets of controlled switches, one set on the input side (i) and one on the output side (j) of the circuit. One switch on the voltage input side is closed (thereby energizing one conductor) followed by the sequential closing-measurement-opening of each measurement side switch. Each sequential switching configuration measures leakage currents between one energized "source" conductor and one non-energized "target" conductor, and the various pairs are systematically evaluated in sequence.

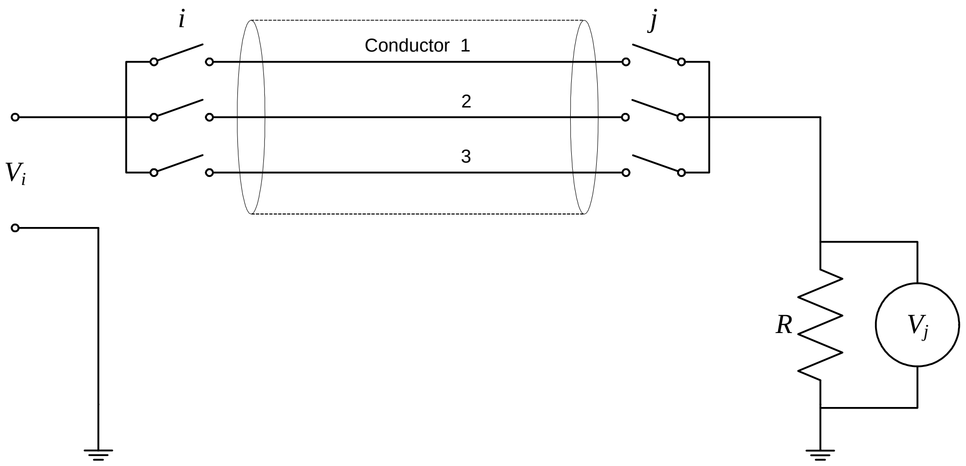

Figure C-2 Circuit for measuring insulation resistance between any conductor pair in a cable.

The insulation resistance between pairs of conductors can be determined in the same way as discussed above. Note that when the input and measurement side switches are connected to the same conductor (i = j), the full input voltage will be measured across R. Since this provides no useful information about the isolation existing between any of the conductor pairs, these measurements can be ignored for the purpose of determining IR. (The presence of the full voltage, $V_j = V_i$, does how-ever indicate conductor continuity and otherwise could be useful in identifying an open circuit condition.)

This approach is fine as long as the cable can be kept electrically isolated from ground. If that is not possible (or not desirable, e.g., because short to ground failures are of interest) then changes to the design (simple ones) and resistance calculations (significant) are required.

Figure C-3 shows how the number of possible leakage paths for each of the three conductors in the previous example changes when a ground path is considered. By adding a path to ground for each conductor, the complexity of determining the insulation resistance between pairs of conductors has grown from one resistance determination to now having to determine three resistances for each pair of conductors. A circuit change is required to enhance the number of independent measurements so as to retain a solvable problem. The revised circuit is shown in Figure C-4, and includes a ballast/load resistor on the input side in addition to the output side ballast/load resistor.

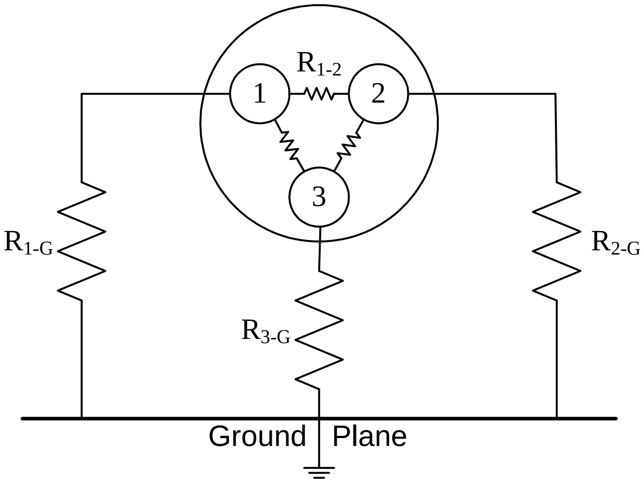

Figure C-3 Resistive leakage paths for each conductor with a ground present.

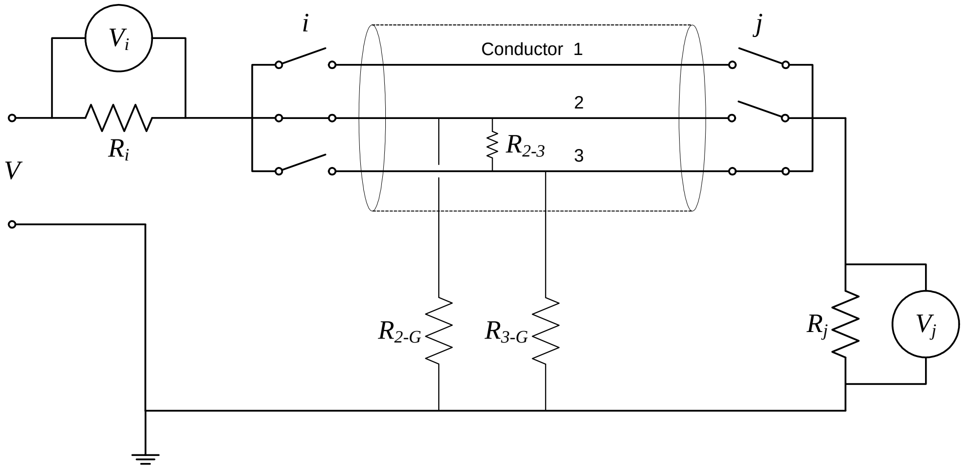

Figure C-4 Insulation resistance measuring circuit with ground paths.

The calculation of the three resistances for each conductor pair (one conductor-to-conductor path and each of the two conductor-to-ground paths) requires the measured voltages (V_i and V_j) for two complementary switching configurations. For example, the complement for the case illustrated in Figure C-4 is shown in Figure C-5. As illustrated in Figure C-4, conductor 2 is connected to the input side and conductor 3 is connected to the measurement side. The complementary case shows conductor 3 on the input side and conductor 2 on the measurement side (shown in Figure C-5). This complementary pair provides four separate voltage readings that can be used to determine the three resistance paths affecting these two conductors; namely, R_{2-3}, R_{2-G}, and R_{3-G}.

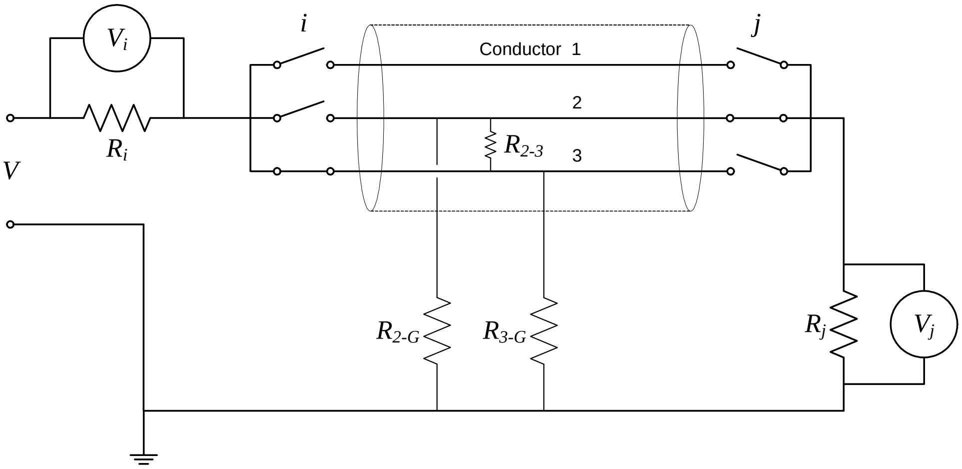

Figure C-5 Complementary IR measuring circuit with respect to the circuit shown in Fig. C-4.

The equations for determining the three resistances for this case are as follows:

$R_{2\text{-}G} = [V_{j2}V_{j3} - (V - V_{i2})(V - V_{i3})] / [(V_{i3} / R_i - V_{j2} / R_j)V_{j3} - (V_{i2} / R_i - V_{j3} / R_j)(V - V_{i3})]$

$R_{3\text{-}G} = V_{j3} / [(V_{i2} / R_i - V_{j3} / R_j) - (V - V_{i2}) / R_{2\text{-}G}]$

$R2\text{-}3 = [(V - V_{i2}) - V_{i3}] / [(V_{j3} / R_{3\text{-}G}) + (V_{j3} / R_j)]$

This concept is scalable for virtually any number of conductors in a cable or bundle of cables. Another advantage is that only the two voltage measurements for each switching configuration need to be recorded in real time; determination of the resistances can be deferred until after the test has been completed. This is the basic concept utilized in the design and application of the IR Measurement System.

Design

The Sandia National Laboratories (SNL) Insulation Resistance Measurement System (IRMS) as presently configured can monitor the insulation resistance of up to ten separate conductors. The choice of a maximum of ten conductors was based on the cable configurations previously tested; namely, each test sample was comprised of one seven-conductor multi-conductor cable bundled with three single conductor cables. The capability to test with either an AC or DC power source was added at the request of the USNRC.

Figure C-6 provides a block diagram identifying the principal functional areas of the IRMS. A schematic diagram of the complete system is provided in Figure C-7. Each of the functional areas is described in some detail in the following sections.

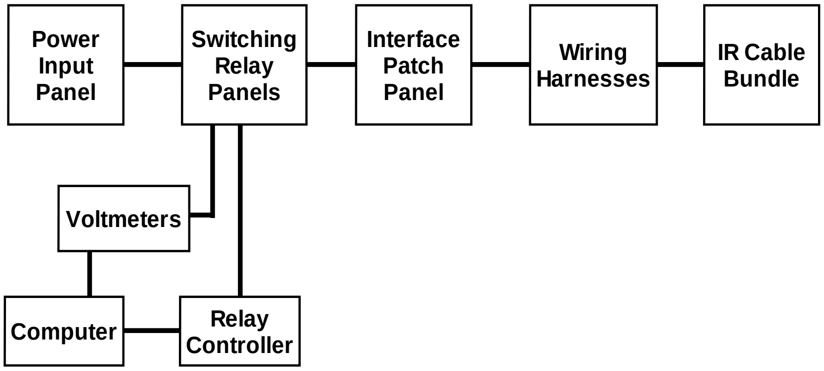

Figure C-6 IR Measurement System block diagram of functional areas.

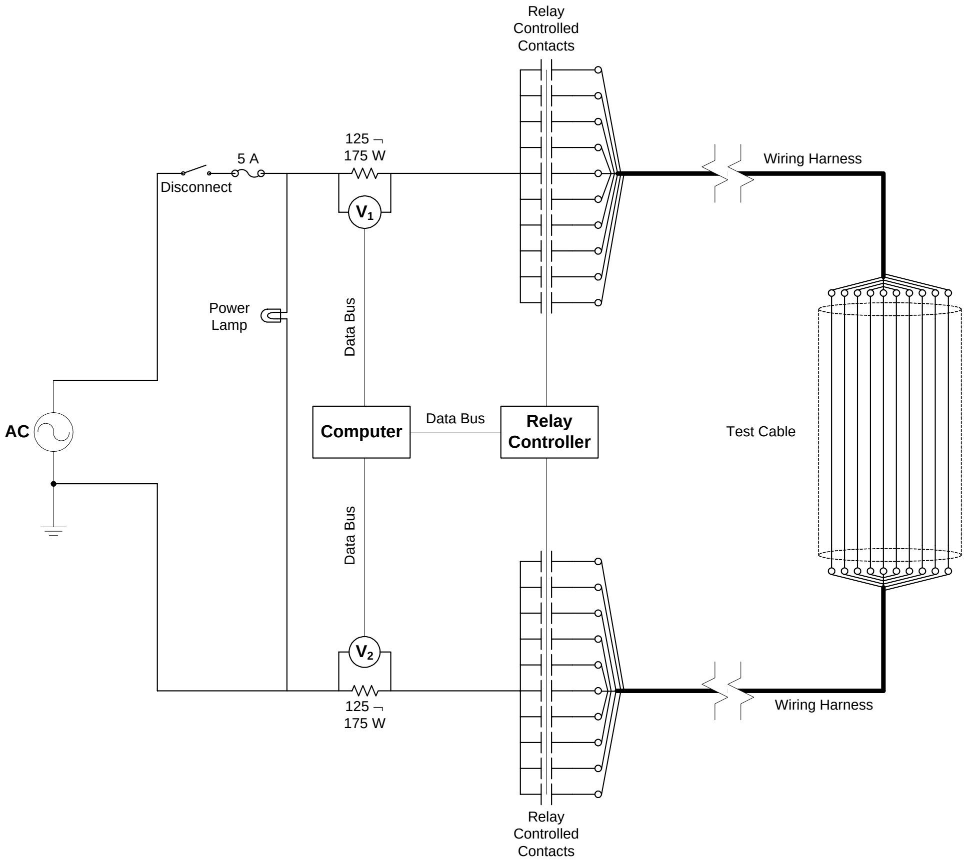

Figure C-7 Schematic diagram of the IR Measurement System.

Power Input Panel

The power input panel consists of a small terminal block for connecting the input power cables, a master disconnect switch to isolate the system from the power input, a 5-amp fuse, and a power indicating light. Changing the power connection to the system via the terminal block is one of the few manual modifications that are needed to be made to reconfigure the system from AC operations to DC-powered tests.

Switching Relay Panels

Each of the two switching relay panels consists of a 125-ohm ballast resistor, across which a voltmeter is connected, and ten relays that are separately controlled by the relay controller. Two connections on each relay panel must be changed to convert from AC to DC operation.

Voltmeters

Two HP 34401A digital multimeters are used to measure the voltage drops across the two current limiting ballast resistors in the IR measurement circuit. Both meters used in this program were subject to regular calibration via the SNL internal calibration program. This is calibration program is compliant with all applicable calibration standards and guidelines of the National Institute of Standards and Technology (NIST) and the U.S. Department of Energy (DOE).

Relay Controller

An HP 3497A Data Acquisition/Control Unit is used to control the closing and opening of the relays to connect specific conductors to the voltage source and the measurement side of the circuit. The data logger used in testing is also subject to the SNL calibration process, although the unit's built-in voltmeter was not utilized in these tests. The data logger was used only as a controller.

Computer

A standard personal computer running with Microsoft Windows NT™ was used as the master control unit and data recorder. A general-purpose interface bus (GPIB) was installed and used for device communication between the computer, the relay controller, and the two voltmeters. Control was exercised using a program under LabView™. Data from the voltmeters was logged directly to the computer's hard drive.

Interface Patch Panel

The interface patch panel is composed of a number of jacks compatible with banana plugs to make connection of the wiring harnesses to the output sides of the individual relays a simple matter.

Wiring Harness

Two fifteen meter, ten-conductor cables are used to interface the IR Measurement System with the test cable.

Test Cables

Test cable configurations may include any combination of cable types for a maximum total of ten conductors to be monitored. The IRMS requires, as a minimum, at least two-conductors to be monitored during a test run.

Operation

Operation of the SNL IR Measurement System is a relatively simple matter of connecting the two wiring harnesses to each end of the test cable bundle, turning on power to the two voltmeters and the relay controller, closing the main disconnect switch, and finally, starting the IR measurement program on the computer.

Connection of the wiring harnesses to the test cable during the EPRI-NEI tests was accomplished using commercially available wire nuts. It is important that each end of a specific conductor in the test cable be connected to the corresponding conductors in both wiring harnesses. For example, the conductors marked "1" in each wiring harness needed to be connected to the ends of the same conductor in the test cable. This also applied to the conductors marked "2" through "10" in the harnesses. Proper connections are checked by performing a continuity check of the pairs of harness conductors at the patch panel ends of the wiring harnesses.

The LabView™ control program begins by reading the date and time from the computer's internal clock, and the user-defined file name and comments from the associated block on the front screen. It then re-writes this information to the data file (file name), communicates with the GPIB devices (two voltmeters and relay controller) to initialize them and then begins commanding the closing of the appropriate relays in sequence. For each switch configuration, the voltmeters send their readings back to the computer, which logs the information to the data file and configures the relay switches for the next measurement. This process continues until the user has changed the state of the "SCAN" switch on the front panel to "STOP SCAN" using the mouse. At this time the program closes the data file and stops running.

The data files are imported into an Excel™ spreadsheet and the necessary IR calculations are performed to determine the IRs as part of the post-test data analysis. The resulting IR data can then be used to determine the nature (e.g., conductor-to-conductor versus conductor-to-ground) and order (i.e., which conductors shorted and when) of any short-circuit failures observed. The data analysis can also include the generation of IR versus time plots for each conductor in each test.

Appendix D
Surrogate Circuit Diagnostic Units (SCDU)

In part, the objectives of the CAROLFIRE test project include the determination of the onset of damage to cables exposed to thermal/fire conditions and the nature and duration of the functional failure. The proposed approach to evaluating the electrical response of the damaged cables is two-fold: continuously monitoring the insulation resistance of the cable's conductors and to connect the cable to a simulation circuit. The implementation of the first of these schemes is discussed in Appendix C. The second approach, monitoring the impact of cable damage on a control or instrument circuit, is the basis of this discussion.

The electrical response behavior of selected cables will be monitored using surrogate control/instrument circuits connected to some of the cables under test. These "Black Box" circuits are designed to simulate the control circuits representative nuclear plant safe shutdown components: motor operated valves (MOV), solenoid operated valves (SOV) and instrument loops. A number of circuit conditions can be implemented to assess the effects of control power transformers (CPT), voltage/current form (AC or DC) and circuit grounding (grounded and ungrounded) on the cable failure modes and likelihoods.

Electrical parameters to be varied using these SCDU circuits will include the numbers of target, source and ground conductors that make up the surrogate control/instrument circuits. Different sizes of CPTs can also be included in some of the circuit tests to evaluate their impact on circuit failure mode.

The concept we intend to field for these tests is to utilize multiple units of the same base design wherein the choice of components and devices connected to the basic circuit determine its surrogate function. Figure D-1 shows the fundamental SCDU design. As shown in the figure, the power source is connected to the supply terminals while the individual conductors of the cable under test are connected to the cable connection terminals on the right-hand side of the figure. The number of energized conductors is determined by the position of switches 1 - 3 and the number of conductors connected to ground is governed by switches 4 - 6. The number and types of targets connected to the cable depends on the nature of the devices installed at the available connection points.

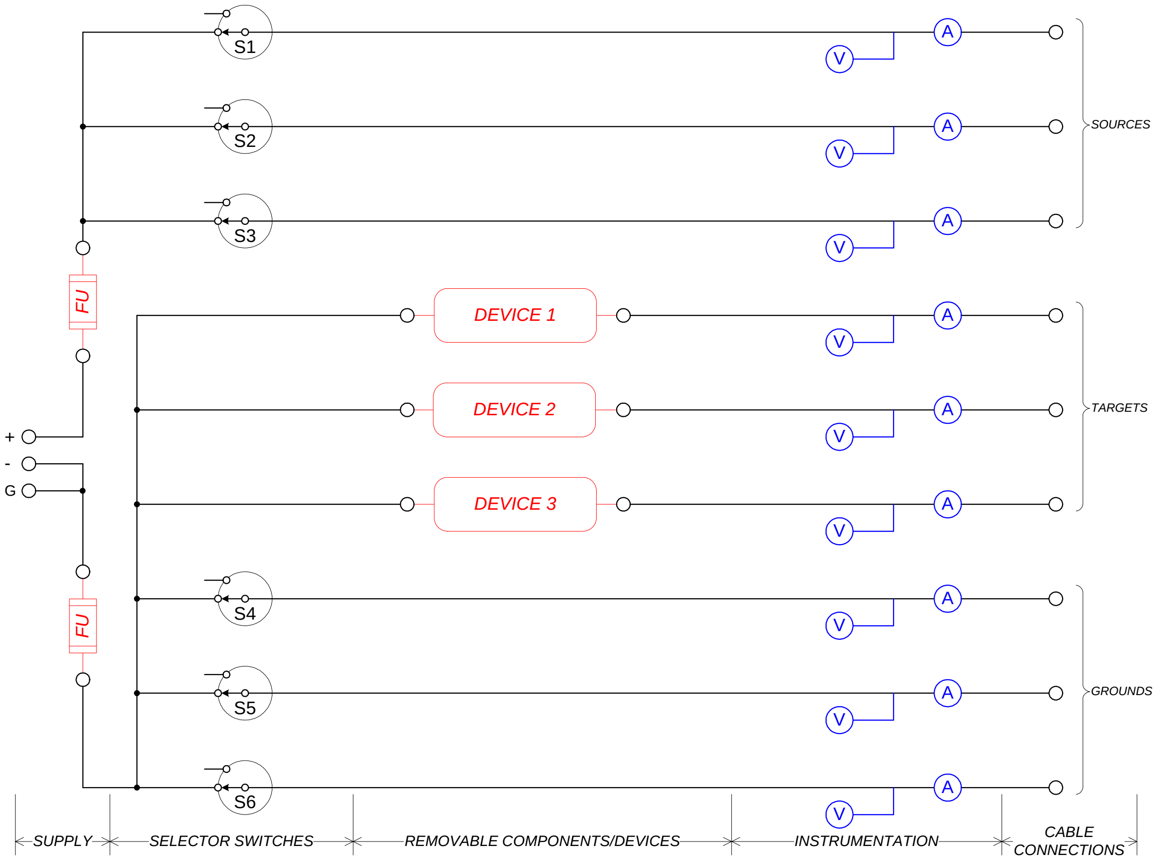

Figure D-1 Basic Control Circuit Simulator Design.

Each of the cable connection points is monitored for voltage (referenced to ground or the common side of the power supply) and current flow. These readings will be used to indicate interactions between individual conductors and/or the conductors to ground. The magnitude of the readings will enable the monitoring of insulation resistance degradation as the cable damage progresses. Also, actuation of the target devices will help demonstrate that the severity of the short circuit is sufficient to meet the pickup and hold requirements of the target component(s).

These surrogate circuit simulation units will be used to obtain circuit behavior data in a manner similar to the motor operated valve (MOV) surrogate test circuits utilized during the EPRI/NEI test series. Specifically we will be interested in the timing and duration of any spurious actuations of the target devices, fuse blows, etc. The intent of this design is 1) to provide for a wider variety of surrogate test circuits than those previously tested, 2) to simplify and standardize the testing process and procedures while allowing for flexibility in the test circuits, and 3) to allow for portability of the surrogate circuit units to support testing at alternate test facilities.

Figures D-2 through D-5 show the variety of simulated control circuit application capabilities of these units that are determined primarily by the selection of appropriate target devices and power sources. Figure D-2 shows an analog of the simulated MOV control circuit that was employed during the early EPRI/NEI tests. The shaded area represents the basic control circuit simulator. Connected to it are an AC power source, a 1750-ohm resistor, representing an indicator lamp, and two relay coil targets. A seven-conductor cable is connected to the SCDU as the device under test.

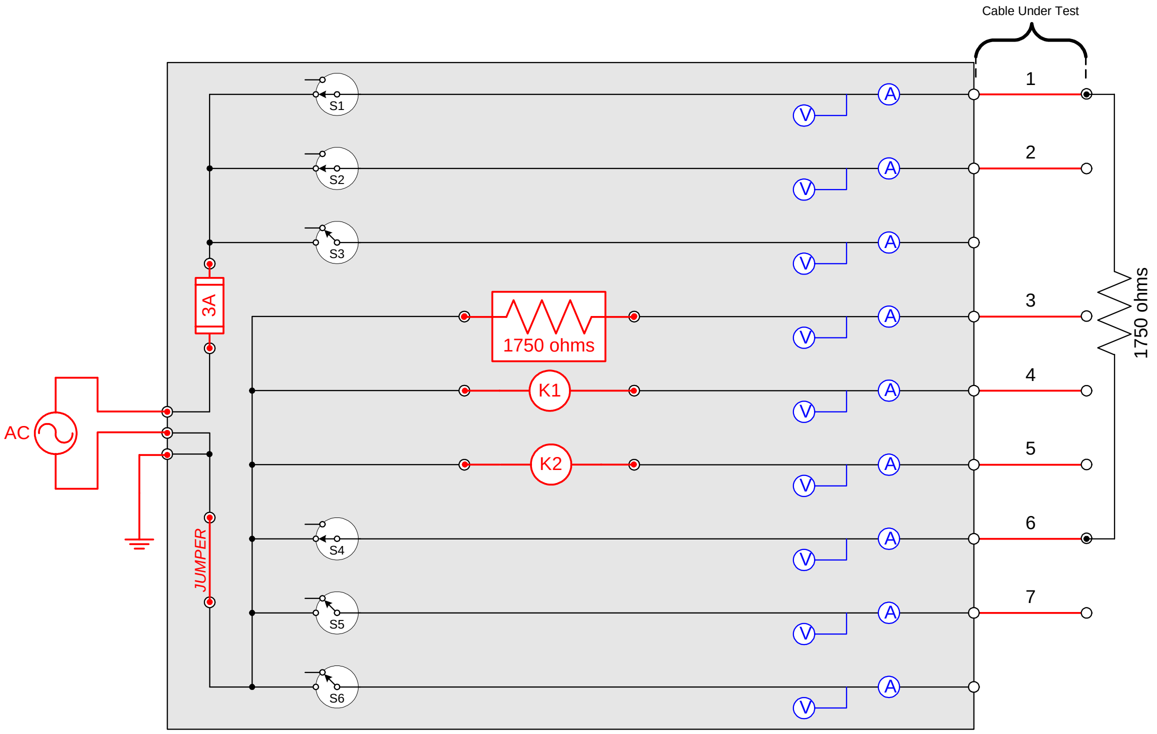

Figure D-2 Simulated Motor Operated Valve Control Circuit, Without CPT.

Figure D-3 shows the same control circuit being powered through a control power transformer. It should be noted that by changing the switch arrangements these cable configurations can be easily changed, for example, to connect the ungrounded spare conductor (#7) to ground, or, if desired, to change conductor #2 from an energized state to an ungrounded spare.

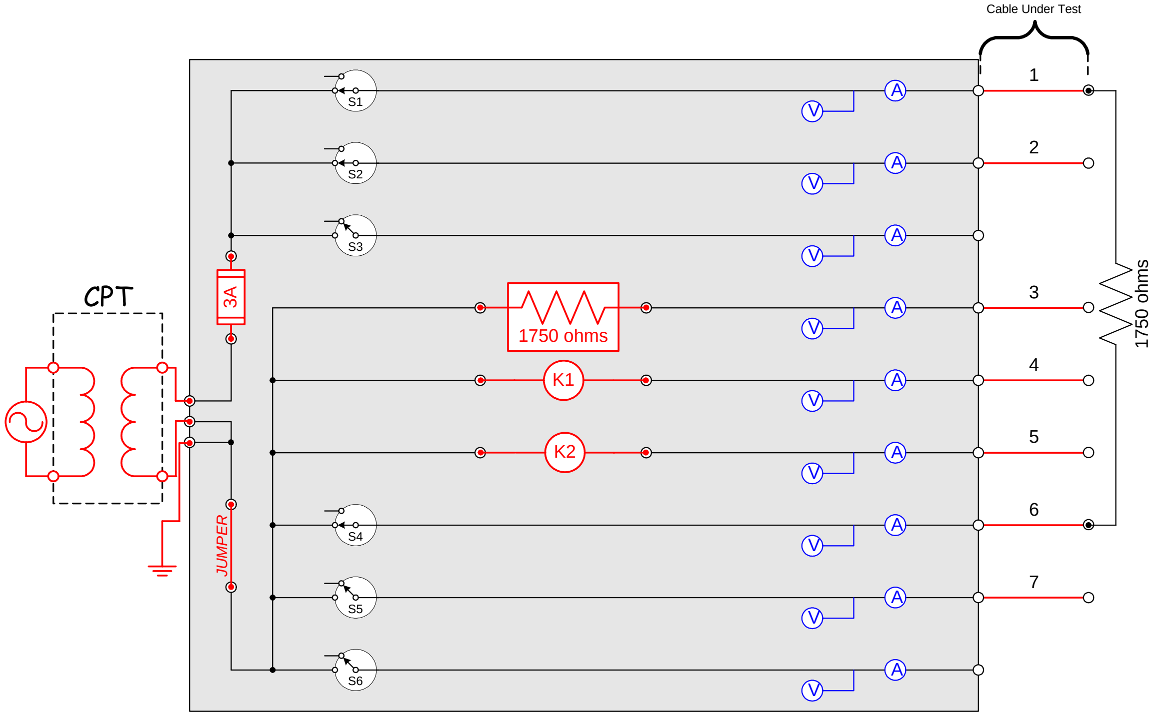

Figure D-3 Simulated Motor Operated Valve Control Circuit, With CPT.

A simulated solenoid operated valve (SOV) control circuit is provided in Figure D-4. Here again the versatility of the SCDU design is demonstrated in that the power source has been changed to an ungrounded DC supply to provide power to a single target control circuit through a pair of 10-amp fuses (versus the single 3-amp fuse used in the MOV circuits above).

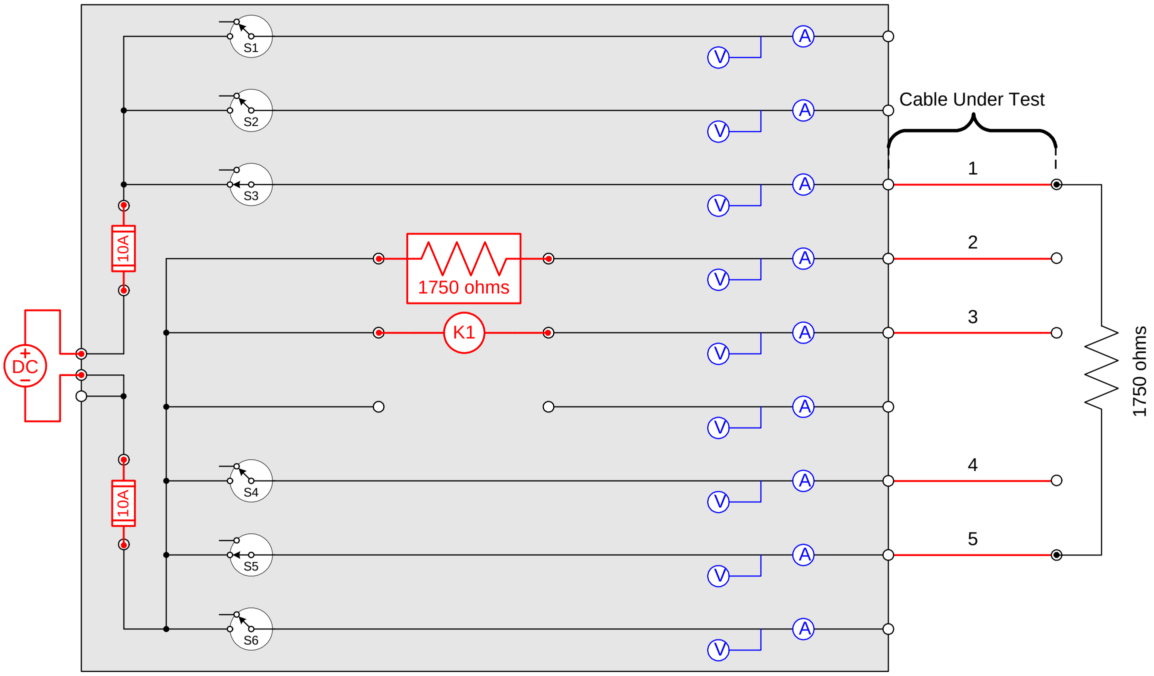

Figure D-4 Simulated Solenoid Operated Valve Control Circuit, Ungrounded DC Power Supply.

Finally, a simulated instrument loop is shown in Figure D-5. Note that the power supply is now a constant current source, to represent the output from a transmitter, and the shield is connected to electrical ground through one of the target connection points.

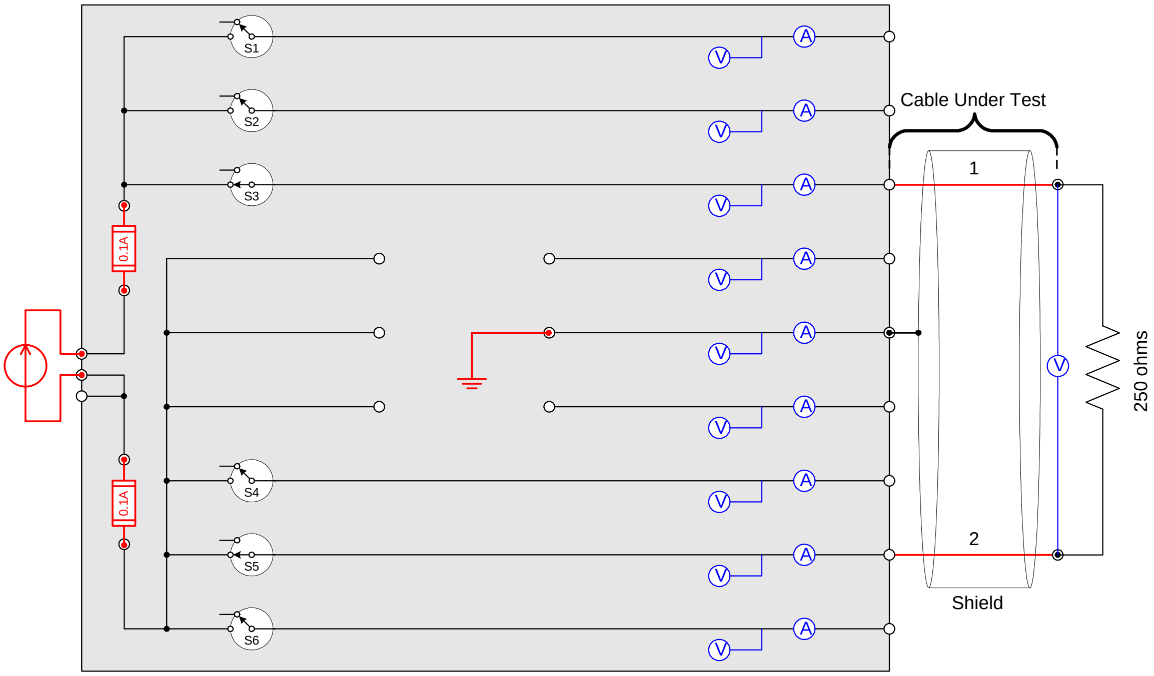

Figure D-5 Simulated Instrument Loop, Ungrounded DC Constant Current Supply.

Appendix E
Cable Material Selection Bases

Table E1 provides highlights of the cable selection process relative to each of the insulation/jacket material configurations considered. The information provides more detailed commentary to supplement the general discussion provided in Section 3.3 of the body of this document including the particular basis upon which each of the individual material configurations was selected.

Table E1: Summary comments on cable materials (insulation/jacket) configurations and the basis for their selection.

Material Configuration	Selection basis and comments:

XLPE/CSPE	• This is the core thermoset configuration for the CAROLFIRE test matrix.
	  • CSPE is also known by the trade name Hypalon.
	• Highly popular material configuration quite common in U.S. NPPs.
	  • XLPE is arguably the single most popular cable insulation material in use in U.S. NPPs.
	  • CSPE jacket is one of two common XLPE insulated cable configurations (along with Neoprene jacketed cables).
	  • The dominant manufacturer of XLPE cables for US NPPs has long been Rockbestos and in particular the Firewall III™ line of products. For this reason Rockbestos was chosen as the supplier for this material configuration.
	  • Other suppliers of this cable have included Anaconda and Brand Rex although neither company ever matched Rockbestos in market share. Both of these companies have been bought out by General Cable, and General Cable still supplies XLPE cables under the Brand Rex name. (General/Brand Rex was considered as an alternative supplier.)
	• The XLPE insulation is considered highly typical mid-range durability thermoset material.
	  • Past testing indicates failure temperatures in the range of 350-375 C which is well within the range of temperatures expected in a larger fire.
	• XLPE insulated Rockbestos Firewall Cables were also used in the NEI/EPRI cable tests.

PE/PVC
&
PVC/PVC
	• PE and PVC are by far the most common of the thermoplastic cable insulation and jacket materials (also see Tefzel below).
	  • PE/PVC is the most common configuration of a thermoplastic cable that might be used in U.S. NPPs.
	  • PE and PVC cables lost much favor with the U.S. NPP industry in the wake of the 1975 Browns Ferry cable fire.
	  • PVC/PVC remains extremely popular as an industrial grade cable configuration and remains popular in nuclear plant applications outside the U.S. (e.g., in European and Canadian reactors).
	• Both PE and PVC are commonly used as both insulation and jacket materials for *industrial* grade cables. These cables are not, however, available as nuclear qualified cables (e.g., in the context of IEEE-383 aging and severe accident testing).
	  • PE/PVC would not be used inside containment in a U.S. plant.
	  • Based on discussions with industry experts, NPP use would typically be in non-containment areas where radiation aging and severe accident environments are not at issue.
	• The material procured is being supplied by General Cables under the BICC brand name from their Willimantic Connecticut mill.
	  • The Willimantic mill is originally associated with Brand Rex which was later acquired by BICC, and ultimately BICC was acquired by General Cable.
	  • Brand Rex/BICC is a well-known supplier of nuclear grade cables from the 1970's and 1980's.

Tefzel	• A thermoplastic material that is both more expensive and somewhat more robust (i.e., resistant to thermal damage) than either PE or PVC.
	• Widely popular in aerospace applications because its high electrical insulating value allows for a thinner insulation layer at a given voltage rating making the cable both more compact and lighter.
	• Not widely popular in U.S. NPPs, but certainly present in a number of operating reactor sites.
	• Available in two base formulations: Tefzel 200 and Tefzel 280
	  • Both formulations are advertised by the manufacturer (DuPont) as nuclear qualified materials.
	  • Discussion with industry experts indicated that the Tefzel 280 formulation was generally preferred as the insulation material for U.S. NPP applications (jacket may be either formulation).
	  • One cable manufacturer indicated that the 280 formulation must now be obtained from a single DuPont plant in Japan, and has become more costly and difficult to obtain as a result.
	  • This same manufacturer indicated that the 280 material formulation appears to have been changed over the past 10 years or so. This does introduce some question relative to the traceability between the new cables procured for CAROLFIRE and older cables that cannot be easily resolved.
	• Tefzel resin is applied *unmodified* by the cable manufacturer.
	  • Other materials such as PE will be heavily customized and modified by manufacturers (who each may add various plasticizers, fillers, and fire-retardants).
	  • Tefzel is applied as supplied by DuPont and without modification.
	  • Hence, an industrial grade Tefzel cable would be essentially identical to a nuclear qualified Tefzel cable of the same base resin (i.e., so long as one compares cables made from the same base resin).
	• The cost for a cable certified as nuclear qualified was approximately 3 to 6 times the cost of an industrial grade Tefzel 280 cable:
	  • Manufacturer 1 - Nuclear Grade: $16.78/ft
	  • Manufacturer 2 - Nuclear Grade: $7.66/ft
	  • Manufacturer 3 - Industrial Grade: $2.94/ft
	• The cost of cables with a nuclear grade certification was prohibitively expensive given that the program required 300 feet (with Manufacturer 1 that would have cost over $50,000 for just this one cable).
	• Given that questions of traceability were identified, that the base resin is not modified during the manufacturing process, and the prohibitive cost of the nuclear grade materials, CAROLFIRE chose to purchase the industrial grade product.
	  • This does introduce some uncertainty relative to the performance of a true nuclear grade cable, but the results are expected to be generally representative of the performance of Tefzel 280 cables.

XLPE/PVC	• This material configuration represents the prototypical thermoset insulated, thermoplastic jacketed mixed cable type. • The most common brand of XLPE/PVC cables currently installed in U.S. NPPs are those manufactured by GE for use primarily in GE designed plants. • GE no longer manufactures cables, so these cables can no longer be purchased in their original GE formulations. • The cable being procured for CAROLFIRE is not explicitly nuclear qualified, but is again considered typical of the cable of this type that might be used by NPPs in locations outside of containment. • Because nuclear qualification is far more dependent on the insulation material rather than the jacket, it is conceivable that a XLPE/PVC cable could pass the IEEE-383 qualification tests. • However, no manufacturer currently marketing a nuclear grade XLPE/PVC cable was identified. • This review did not establish the extent to which the original GE formulations were considered nuclear qualified (i.e., in the context of IEEE-383 aging and severe accident equipment qualification testing). • The cable used for CAROLFIRE was procured from General Cable, and again, under the BICC brand name through their Willimantic Connecticut mill as an industrial grade cable. • The Willimantic mill is originally associated with Brand Rex which was later acquired by BICC, and ultimately BICC was acquired by General Cable. • Brand Rex/BICC is a well-known supplier of nuclear grade cables from the 1970's and 1980's.

Silicone	• Silicone insulated cables are considered one of the most robust cable configurations (excepting mineral insulated fire-rated cables) in use in U.S. NPPs.
	  • Silicone cables are typically rated for continuous operation in ambient environments up to 200°C as compared to most polymeric cable insulations which are rated for continuous operation at no more than 90°C ambient temperatures.
	• Silicone insulated cables typically come with either a fiberglass or Aramid (the base fiber in Kevlar) braid over each insulated conductor, and a fiberglass braid over the jacket.
	  • Discussion with industry experts indicated that the Arimid braid configuration would be more typical of NPP use.
	  • For CAROLFIRE a Silicone insulated / Aramid inner braid / silicone jacketed / fiberglass outer braid configuration has been procured consistent with the predominant NPP configuration.
	• The cables procured for CAROLFIRE are again an industrial rather than nuclear grade cable:
	  • Several manufacturers known to have produced nuclear grade silicone cables in the past were solicited and most came back “no bid” or indicated that they no longer produced that type of cable.
	  • One manufacturer was identified that still supplies a nuclear grade silicone cable, but the cost and delivery times were prohibitive. The cost was approximately 4 times that of the corresponding industrial grade silicone insulated cables (nearly $18 per linear foot), and the delivery times were 12-14 weeks.
	  • The cables procured by CAROLFIRE are being supplied by the “sister company” to the one source of nuclear grade cables identified and the supplier has indicated that the base resin is the same as that used in the nuclear grade cables (additives may differ).
	  • The based compound for the industrial grade cables procured for CAROLFIRE appears to be the same as that used in production of the nuclear grade cables provided by the sister company (additives may differ).
	• Even in an industrial grade configuration, the Silicone/Aramid/Fiberglass cable is expected to far out-perform any other cable in the matrix.
	• The use of industrial grade cable for this configuration was deemed to be an acceptable compromise. The cables tested are expected to provide results that are representative of the performance of nuclear grade cables under similar fire conditions.

XLPO	• Initially, XLPO was expected to represent the least robust (i.e., most susceptible to thermal damage) member of the thermoset class of cable insulations.
	    • Given the new formulations of XLPO and this initial expectation may not prove valid.
	    • Very little information is available regarding the failure thresholds for XLPO cables, and the formulations currently being marketed bear little resemblance to the XLPO formulations marketed in the 1960's-1980's.
	• XLPO is a very generic and often mis-used material designation
	    • For example, XLPE is a specific type of the more general class XLPO.
	    • Discussion with industry experts indicates that cables advertised during the 1960's, 70's and 80's as XLPO may be any one of a number of material formulations, including some (such as vinyl-acetate based compounds) that should not strictly be identified as XLPO.
	    • XLPO has been used as the base compound for most of the “low-smoke, zero halogen” cable formulations being manufactured today (material formulations that were not commercially available 10-15 years ago) and no manufacturer of an XLPO cable that was not advertised “low-smoke, zero halogen” could be identified.
	    • Hence, traceability between any of the current XLPO formulations and older XLPO cables is questionable at best.
	• The one XLPO cable that was known to have been used in U.S. NPP applications was a product known as Kerite FR.
	    • The Kerite company remains in business as a manufacturer of larger power cables, but no longer manufacturers the FR insulation material, nor the control cable configurations of primary interest to CAROLFIRE. Their product lines are limited to higher voltage power distribution cables.
	    • No supplier of a XLPO cable that would be considered equivalent to the Kerite FR cable could be identified.
	• The XLPO cables procured for CAROLFIRE are a “low-smoke, zero halogen” cable supplied by a major manufacturer as an industrial grade cable product.
	    • These cables were retained in the test matrix primarily to assess the performance of a cable expected to be at the lower end of the robustness range for thermoset insulations.
	    • No direct traceability to actual cables used by U.S. NPPs is anticipated or assumed.

EPR/CSPE	• EPR is a rubber-based polymer that is relatively common as a nuclear qualified cable insulation and/or jacket material.
	• EPR is considered typical of a moderately robust Thermoset insulation.
	  • The thermal damage thresholds for an EPR insulated cable are generally on a par with a XLPE insulated cable.
	• Common suppliers of EPR cables to the U.S. NPP industry included BIW, Samuel Moore, Anaconda, and Okonite.
	  • None of these companies still advertises EPR-insulated control cables.
	• For CAROLFIRE, a General Cable EPR cable has been procured.
	  • The General Cable EPR product is not explicitly advertised as nuclear qualified.

Vita-Link®	• This cable was added to the CAROLFIRE test matrix after discussion with the Rockbestos Surprenant Western Regional Manager and NRC Staff. • The Vita-Link cable is a new product that has not yet found widespread use among the existing fleet of NPPs. • It is a silicone based insulation that is designed to “ceramify” on burning such that circuit integrity would be maintained despite the fire. • This is a variation on the new classes of “fire-rated” cables. • NRC Staff determined that the addition of this cable as proposed by Rockbestos was a valuable addition that allows the program to look forward to at least one cable product that may be used in the next generation of nuclear power plants.

Appendix F

Modeling Cable Failure - the NIST and UMd Activities

Two separate thermal models are to be developed to complement the experimental program. At NIST, a simplified model of cable failure is to be developed to be incorporated into any large scale fire model. At the University of Maryland, a more detailed model will be developed, which will include both thermal and chemical kinetic effects. Following is a description of each model.

The Simplified Cable Failure Model (NIST)

Numerous models of cable failure have been developed over the years, ranging from empirical correlations of experimental data (Steve, add an appropriate reference here if you like) to detailed heat transfer calculations (Andersson, 2005). 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. Recently, Petra Andersson and Patrick Van Hees of the Swedish National Testing and Research Institute (SP) proposed that cable failure can be modeled via a simple one-dimensional heat transfer calculation through the cylindrical cable, under the assumption that the cable can be treated as a homogenous plastic cylinder. Obviously, this is a considerable assumption, but their results for various PVC cables suggest that it may be sufficient for engineering analyses of a wider variety of cables. The proposed simplified model is essentially the model of Andersson and Van Hees. The only difference is that the heat transfer equation will be solved numerically rather than analytically. The analytical solution derived by the SP researchers, while correct, is fairly complicated and a simple numerical solution is easier to implement in a large scale fire model. The accuracy of either the analytical solution or the numerical solution are 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 has less restrictions, which is important if it is discovered halfway through the test program that the homogenous cylinder assumption does not predict cable failure to an accuracy demanded by the risk analysts.

The simplified model can only predict the temperature profile within the cable as a function of time, given a specified heat flux at the exterior. The penlight tests will be used to determine at what radial location failure has occurred, and what the temperature is at that location. Assuming that the model predicts the interior temperatures measured in the penlight tests, a failure temperature and location will be assigned to that particular type of cable. 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 Detailed Cable Failure Model (UMD)

Given the considerable simplification of the model described above, it is prudent to consider a more detailed description of the heat conduction through a non-homogenous cylindrical cable. Even if the simplified model produces predictions of cable failure that are sufficient for risk analyses, we need to understand why it works and its uncertainties. Consider, for example, the simple RTI (Response Time Index) concept that was developed to predict automatic fire sprinkler activation. Its wide acceptance in the fire protection engineering community was due to its ease of implementation in fire models and its good performance in large scale validation tests. Its acceptance by the heat transfer community was due to its grounding in the fundamental physics of heat transfer. The development of a detailed heat transfer model for a cable will lead to wider acceptance of the simplified model if it can be demonstrated that the simpler model sufficiently describes the penetration of heat leading to cable failure.

Detailed heat transfer simulation can be done either analytically or numerically. Heat transfer textbooks (Massoud, 2005) point to the fact that analytical solutions for transient heat transfer are available only for the most basic cable configurations, i.e., a homogenous cylinder. Real cables consist of multiple insulated conductors, bundled within an outer jacket. In cases where the conductors do not fill the jacket in a compact way, a filler material is added to maintain the shape of the cable. Given the complexity of the cables under study, a detailed heat transfer simulation can be achieved only by a numerical method. The simulation will consider the structure of each cable type, as well as the materials used. ANSYS, which is a commercial finite element program, will be used for the numerical analysis. Following are assumptions and considerations:

Geometry – Two-dimensional cross section (see figures below)

Cable structure modeling – Each cable is assumed to consist of a jacket, multiple conductors, conductor insulation, and filler (possibly air). Each region is meshed into finite elements. The elements are chosen and the meshing is done such that, to the extent possible, the elements will fit the area's contours. Fig. 1 is an example of a #12/7 conductor cable. Fig. 2 depicts the elements of the gap areas. Fig. 3 shows the elements in the insulation areas of the conductors.

Material properties – Since most of the cable's insulation materials are designed by the cable manufacturer according to specific performance objectives, material properties are usually kept as a trade secret. Also, if conforming to standard testing requirements does not necessitate determination of insulation materials thermal properties (i.e. specific heat and conduction coefficient), manufacturers are not inclined to invest resources to find those. Even if they did they are unlikely to divulge their results. Given the above, in any case that a thermal property for a specific material is not known, a generic value based on the available data for that product family will be used.

Thermal Load - The incorporation of the thermal load is done as a boundary condition, with a capability for steady or transient load.

Solution -- The solution of the heat transfer equation is found by applying the boundary conditions, and processing conduction heat transfer equations among all elements, taking into consideration each element properties, and the elements' spatial relationships. Results can be presented for any time step, and/or for any location in the cable. The goal of the analysis is to simulate the cable testing, and specifically to predict the temperature at the time and location where an electrical short occurs. The hypothesis is that the insulation material will fail once its temperature reaches a certain level, which might be its melting temperature.

In the past few years there has been some controversy regarding the types and relative likelihood of certain fire-induced failure modes of electrical circuits. From all possible fire-induced electrical circuit failure modes, of greatest interest are those that produce conductor to conductor shorting such that certain equipment may be spuriously energized (or de-energized) through erroneous conduction paths. Up to now, most of the effort has been concentrated in running fire tests. Industry and regulatory organizations have undertaken fire test programs to obtain quantitative data regarding circuit behavior during a fire. However, the available data have not undergone full and complete statistical analysis to correlate primary influence factors (e.g., physical conditions) to key circuit failure modes.

A further objective of the UMCP research is to develop a probabilistic model to predict the likelihood of fire-induced circuit failure modes, and particularly short circuit fire-induced circuit failure modes through the probabilistic analysis of available test data and the characterization of the underlying causalities and mechanisms of failures. This approach not only will be based on statistical analysis of the existing data, but also to the extent possible, it will use physics-based principles to describe the underlying mechanism of failures that take place among the electrical cables upon heating due to external fires. Those principles include a thermal degradation model based on kinetic equations (Gupta 2004), and the "K factor model." (Nowlen 2000)

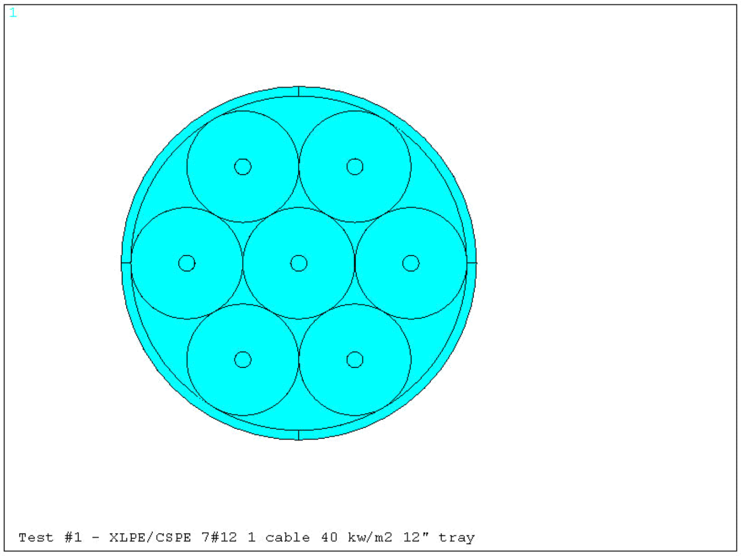

Figure 1 - #12/7 conductor cable – areas within cable cross section

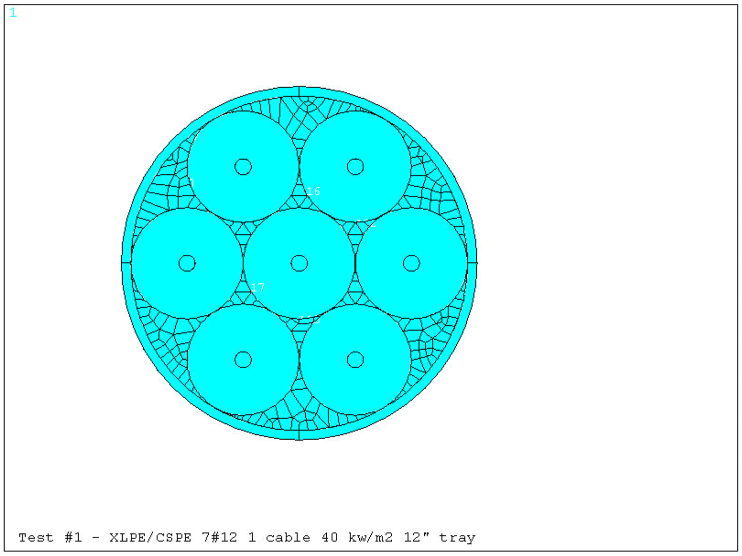

Figure 2 - #12/7 conductor cable – meshed elements within the gap areas

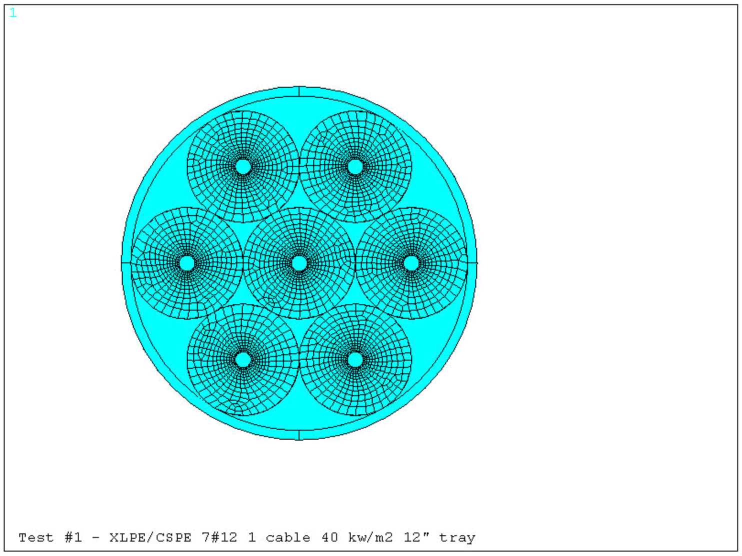

Figure 3 - #12/7 conductor cable – meshed elements within conductors' insulation areas

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