The CAROLFIRE Project: Cable Response to Live Fire

Presented to:
Advisory Committee on Reactor Safeguards
Meeting Of the Joint Subcommittees on Thermal-Hydraulic Phenomena and on Reliability and Probabilistic Risk Assessment

Presented by:
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Project Status

- **The CAROLFIRE project at SNL is largely complete**
  - **SNL's two-volume report has been through public comment, revised, and is in final pre-publication review at NRC**
    - **Review included ACRS review of the Draft for Public Comment**
  - **A copy of the final pre-publication report (SNL Volumes 1&2) was provided to the ACRS in December**

Presentation content and objectives

- **Content of this presentation:**
  - **Detailed description of the CAROLFIRE project**
    - **Objectives, approach, results, implications**
  - **Summary of the Public Comment process**
    - **Major comments, responses, impact, changes to report**
- **A presentation from NIST on their fire modeling efforts will follow**
- **Our objective:**
  - **Ensure that ACRS has a clear and concise understanding of what CAROLFIRE has done and the implications for the future**

CAROLFIRE Project Objectives Included Two Areas of Investigation

- **Resolution of the 'Bin 2' circuit configurations:**
  - **Regulatory Issue Summary 2004-03, Rev 1 - "Risk-informed Approach For Post-Fire Safe-Shutdown Circuit Inspections"**
  - **Documents findings from a February 2004 NRC facilitated workshop which put cable/circuit configurations in one of three bins:**
    - **Bin 1: Configurations that are most likely to fail (e.g., leading to spurious operation**
    - **Bin 2: Configurations that need more research**
    - **Bin 3*: Configurations that are unlikely or least likely to fail (e.g., leading to spurious operation).**
- **Fire Modeling Improvement**
  - **To reduce uncertainty associated with predictions of fire-induced cable damage**

*** The Bin 3 items were identified in the original draft of the RIS but were deleted from the final revision**

‘Bin 2’ Item A: configuration background

Spurious actuations caused by inter-cable shorting for thermoset cables

- **NEI/EPRI test results:**
  - **Several spurious actuations caused by intra-cable* shorting of both thermoset and thermoplastic cables**
  - **A few spurious actuations caused by inter-cable** shorting among thermoplastic cables**
  - **No spurious actuations attributed to inter-cable shorting between thermoset cables**
- **Potential explanation:**
  - **Thermosets don’t melt, but rather, char.**
  - **There are internal stresses within a given cable that may drive the conductors to form intra-cable shorts whereas these internal forces don’t act between cables**
  - **For thermoset cables the char may be enough to prevent inter-cable interactions**

*** intra-cable shorting: shorting between the conductors of a single multi-conductor cable**

**** inter-cable shorting: shorting between the conductors of two separate cables (either multi-conductor or single conductor)**

Bin 2 Item B: configuration background

Spurious actuations caused by Inter-cable shorting between thermoplastic and thermoset cables

- **The NEI/EPRI tests had not included any "mixed" bundles**
- **Possible theory for why such interactions might be low likelihood:**
  - **Thermosets are more robust than thermoplastics in terms of vulnerability to fire-induced electrical failure**
  - **Thermosets will likely fail only after longer exposure times, perhaps well after any thermo-plastic cables had failed**
  - **Thermoset and thermoplastic cables are not likely to interact because of the likely time differences associated with their times to failure**
- **Before CAROLFIRE, there was no data on mixed-type bundling arrangements**

Bin 2 Item C: configuration background

Concurrent spurious actuations associated with failures impacting three or more cables

- **Generally, the NEI/EPRI tests showed that multiple spurious operations could occur during a single test, but that timing and hot-short duration issues could play a significant role in such behaviors**
- **The NEI tests provided limited variations in the test configuration and were generally limited to cables co-located in a common single raceway**
- **Hence, initial guidance was to focus on spurious actuations potentially arising from shorts impacting any two cables, and to defer higher order failure combinations pending additional data**

Bin 2 Item D : configuration background

Multiple spurious operations in control circuits with properly sized control power transformers (CPTs)

- **The use of control power transformers (CPTs) is common for many AC control circuits**
- **NEI tested both with and without CPTs**
- **The CPTs appeared to have a substantive impact on the likelihood of spurious actuations based on the NEI/EPRI tests**
  - **Likelihood estimates were nominally cut in half given a CPT in the circuit (EPRI expert panel results)**
- **NEI only explored one circuit configuration and one CPT size leaving many unanswered questions**
- **Interim guidance was to consider only single spurious actuations for circuits using "properly sized" CPTs (generally taken as no more than 150% of the circuit design power demand)**

Bin 2 Item E : configuration background

Fire-induced hot shorts lasting more than 20 minutes

- **The duration of hot shorts could be a definitive factor in both the likelihood of multiple concurrent spurious actuations and the potential impact of spurious actuations on certain types of devices (e.g., “fail safe” devices such as an AOV or SOV)**
- **The NEI tests saw a maximum hot short duration of about 11 minutes**
- **Interim guidance was to consider hot shorts persisting for nominally twice this time (20 minutes)**

Bin 2 Item F : configuration background

Consideration of spurious actuations for cold shutdown circuits

- **Item is related to cold shutdown requirements included in 10CFR50 Appendix R**
- **Fire PRAs typically consider hot shutdown to be success so risk implications of cold shutdown circuits were unclear**
- **Fundamentally, the cable behaviors should be no different for a cold shutdown circuit**
- **Hence, this item was not considered amenable to resolution via testing and new data**
- **No investigation of Item F was undertaken as a part of CAROLFIRE**

Fire Model Improvement Background

- RES has separate efforts underway dealing with Verification and Validation of fire models
  - CAROLFIRE compliments these efforts
- Data needed to:
  - Support improved cable thermal response and electrical failure fire modeling tools
  - Reduce modeling uncertainties
- Collaborative partners at NIST and UMd are leading the modeling efforts
- SNL did the testing:
  - Extensive efforts to gather data that correlates thermal response to electrical response
  - Range of exposure conditions from simple to complex
  - Range of cable products
  - Disseminate the data

CAROLFIRE was a Collaboration Involving RES, NRR, NIST, UMd, and SNL

- **RES: Sponsor and overall responsibility for program direction**
- **NRR: Advisory and observational role**
- **NIST and UMd had similar roles:**
  - **Advisory role for experimental design, planning, and data reporting**
  - **Particular emphasis on fire model improvement goals – data analysis and application**
    - **NIST focused on simple modeling approaches**
    - **UMd focused on statistical and detailed modeling approaches**
- **SNL: Primary testing laboratory**
  - **Test design, procurement, and test execution**
  - **Analysis of electrical performance data and the RIS Bin 2 items**
  - **Dissemination of the all experimental data including limited preliminary analysis of fire modeling related data**

Peer Review

- **SNL was responsible for development of the test plan, but the test plan was subject to peer review**
- **All collaborative partners actively participated in this peer review**
  - **Nathan Sui (RES)**
  - **Dan Frumkin and Naeem Iqbal (NRR/AFPB)**
  - **Anthony Hamins (NIST)**
  - **Mohammad Modarres (UMd)**
  - **Vern Nicolette (SNL)**
- **We also included one outside expert – the author of the EPRI report on the original NEI/EPRI circuit tests:**
  - **Dan Funk (EDAN Engineering)**

The Testing Approach

- Two Scales of testing were pursued
  - Small-scale radiant heating experiments
  - Intermediate-scale open burn tests

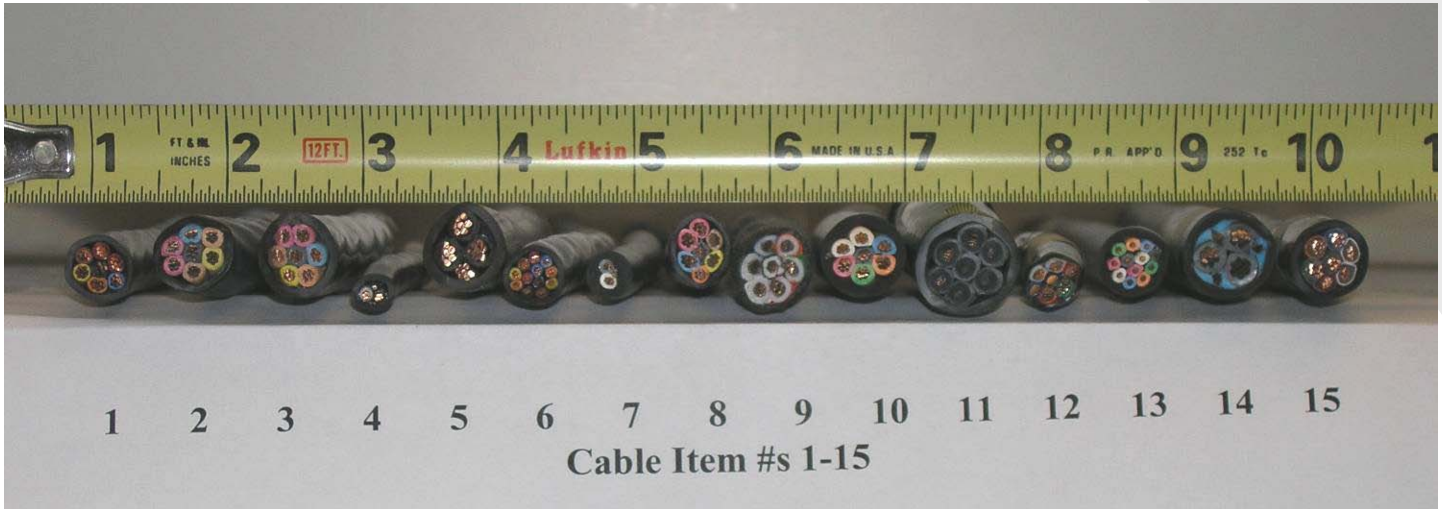
- Testing a broad range of cable products (list follows)
  - Note that CAROLFIRE did exclude armored cables
  - Armored cables were being tested by Duke during the same time period and using similar methods

Cable types tested represent a wide range of NPP products

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

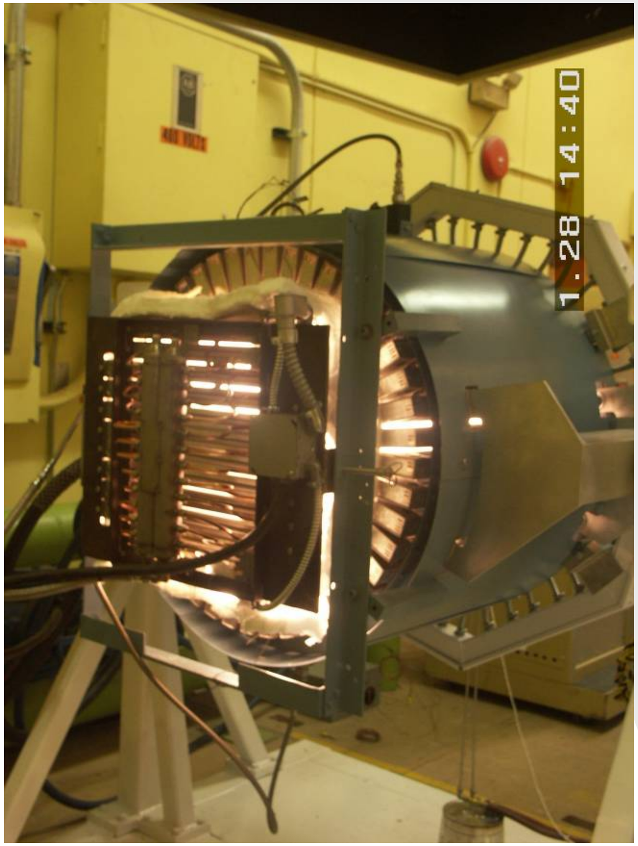
Additional Notes:
(1) - XLPE = Cross-linked polyethylene; CSPE = Chloro-sulfanated polyethylene (also known as Hypalon); XLPO = Cross-linked polyolefin; SR = Silicone rubber; EPR = Ethylene-propylene rubber; PVC = Poly-vinyl chloride; PE = Polyethylene (non cross-linked).
(2) - TS = Thermoset; TP = Thermoplastic; shown as: (insulation type)/(jacket type).
(3) - All power and control cables are un-shielded.

Photo that Compares the Tested Cables

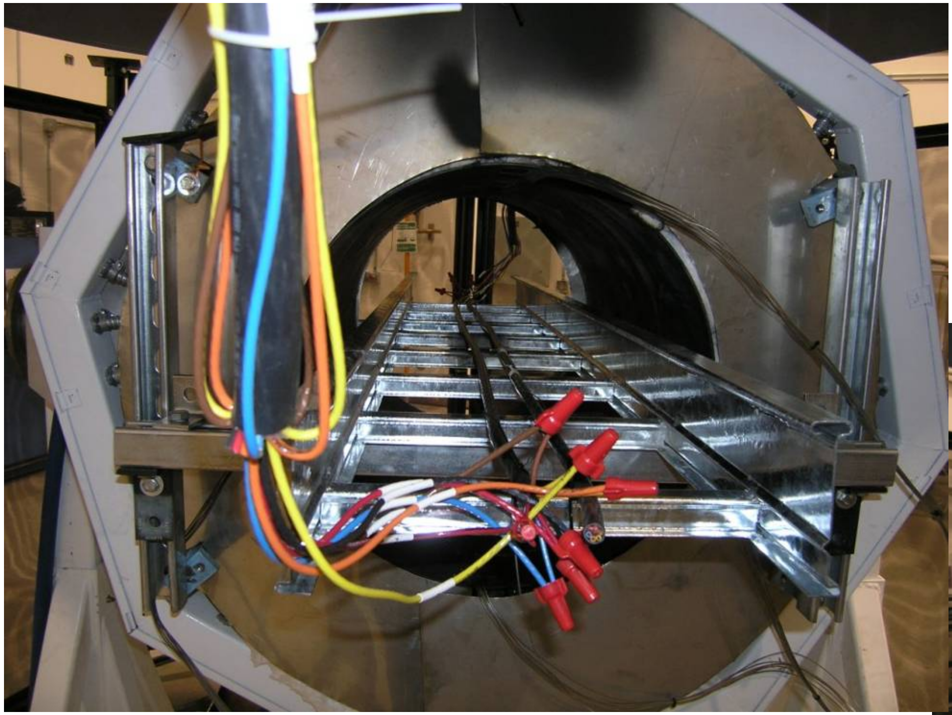


Small Scale Tests

- *Penlight* **heats target cables via grey-body radiation from a heated shroud**
- *Penlight* **was originally developed to support RES testing in the 1980's and has been used in a number of prior test programs**
- **Well controlled, well instrumented tests**
- **Allows for many experiments in a short time**
- **Thermal response and failure for single cables and small cable bundles (up to six cables)**
- **Cable trays, air drops, conduits**

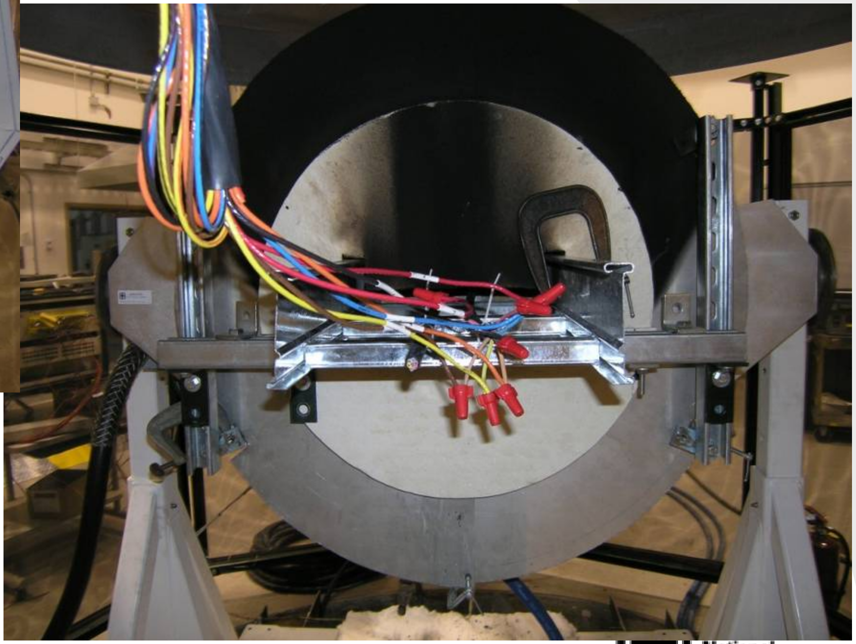


Typical Penlight Setup for CAROLFIRE

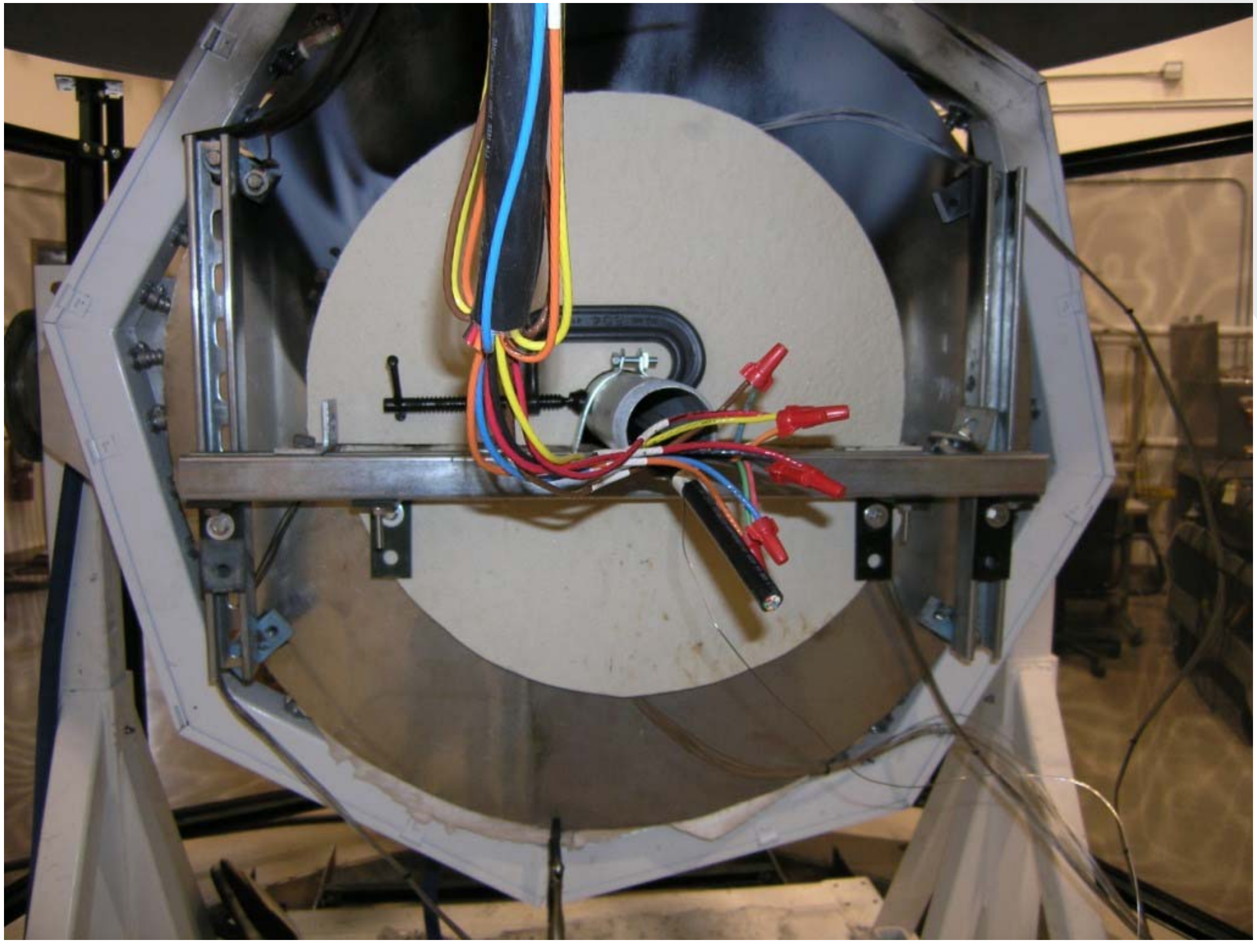


This is a typical cable tray setup, in this case, with one electrical performance cable and one thermal response cable. The cable dropping from the upper left connects to the electrical performance monitoring system

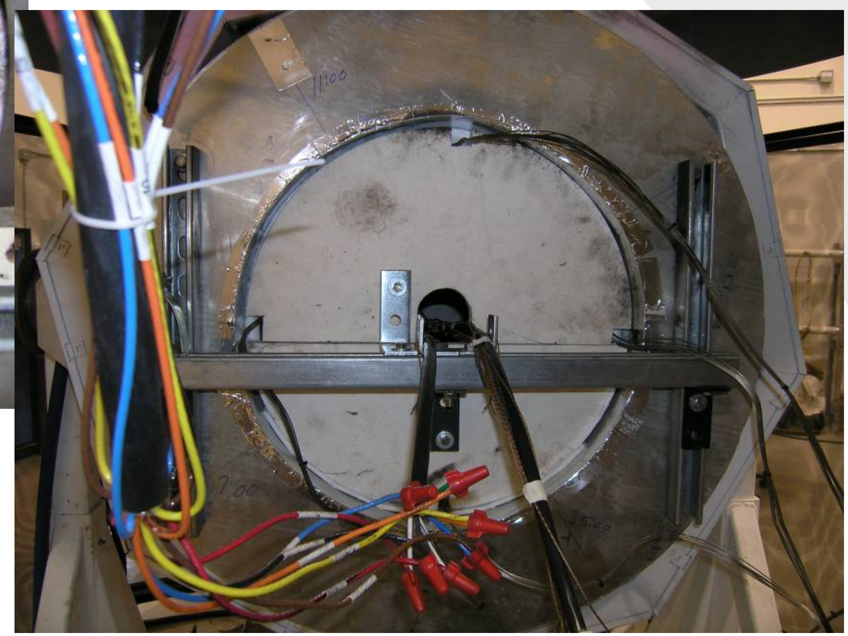
This figure illustrates the use of end covers closing off the shroud as were used during most of the tests



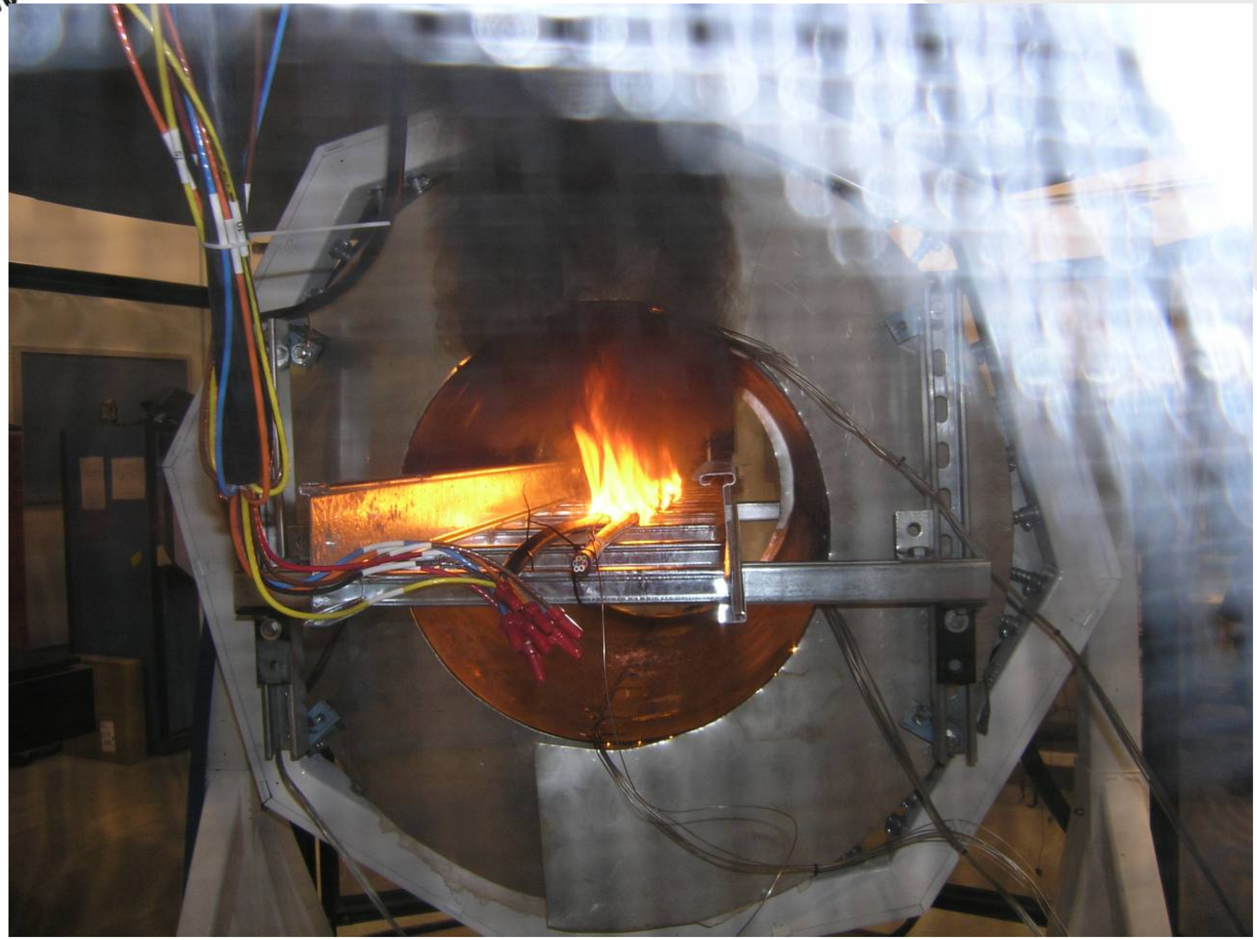
Typical Penlight Conduit Setup



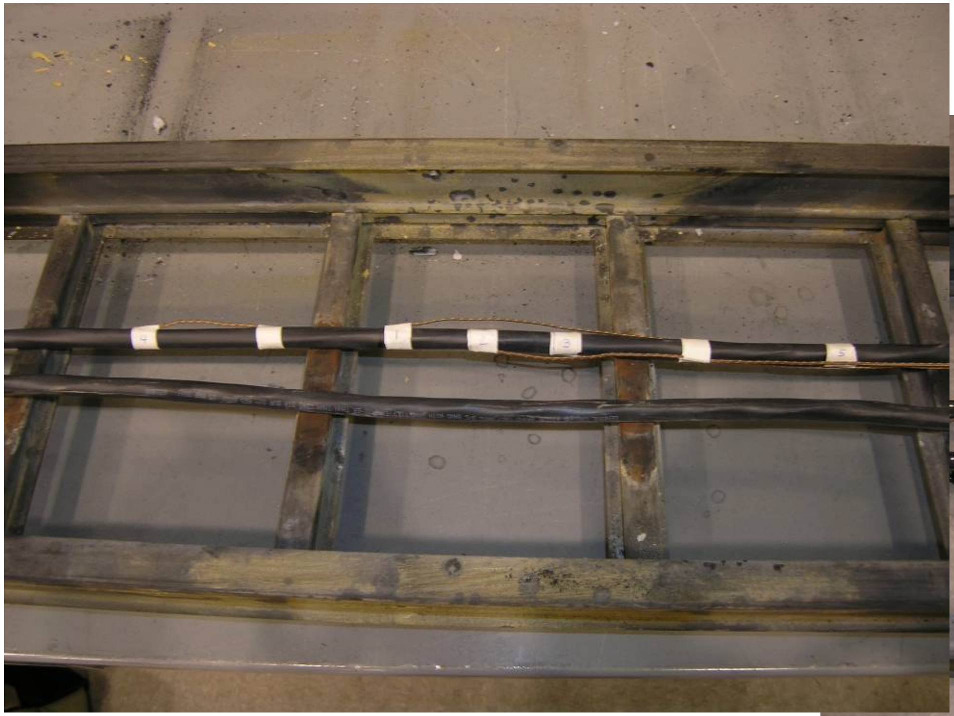
Typical Penlight Airdrop Setup



Note that Penlight did allow for cable burning, and this was common



Typical Before/After for Thermoplastic Cables



Note the obvious melting behavior typical of thermoplastics

Typical Post-Test Conditions for Thermoset Cables

Note the remnants of charred insulation and jacket, but no melted materials. These cables did burn during the test.

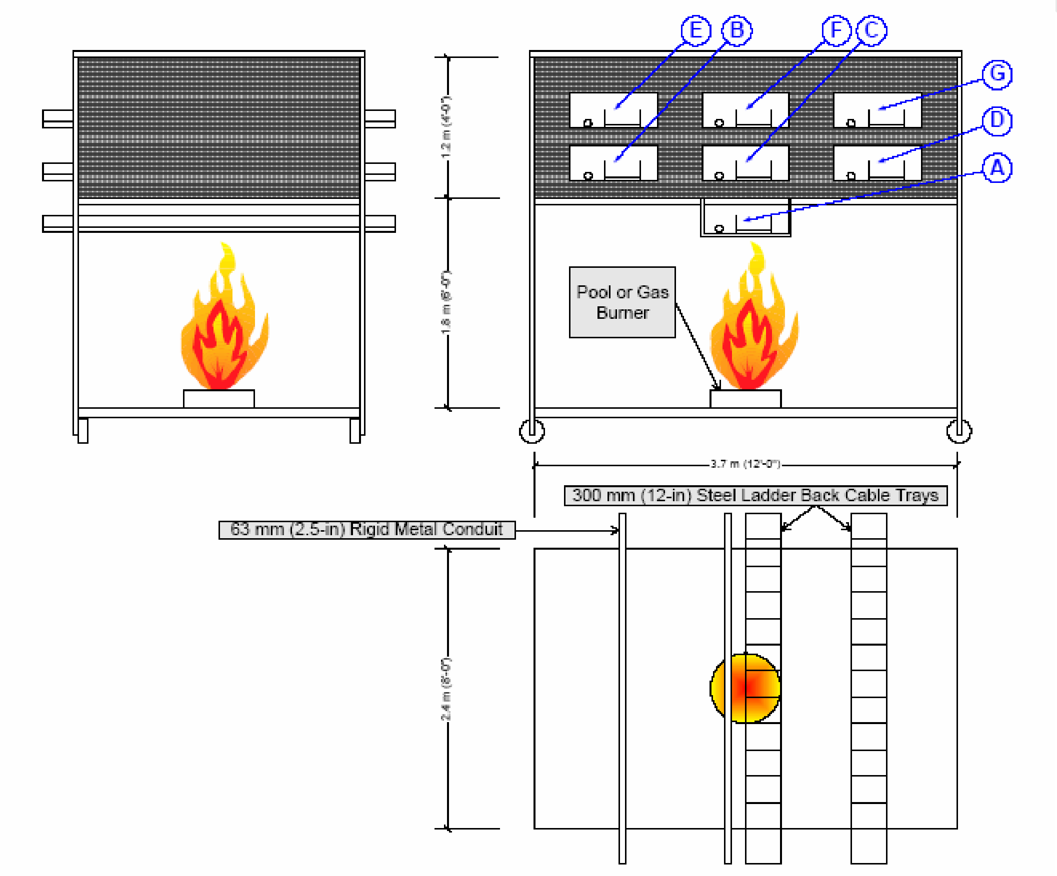
Typical Bundle Test

In this case, the bundle was monitored for electrical performance with just one single thermal response cable. There was a limit to how many cables we could test at one time in Penlight because the facility is not designed to withstand a large fire

Intermediate-Scale Tests

Layout of the intermediate-scale test structure.

Structure was located within a larger test facility.



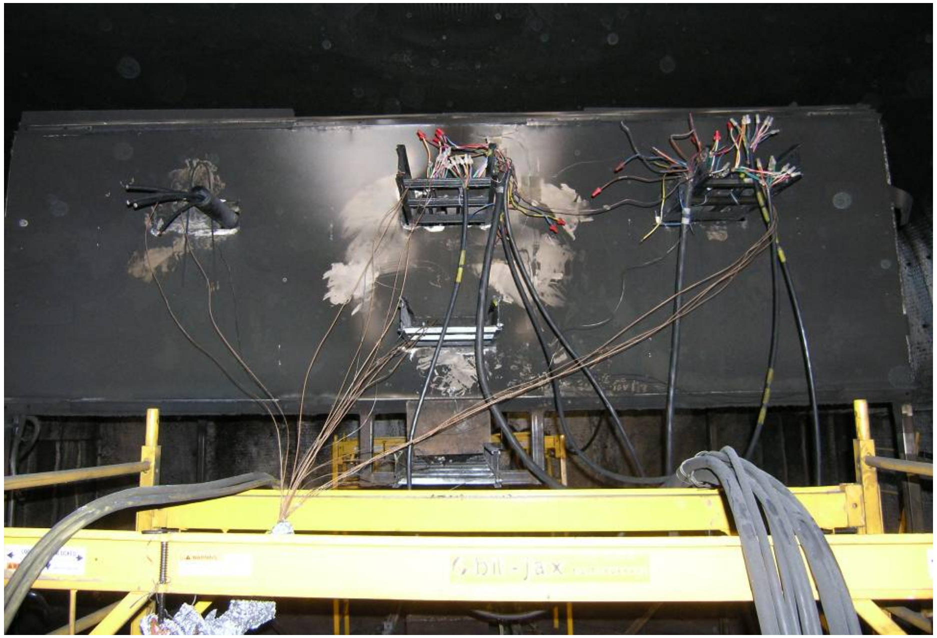
Intermediate-Scale Tests

- **Less controlled, but a more realistic testing scale**
- **Hood is roughly the size of a typical ASTM E603 type room fire test facility (more open to allow for ready access)**
- **Propene (Propylene) burner fire source (200 kW typical)**
- **Cables in trays, conduits and air drop**

Photos to Illustrate Intermediate-Scale Test Structure

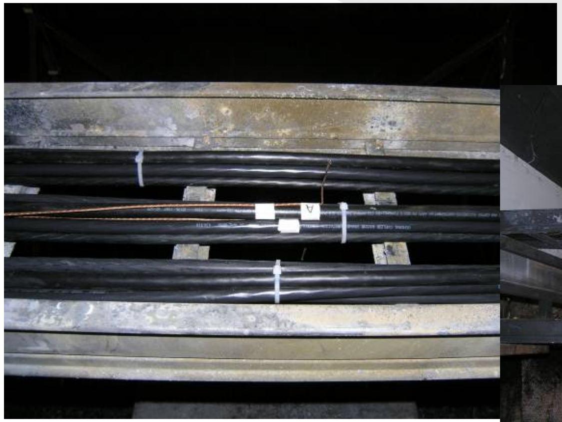
The Gas Diffusion Burner

Photo of the Intermediate Scale Test Structure Just Prior to a Test



Typical Setups

Single cables



Bundles

Airdrops

Random fill trays

Typical Post-Test Conditions

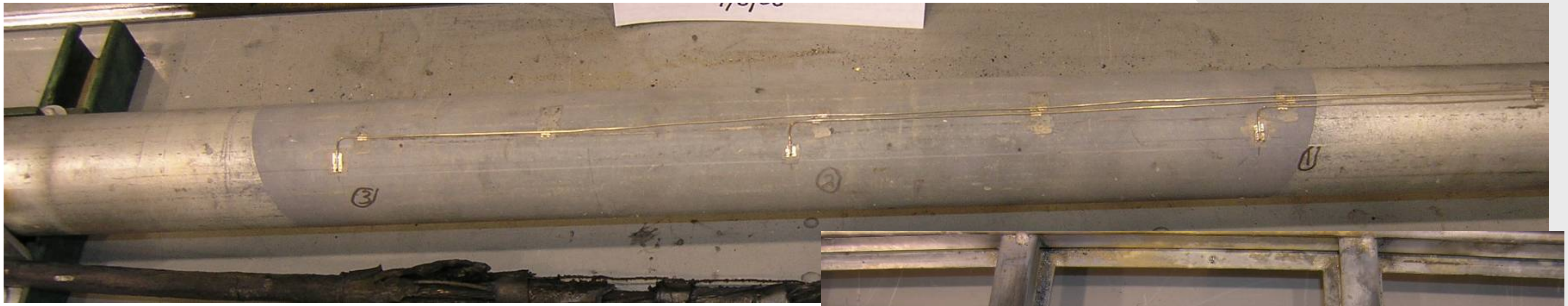
Instrumentation for both electrical performance and thermal response

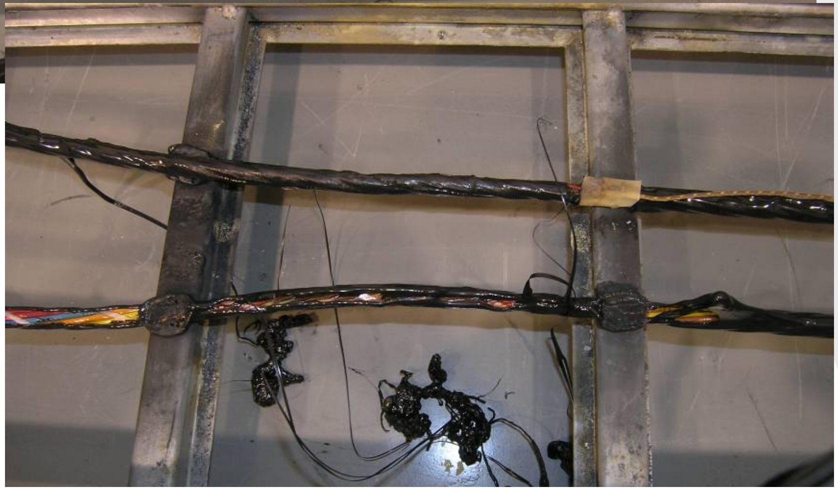
- **Cable thermal response (surface and interior)**
  - Direct measurement of the cable temperatures during the tests
  - Can be used to calculate fire-to-cable net heat transfer (i.e., every cable is in effect a target specific slug calorimeter)
- **Raceway surface temperatures**
  - Conduits and cable trays
- **Exposure environment temperatures**
  - Air and surface, additional slug calorimeters
- **Cable electrical response via two monitoring systems**
  - The SNL Insulation Resistance Measurement System
  - Surrogate Circuit Diagnostic Units (circuit simulators)

Sub-jacket Thermocouples

Measurements made of sub-jacket cable temperatures are one of the key measurements of interest to the fire model improvement efforts. Every test included one or more such measurements.

Raceway Temperatures

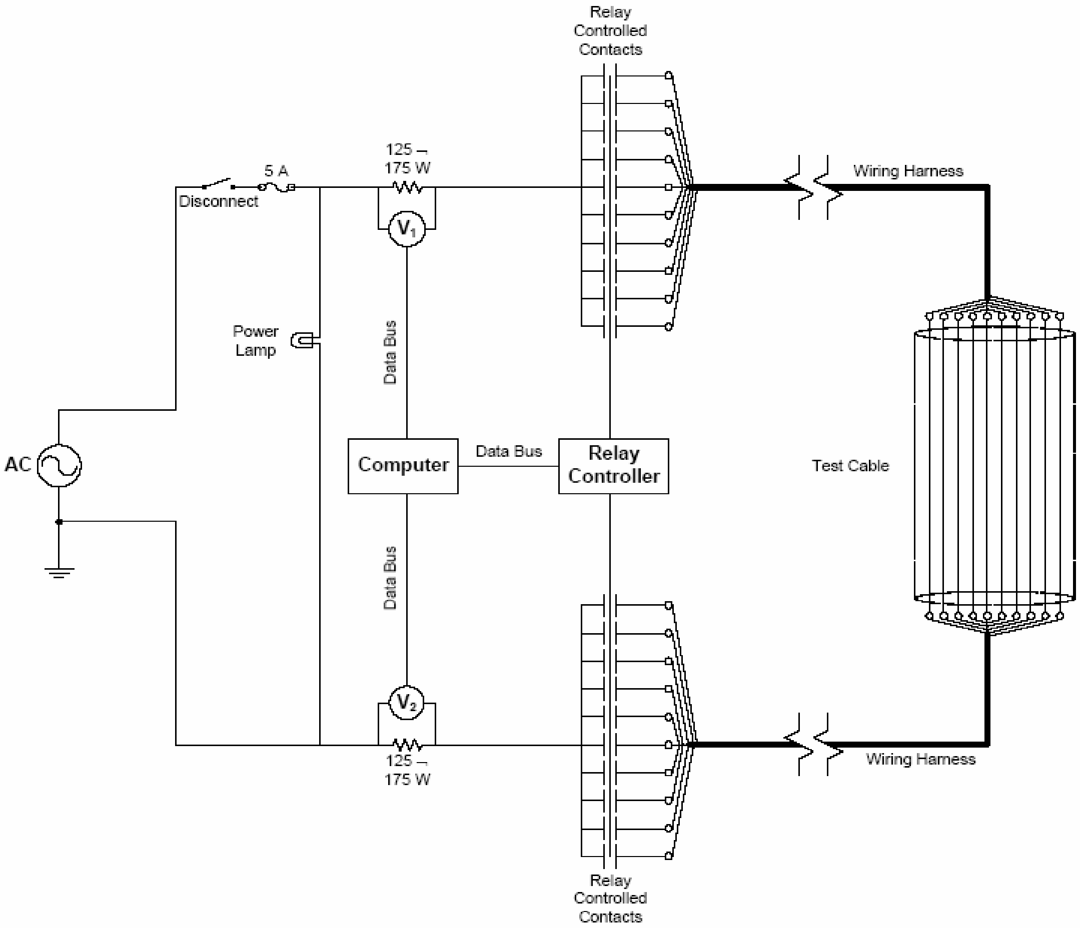




Conduit and cable tray surface temperatures are also important to fire modeling efforts.

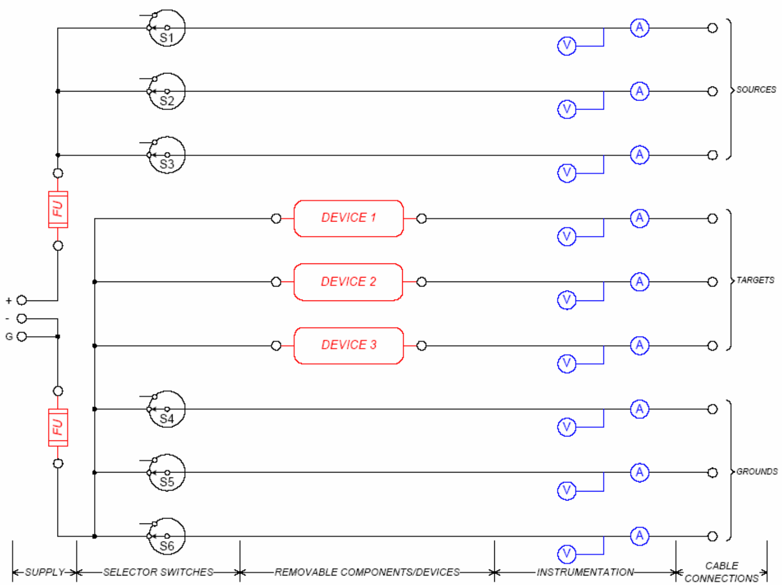
Instrumentation (2)

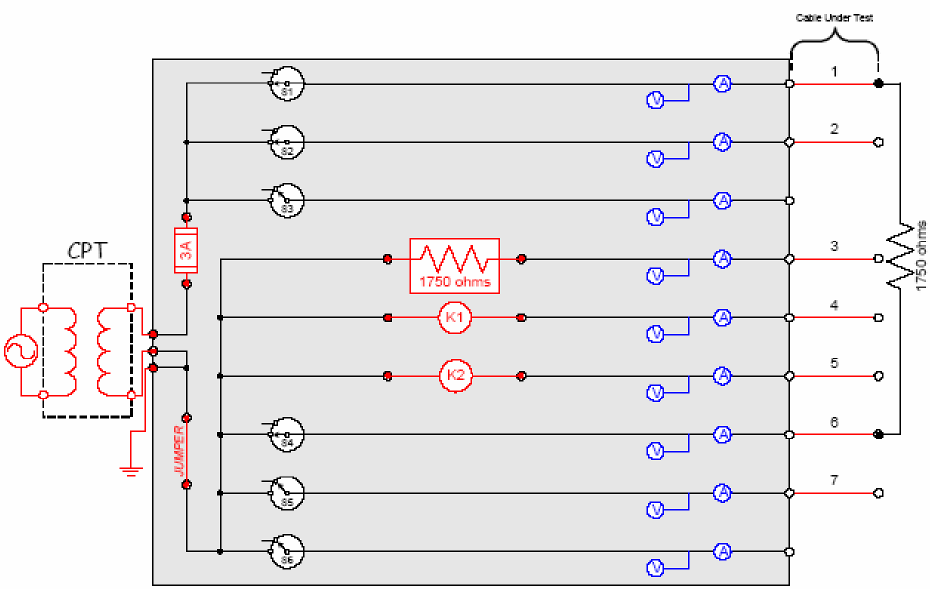
- All tests – SNL Insulation Resistance Measurement System (IRMS)
- Continuous measurement of cable degradation and functionality
- Very detailed look at conductor interactions
- Patented system developed and deployed originally during the NEI/EPRI tests (NUREG/CR-6776)



Instrumentation (3)

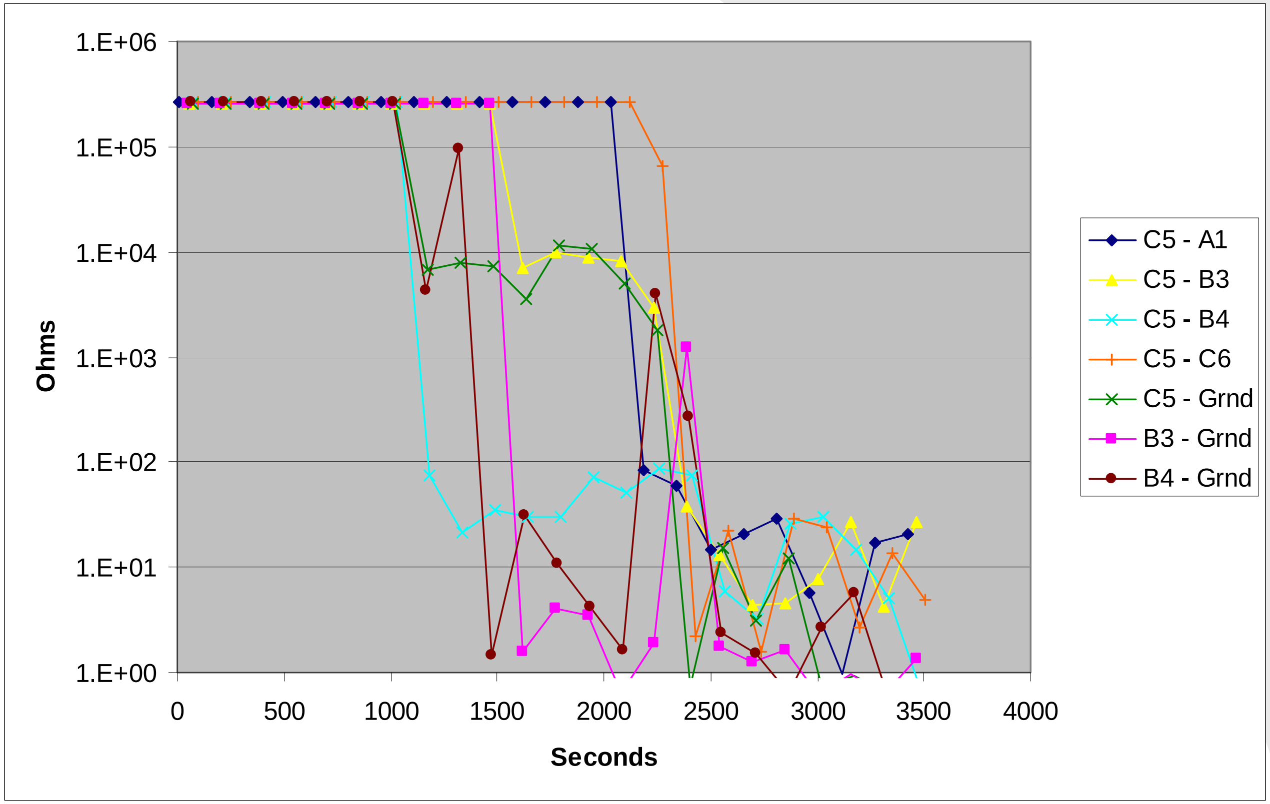
- **Intermediate-scale only: control circuit simulators allow for testing of various circuit configurations**
- **Base configuration is the typical MOV control circuit**
  - **Same as that used in all previous testing by industry**





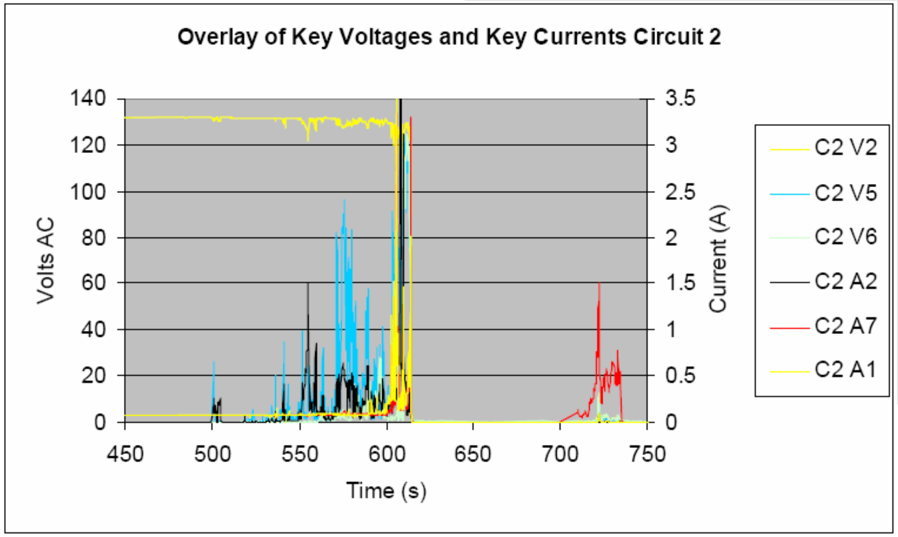
Item A – Thermoset-to-Thermoset

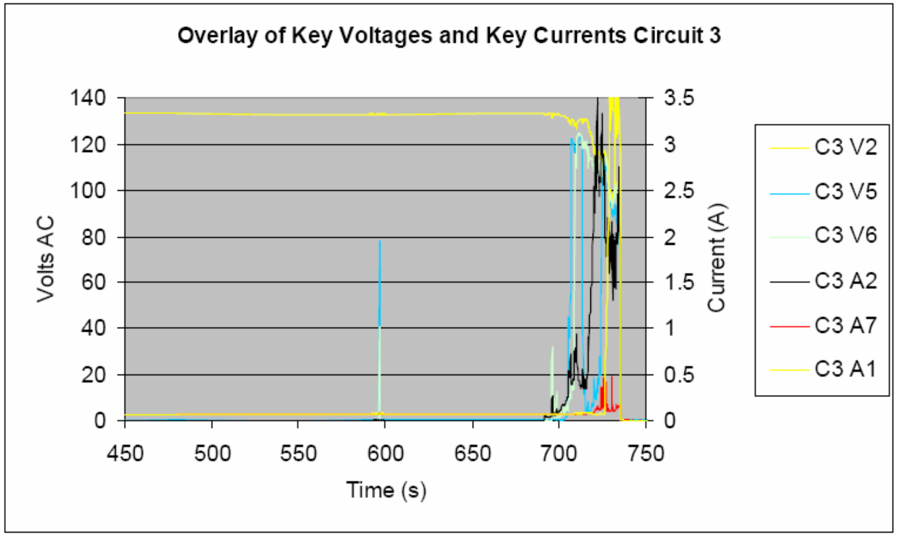
- One solid case of inter-cable shorting as primary failure mode observed on IRMS
- Several cases where inter-cable shorting was secondary or tertiary failure mode on IRMS
- No spurious actuations on the SCDUs



Item B – Thermoset-to-Thermoplastic

- No cases of spurious actuation on SCDUs
- One case of a hot short from a TS to a TP cable
- No cases where inter-cable shorting was primary failure mode for both cables
- One case where inter-cable shorting was secondary mode for one cable, primary for second cable
- Several cases involving secondary/secondary or tertiary failures





Item C: Concurrent for three or more cables

- **Every test program conducted to date has seen as many as four out of four simulated control circuits spuriously actuate, CAROLFIRE included**

- **CAROLFIRE did explore different exposure locations and conditions and this does impact timing significantly**

Item D: Concurrent spurious actuations given properly sized CPT

- CAROLFIRE could not confirm NEI/EPRI results relative to CPTs
  - Testing of larger CPTs
  - No apparent affect on spurious actuations
  - No cases where voltage collapse was thought to have prevented spurious actuation
- What is meant by 'properly sized' is a key question
  - Relay coil pick-up current NOT in-rush
  - May be issue with interpreting manufacturer specs.

Item E: Hot shorts lasting more than 20 min.

- **CAROLFIRE saw no hot shorts lasting greater than 7.6 minutes**
- **NEI/EPRI saw max duration of 11.3 minutes**
- **All data appear to indicate that once cable degradation begins, it will cascade through all modes within a relatively short time**

Public Comment Process

- **There were two sources of public comments:**
  - **Industry comments collected and submitted through NEI**
  - **ACRS review comments were also treated as public comments**
- **Additional NRC staff comments were also addressed in the post-public comment document revision process**

General nature and impact of the public comments

- **The majority of comments were editorial in nature**
  - **All of these were accepted and the report revised accordingly**
- **Some comments (from both the ACRS and industry) suggested expanded data analysis and reporting**
  - **These comments were accepted and addressed within the limits allowed by scope and funding constraints.**
  - **Not all comments could be addressed, but several significant report additions and enhancements were implemented. (Examples are provided in following slides.)**
  - **One issue here was that SNL's role *explicitly excluded* data analysis beyond the needs of the Bin 2 items and the needs of data dissemination.**
  - **While the analysis and presentation of test data has been expanded in key areas, some suggestions for additional data analysis had to be deferred to future efforts.**
  - **NIST and UMd are also explicitly contributing to further data analysis, application, and interpretation.**

General nature and impact of the public comments (2)

- **Certain comments (from industry) asked for clarification as to how the results would be interpreted in a regulatory context or how they would impact future regulatory applications and positions**
  - **Such decisions lie outside the scope of a RES project and could not be addressed via the NUREG/CR revision**
  - **These comments have been forwarded to NRR for their consideration**

Significant report revisions that resulted from the public comment process

- The Foreword was modified in its discussion of the potential risk significance of spurious actuations
  - Words added that these might be risk-significant "under certain conditions"
- All of the data plots have been revised so that the exposure/fire start at time zero
  - This was a time/data offset issue that the RES staff helped resolve
  - Adds to consistency of the report with regard to test sequences and event timing

Significant report revisions that resulted from the public comment process (2)

- **Clarification was provided relative to the term "risk-relevant" and its intent as used in the report**
  - **This term had been used a number of times in the report (e.g., "risk-relevant conductor interactions)**
  - **The phrases meaning was questioned by industry**
  - **Report clarifies that intent was *not* to say "risk-significant" but rather, to identify factors or configurations that could have a bearing on a fire PRA circuit failure modes and effects analysis**

Significant report revisions that resulted from the public comment process (3)

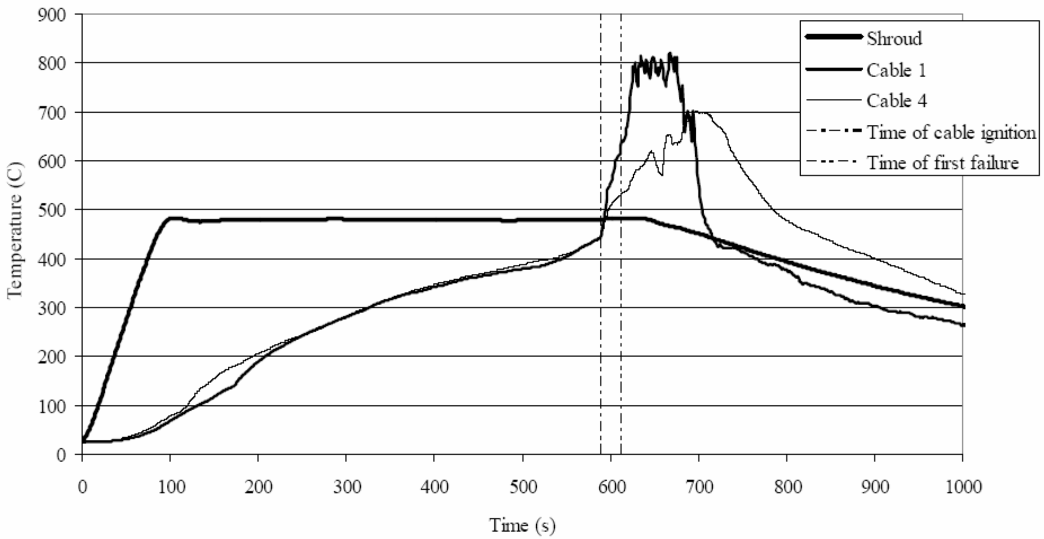
- The "cable physical characteristics" table was expanded to include quantitative copper/plastic ratios
  - Values had been gathered by NIST for their work and these have now been imported into the SNL reports
- Unfortunately, thermal (heat transfer) properties are not available for the materials and could not be provided
  - Manufacturers are typically not concerned with heat transfer behaviors at this level (e.g., thermal conductivity, heat capacity, thermal diffusivity)
  - Material formulations are held as proprietary information by manufacturers
  - NIST work appears to show that generic material properties for (e.g., Hilado's Flammability Handbook for Plastics) work quite well in their modeling

Significant report revisions that resulted from the public comment process (3)

- A summary table of the Penlight (small-scale) test results has been added
  - The table provides time to electrical failure results for each test and, where possible*, correlates temperature response data and reports cable sub-jacket temperature at time of failure

    *in some cases cables ignited prior to failure so temperature at failure time is not considered reliable
- New plots that provide overlays of cable thermal response and electrical performance data
- Three new plots illustrating the results from the temperature at failure time data from the new summary table

Examples of New Data Plots



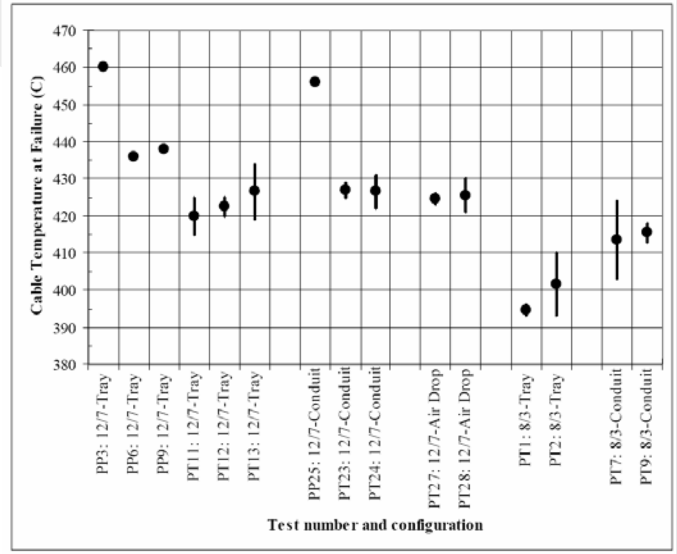


Figure 5.31: Compilation of test results for the XLPE-insulated cables.

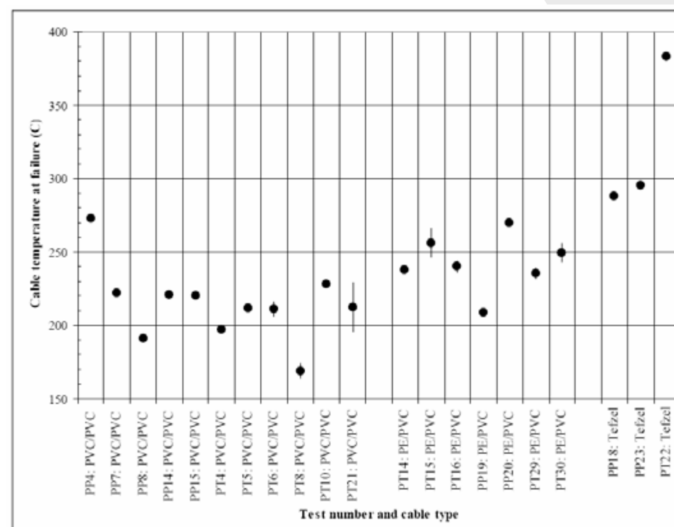


Figure 5.32: Compilation of the test results for the TP cable types.

Significant report revisions that resulted from the public comment process (4)

- Additional discussions have been added relative to the use of cables as thermal targets and the potential for analyzing these data to estimate net fire-to-cable heat transfer
  - Unfortunately, available scope did not allow SNL to actually perform the required calculations
- Additional discussions added relative to the “pulsing” behavior of the gas burner to clarify that this is an anticipated and expected behavior for a gas diffusion burner operating in the turbulent regime
- Some additional discussion of burner efficiency as an uncertainty factor have been added

Summary

- **CAROLFIRE has contributed to two critical need areas:**
  - **Resolution of deferred spurious actuation circuit configurations**
  - **Improving the fire modeling of cable response and failure**
- **Status of publications:**
  - **SNL's two-volume test report is in final stage of publication process**
    - **Public comments have been addressed**
    - ***All* of the raw and processed data is being included with the published report**
  - **NIST has drafted a "third volume" documenting their fire modeling work**
    - **See the following presentation for more on NIST's efforts**
  - **UMd has published at least one PhD thesis based on the CAROFIRE project**

Summary (2)

- **CAROLFIRE represents a “gold mine” that the fire protection community world-wide will likely be mining for many years to come**
- **There is a wealth of data now available to support additional analysis and additional developments in the fire modeling arena – we have only scratched the surface!**
- **All of the CAROLFIRE test data is being included along with SNL’s final report (both the raw and processed data files)**