

Response Bias of Electrical Cable Coatings at Fire Conditions and Aged Cable Coating Research

RES/DRA/FXHAB

Presented by:

Adam Lee

Gabriel Taylor, P.E.

ADAMs Accession No. ML25191A208

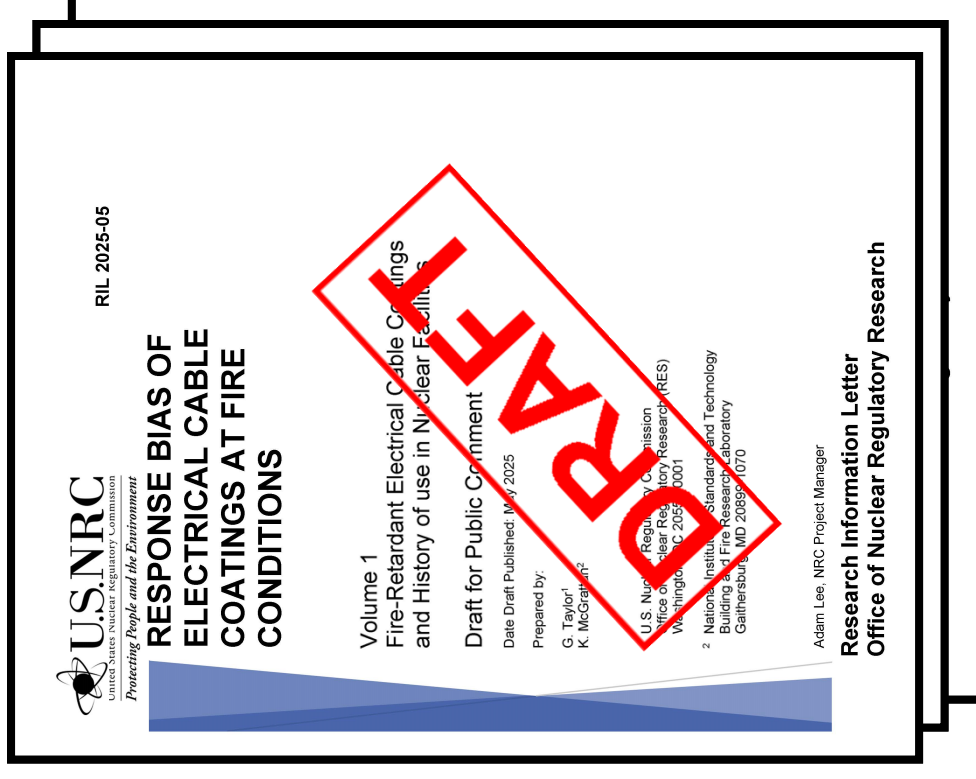
July 14, 2025

Agenda

<i>Time</i>	<i>Topic</i>	<i>Speaker</i>
9:00 AM	Introduction	NRC
9:15 AM	Fire-Retardant Electrical Cable Coatings and History of use in Nuclear Facilities (Vol. 1)	NRC
9:30 AM	Q&A for Volume 1	All
9:45 AM	Fire Properties of Cables (Vol. 2)	NRC
10:00 AM	Q&A for Volume 2	All
10:15 AM	Cable Functionality (Vol. 3)	NRC
10:45 AM	Q&A for Volume 3	All
11:00 AM	Aged Cable Coating Research	NRC
11:30 AM	Q&A for Aged Cable Coating Research	All
11:45 AM	Closing Remarks	NRC

Project Overview

- Phase 1
 - Draft Research Information Letter (RIL) for stakeholder feedback
 - Volume 1 : Fire-Retardant Electrical Cable Coatings and History of use in Nuclear Facilities
 - Volume 2 : Fire Properties of Cables
 - Volume 3 : Cable Functionality
 - Final publication of RIL
 - Draft Research Project Plan for Aged Cable Coatings
- Phase 2
 - Testing and Draft Aged Cable Coating RIL



Project Overview

- Phase 3
 - Use unaged and aged data to develop/update fire PRA methodology with EPRI
 - NUREG/CR-6850 Appendix Q
- Phase 4
 - Publish aged cable coating research in a RIL
 - Publish methodology update report to NUREG/CR-6850 Appendix Q

Volume 1: Fire-Retardant Electrical Cable Coatings and History of use in Nuclear Facilities

Short History: Non-Nuclear

Expanded use of electrical cables and fire hazard

- 1800's, Cable development
 - Electric telegraph and power industry
 - Mining industry focused on cable coatings after large losses
 - 1917 Granite Mountain Copper Mine (168 fatalities)
 - Natural resins were preferred material
 - Flammability was a concern
 - Fire incidents indicated that insulation contributed to fire growth
- Late 1800's
 - Asbestos started to be used as component to reduce hazard (marketed as “non-ignitable”)

Short History: Non-Nuclear

Use of fire-retardant coatings

- 1891 - Isaac Merrell patented a fireproof paint product composed of pulverized ceramics and asbestos
 - 1906 - First documented health concerns from asbestos
 - 1973 Environmental Protection Agency (EPA) passed a law to limit asbestos use
 - 1930s - Polyvinyl chloride (PVC) was invented (cheap and easy to produce)
 - Polychlorinated Biphenyl (PCB) added to polyvinyl chloride insulated cables to increase resistance to heat and flame
 - 1979 EPA issued regulation to ban PCB use
-

Short History – US Nuclear

Need to reduce combustible loading

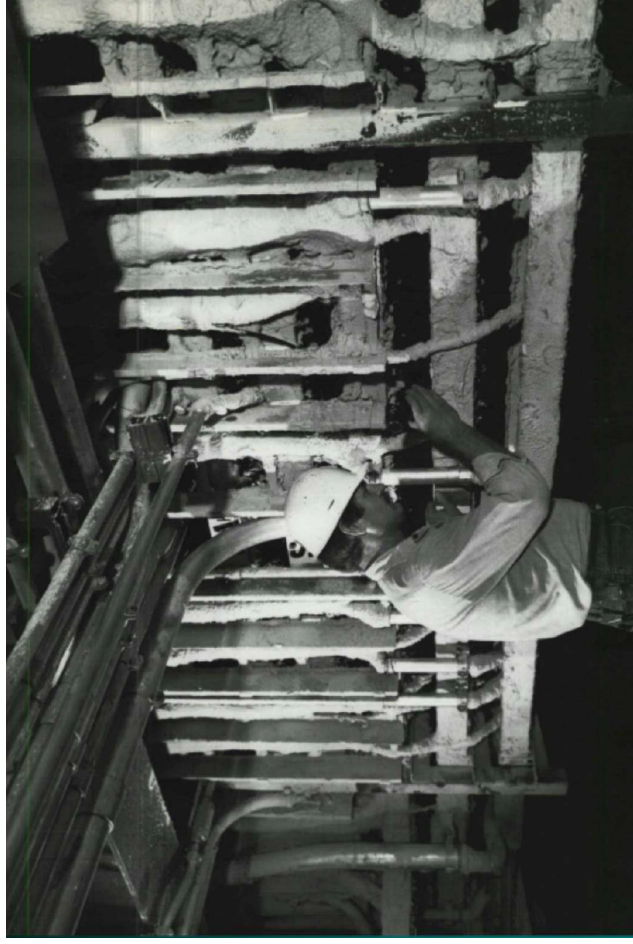
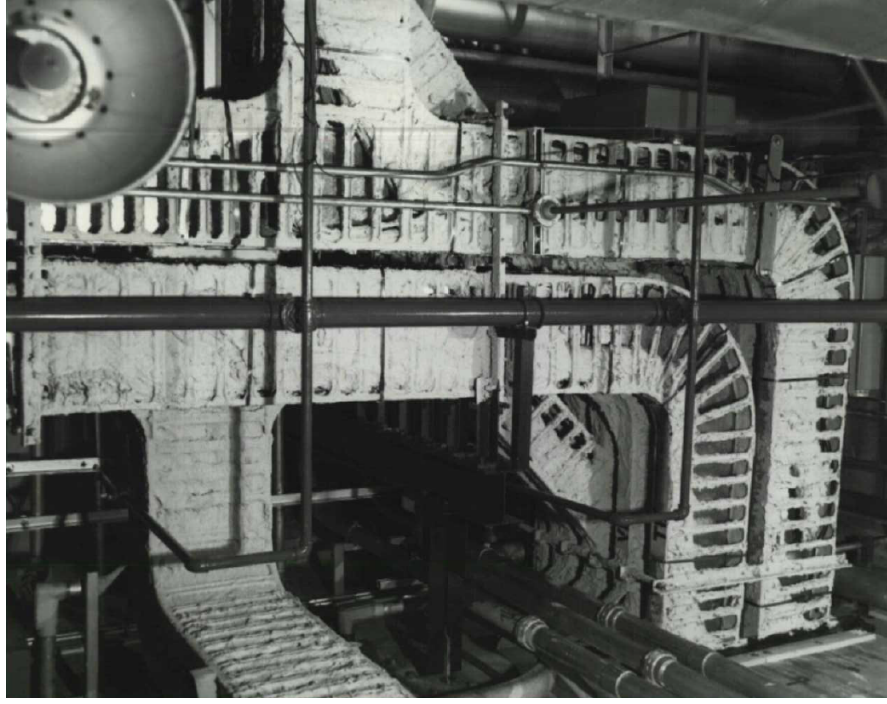
- 1975 – Brown Ferry Nuclear (BFN) Fire
 - Special Review Group (NUREG-0050)
 - Suggested use of **fire-retardant coatings**
- 1976-1980
 - Development of Branch Technical Positions (BTPs) per recommendations from special review group
 - Research: Sandia National Laboratories and BFN cable fire tests
- 1998: SECY 98-058: alternative performance-based fire protection
 - 2004 Rulemaking to endorse NFPA standard as alternative
- 2005 – NUREG/CR-6850 Fire PRA Methodology,
Appendix Q: Passive Fire Barriers



Brown Ferry Nuclear (BFN) Plant

Short History – US Nuclear

Installation of Fire-Retardant Coatings

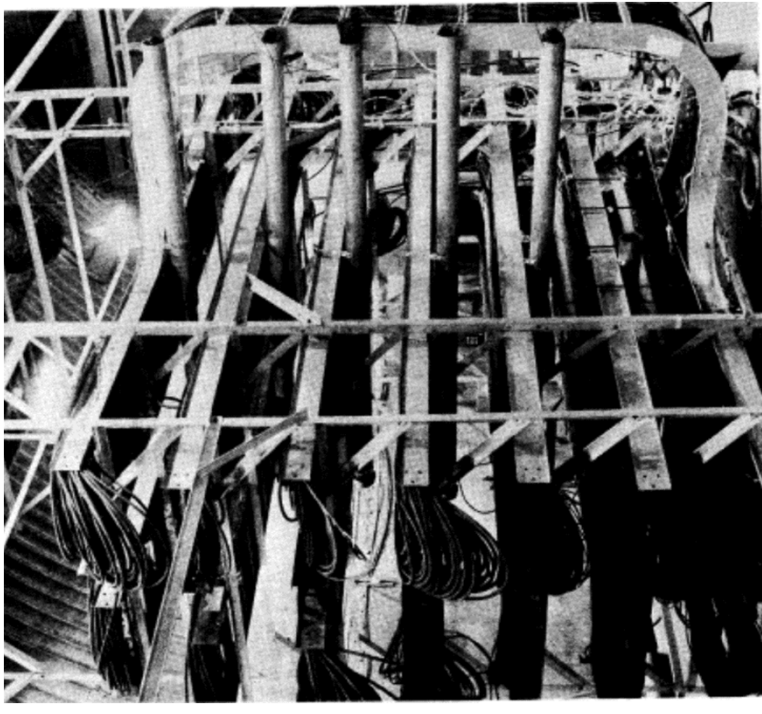


Post BFN fire, fire retardant cable coatings installed in cable tray (left) and being inspected (above).

Short History – US Nuclear

Fire Protection Research Program, 1975 - 1987

- Confirm regulatory guidance
 - Cable separation
 - IEEE 384
 - Cable coating research
 - SAND 77-1424
 - SAND 78-0518
 - NUREG/CR-0381
 - NUREG/CR-0366



Full-scale test apparatus.

Regulatory Guidance

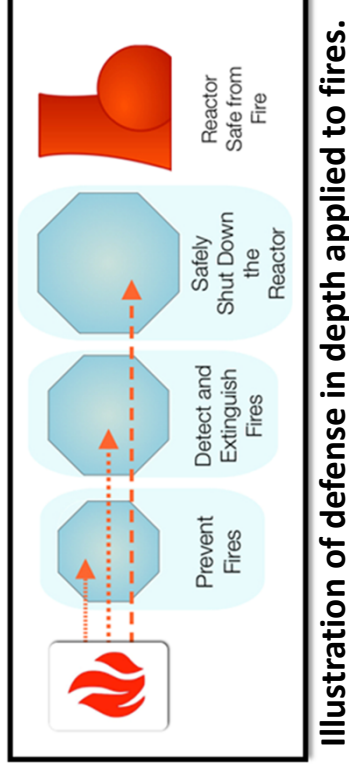
What prompted the use of fire-retardant coatings

- BTP APCSB 9.5-1 “Guidelines for Fire Protection for Nuclear Power Plants”
 - Refers to IEEE 383 flame test criteria, as minimum
- Appendix A to BTP APCSB 9.5-1 also stated
 - If IEEE 383 flame test criteria can not be met, all cable must be covered with an approved fire retardant coating
- NUREG-800 – Standard Review Plan
 - Refers to IEEE 383 flame spread criteria or IEEE 1202
- Regulatory Guide 1.189
 - Refers to IEEE 383 flame spread criteria or IEEE 1202

US NRC Fire Protection Regulations

10 CFR 50.48

- Title 10 *Code of Federal Regulations* (10 CFR)
 - Appendix A to Part 50: General Design Criteria, Criterion 3 “Fire Protection”
 - 50.48 “Fire Protection”
- Deterministic Fire Protection Plan
 - 10 CFR 50.48(b)
 - Appendix R to 10 CFR 50
- Performance-Based Fire Protection Plan
 - 10 CFR 50.48(c), National Fire Protection Association Standard NFPA 805, 2001 edition
 - Alternative regulation for meeting deterministic regulations or license conditions
 - NRC incorporated NFPA 805 2001 edition by references, *with exceptions, modifications, and supplementation*



Regulatory Exception to NFPA 805

Existing cables and cable coatings

- Exception “v”
 - *Existing cables*. In lieu of installing cables meeting flame propagation tests as required by Section 3.3.5.3 [of NFPA 805], a flame retardant coating may be applied to the electric cables, ..., to provide an equivalent level of protection. In addition, the italicized exception is not endorsed.
- 3.3.5.3 specifies that electric cables shall meet flame propagation tests as specified by AHJ
- Annex 3.3.5.3 identifies recognized flame spread tests, such as
 - IEEE 817, Standard Test Procedure for Flame-Retardant Coatings Applied to Insulated Cable in Cable Trays [IEEE Withdrawn]
 - IEEE 1202, Standard for Flame Testing of Cables for Use in Cable Tray and Industrial and Commercial Occupancies

Fire probabilistic risk assessment (PRA)

Supports use of NPFA 805 via risk evaluations

- NUREG/CR-6850 (EPRI 1011989)
 - Joint technical document presenting methods to perform Fire PRA.
- Appendix Q, *Passive Fire Protection*
 - Diesel Pool Fire Tests
- Guidance

- Ignition at 12 minutes
- Cable Damage
 - 3 minutes for severe exposure
 - 10 minutes for cable tray

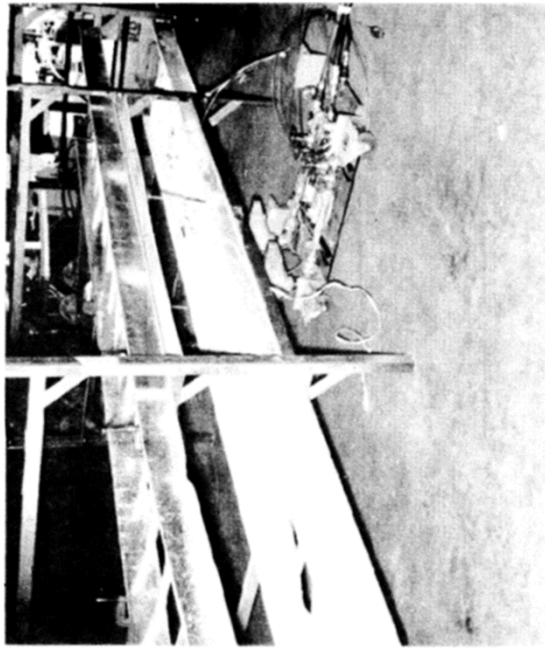
Table Q-1 of NUREG/CR-6850

Time to Ignition (min)	Time to Damage (min)
13	10
13	6
12	3
No	10
12	11
No	11
No	11
12	7
No	19
12	11

Research Need

Why perform this research?

- NUREG/CR-6850 based on limited dataset
 - SNL diesel pool fire tests from the 1970's
- Expand flame retardant materials performance data
 - Burning behavior
 - Electrical functionality response



Full-scale single-tray test apparatus.

Testing Approach

- Volume 2: Fire properties of cables
 - Thermal response
- Volume 3: Cable functionality
 - Electrical response

Questions for Volume 1

Meeting Feedback

<https://feedback.nrc.gov/pmfs/>

Meeting Code: 20250771

Contact:

Gabriel.Taylor@nrc.gov

Adam.Lee@nrc.gov

ADAMs Accession No. ML25191A208

Volume 2 : Fire Properties of Cables

Coatings

What materials were evaluated? Why?

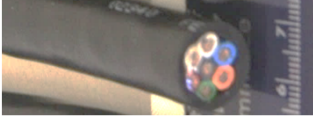
- Coating A (Carboline Intumastic 285)
 - Intumescent
- Coating B (Flamemastic F-77)
 - Thermoplastic resin
- Coating C (Vimasco 3i)
 - Ablative
- Coating D (Fire Security FS15)
 - Water based mastic



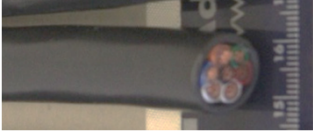
Electrical Cables

What is the base configuration (control)

Cable No.	Insulation Material	Jacket Material	Class	Year Manufactured	Description
#802	XLPE	CSPE	Thermoset (TS)	2006	Qualified, 7-conductor cable
#807	PE	PVC	Thermoplastic (TP)	2006	Unqualified, 7-conductor control cable
#813	XLPE	CSPE	Thermoset (TS)	2006	Qualified**, 12-conductor cable
#900	PE	PVC	Thermoplastic (TP)	2015	Unqualified, 7-conductor control cable
#902	PE	PVC	Thermoplastic (TP)	1975	Unqualified, 3-conductor cable
*Other cables have been evaluated under past NRC research programs.					
**Qualified cables - pass the flame test of the Institute of Electrical and Electronic Engineers (IEEE) standard IEEE 383-1974					



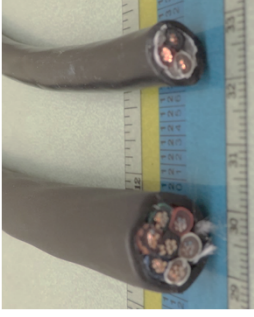
#802



#807



#813



#900

#902

Testing Approach - Small Scale Tests

What was done and how will results be used

- Thermogravimetric analysis (TGA) (Vol 2)
 - Fire properties of cables with/without coatings – Vol 2
- Calorimetry (micro-combustion and cone calorimetry)
 - Fire properties of cables with/without coatings – Vol 2
- Furnace ignition tests
 - Ignition temperature – Vol 2
- Circuit integrity test (IEC 60331-11)*
 - Cable time to circuit failure and thermal failure temperature – Vol 2, Vol 3



Cable 802 coated with Flamemastic F-77.



The completed assembly for uncoated cables.

* Modified version of standard test

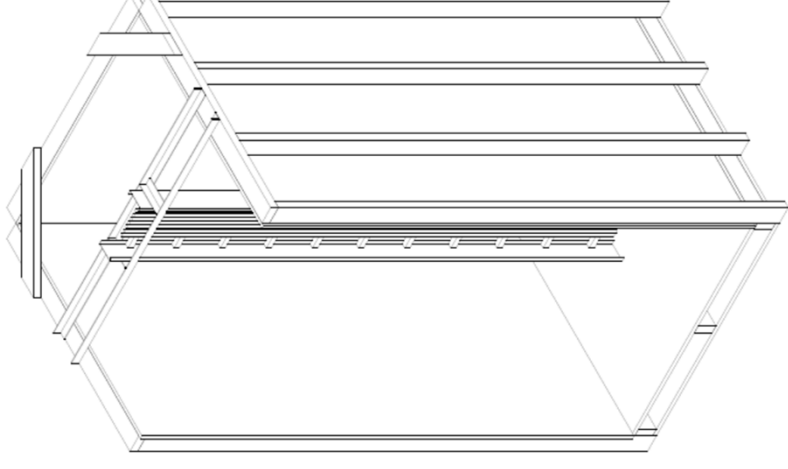
Testing Approach - Full Scale Tests

What was done and how will results be used

- Penlight apparatus radiant heat test
 - Cable time to circuit failure and thermal failure temperature – Vol 3
- Vertical flame spread test (IEEE 1202-1991)*
 - Flame spread distance – Vol 2
- Multi-tray horizontal test
 - Cable time to circuit failure and thermal failure temperature – Vol 2, Vol 3



Typical configuration of uncoated cables attached to a tray.



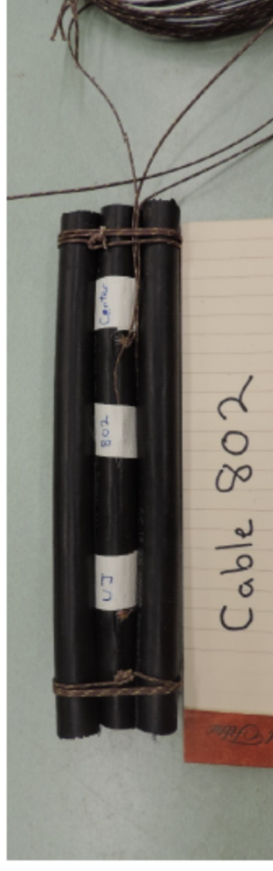
Drawing of the vertical flame experiment apparatus.

* Modified version of standard test

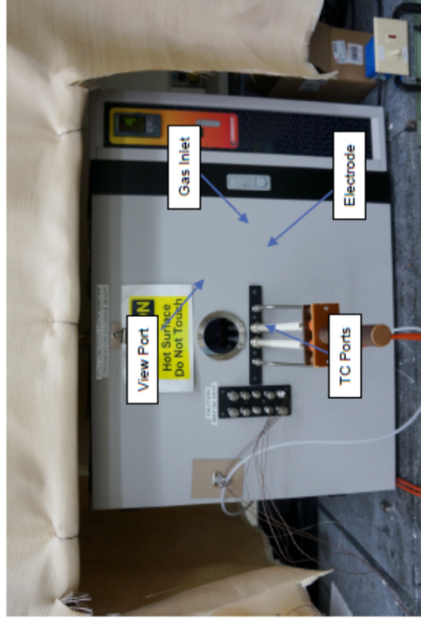
Measurements

Thermal

- Heat of combustion, ΔH_c (MJ/kg)
- Specific heat, c (J/g*K)
- Thermal conductivity, k (W/m*K)
- Reaction rate and char yield
 - ASTM E1131 (TGA)
 - ASTM D7309-13 (MCC)
- Heat release rate
 - ASTM D 6113-03 (Cone calorimetry)
- Ignition temperatures
 - Cable temperatures (beneath cable's outer jacket)



Instrumentation of a cable segment for an uncoated experiment.

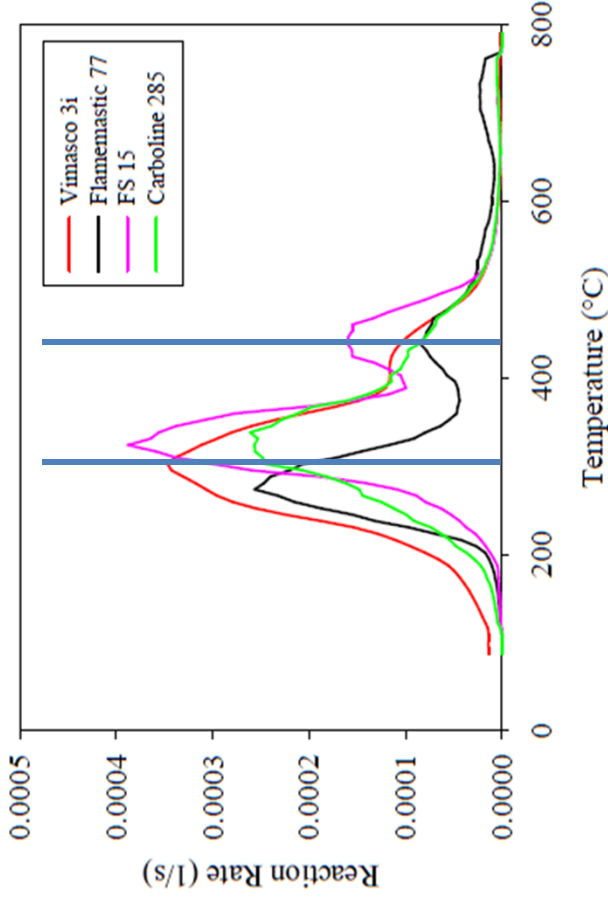


Oven exterior showing electrodes, gas inlets, and thermocouple wire ports.

Observations – Cable Coatings

TGA, Microcombustion Calorimetry

- The first at approximately 300°C (572°F).
- The second at approximately 450°C (842°F).
- Coatings do burn and leave a relatively large amount of residue.



TGA results for the cable coatings, expressed in terms of reaction rate.

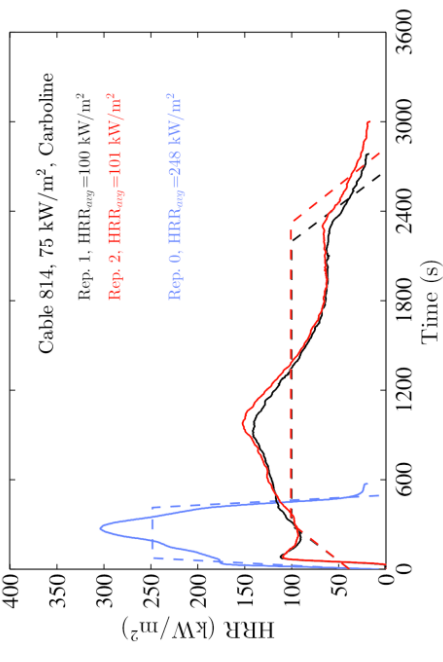
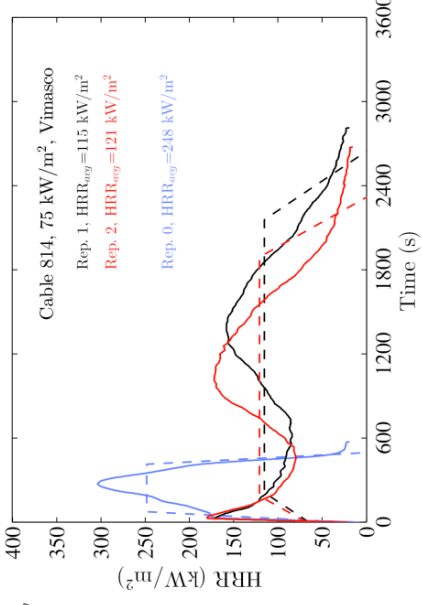
Material	Heat of Combustion (kJ/g)	Char Yield (%)
Carboline 285	16.5 ± 0.1	50.5 ± 0.4
Vimasco 3i	15.4 ± 0.3	26.4 ± 0.3
Flamemastic 77	12.0 ± 0.2	56.9 ± 0.8
FS15	17.6 ± 0.4	47.4 ± 0.3

Heat of combustion and char yield with standard uncertainty.

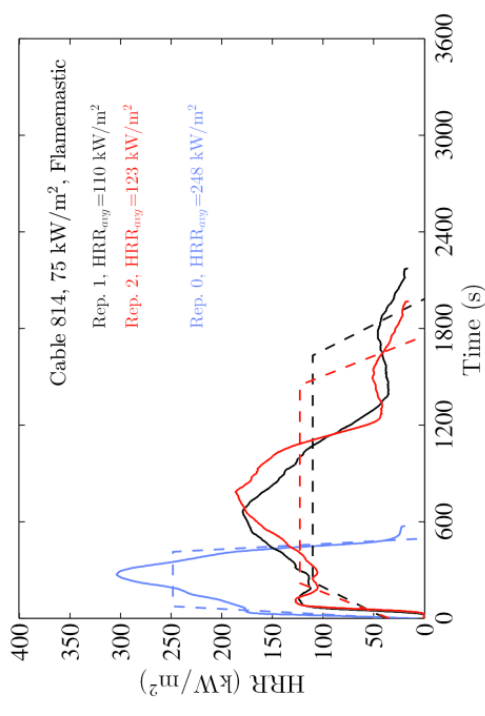
Observations – Coated vs Uncoated Cables

Cone Calorimetry

- Doubled the ignition time.
- Halved the peak HRR.
- Doubled the total energy released.



Cone calorimeter results for cable 814. Rep. 0 denotes the uncoated sample.



Observations – Ignition Temperature for Coated vs Uncoated Cables

Furnace

- Uncoated thermoplastic cables ignited at temperatures around 300°C (572°F).
- Uncoated thermoset cables ignited around 400°C (752°F).
- Coatings did not necessarily raise ignition temperature.

Table 5-1. Summary of cable surface ignition temperatures—high temperature.

Cable #	Manufacturer	Insulation	Jacket	T _{ig} (°C)
802	Rockbestos	XLPE	CSPE	429
805	Cable USA	Tefzel	Tefzel	474
806	Rockbestos	XLPE	XLPO	435
809 x2	First Capitol	SR	Aramid Braid	410
811	Rockbestos	XLPE	CSPE	420
813	Rockbestos	XLPE	CSPE	428
817	Rockbestos	XLPE	CSPE	428
818 x2	Rockbestos	PE	PVC	408
819	First Capitol	SR	Glass Braid	472
823 x6	Rockbestos	XLPE	-	428

Table 5-2. Summary of cable surface ignition temperatures—low temperature.

Cable #	Manufacturer	Insulation	Jacket	T _{ig} (°C)
807	General Cable	PE	PVC	292
808	Rockbestos	VITA-LINK	VITA-LINK	362
812	Rockbestos	XLPE	CSPE	338
816	Rockbestos	XLPE	CSPE	333
817 x2	Rockbestos	XLPE	CSPE	344
844	General Cable	PVC	PVC	285

Observations

Vertical Flame Spread Test (IEEE 1202-1991)

- 20 kW burn test.
- Undersized coating thickness led to upward fire spread.
- Properly applied coatings prevented repeat of fire behavior.



Photograph of experiment I-8, cable 900 coated with FS15.

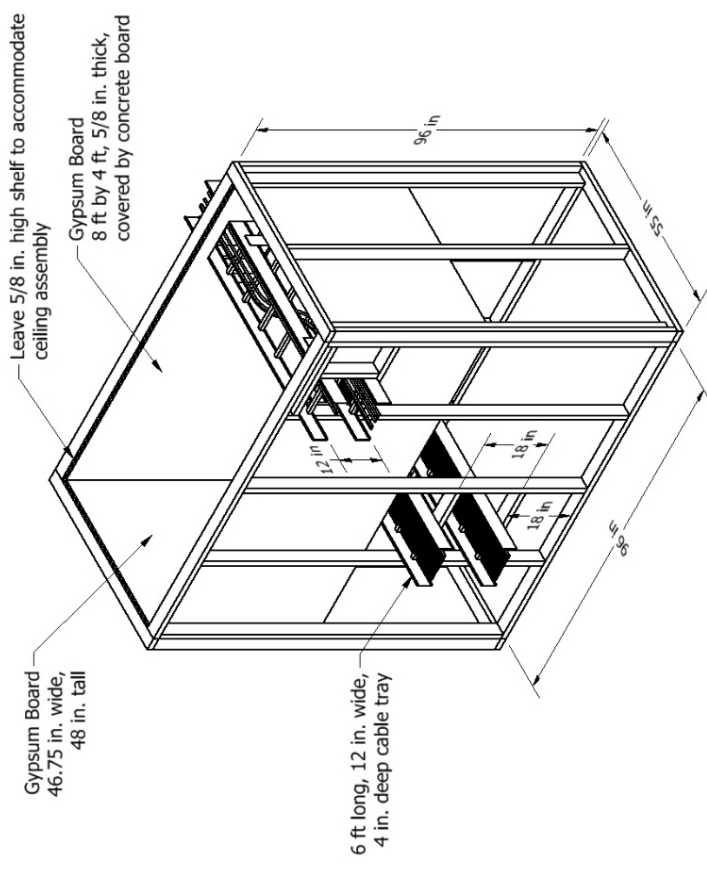


Photograph of experiment I-4, cable 900, uncoated.

Observations

Full-Scale Horizontal Tests

- Average interior cable temperature at the time of failure was approximately 300°C (572°F).
- Range of failure temperatures was considerable.
 - Less than 200°C (392°F) to over 500°C (932°F).
- Cables in Tray 3, immersed in the hot gas layer, tended to fail at lower temperatures than the cables in Trays 1 and 2.



Compartment to be used for the horizontal cable experiments.

Conclusions – Fire Properties

- Uncoated thermoplastic cables ignited at temperatures about 300°C (572°F).
- Uncoated thermoset cable ignited at about 400°C (752°F).
- Coatings decrease the peak burning rate and increase the total energy released (i.e., coatings do add to the fuel load).
 - The amount of additional energy released due to the application of coatings is negligible.
- Coatings **did not** systematically increase the effective ignition temperature of the cables.
 - Rather increased delay time to reach the ignition temperature.
- Coatings prevented the upward spread of fire from the 20 kW burner when applied according to the manufacturers' recommendations.

Questions for Volume 2

Meeting Feedback

<https://feedback.nrc.gov/pmfs/>

Meeting Code: 20250771

Contact:

Gabriel.Taylor@nrc.gov

Adam.Lee@nrc.gov

ADAMs Accession No. ML25191A208

Volume 3 : Circuit Integrity

Measurements

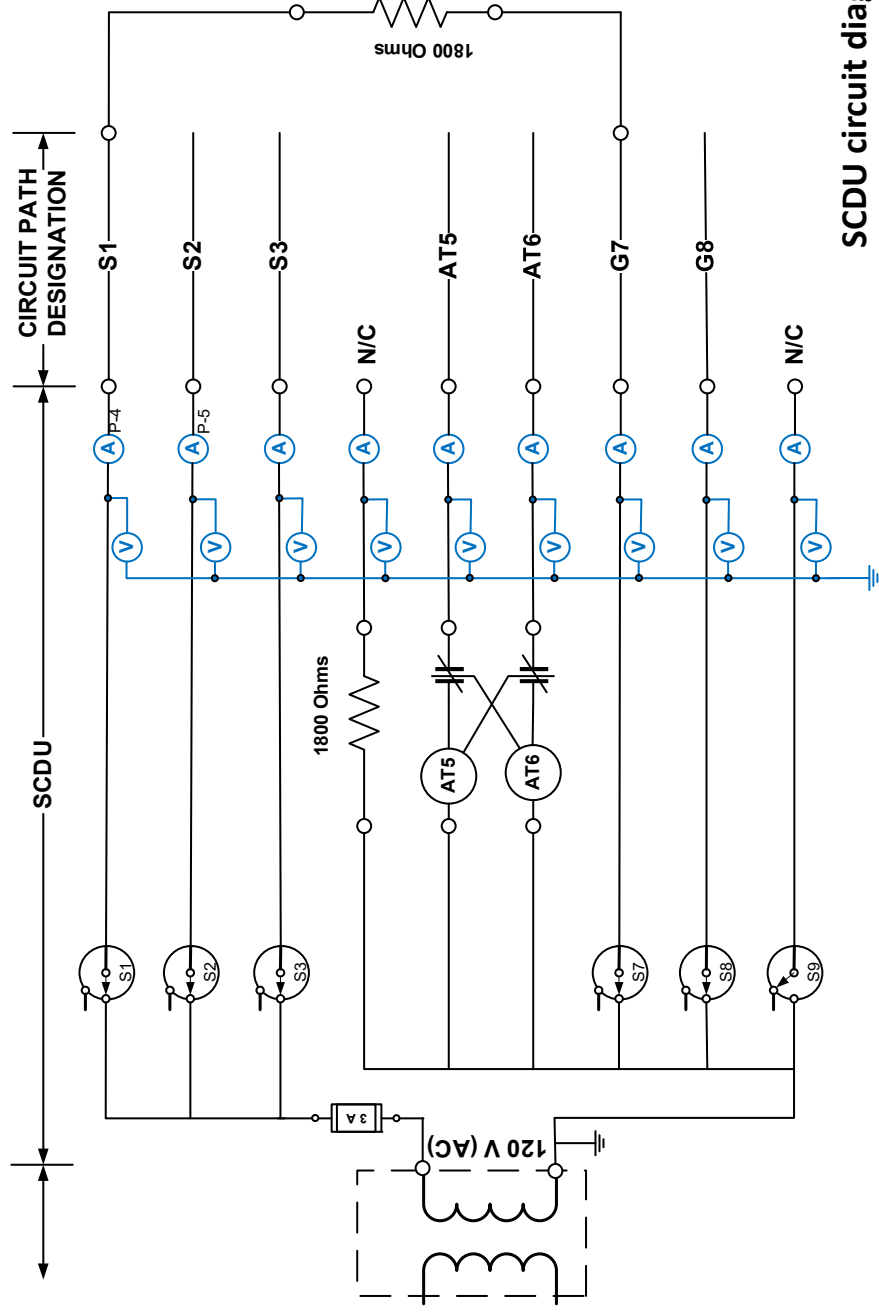
Electrical

- Insulation Resistance Measurement System (IRMS).
- Surrogate Circuit Diagnostic Unit (SCDU)



Experiment configuration: SCDU (left); data acquisition (right); experiment 3 assembly (background).

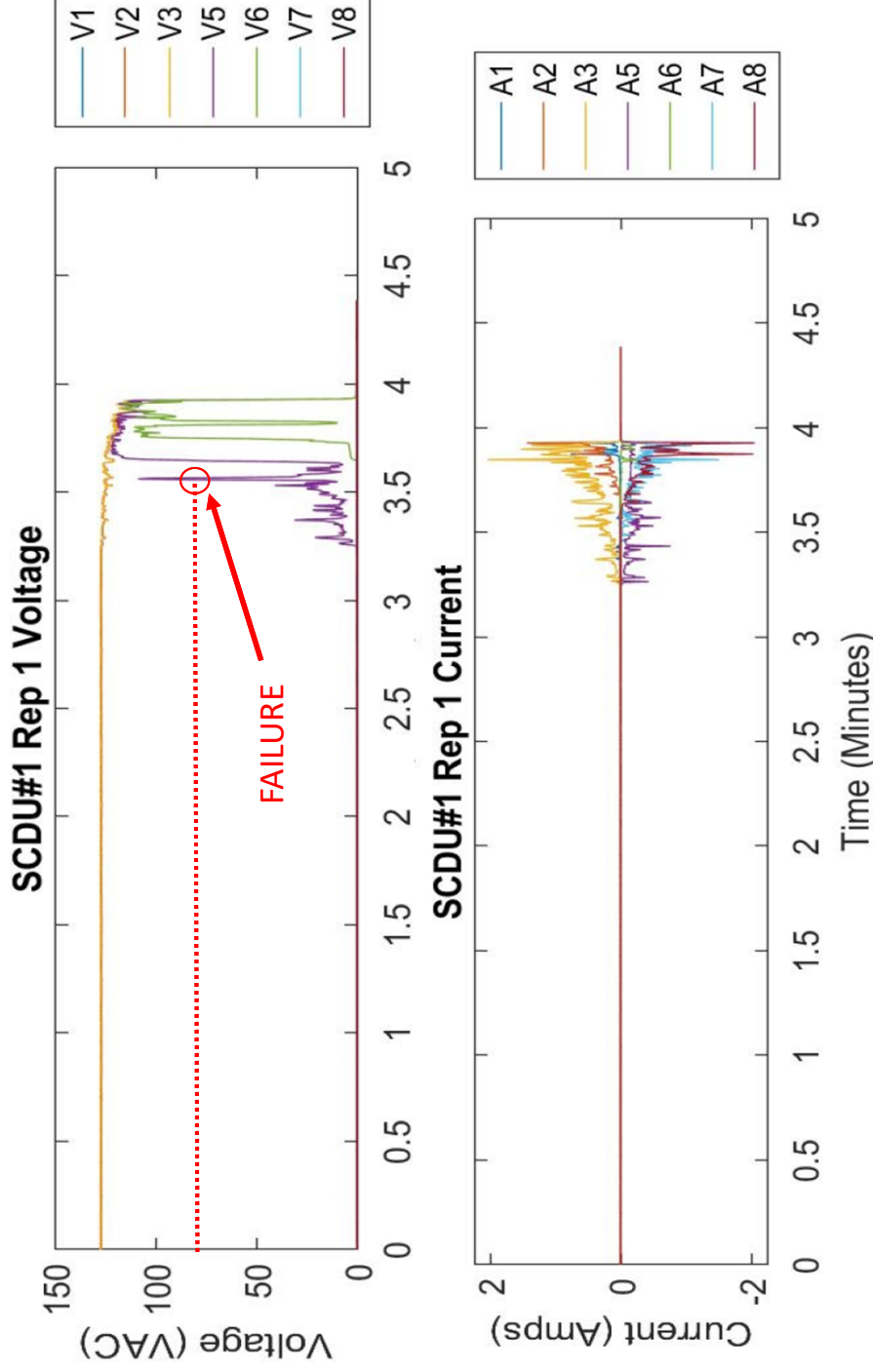
SCDU – MOV control circuit



SCDU circuit diagram

Failure Data

Spurious Operation, Circuit Failure



Experiment configuration BSCI-10—bare cable—cable 813—thermoset—replicate 1.

Bench-Scale Tests

IEC 60331-11



Photograph of a typical circuit integrity experiment.

Observations – Coating Thickness

Thermoplastic – IEC 60331-11

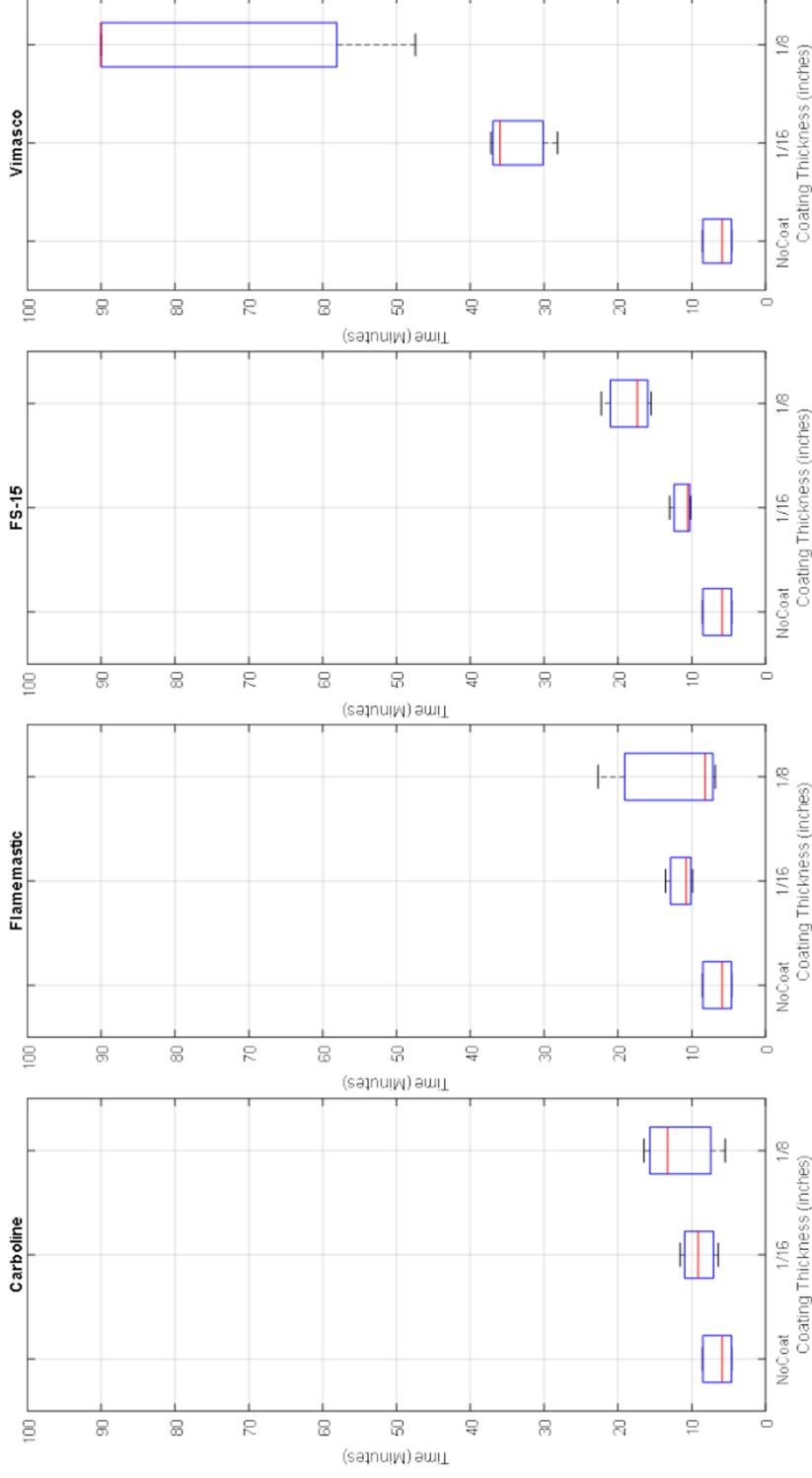


Figure 5-1. Time-to-failure box plots of IEC 60331 for TP-insulated cable 900 coating material and coating thickness.

Added thickness above the vendor's recommended minimum 'typically' resulted in an additional delay in time to failure.

Observations – Coating Thickness

Thermoset – IEC 60331-11

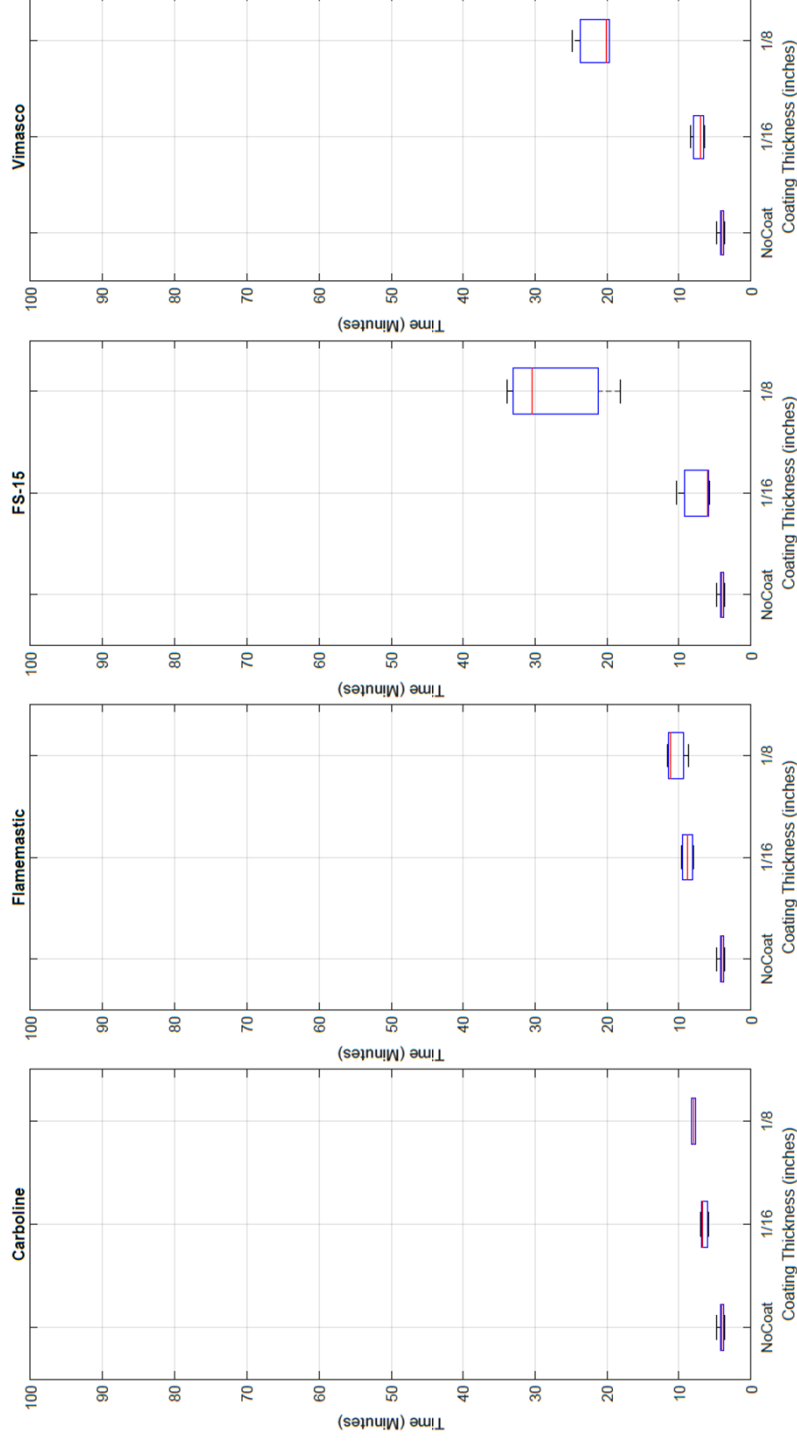


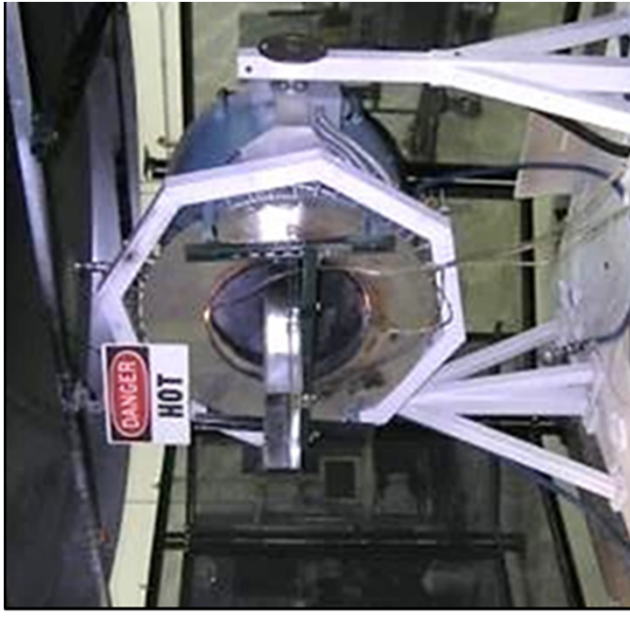
Figure 5-2. Time-to-failure box plots of IEC 60331 for TS-insulated cable 813 coating material and coating thickness.

Added thickness above the vendor's recommended minimum 'typically' resulted in an additional delay in time to failure.

Observations – Radiant Heat

Penlight Apparatus

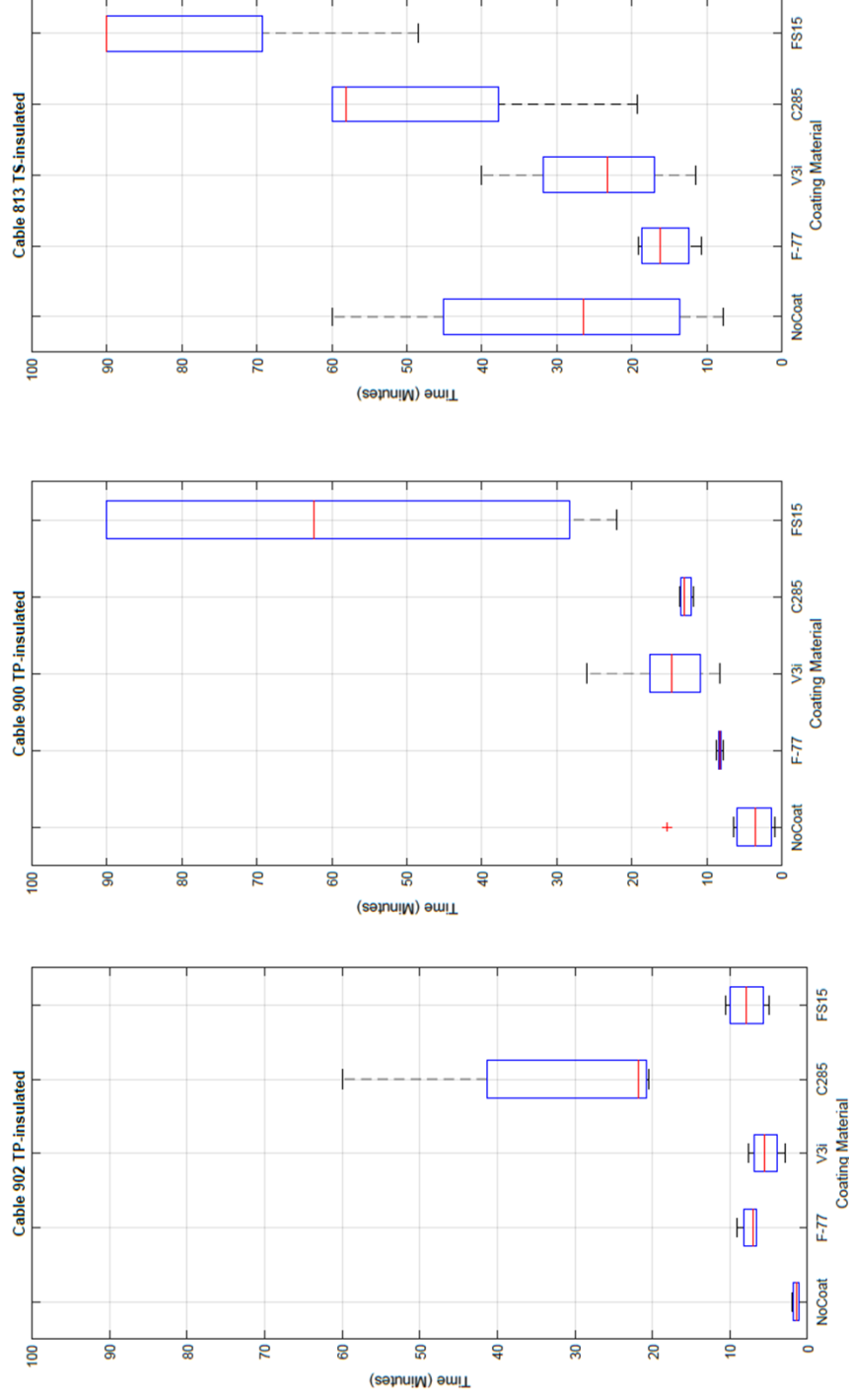
- Coated samples had little to no delay in electrical failure time when compared to the uncoated sample failure time.
- TP cables showed little degradation until their insulation and jacket materials melted.
 - Corresponds with the point of electrical failure.
- TS coated cable assembly was heated and expanded, cracks in the coating developed.
 - Resulted in better heat transfer.



Penlight apparatus.

Observations – Vertical Tests

Circuit Integrity

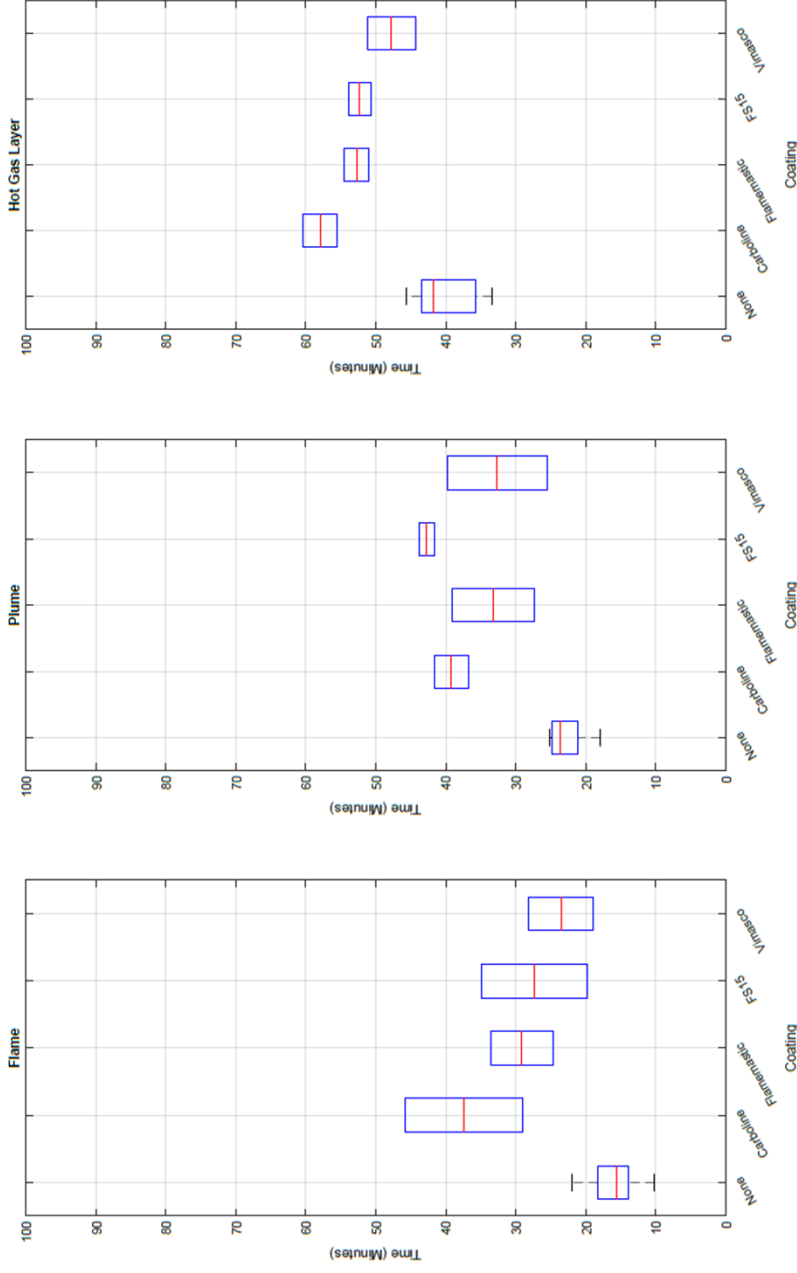
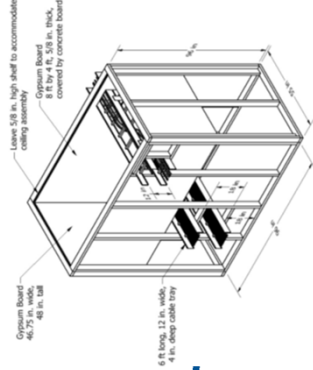


Time-to-failure box plots of IEEE Standard 1202 experiments.

Observations

Full-Scale Horizontal Tests

- The full-scale series consisted of eight experiments. In each experiment, 12 cables were
- monitored for electrical functionality.
- In all instances, the cables under experiment failed electrically.



Results multilayer nonqualified (cable 900).

Schematic diagram of the full-scale horizontal flame spread experiment.

Conclusions – Cable Functionality

- **Delay in time to damage**
 - Nonqualified electrical cables coated with a fire-retardant cable coating demonstrate a delay in time to damage, regardless of coating type.
 - Qualified electrical cables coated with a fire-retardant cable coating demonstrated mixed results.
 - Bench-scale tests demonstrated a delay,
 - Full-scale vertical flame spread testing did not demonstrate a delay.
- **Coating thickness**
 - Additional cable coating thickness beyond the manufacturer's specified minimum thickness provides additional delay in time to damage
- **Cable construction**
 - Cable construction attributes such as conductor size, insulation thickness, conductor count, etc., will impact the performance of a cable under fire conditions regardless of coating type.
 - Important to note that the primary qualified and nonqualified cables experimented within this program are of different construction

Questions for Volume 3

Meeting Feedback

<https://feedback.nrc.gov/pmfs/>

Meeting Code: 20250771

Contact:

Gabriel.Taylor@nrc.gov

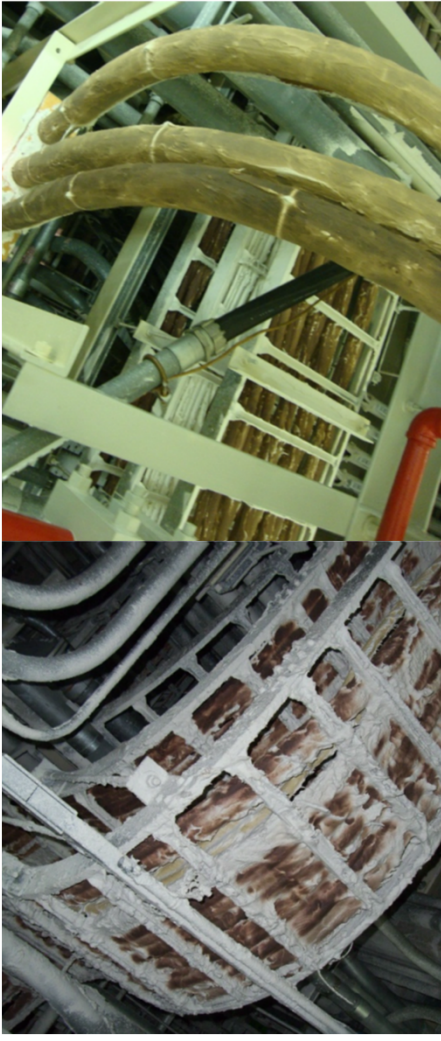
Adam.Lee@nrc.gov

ADAMs Accession No. ML25191A208

Aged Cable Coating Research Plan

Purpose and Use of Results

- Understand the functional performance of aged cable coatings
- Understand the fire protection aspects of aged cable coatings
 - Inform how (aged) cable coatings may be credited in fire PRA
- Update NUREG/CR-6850 Appendix Q
- Not environmental qualification (EQ) testing



Cable coatings showing change from their original white color.

Roles and Responsibilities

Name	Role and Responsibilities	Org.	Contact
Kevin McGrattan	Principle Investigator, Experimental Director	NIST	kevin.mcgrattan@nist.gov
Adam Lee	Project Manager / Test Personnel	NRC	adam.lee@nrc.gov
Gabe Taylor	Circuit Functional Testing / Test Personnel / Data Analysis	NRC	gabriel.taylor@nrc.gov

Schedule and Milestones

1. Finalize Research Project Plant	2. Perform TGA on coatings	3. Determine accelerated age time and temperature and prepare samples	4. Samples aging in the oven				5. Gather Results and Draft Research Information Letter (RIL)	
			At a simulated age of 0 years	At a simulated age 40 years	At a simulated age of 80 years	At a simulated age of 120 years		
			Perform cone calorimetry and circuit integrity test	Perform cone calorimetry and circuit integrity test	Perform cone calorimetry and circuit integrity test	Perform cone calorimetry and circuit integrity test		

Arrhenius Model

$$\frac{t_s}{t_a} = e^{\left(\frac{\Phi}{k}\right)\left(\frac{1}{T_s} - \frac{1}{T_a}\right)}$$

where:

Φ = activation energy (eV) (1 eV = 23.06 kCal/mole)

k = Boltzmann's constant = 8.617×10^{-5} eV/K

t_a = accelerated aging time

t_s = service time being simulated

T_a = aging temperature (K)

T_s = service temperature (K)

Can be used to determine the required accelerated aging time and oven temperature that results in the simulated service time

Aging Considerations

- Simulated age is sensitive to the activation energy
 - Will need the activation energy of the cables and the cable coatings
 - Use the activation energy that yields the minimal target age of both cables and cable aging – ensures conservatism
- Oven temperature
 - Operating service temperature assumption
 - Use an oven temperature close to operating temperature
 - Extends the time in the oven
- Time in the oven

Aged Cable Coating Research

Cable Class/Material	TS/XPLE	TP/PVC		Cable Coating/Carboline Intumescent 285	
Activation Energy (eV)	1.34	1.23		1.19	
	t _a (months)	t _s (years)	t _a (months)	t _s (years)	t _s (years)
	0	0	0	0	0
	6.83	64.4	9.7	11	40
	13.7	128.8	19.4	22	80
	20.5	193.1	29.1	33	120

Assumed T_s = 90 °C (403 K)

Assumed T_a = 130 °C (363 K)

*Values are fictitious to illustrate activation energy conservatism.

Aged Cable Coating Research

- Obtain activation energy
 - Obtain activation energy of coatings using TGA
 - Obtain activation energy of cables from manufacturer and/or literature review
- Perform two tests on specimen
 - Cone calorimetry
 - Bench-scale circuit integrity test
- Specimen
 - Two sets cables (TS and TP)
 - Each set of cables (4 coatings + 1 bare)
 - Repeat for unaged, 40, 60, 80, 120 year* accelerated aged cables

	Cable A	Cable B
Class	Thermoset (TS)	Thermoplastic (TP)
Insulation Material	XPLE	PVC
Jacket Material	CSPE	PVC
Number of Conductors	2-7	2-7
Conductor Size (AWG)	8-16	8-16
Activation Energy	Obtained from manufacturer	Obtained from database/literature review
Similar to CAROLFIRE Number	14	5

*Accelerated aged years and intervals are expected to change as activation energy information becomes available.

Activation Energy of Coatings

- Activation energies on fire retardant coatings are not well captured in literature review
 - Formula varies from manufacturer to manufacturer and from year to year
- Perform thermogravimetric analysis (TGA) to obtain specific activation energy of coatings
- ASTM E1641-18, *Standard Test Method for Decomposition Kinetic by Thermogravimetry Using the Ozawa/Flynn/Wall Method*
 - Perform mass loss of the same coating at various heating rates

Aged Cable Coating Experiments

- Cone Calorimetry
 - Heat release rate (HRR)
- Circuit Integrity
 - Failure time (i.e., resistance monitoring using IRMS or breaker trip using SCDU)
 - Temperature at time of failure



Questions

Meeting Feedback

<https://feedback.nrc.gov/pmfs/>

Meeting Code: 20250771

Contact:

Gabriel.Taylor@nrc.gov

Adam.Lee@nrc.gov

ADAMs Accession No. ML25191A208