FIRE-RETARDANT CABLE COATINGS – A FRESH LOOK INTO THEIR ROLE IN RISK-INFORMED PERFORMANCE-BASED APPLICATIONS

Felix Gonzalez[1], Gabriel Taylor[1], Kevin McGrattan[2], David Stroup[1], Mark Henry Salley[1]

[1] U.S. Nuclear Regulatory Commission (NRC), Washington, DC, USA

[2] National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA

ABSTRACT

Flame or fire-retardant electrical cable coatings have been used in commercial nuclear power plants to limit the spread of fire. A limited set of empirical data from the 1970s provides the basis for regulatory guidance. Over the past decade, nearly one-half of the U.S. nuclear fleet has voluntarily transitioned from prescriptive- to performance-based, risk-informed fire protection programs. Performance-based programs require quantification for the performance of these coatings. Difficulties were encountered using the prescribed guidance in a performance-based context, necessitating a fresh look into the performance of fire-resistive cable coatings.

In an effort to quantify the performance of flame-retardant cable coatings, the U.S. Nuclear Regulatory Commission (NRC) has sponsored a variety of experiments at Sandia National Laboratories (SNL) and the National Institute of Standards and Technology (NIST). A literature survey and regulatory review of the subject has been performed to provide a historical perspective on the use of cable coatings in nuclear facilities. An experimental series has evaluated the burning behaviour and temporal effects on circuit functionality for a variety of flame-retardant cable coatings. The experiments ranged from bench to full scale, using both standardized and non-standardized testing techniques.

Ignition temperatures have been measured using a well-controlled convection oven. Burning behaviour of coated cables has been measured using a cone calorimeter to determine burning rate, heat of combustion, and other properties. Full-scale horizontal and vertical flame spread experiments have been conducted to determine lateral and upward spread of fire. Finally, the impact of flame-retardant cable coatings on preserving circuit integrity during fire exposure has been evaluated. The results from this experimental series support updates to existing fire probabilistic safety assessment methods and fire modelling input parameters.

INTRODUCTION

The Browns Ferry Nuclear Plant Fire of 1975 prompted a new series of fire protection regulations and research including research in cable fires and flame-retardant cable coating materials [1]. The NRC Branch Technical Position (BTP) APCSB 9.5 1 “Guidelines for Fire Protection for Nuclear Power Plants” [2], provided the guidelines for protecting nuclear power plants from the adverse effects of fire. The BTP document directed licensees to have a fire protection program (FPP) and conduct a fire hazard analysis (FHA). As part of the FPP and FHA, the licensee performed bounding deterministic evaluations to estimate the area’s fire fuel loads of combustible material. These fire loads included contributions from in-situ cables as well as transient combustibles. The fuel loads were used to establish the adequacy of passive fire barriers and fire protection systems in place at the time. During plant modifications, the fire fuel load and fire protection ratings also served as the basis to evaluate the possibility of adding transient combustibles.

In the first revision of the BTP ASB 9.5 1, the NRC required that electrical cable construction should, as a minimum, pass the flame test of the Institute of Electrical and Electronic Engineers (IEEE) standard IEEE 383-1974 [3] (typically referred to as qualified cables) and specified that even cables meeting the passing criteria could require other forms of fire protection. In this document, the NRC recommended that nuclear power plants (NPPs) add fire breaks along vertical and horizontal cable routings, and many plants applied fire-retardant cable coatings to satisfy the requirement.

In the late 1990s, the NRC staff revisited the strategy described in SECY-98-058 [4] and initiated work on an alternative risk-informed/performance-based fire protection rule. In the early 2000s, the NRC reviewed and accepted, with exceptions, NFPA 805 “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants” as an alternative method for fire protection requirements of 10 *Code of Federal Regulations* (CFR) 50.48. In 2005, the Electric Power Research Institute (EPRI) and the NRC jointly published a fire probabilistic risk assessment (PRA) methodology for NPPs, EPRI-1011989 / NUREG/CR-6850, “Fire PRA Methodology for Nuclear Power Facilities” [5]. This Fire PRA methodology supported licensee use of risk tools to support NFPA 805 licensing applications to evaluate a fire’s impact on reactor safety. Implementation of the fire PRA methodology necessitated the use of fire models, which require specific input parameters (e.g., heat release rate). Appendix Q of NUREG/CR-6850 addressed passive fire barriers including flame-retardant cable coatings. However, the data and criteria specified in this appendix were based on the limited data that was developed during previous research programs of the 1970s.

In the early 2010s, questions arose about the adequacy of the flame-retardant cable coating data of the 1970s and the implementation guidance provided in NUREG/CR-6850. A new research program was developed to obtain data of burning behaviour (e.g., ignition temperatures, flame spread, heat release rates, etc.) and electrical functionality response (i.e., circuit failure times) typically used in fire protection analysis, fire modelling, and fire risk assessment of NPPs. This paper will discuss preliminary results that were obtained under the testing performed at SNL and NIST under the auspices of the NRC.

RESEARCH PROGRAM DESCRIPTION

Under this research program, the properties of several cables and flame-retardant, cable-coating materials typically used at NPPs were evaluated. Two cable types were primarily tested; a thermoset cable with good fire resistive properties (i.e., passes flame spread test such as that in IEEE 383-1974 and/or IEEE 1202-1991) and thermoplastic cable with poor fire resistive properties (i.e., will not pass the flame spread test in IEEE-383/1202). Combinations of the cables and flame-retardant materials were tested. The cables and flame-retardant materials tested are listed in Table 1 and Table 2, respectively. The cables described in Table 1 are referred to as qualified if they have passed requirements of IEEE-1202 standard or as unqualified when not meeting the standard passing requirements.

Table 1 Primary test cable descriptions*

Test Cable No. ID	Insulation Material	Jacket Material	Year Manufactured	Description
802	XLPE	CSPE	2006	Qualified, Thermoset, 7-conductor cable
807	PE	PVC	2006	Unqualified, Thermoplastic, 7-conductor control cable
813	XLPE	CSPE	2006	Qualified, Thermoset, 12-conductor cable
900	PE	PVC	2015	Unqualified, Thermoplastic, 7-conductor control cable
902	PE	PVC	1975	Unqualified, Thermoplastic, 3-conductor cable
*Other cables have been evaluated under past NRC research programs.				

Table 2 Flame-retardant coating material used in testing

Flame-retardant material	Description
Carboline Intumastic 285	Product of the Carboline Company. The coating material is described as a water-based mastic that can be applied to impede fire propagation along the length of coated electrical cables.
Flamemastic F-77	Product of the Flamemaster Corporation. Manufacturer literature describes the coating material as consisting of water-based thermoplastic resins, flame-retardant chemicals, and inorganic, incombustible fibers. Moreover, literature describes It as a non-intumescent, thixotropic compound with no asbestos. Two product variations are available—one is appropriate for spraying and the other is mastic, the latter of which was used in the experiments.
Vimasco 3i	Product of the Vimasco Corporation. The manufacturer described the material as “a heavy-bodied, water-based intumescent coating that is designed to prevent flame spread along the jacketing of electrical (or other) cables and to provide a thermal barrier for protection against heat damage.”
Fire Security Systems FS15	Product of Fire Security Systems. Water-based ablative coating made be Fire Security Systems. Its primary mode of protection is ablation as opposed to thermal insulation. This product is not used in U.S. NPPs.

To obtain data on the fire properties of these materials and their electrical response (i.e., circuit failure times) under fire conditions, several bench-scale and full-scale tests were performed. Bench-scale tests were performed to obtain data on properties of the materials while the purpose of full-scale tests was to have representative data on more representative configurations found at NPPs.

Thermogravimetric Analysis, Calorimetry, and Furnace Ignition Tests

The purpose of the bench-scale thermogravimetric analysis (TGA), micro-combustion calorimetry (MCC), cone calorimeter, and furnace ignition tests was to obtain data on the cable coating materials. This data includes density, heat capacity, thermal conductivity, mass loss as a function of temperature, heat of combustion, heat release rate, and ignition temperatures of the materials.

For the furnace ignition tests, coated and uncoated cable segments were placed within a convection oven and heated gradually until ignition was observed, and the temperature was measured with thermocouples at various depths within the cable. The objective of the experiments was to determine if the coatings increased the “effective” ignition temperature of the cable. The quotation marks are added to emphasize that ignition temperature is not a well-defined quantity in fire science. The temperature at which a solid object ignites is not only a function of the material properties but also the geometrical configuration of the solid. For example, bundled cables might ignite at a lower effective temperature than a single cable simply because the bundle produces fuel vapours at a high enough concentration to sustain flames whereas the single cable does not.

In general, uncoated thermoplastic cables ignited at temperatures in the neighbourhood of 300 °C (572 °F), whereas thermoset cable ignited in the neighbourhood of 400 °C (752 °F). However, some cables would exhibit periodic “flashing” at relatively low temperatures but would not experience sustained flaming conditions until higher temperatures were reached.

The results from this work indicate that the coatings did not systematically increase the effective ignition temperature of the cables. In fact, the bench-scale TGA and MCC and the cone calorimeter measurements indicate that the coatings pyrolyze in the neighbourhood of 350 °C (662 °F) and do contribute to the volatized fuel vapours, albeit weakly. The coatings are not designed to prevent pyrolysis and ignition but rather to delay it by slowing the heat penetration through the coating and into the cable.

These test methods have been used in past NRC tests to obtain this data on cable properties (e.g., NUREG/CR-7010 [6]) and have been used in the development of uncoated cable fire models such as the Flame Spread over Horizontal Cable Trays [6] and the Thermally-Induced Electrical Failure (THIEF) model [7].

Circuit Integrity Test

The circuit integrity test found in the International Electrotechnical Commission (IEC) Standard 60331-11 [8] was used with some variations to measure the effect of cable coating thickness on the electrical response of the cables to fire conditions. The experiments are similar to those described in the IEC international standard 60331-11 with the main deviation from the test standard being that the burner had a nominal face length of 25 cm (10 in) rather than 50 cm (20 in) as specified in the standard. The width of the burner was nominally 1 cm. The propane and air flow rates flowing into the pre-mixed burner were half of what is called for in the standard—2.5 l/min propane and 40 l/min air at 1 bar and 20 °C, producing a 3.6 kW flame. Another deviation included the use of the Surrogate Circuit Diagnostic Unit (SCDU) to characterize the electrical response rather than the “light bulb” test specified in the standard[1]. Figure 1 shows a typical experiment. In this experiment, a single cable, either coated or uncoated, was immersed in a pre-mixed propane-air flame generated by a line burner.

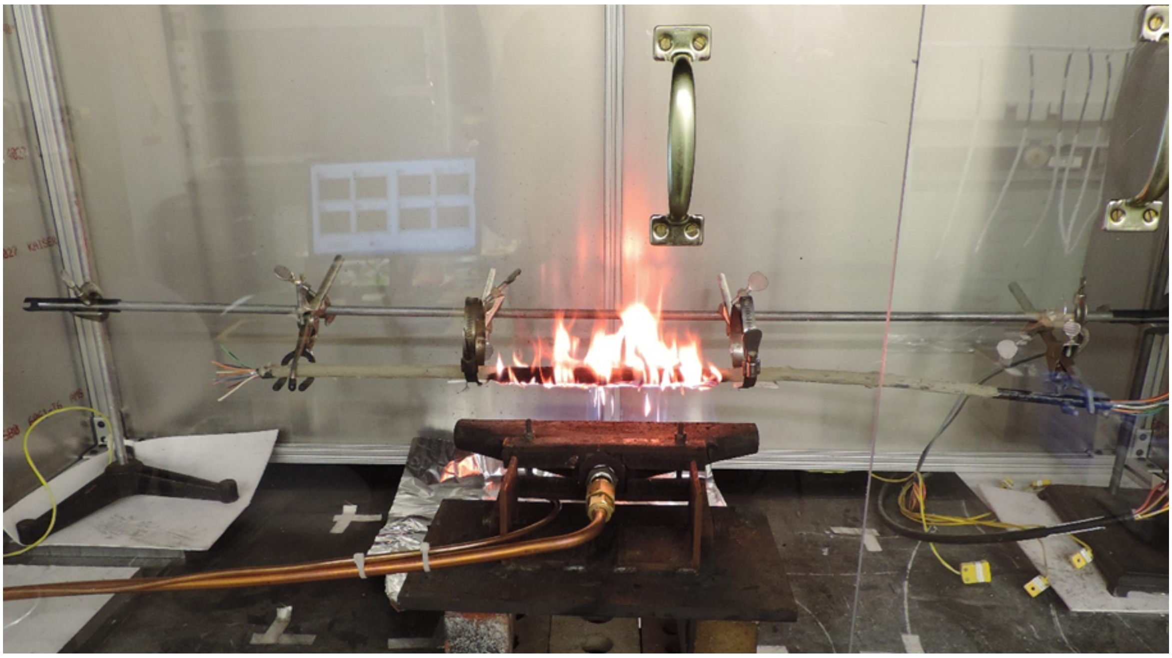

Figure 1 Photograph of a typical circuit integrity experiment

Per the standard, each test evaluated a single cable and as such, temperature and electrical integrity measurements could not be done within the same cable due to electrical “cross talk” between the instruments. Thus, for each test sample, separate experiments were conducted - one for circuit integrity and one for temperature measurement. Experiments involving coated cables were repeated three times (i.e., three circuit integrity experiments were performed and three temperature measurements were performed). For the circuit integrity experiments, three circuit pairs were energized with 120 V AC, and the cable was heated until a 3 A fast-acting fuse cleared, indicating circuit failure.

The average time to circuit failure of three replicate experiments and the corresponding cable interior temperature at the time of failure was obtained. The results exhibit variations among cable type and coating materials. Figure 2 shows the box plots for the results of circuit integrity tests for all unqualified thermoplastic cables uncoated and coated. Table 3 summarizes the results of the circuit integrity experiments.

[1] Previous NRC experience with “light bulb” functionality testing, also referred as circuit integrity monitory, indicated a weakness in test acceptance criteria where the fire could damage the cable insulation, but the electrical conductors did not come in contact with each other or short to ground. This would provide false acceptance of the test [11], [12].

Table 3 Summary of results of the circuit integrity experiment

Cable	Average Failure Time Uncoated cable	Delay in Failure Time	
		Coated to 1.6 mm (1/16 in or 62.5 mil)	Coated to 3.2 mm (1/8 in or 125 mil)
Unqualified cable 900	6.3 min	10.1 min	23.3 min
Qualified cable 913	4.1 min	3.4 min	12.8 min

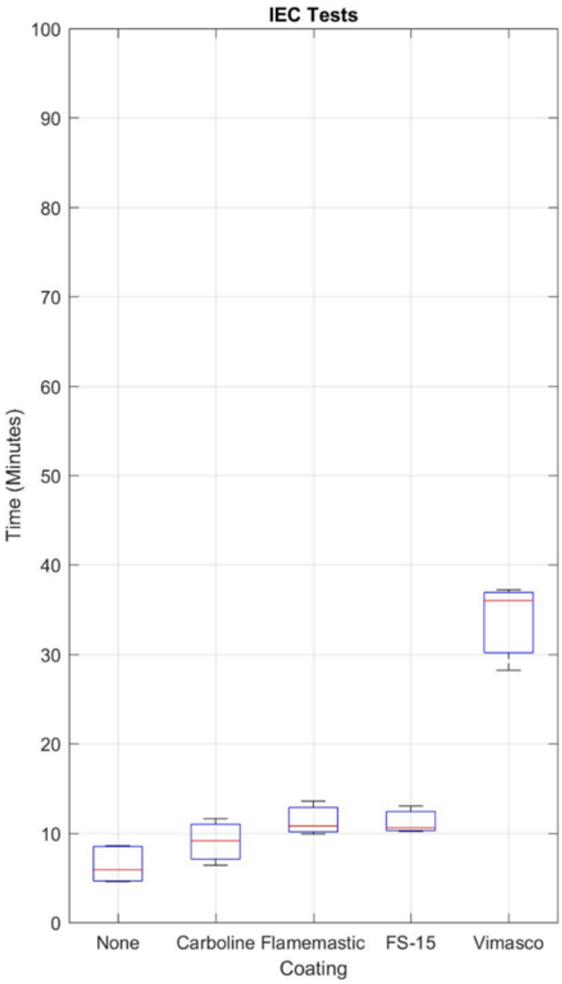

Figure 2 Time to failure box plots of circuit integrity (IEC) tests for all unqualified thermoplastic cables uncoated and coated

Full-scale Tests

The full-scale tests that were performed included radiant heat (described in section 3.2 of NUREG/CR-6931 [9]), IEEE standard 1202-1991 [10] (supersedes the flame spread requirements of standard IEEE 383-1974 [3] in nuclear industry requirements) vertical flame spread test, and multi-tray horizontal fire tests intended to represent typical tray configurations at NPPs.

For full-scale tests, cable electrical and temperature response were monitored. Two different electrical integrity measurement systems were used to monitor electrical response. The first system, the Insulation Resistance Measurement System (IRMS), measures actual insulation resistance between the conductors of a multi-conductor cable and between the conductors and ground. This system was only used during the SNL radiant experimental series. The second system, the SCDU, simulates a 120 V AC control circuit for a motor-operated valve (MOV). Both SNL and NIST experimental series used the SCDU system to monitor circuit integrity[2]. The cable's temperature response was measured beneath the cable's outer jacket (sub-jacket). This technique has been used in several prior test programs [6], [9]. Prior testing has shown that the cable insulation temperature is well correlated to electrical failure, and the sub-jacket thermocouples provide a reasonable measure of the cable insulation temperature.

Penlight Apparatus Radiant Heat Tests

The Penlight is a radiant heating apparatus shown in Figure 3 a., which uses computer-controlled, water-cooled quartz lamps to heat a thin, intermediate Inconel steel shroud. The shroud is painted flat black and acts as a grey-body radiant heating source, re-radiating heat to a test sample (cables for these experiments) located within the shroud. The exposure temperature is monitored and computer-controlled based on thermocouples mounted on the inner surface of the shroud. Penlight creates a radiant heating environment analogous to that seen by an object enveloped in a fire-induced, hot-gas layer or in a fire plume outside the flame zone. Test included cable trays loaded with a mirror image of two cables or bundles where one was monitored for temperature and the other for electrical response.

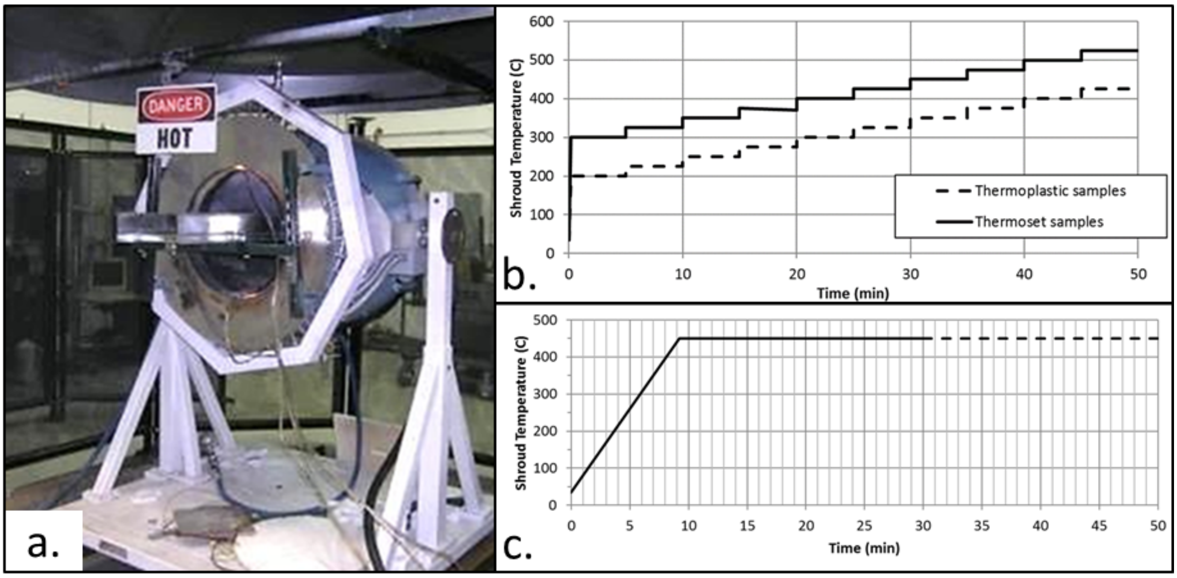

Figure 3 a. Penlight apparatus; b. Heating profiles using step-wise increases 25 °C (77 °C); c. Shroud temperature profile used in the final test set involving ten-cable bundles

All of the experiments performed in this series were conducted on a 30 cm wide (12 in), ladder-back style cable tray suspended through the centre of the Penlight shroud. Two temper-

2 A detailed discussion of the IRM and SCDU instrument hardware can be found in Appendix B and C of NUREG/CR-6931 Volume 1 [9].

ature profiles were used for the tests shown in Figure 3 b. and Figure 3 c.. The step-wise profile was designed to nominally represent a transient fire development profile. For the larger 10-cable bundle tests, a ramp-and-hold profile was used to represent typical fire behaviour.

Cables 802 and 807 were used for this test. Samples tested were either in single cable, 7-cable bundle, or 10-cable bundle configurations and were tested uncoated or coated with one of the flame-retardant coatings (FS15 was not tested in this test as this coating was added later in the research program).

A total of 35 tests were performed. For single cable configurations, the test showed that coated samples (at the manufacturer recommended coating thickness of 1/16 inch (1.6 mm)) had little to no delay in electrical failure time when compared to the uncoated sample failure time. The bundle configurations showed at least five minutes of delay to electrical damage from that of the uncoated sample failure time.

Vertical Flame Spread Test

The vertical flame spread test was based on modified version of the flame spread test found in IEEE 1202-1991. Modifications included a removal of one of the walls to allow for video recording, increased burner times (i.e., test until electrical failure or 90 min, whichever came first), and use of the SCDU to monitor electrical response during the test. Two sets of tests were performed - one involving non-energized cables and the second with cables energized and thermally monitored. The objective of the experiments is to confirm that cable coatings prevent upward flame spread and to quantify the delay in electrical failure afforded by the flame-retardant coatings.

Cables 813, 900, and 902 were tested uncoated and coated with coatings identified in Table 2. A total of 41 tests were performed. Electrical response with the SCDU was monitored only in 20 of these tests. Flame spread beyond the test failure criteria (i.e., 1.5 meter above burner) and to the top of the tray in tests with uncoated cable 900 and 902. In one test of cable 900 coated with Flamemastic F-77, the flame spread 1 meter above the burner. In one test of cable 900 and Vimasco 3i, the test spread to 2 meters above the burner. In both these tests, the applied thickness was slightly less than the manufacturer-recommended value. All other coated samples (including repeats of cable 900 coated with Flamemastic F-77 and Vimasco 3i) as well as the uncoated cable 813 flame did not spread. Figure 4 shows a photo of the vertical flame spread test of uncoated Cable 900 and three of the coatings at nine minutes. The HRR for the uncoated test is about 220 kW while for the coated samples remained below 30 kW for each test.

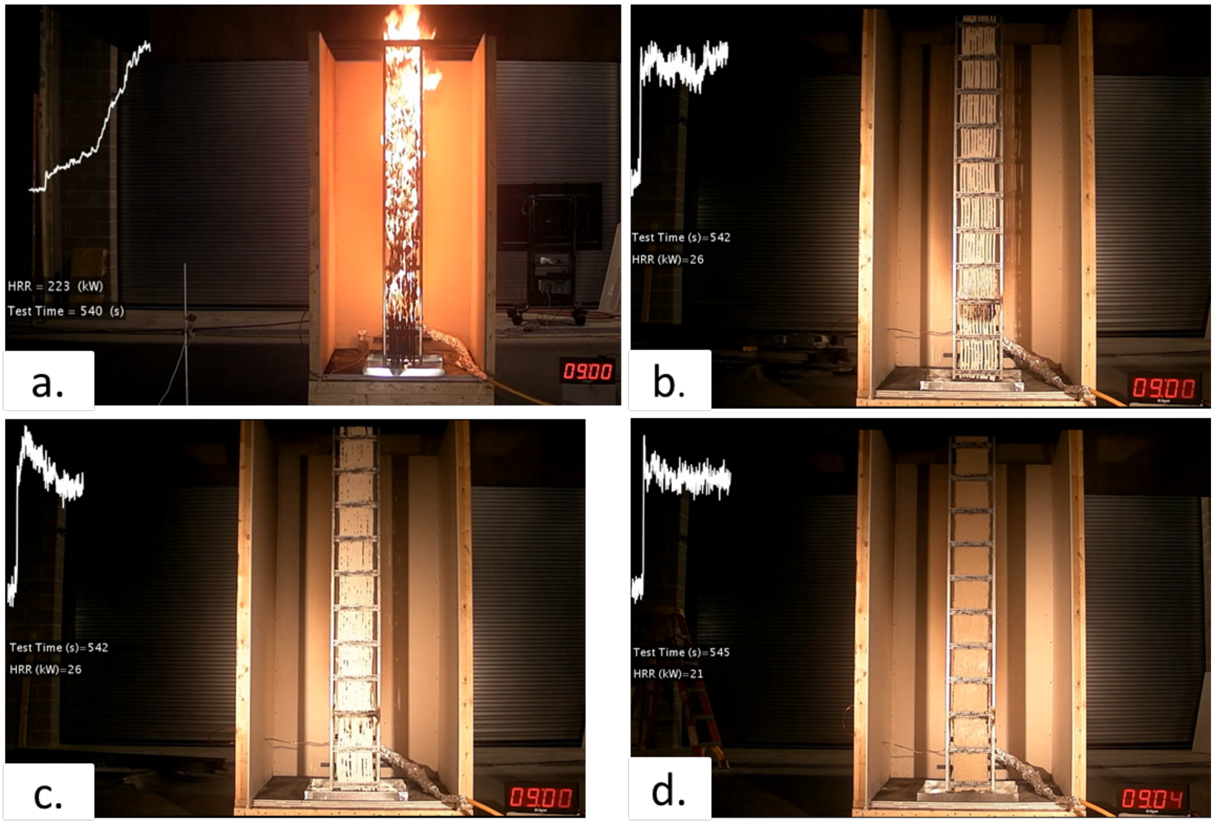

Figure 4 Vertical flame spread test with uncoated Cable 900 and the approximate HRR [kW] of the cable and burner at nine minutes: a. uncoated (approx. 223 kW); b. coated with Flamemastic F-77 (26 kW); c. coated with Vimasco 3i (26 kW); d. coated with Carboline Intumastic 285 (21 kW)

The electrical response of the cables was monitored on four cables located in the tray. The objective of the test was to determine the time when the electrical cable loses functionality and to compare the times of the uncoated sample to those of the coated samples to determine the delay in damage, if any. For thermoplastic cables, it was found that on average the application of cable coatings would delay the time to damage for at least several minutes. For thermoset cables, the application of cable coatings did not delay the time to damage. Figure 5 shows electrical time to failure box plots for IEEE 1202 test for cable 900 and cable 813 uncoated and coated. It is important to note that thermoset cables are typically not coated with flame-retardant cable coating materials unless they would share a tray with thermoplastics.

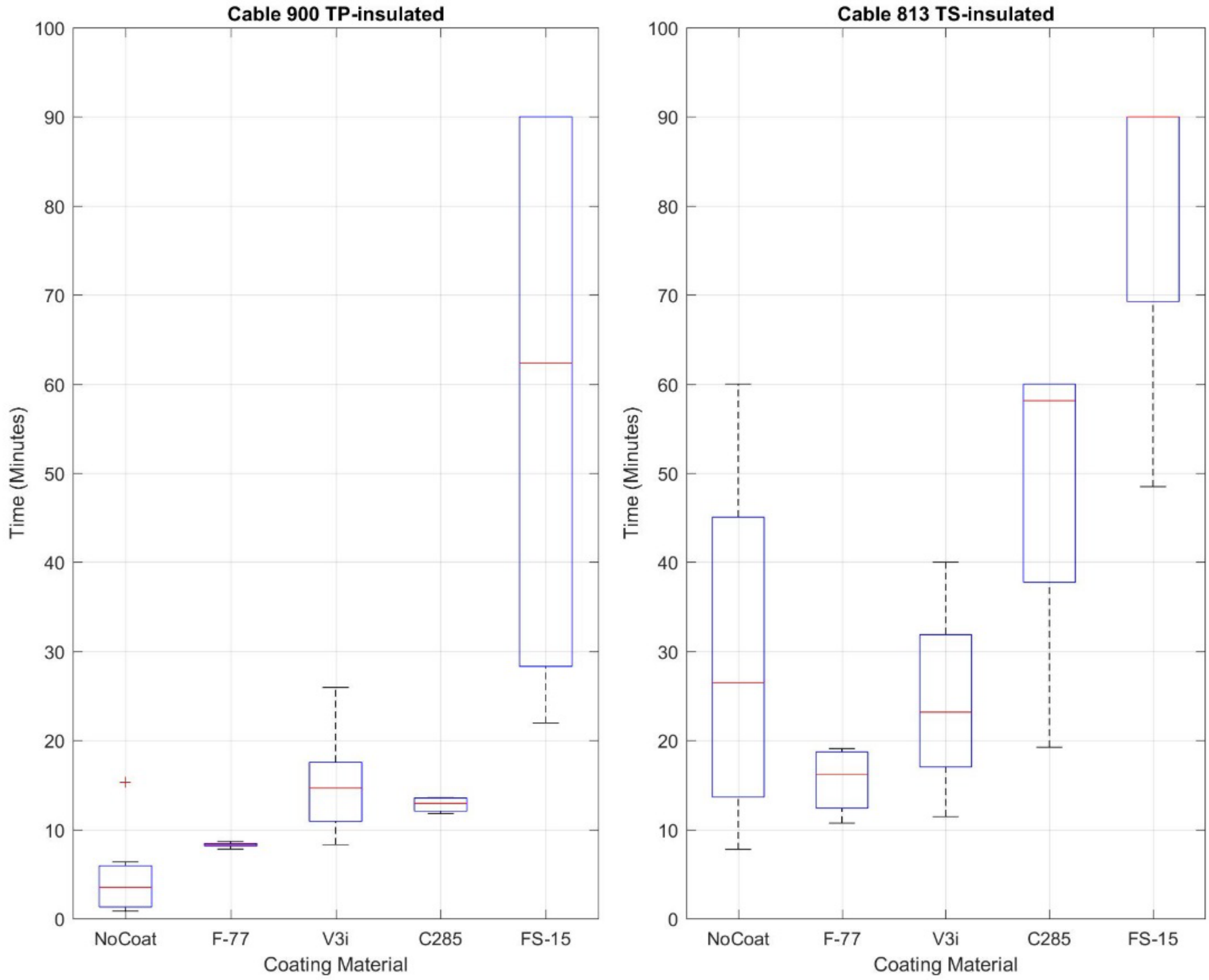

Figure 5 time to failure box plots of IEEE 1202 experiments for Cable 900 (left) and Cable 813 (right)

The test concluded that the four cable coatings tested in the vertical flame spread test prevented the flame spread of a fire from the 20 kW burner when applied according to the manufacturer recommendations. When flame-retardant coatings are applied, the HRR is substantially reduced as shown in Figure 6. The electrical response data shows that some delay to electrical failure could be assigned for unqualified thermoplastic cables coated with flame-retardant materials.

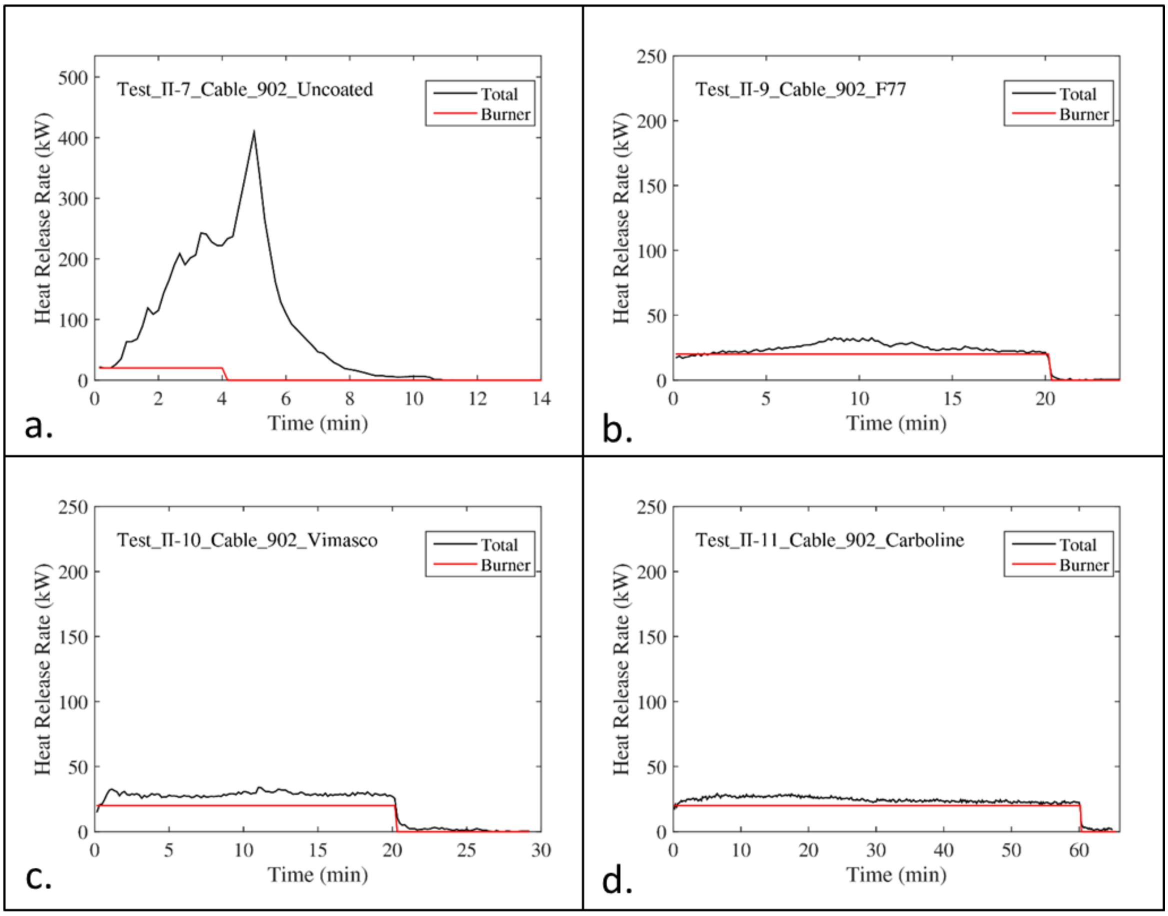

Figure 6 Cable 902 HRR a. uncoated; b. coated with Flamemastic F-77; c. coated with Vimasco 3i; d. coated with Carboline Intumastic 285

Multi-tray Horizontal Test

In this experimental series, horizontal cable trays containing coated and uncoated cables are exposed to a variety of thermal exposure conditions. The purpose of the experiments is two-fold. First, the circuit functionality will be evaluated using the SCDU unit to determine to what extent the various coatings delay electrical cable failure. Second, the experiments provide specific input parameters for performing fire model calculations including the HRR per unit area of tray, the lateral spread rate, and the vertical spread rate.

Figure 7 shows the test compartment, which is about 2.4 m (8 ft) long, 1.2 m (4 ft) wide, 2.4 m (8 ft) tall and is open all around the lower half. The upper half was lined with a layer of 1.6 cm (5/8 in) thick gypsum board covered with 0.6 cm (1/4 in) thick concrete board. The frame was constructed of steel studs. The compartment was positioned under an oxygen consumption calorimeter with a capacity of about 5 MW.

Four 30 cm (12 in) wide, 1.8 m (6 ft) long horizontal trays were positioned as shown in the figure, containing equal numbers of uncoated and coated cables. This arrangement allowed for direct flame impingement on the lowest tray, exposure to plume temperatures on the middle tray, and a gradual heating for the upper trays. All eight experiments used the un-qualified thermoplastic cable 900. Figure 8 shows the cables were arranged in the trays in two different configurations. For a given experiment, one coating and one cable arrangement was applied in all trays. The cables in the uppermost two trays dropped down from one tray to the other. In each tray, four cables were energized (yellow) and four cables were instrumented with thermocouples (red). Given that there were two cable configurations and four coatings, eight experiments were conducted.

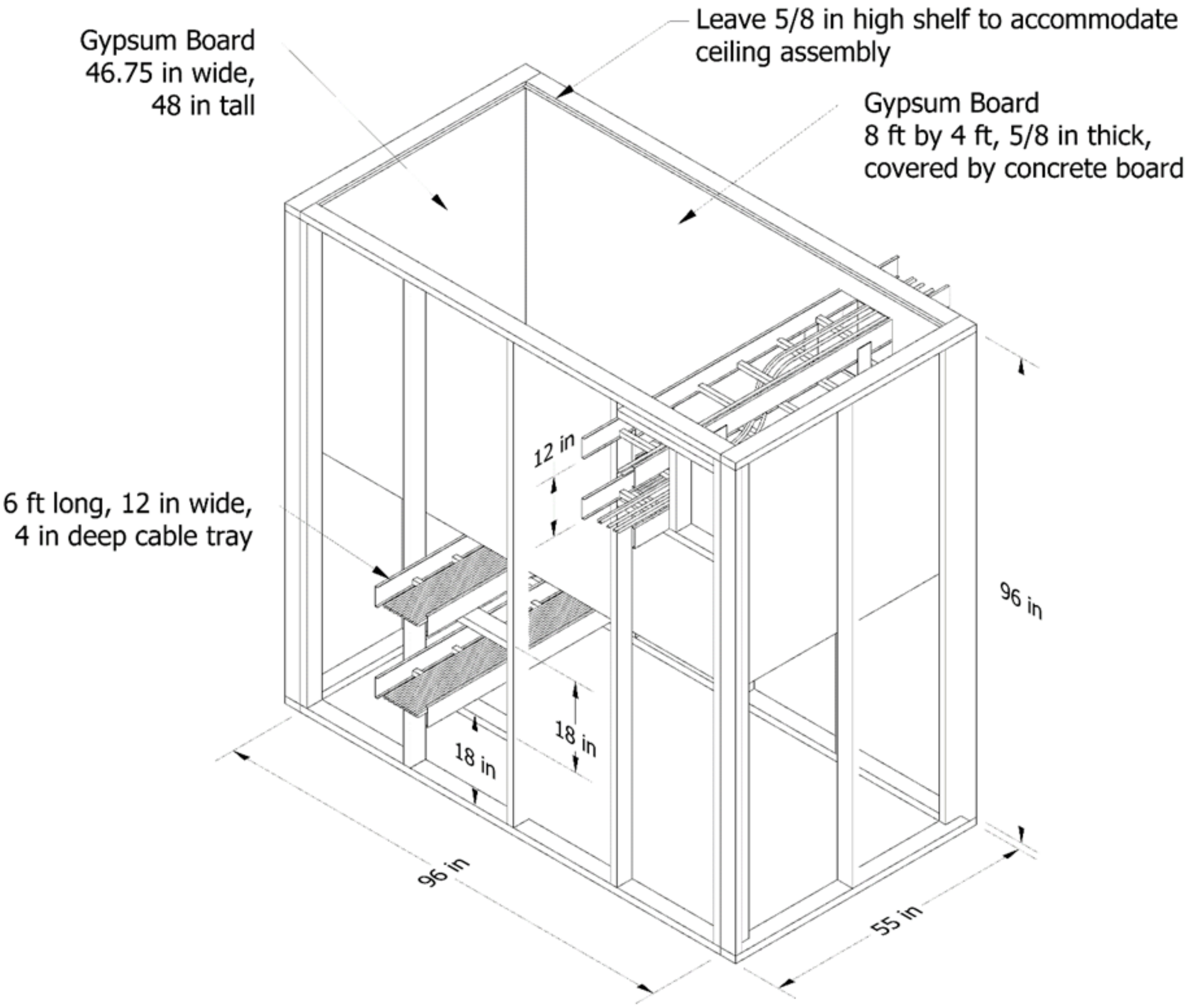

Figure 7 Compartment used on horizontal cable experiments

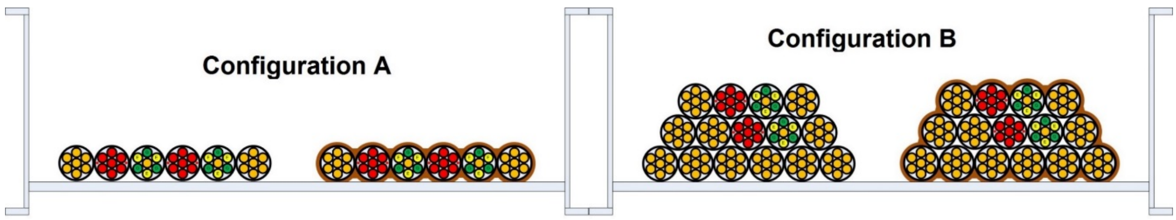

Figure 8 Schematic diagram of cable layouts. Configuration A is referred to as a “single row”, while B is referred to a “bundle”. Cables on the left of each configuration were uncoated, while the ones on the right were coated

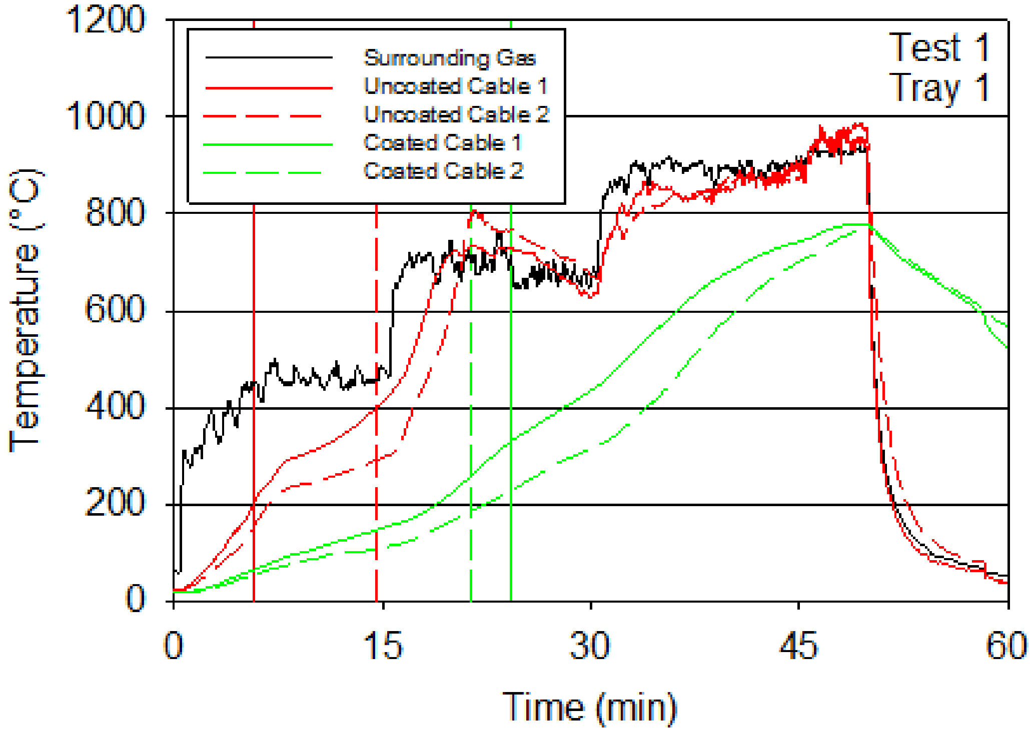

Figure 9 Horizontal Test 1, Carboline Intumastic 285 Coating, Tray 1 (i.e., lower tray) temperatures and electrical failure times

As shown in Figure 9, the temperatures and electrical response were monitored and plotted vs. time for each test tray. It was observed that the average time to failure for all uncoated cables in the single row configuration in Tray 1 was 7.8 min. The average delay time brought about by applying a protective coat for these same cables was 13.9 min. The average delay time for all cables in all trays was 13.3 min. The average interior cable temperature at the time of failure was about 300 °C (572 °F). The range of failure temperatures was considerable; from less than 200 °C to over 500 °C. The only clear trend for the failure temperature is that the cables in Tray 3, immersed in the hot gas layer, tended to fail at lower temperatures than the cables in Trays 1 and 2. Two possible explanations for this are that (1) these cables were subjected to a more gradual heating rate, and (2) these cables dropped from the upper tray to the lower tray, which were separated by 30 cm (12 in). This drop subjected the cables to a fairly tight bend radius (not exceeding the minimum bend radius) that would tend to draw the individual conductors closer together as the insulation underwent thermal and mechanical degradation.

In these experiments, the difference in performance among the four different coatings was not nearly as pronounced as in the bench-scale circuit integrity experiments discussed previously. Table 4 shows the average delay in time to failure for each cable coating and all trays and configurations.

Table 4 Average delay in time to failure for each cable coating

Flame-retardant cable coating	Average delay in time to failure
Carboline Intumastic 286	14.9 min
Vimasco 3i	11.6 min
Flamemastic F-77	10.4 min
FS-15	15.9min

CONCLUSIONS

The objective of this research program was to obtain thermal properties, ignition temperatures, burning rates, flame spread, and electrical response data of flame-retardant cable coating materials commonly used in U.S. NPPs. This data can be used to develop new models or to expand fire models that were developed to analyse uncoated cables. The data can also be used as input to fire risk assessments.

The furnace ignition tests did not demonstrate that the coatings increase the effective ignition temperature of the cables but rather delay the time to reach the ignition temperature. The burning rate of coated cables was measured at bench scale in the cone calorimeter. In general, the coatings delay the time to ignition, decrease the peak burning rate, and increase the total energy released because the coatings do add to the fuel load. The full-scale vertical and horizontal tray experiments indicate that even though the coatings might add to the overall combustible mass, they do effectively prevent the spread of fire and restrict it to the point of flame impingement. The amount of additional energy released due to the application of coatings is negligible.

The vertical flame spread tests showed that the coatings prevented the upward flame spread of fire from the 20 kW burner when applied according to the manufacturers' recommendations. In several experiments where the coatings were applied at a thickness just less than the recommended value, the fire did spread upwards to various extents, but this behaviour was not repeated when the coatings were applied as directed. This illustrates the importance of following the coating manufacturer installation requirements.

Application of flame-retardant coatings on non-qualified cables (i.e., that would not meet passing criteria of the vertical flame spread test) demonstrate a delay in time to damage of at least five minutes regardless of coating type when applied according to the manufacturers recommendations. Qualified electrical cables coated with a flame-retardant cable coating demonstrated mixed results. Bench-scale tests demonstrated a delay while full-scale vertical flame spread testing did not demonstrate a delay. Coating thickness beyond the manufacturer's specified minimum thickness appears to provide additional delay in time to electrical damage.

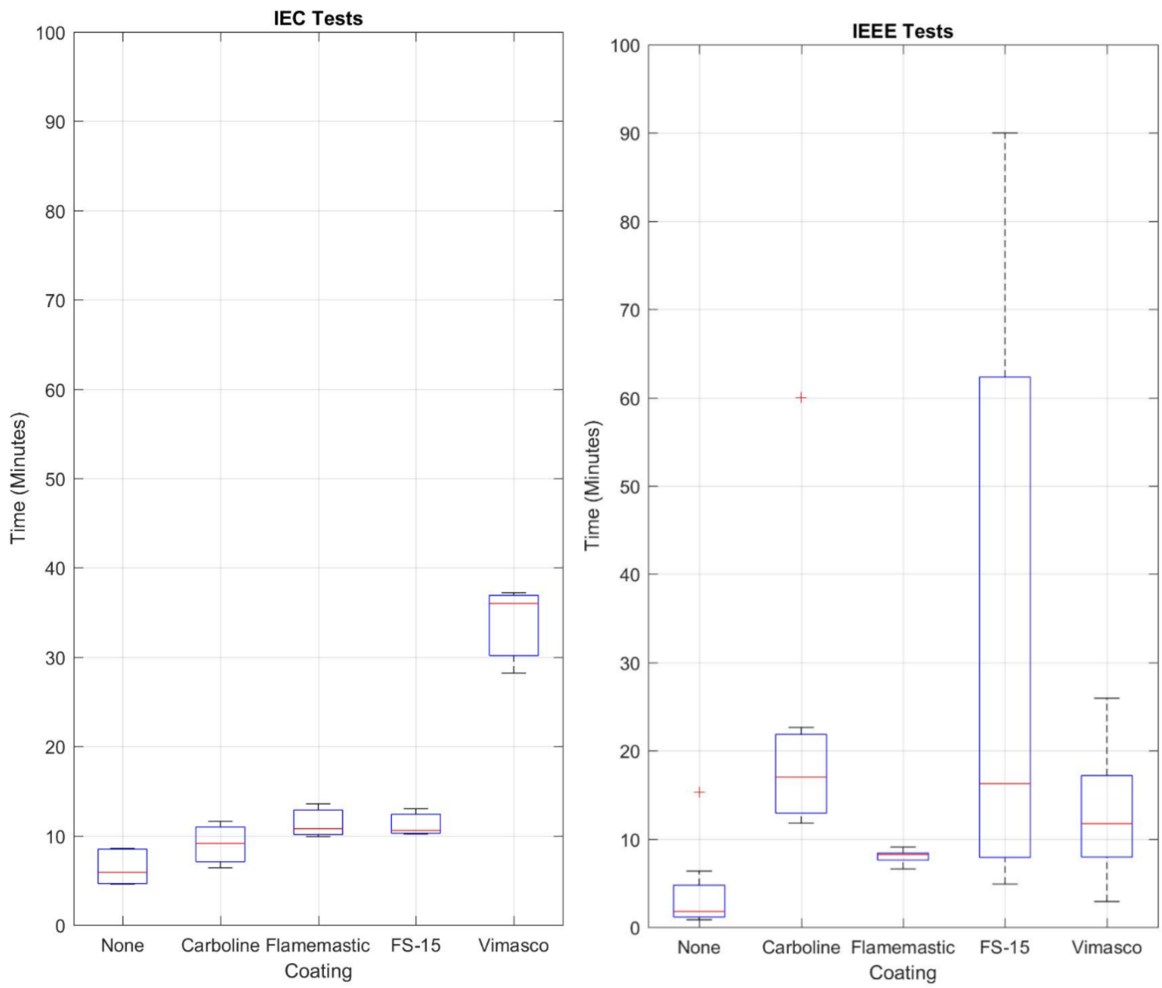

Figure 10 Time to failure box plots of circuit integrity, IEC tests (left) and vertical flame spread, IEEE-1202 tests (right) for all thermoplastic cables uncoated and coated

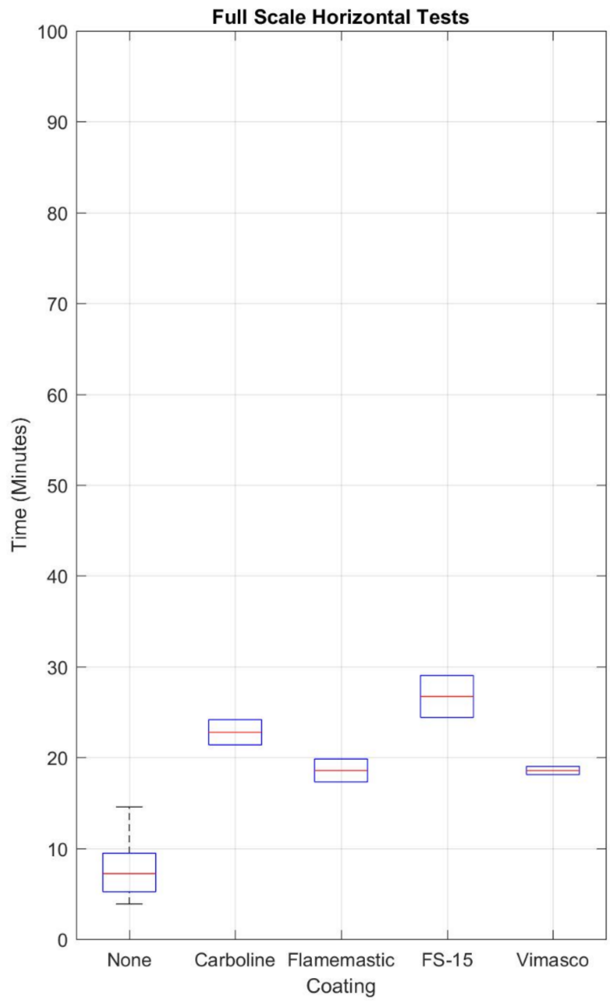

Figure 11 Time to failure box plots of full-scale multi-tray horizontal tests for all thermoplastic cables uncoated and coated

Figure 10 and Figure 11 present the results of the circuit integrity tests, vertical flame spread tests, and full-scale multi-tray horizontal tests for the unqualified thermoplastic cables 900 and 902, uncoated and coated. In general, it was concluded that use of flame-retardant cable coating materials delays the time to electrical damage by several minutes and limits the flame spread of a cable fire.

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Gabriel Taylor, PE
David Stroup, PE
Mark Henry Salley, PE

NIST
Kevin McGrattan, PhD.

NIST

engineering laboratory

Outline

Plan for presentation

- Short History
- Regulatory Guidance
- Need for Research
- Approach
- Results
- Conclusion

Short History

Need to reduce combustible loading

- 1975 – Brown Ferry Nuclear (BFN) Fire
- 1976-1980
  - BTP APCSB 9.5 1 "Guidelines for Fire Protection for Nuclear Power Plants" requires cables to pass IEEE 383-1974 flame spread test
  - Sandia National Laboratories and BFN cable fire tests
- 1998 – SECY 98-058: alternative performance based fire protection
- 2005 – NUREG/CR-6850 Fire PRA Methodology, Appendix Q: Passive Fire Barriers

Regulatory Guidance

What prompted the use of fire-retardant coatings

- BTP APCSB 9.5 1 “Guidelines for Fire Protection for Nuclear Power Plants”
- 10 Code of Federal Regulations (CFR)
  - Appendix A to Part 50: General Design Criteria, Criterion 3 “Fire Protection
  - 50.48 “Fire Protection”
- NUREG/CR-6850 Appendix Q “Passive Fire Protection”

Research Need

Why perform this research?

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

Approach

What was done and how will results be used

- Small scale tests
  - Thermogravimetric analysis (TGA)
  - Calorimetry (micro-combustion and cone calorimetry)
  - Furnace ignition tests
  - Circuit integrity test (IEC 60331-11)

- Full scale tests
  - Penlight apparatus radiant heat test
  - Vertical flame spread test (IEEE 1202-1991)
  - Multi-tray horizontal test

Coatings

What materials were evaluated?

- Carboline Intumastic 285
- Flamemastic F-77
- Vimasco 3i
- Fire Securty Systems FS-15

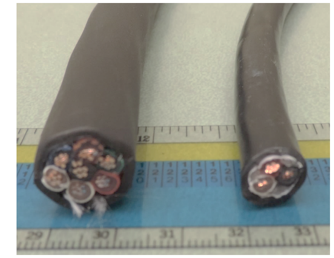
Electrical Cables

What is the base configuration (control)

Insulation Material	Jacket Material	Year Manufactured	Description
XLPE	CSPE	2006	Qualified, Thermoset, 7-conductor cable #802
PE	PVC	2006	Unqualified, Thermoplastic, 7-conductor control cable #807
XLPE	CSPE	2006	Qualified, Thermoset, 12-conductor cable #813
PE	PVC	2015	Unqualified, Thermoplastic, 7-conductor control cable #900
PE	PVC	1975	Unqualified, Thermoplastic, 3-conductor cable #902

*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



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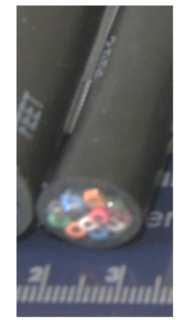

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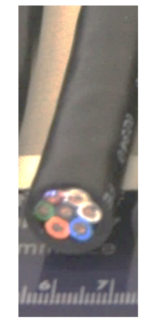

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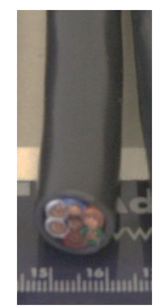

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Measurements

Thermal

- Heat of combustions
- Thermal conductivity
- Mass loss as a function of temperature
- Ignition temperatures
- Cable temperatures (beneath cable's outer jacket)

Measurements

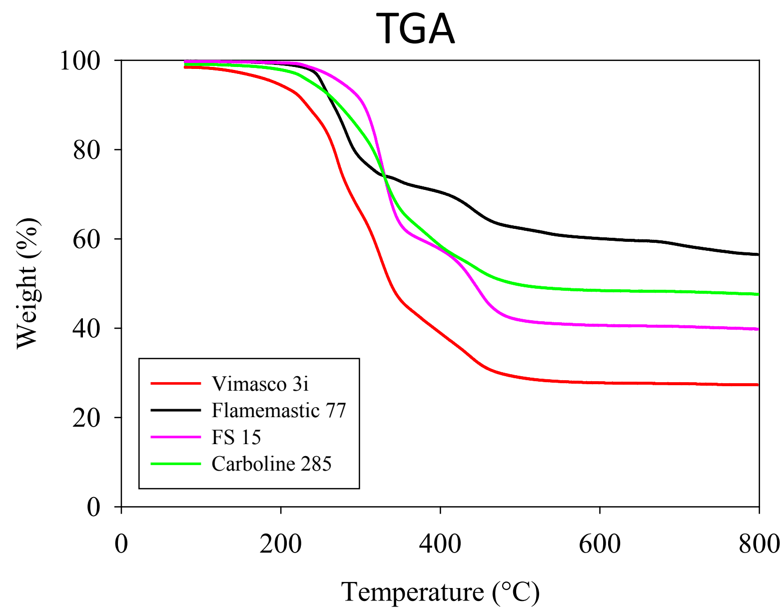
Electrical

- Insulation Resistance Measurement System (IRMS)

- Surrogate Circuit Diagnostic Unit (SCDU)

Results

Small-Scale Thermal Tests:



- Uncoated thermoplastic cables ignited at temperatures around 300°C (572°F).
- Thermoset cables ignited around 400°C (752°F).
- Coatings did not systematically increase the effective ignition temperature of the cables.
- Measurements indicate that the coatings pyrolyze around 350 °C (662 °F) and do contribute to the volatized fuel vapors, albeit weakly.

Results

Circuit integrity / IEC-like horizontal tests

Table 2: Summary of results of the circuit integrity experiment

Cable	Average failure time uncoated cable	Average delay in failure time	
		Coated to 1.6 mm (1/16 in or 62.5 mil)	Coated to 3.2 mm (1/8 in or 125 mil)
Unqualified cable 900	6.3 min	10.1 min	23.3 min
Qualified cable 913	4.1 min	3.4 min	12.8 min

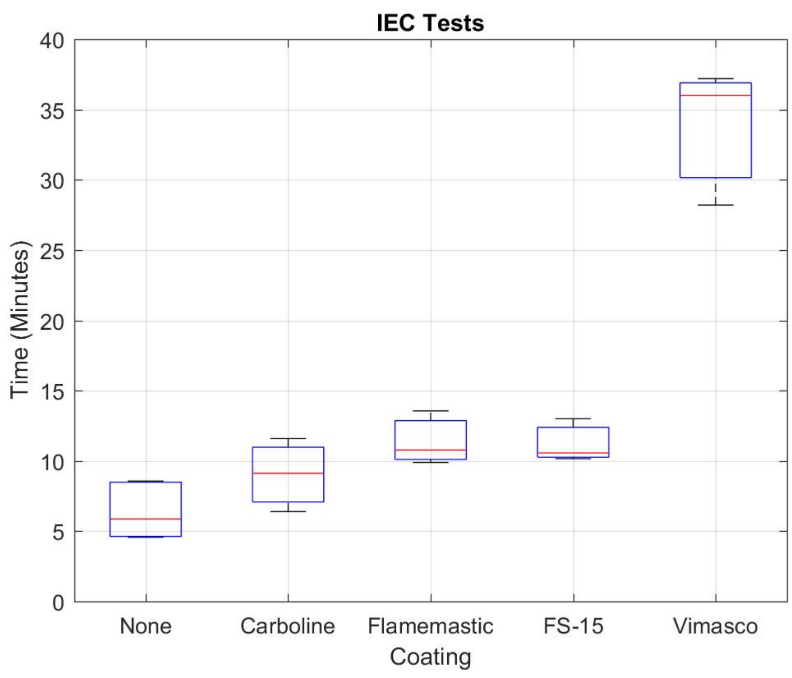


Figure 1: Time to failure box plots of circuit integrity (IEC) tests for all unqualified thermoplastic cables uncoated and coated

Results

Penlight apparatus radiant heat tests

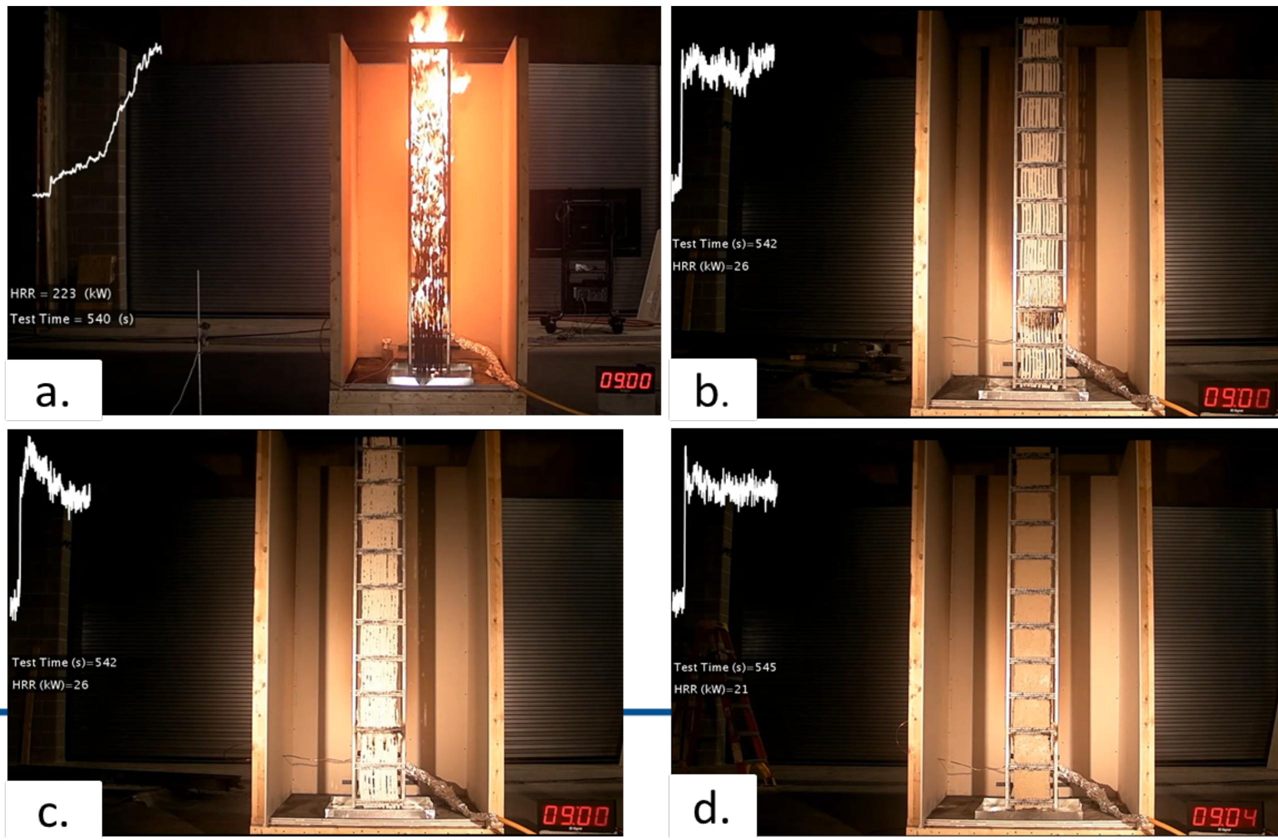
- Coated samples had little to no delay in electrical failure time when compared to the uncoated sample failure time
- Samples coated at the manufacturer recommended coating thickness of 1/16 inch (1.6 mm)

Figure 2: Penlight apparatus

Results

Circuit integrity / IEEE-like vertical tests

Figure 3: Vertical flame spread test with uncoated Cable 900 and the approximate HRR (kW) of the cable and burner at nine minutes: a. uncoated (approx. 223 kW); b. coated with Flamemastic F-77 (26 kW); c. coated with Vimasco 3i (26 kW); d. coated with Carboline Intumastic 285 (21 kW)



Results

Circuit integrity / IEEE-like vertical tests (continued 2)

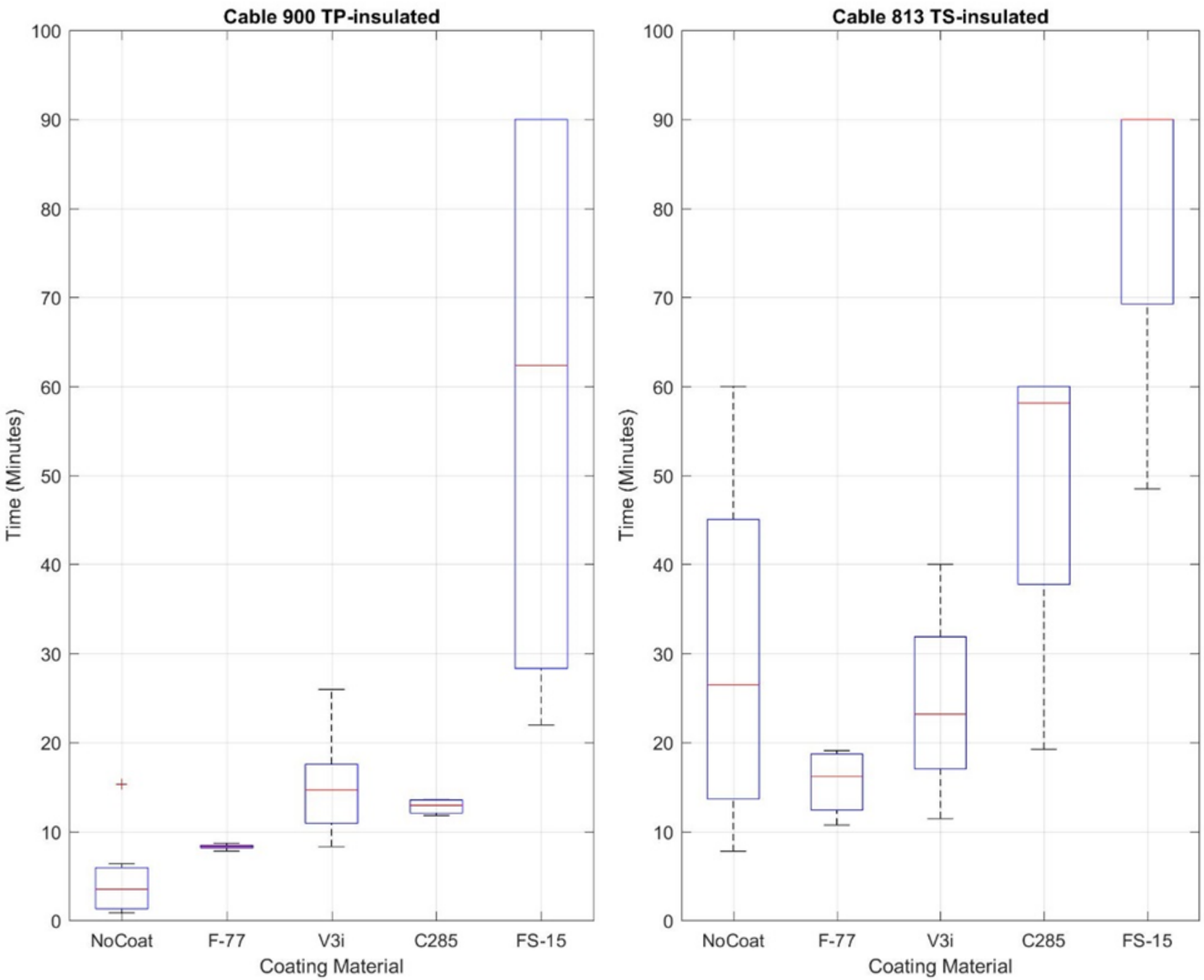


Figure 4: Time to failure box plots of IEEE 1202 experiments for Cable 900 (left) and Cable 813 (right)

Results

Circuit integrity / IEEE-like vertical tests (continued 3)

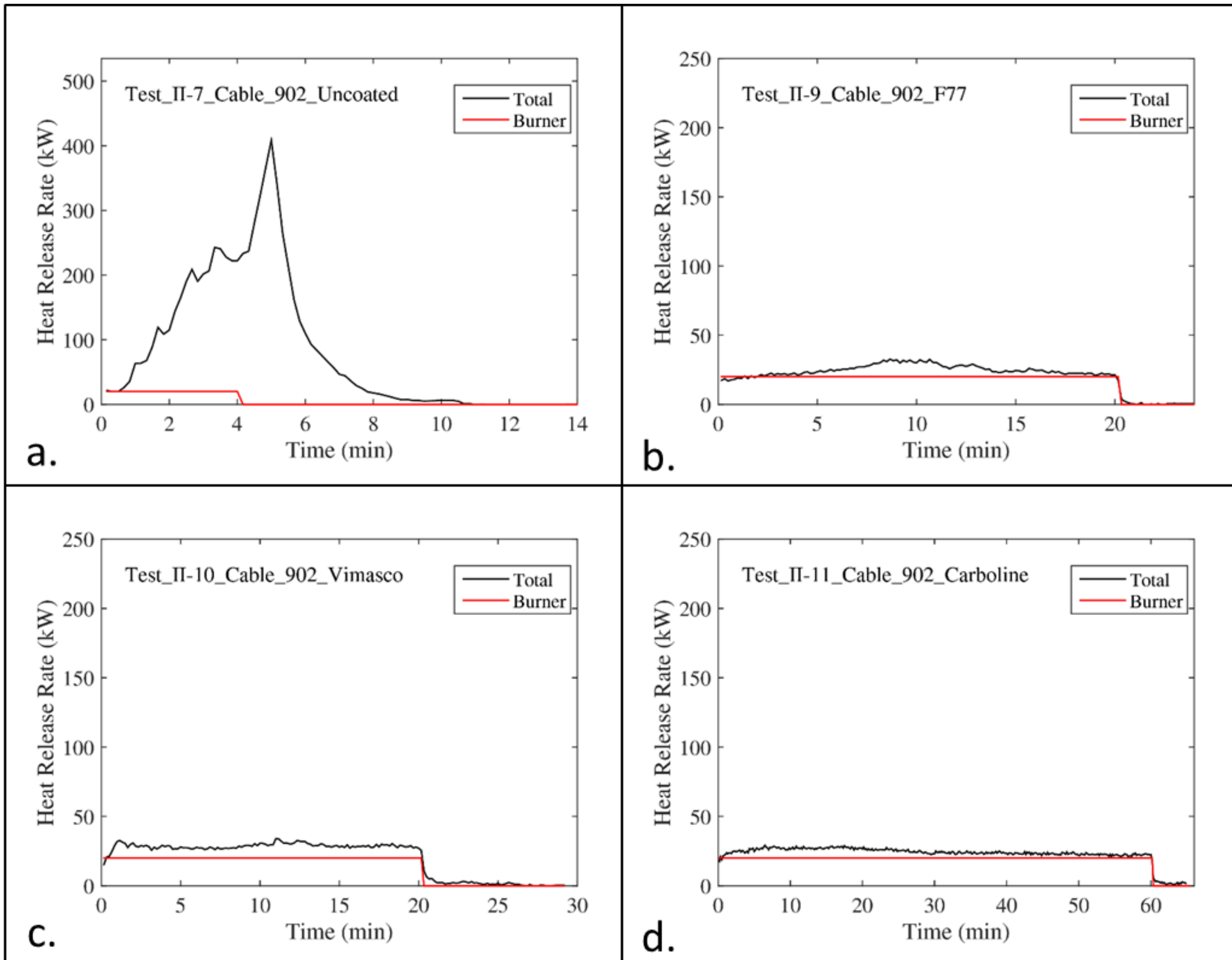


Figure 5: Cable 902 HRR
a. uncoated;
b. coated with Flamemastic F-77;
c. coated with Vimasco 3i;
d. coated with Carboline Intumastic 285.

Results

Circuit integrity / Full-Scale Horizontal Tests

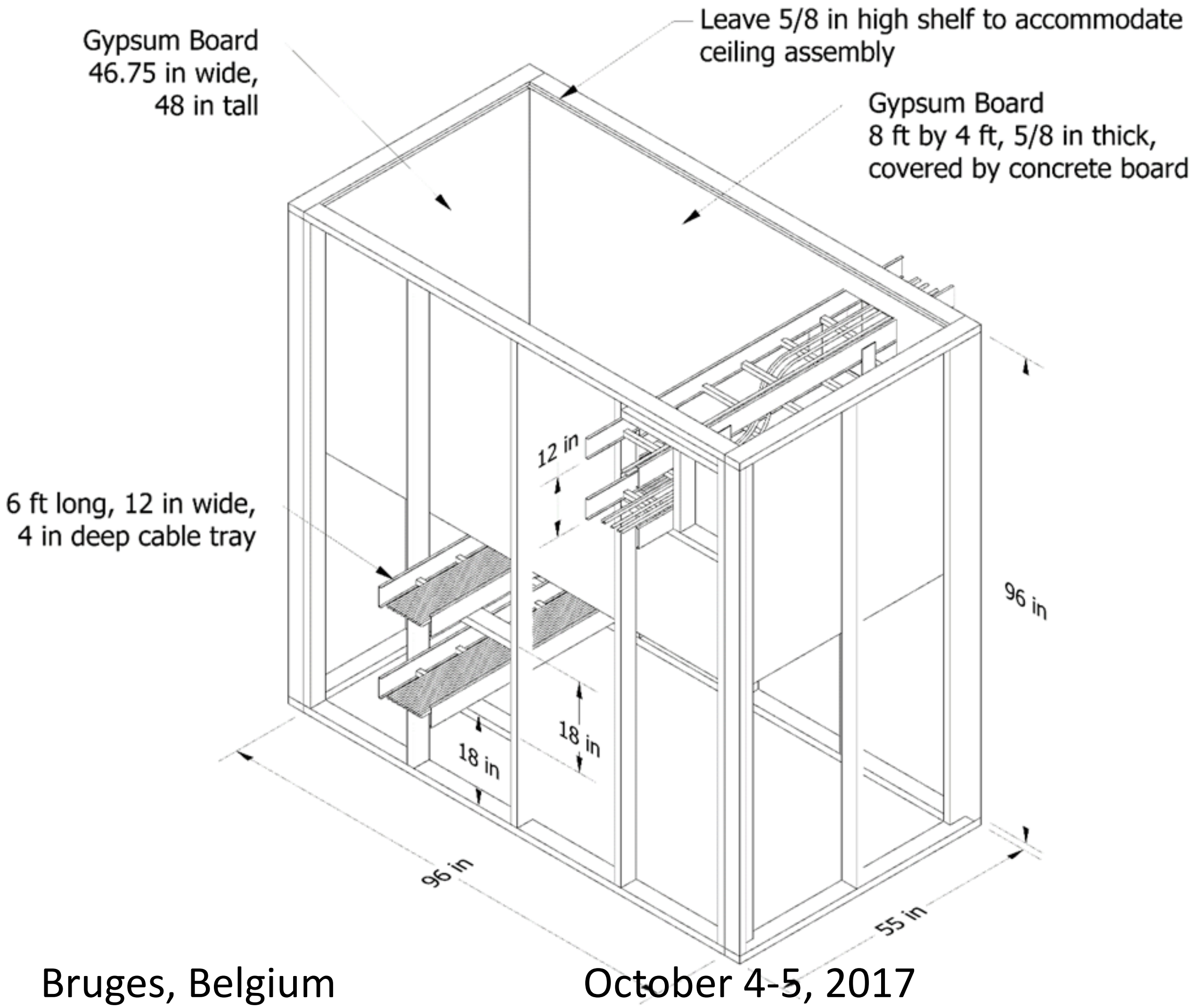
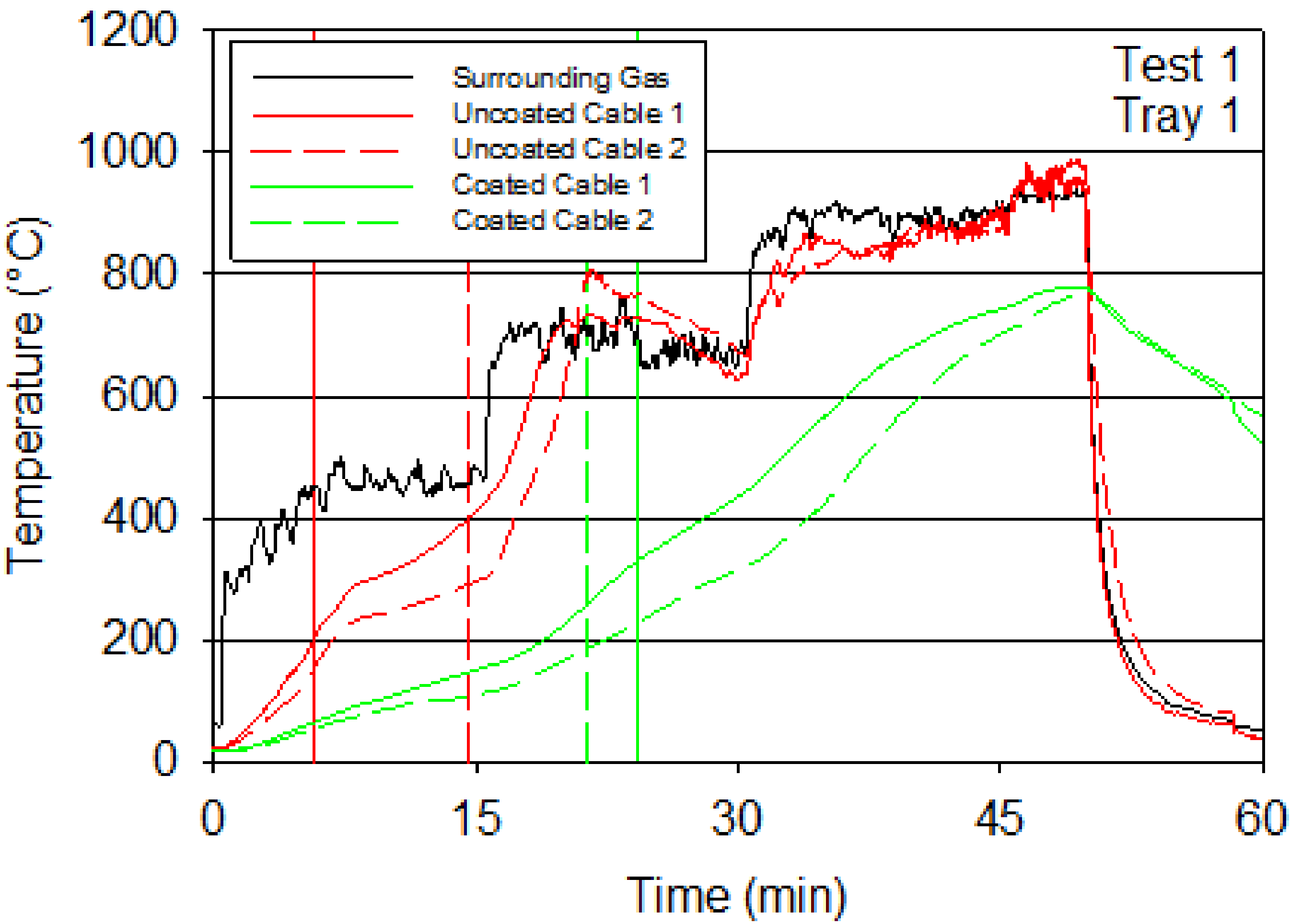


Figure 6: Compartment used on horizontal cable experiments.

Results

Circuit integrity / Full-Scale Horizontal Tests (continued 2)

Figure 7: Horizontal Test 1, Carboline Intumastic 285 Coating, Tray 1 (i.e., lower tray) temperatures and electrical failure times



Results

Circuit integrity / Full-Scale Horizontal Tests (continued 3)

Table 3: Average delay in time to failure for each cable coating

Flame-retardant cable coating	Average delay in time to failure
Carboline Intumastic 286	14.9 min
Vimasco 3i	11.6 min
Flamemastic F-77	10.4 min
FS-15	15.9 min

- Average interior cable temperature at the time of failure was approximately 300°C (572°F). Range of failure temperatures was considerable; from 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.

Conclusions

What we have learned

- Small scale tests
  - Did not demonstrate that the coatings increase the effective ignition temperature of the cables, but rather delay the time to reach the ignition temperature.
  - The coatings delay the time to ignition, decrease the peak burning rate, and increase the total energy released (i.e., coatings do add to the fuel load).

- Full scale tests
  - Coatings effectively prevent the spread of fire
  - The amount of additional energy released due to the application of coatings is negligible.

Conclusions (continued 2)

What we have learned

- Coated non-qualified cables demonstrated a delay in time to damage of at least five minutes.

- Coated qualified cables demonstrated mixed results.
  - Bench-scale tests demonstrated a delay,
  - Full-scale vertical flame spread testing did not demonstrate a delay.

- Coating thickness
  - Thickness beyond the manufacturers specified minimum thickness appears to provide additional delay in time to electrical damage.
  - Thickness just less than the recommended value, the fire did spread upwards to various extents, but this behavior was not repeated when the coatings were applied as directed.