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HEAF CABLE FRAGILITY TESTING AT THE SOLAR FURNACE AT THE NATIONAL SOLAR THERMAL TEST FACILITY

Experimental Results

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HEAF Cable Fragility Testing at the Solar Furnace at the NSTTF

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ABSTRACT

In order to establish a zone of influence (ZOI) due to a high energy arcing fault (HEAF) environment, the fragility of the targets must be determined. The high heat flux/short duration exposure of a HEAF is considerably different than that of a traditional hydrocarbon fire, which previous research has addressed. The previous failure metrics (e.g., internal jacket temperature of a cable exposed to a fire) were based on low heat flux/long duration exposures. Because of this, evaluation of different physics and failure modes was considered to evaluate the fragility of cables exposed to a HEAF. Tests on cable targets were performed at high heat flux/short duration exposures to gain insight on the relevant physics and failure modes. These tests yielded data on several relevant failure modes, including electrical failure and sustained ignition. Additionally, the results indicated a relationship between the total energy of exposure and the damage state of the cable target. This data can be used to inform the fragility of the targets.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CSPE	chlorosulfonated polyethylene
DAQ	data acquisition system
HEAF	high energy arcing fault
MOV	motor operated valve
PVC	polyvinyl chloride
RTF	run to failure
SCDU	surrogate circuit diagnostic unit
TP	thermoplastic
TS	thermoset
XLPE	cross-linked polyethylene
ZOI	zone of influence

1. BACKGROUND

In order to establish a zone of influence (ZOI) due to a high energy arcing fault (HEAF) environment, the fragility of the targets must be determined. The high heat flux/short duration exposure of a HEAF is considerably different than that of a traditional hydrocarbon fire, which previous research has addressed. The previous failure metrics (e.g., internal jacket temperature of a cable exposed to a fire) were based on low heat flux/long duration exposures. The relevant physics during these types of exposure (i.e., heat conduction through a cable jacket) may not be valid at the HEAF timescale when considering the pyrolysis and ignition at higher heat fluxes. Because of this, evaluation of different physics and failure modes was considered to evaluate the fragility of cables exposed to a HEAF. Tests at high heat flux/short duration exposures were performed to gain insight on the relevant physics and failure modes. Although there are many different targets that may be damaged during a HEAF, this effort only addresses cable targets. As with previous evaluations, two categories of cables (thermoset and thermoplastic) were addressed.

1.1. Theory

Prior to engaging in any tests, a literature review was conducted to evaluate relevant phenomena and develop a hypothesis on which to base the test program. Materials ignite as a function of both the heat flux and fluence exposure conditions. Work in this area was performed by Stan Martin in the 1960s for blackened cellulose [1]. The ignition threshold was calculated as a function of the rate of energy application (heat flux) and the total energy applied (fluence). Figure 1-1 shows the ignition threshold of blackened cellulose for Martin's work. The figure contains two ignition subregions, transient ignition and persistent ignition. The transient ignition mode is defined by conditions that result in a hot surface that emanates flames, but because the bulk material remains relatively cool, the surface temperature rapidly drops and flaming ceases when the exposure is ended. Persistent ignition occurs when the exposure features high normalized fluence and moderate-to-high normalized irradiance, resulting in moderate thermal gradients within the solid. Note that, the cellulose papers exhibited either smoldering or flaming ignition for these conditions [1] [2].

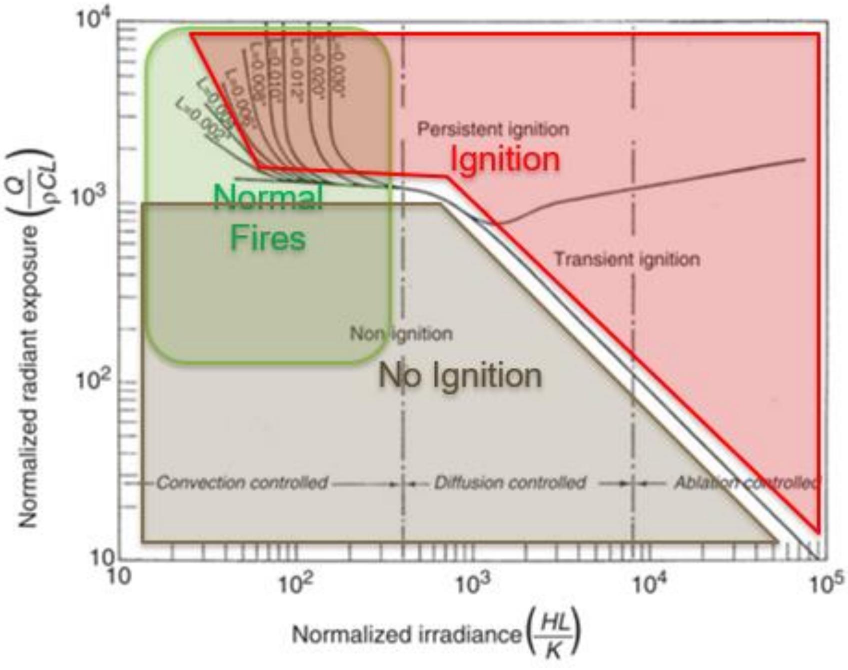


Figure 1-1: Ignition Threshold for Blackened Cellulose (Martin 1965)

Sandia National Laboratories has used the solar furnace at the National Solar Test Facility to extend this work to several different materials [2], including a preliminary lumped-material model derived for the high heat flux exposure conditions resulting from a HEAF. Assuming the conductor is isothermal, and ignoring effects such as pyrolysis and losses, an ignition model for a cable can be developed as a function of the flux and fluence, as well as the material properties of the conductor and insulation. C* is established as the ratio of the conductor and insulation properties below (See Appendix A). Figure 1-2 illustrates the lumped-material model for C* that was derived for an insulated wire. This model may be a reasonable basis for an empirical model for a jacketed cable – test data will be required to reach a conclusion.

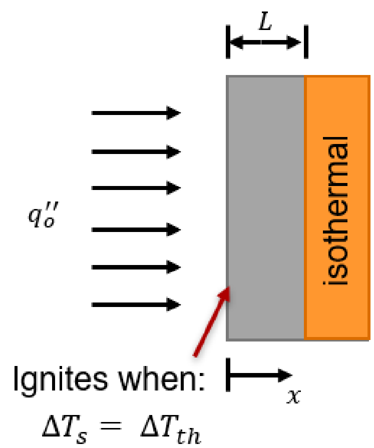


Figure 1-2: Lumped-Material Model with Isothermal Conductor

C* is then calculated as follows.

$$C^* = \frac{(\rho c_p L)_{cond}}{(\rho c_p L)_{insul}}$$

The following equations are used to calculate the normalized values of flux and fluence to determine the ignition regions. The ignition-threshold analysis consists of exposure conditions normalized by the thermophysical properties of the solid. Martin demonstrated that these normalized variables correlate with ignition thresholds in various regimes across a wide range of irradiation, thickness, and density [2].

$$q^* = \frac{aq"_o L}{k}$$

Where

q^*= normalized irradiance (flux) (Kelvin)
$q"_o$= peak or average flux of the exposure (kW/m^2)
a= surface absorptivity
L= thickness
k= thermal conductivity

$$Q^* = \frac{aQ"}{\rho c_p L}$$

Where

Q^*= normalized Fluence (Kelvin)

$Q''=$ exposure Fluence (kJ/m^2)
$a=$ surface absorptivity
$L=$ thickness
$c_p=$ specific heat
$\rho =$ density

Figure 1-3 shows the ignition regimes delineated by different C* values. Note that a C* only augments the ignition curve for low heat flux, long exposure heating curves. For the high heat flux, short duration exposure conditions representative of the HEAF ZOI criteria examined herein, the value of C* does not have a significant impact on the ignition model.

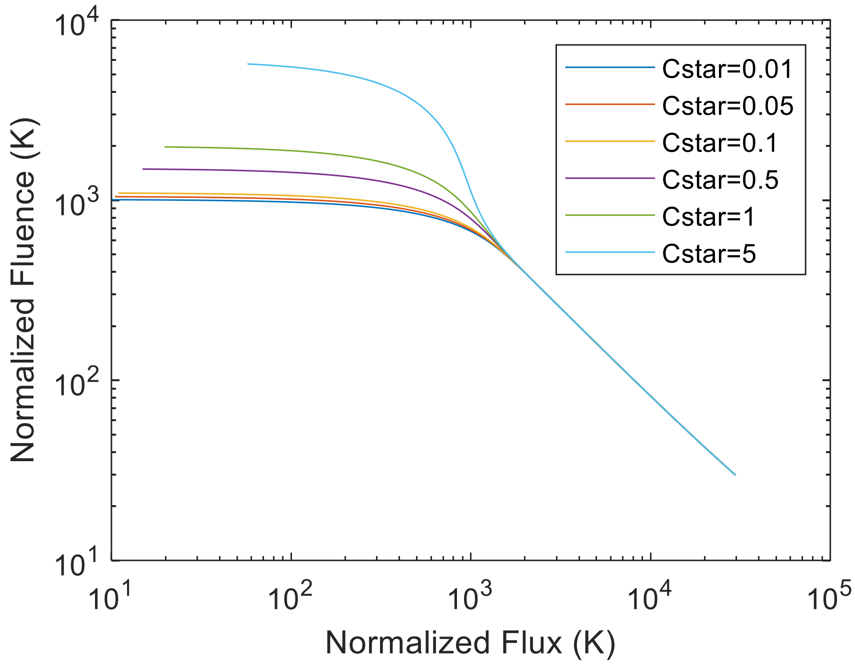


Figure 1-3: Ignition Threshold for Cables

Note, that this model was compared to the full-scale test data as a proof-of concept, which yielded encouraging results. Therefore, it was decided that an exploratory test program (Phase 0) could be conducted to learn more about how the cable reacts when exposed to a HEAF environment.

1.2. Facility

The fragility test series were performed at the Solar Furnace at the National Solar Thermal Test Facility at Sandia National Laboratories in Albuquerque, New Mexico. The Solar Furnace concentrates sunlight to generate intense thermal environments reaching 6 MW/m^2 on a spot roughly ~5 cm in diameter. Figure 1-4 and Figure 1-5 show the components of the solar furnace that reflect the sun and focus the sunlight onto the test article. A heliostat uses flat mirrors with a total reflective surface area of 55 m^2 to reflect the sunlight through an attenuator onto a large reflective parabolic dish. The parabolic dish concentrates the sunlight with 228 individually aligned mirrors [2].

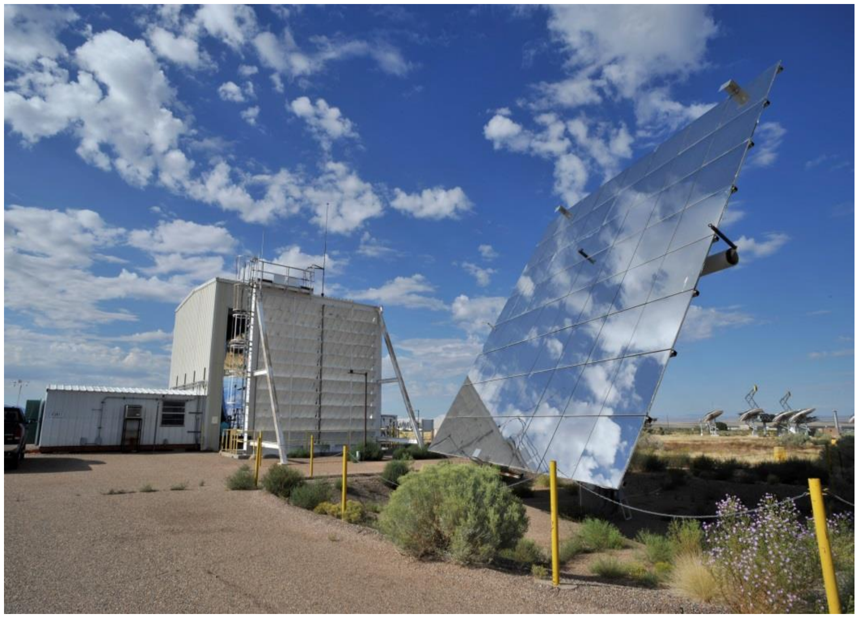


Figure 1-4: Heliostat at the Solar Furnace

Figure 1-5: Parabolic Dish at the Solar Furnace

1.3. Phase 0

Phase 0 testing was conducted at the Solar Furnace at Sandia National Laboratories between 5/18/2020 and 6/3/2020. The purpose of this test program was to provide preliminary model data and verify the viability of the ignition map methodology. The Phase 0 test program provided insight into the failure mechanism of cables when exposed to high heat flux/short duration exposures. The Phase 0 test series focused on two different instrumentation cables. These cables were chosen to provide initial data on the failure mechanism of both thermoplastic (TP) and thermoset (TS) cables when exposed to representative HEAF exposures. Table 1-1 shows the cables evaluated in the Phase 0 test program. Note that these cables were used in previous test programs to evaluate plant instrumentation cables exposed to fire conditions [3].

Table 1-1: Phase 0 Cable Targets

Manufacturer	Short Description	Part Number	Jacket Type	Jacket Thickness (mm)	OD of Cable (mm)
Beldon	PVC/PVC, 16 AWG, 8	HW10501608	Thermoplastic	1.524	19.05
Beldon	FR-EP/CPE, 16 AWG, 8 SH	HW11001608	Thermoset	1.524	22.352

Note that instrumentation cables were used in the Phase 0 (and Phase 0b) test series. These cables were chosen based on their availability and because of their prototypical jacket materials. In the Phase 1 test series, control cables were used to evaluate different jacket thicknesses and accommodate a higher voltage circuit for electrical monitoring.

As a basis for the heat flux magnitude evaluated during the Phase 0 tests, the maximum average heat flux from the NIST instrumentation racks from the 2018 large-scale test series at KEMA was reviewed. Table 1-2 shows the test, rack id, and maximum average heat flux (maximum average flux value from any instrument on a given rack) from these tests as measured by the plate thermometers. As shown, the maximum heat flux exposure at any rack was 3.2 MW/m^2 with nearly all of the rest of the exposures below 1 MW/m^2.

Table 1-2: 2018 KEMA Test Heat Flux Values

Test ID	Rack Number	Maximum Heat Flux (MW/m^2)
Test 2-19 (6.9 kV, 25 kA, 2 s)	1	0.0266
	2	0.1989
	3	0.0329
	4	0.0526
	5	0.0803
Test 2-21 (6.9 kV, 25 kA, 4 s)	1	0.3326
	2	3.1647
	3	0.8191
	4	0.3087
	5	0.2573
Test 2-22 (6.9 kV, 32 kA, 2 s)	1	0.1281
	2	0.6822
	3	0.3387
	4	0.12488
	5	0.1251
Test 2-24 (6.9 kV, 32 kA, 4 s)	1	0.4069
	2	3.1490
	3	3.0408
	4	0.4038
	5	3.0857

Table 1-3 shows the test matrix executed during the Phase 0 tests. The maximum heat flux magnitude of 5 MW/m^2 was used to bound what was recorded in the 2018 large-scale tests at KEMA. The 0.25 MW/m^2 value was chosen to evaluate the lower end of the exposure range, with consideration of the effective exposure range of the Solar Furnace. A single cable sample was used as the target for the tests in Phase 0. These tests yielded positive results on spontaneous ignition when applied to the ignition mapping. However, sustained ignition was not observed during this test phase. The exposure profile did not account for heat feedback from heat sinks or surrounding cables after the initial exposure. Also, the single cable target set-up did not allow for re-radiation from surrounding cables. These items were identified as the reason sustained ignition was not observed, and the Phase 0b test program was planned to address the variables.

Table 1-3: Phase 0 Test Matrix

Test Number	Cable	Jacket Type	Heat Flux Magnitude (MW/m^2)	Exposure Duration (s)	Thermal Monitoring	Electrical Monitoring
0-T	HW4	Thermoset	5	10	Thermocouple	N/A
0-01	HW4	Thermoset	5	10	Thermocouple	N/A
0-02	HW4	Thermoset	0.25	10	Thermocouple	N/A
0-03	HW4	Thermoset	2.25	10	Thermocouple	N/A
0-05	HW2	Thermoplastic	0.25	10	Thermocouple	N/A
0-06	HW2	Thermoplastic	2.25	10	Thermocouple	N/A
0-07	HW4	Thermoset	2.25	30	Thermocouple	Single Pair
0-08	HW4	Thermoset	2.25	30	Thermocouple	N/A
0-09	HW2	Thermoplastic	5	20	Thermocouple	All Pairs in Series
0-10	HW2	Thermoplastic	5	20	Thermocouple	N/A
0-11	HW2	Thermoplastic	1	30	Thermocouple	All Pairs in Series
0-12	HW2	Thermoplastic	1	30	Thermocouple	N/A
0-13	HW2	Thermoplastic	5	10	Thermocouple	N/A
0-14	HW4	Thermoset	5	60	Thermocouple	N/A
0-15	HW4	Thermoset	5	60	Thermocouple	All Pairs in Series

1.4. Phase 0b

The Phase 0b test program was conducted to evaluate the feasibility of achieving persistent ignition at the Solar Furnace scale. The two variables identified in Phase 0 were altered to test a more realistic configuration that adds characteristics that increase the likelihood of sustained ignition occurring. First, a three-cable bundle was used as the target instead of a single cable. This provided a source of re-radiation close to the center cable target. Additionally, the heat flux profile was modified so that a secondary heat flux was provided after the initial exposure to simulate heat feedback. The same cable types from Phase 0 were also used in Phase 0b. The primary heat flux (2.25 MW/m^2) was applied to the cable for 10 seconds. Then, the flux was reduced to the secondary value (250 kW/m^2) for an additional 30 seconds. The samples were observed visually during the test, and it was clear that sustained ignition occurred for both cable types with the modified exposure profile and target set-up throughout the secondary flux duration. Additional tests were run with the modified exposure profile and a single cable target. These tests also resulted in sustained ignition. Because the Phase 0b test program showed that it was possible to sustain ignition at the Solar Furnace, the Phase 1 test program was planned.

2. PHASE 1 TEST PLAN

The results of the Phase 0 test program indicated that sustained ignition of cables exposed to a HEAF is the primary failure mechanism of concern. It is noted that failure during the primary HEAF exposure is also of concern and was evaluated in Phase 1. However, the sustained ignition failure mechanism is more complicated because sustained ignition of a thick material (e.g., cable jacket) is difficult to achieve because of heat loss to surroundings (during small scale tests) and heat diffusion deeper into the material. At scale, heat feedback to the target would occur through the flame sheath, combustion of surrounding materials, and thermal radiation from heated surfaces. Since this cannot be replicated at the solar furnace, a secondary heat flux was applied.

The purpose of the Phase 1 tests was to produce an empirical model for sustained ignition by replicating the heat flux from the HEAF event and the subsequent heat feedback. To do this, the tests conducted in Phase 1 were designed to find the sustained ignition threshold. The three variables of interest for the empirical model are the HEAF heat flux (primary flux), the HEAF duration (delay time), and the heat feedback (secondary flux).

2.1. Sustained Ignition Theory

An analytical expression for first-order effects is first defined to help inform the empirical model. Green's functions were chosen as the analytical expression, which assumes an inert material (no pyrolysis), constant properties (no charring), no surface recession, and a finite thickness. Further refinements to the Green's functions were made by assuming that the cable jacket is a semi-infinite solid and using the finite-thickness calculation to verify that the semi-infinite derivation was appropriate (See Appendix B). This function was evaluated for the step-wise heat flux exposure of a HEAF (primary exposure, then drop to secondary exposure representing heat feedback at scale) for both the finite thickness and non-finite thickness assumptions. Figure 2-1 shows the temporal behavior of the Green's function for various locations as a function of Fourier number (see Appendix A). As shown, the semi-infinite approximation is reasonably well aligned for low Fourier numbers. Therefore, the semi-infinite solid approximation is reasonable.

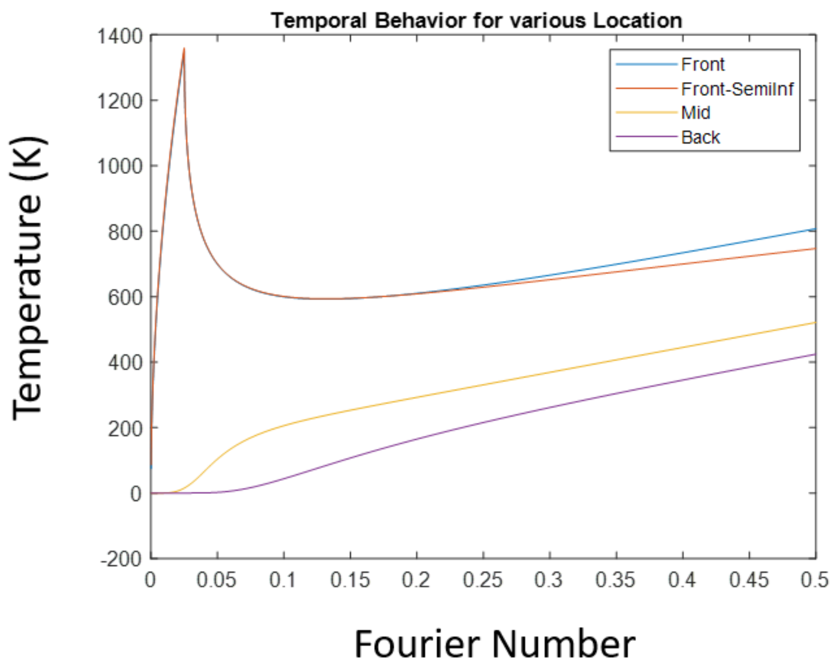


Figure 2-1: Green's Function Evaluated for the Step-wise Heat Flux Application

Based on the analytical model, the semi-empirical model can be defined. As shown in Figure 2-1, a clear minimum exists in the temperature curve at the front of the cable. The hypothesis of the semi-empirical model is that the flame will extinguish (no sustained ignition) if the temperature at the front cable surface falls below the minimum value. The temperature curve takes the following form:

$$T^* = \sqrt{\frac{2}{\pi}}\left(\sqrt{t^*} - H(t - t^*)\chi\sqrt{t^* - t_o^*}\right)$$

Where:

$$T^* = \frac{T}{T_{crit}}$$

$$t^* = \frac{tq_o^2}{k\rho c_p T_{crit}^2}$$

$$\chi = \frac{q_o - q_1}{q_o}$$

$H(t - t^*)$ - Heaviside Function

The minimum temperature can then be derived by solving for $\frac{dT^*}{dt^*} = 0$:

$$t_{min}^* = \frac{1}{1 - \chi^2} t_o^*$$

$$T_{min}^* = \frac{2}{\sqrt{\pi}}\sqrt{t_o^*}\sqrt{1 - \chi^2}$$

This form of the equation cannot be directly used because the experimental variables are implicit. Rearranging the equation and replacing terms results in a form of the equation in which the experimental variables are explicit and is favorable for testing.

$$t_o = \left(\frac{\pi}{8}\frac{k^2}{\alpha}T_{crit}^2\right) q_1^{-1}(q_o - q_1)^{-1}$$

Where:

t_0	Hold time
$\left(\frac{\pi}{8}\frac{k^2}{\alpha}T_{crit}^2\right)$	Experimental constant
q_1	Secondary Flux
q_o	Primary Flux

The basis of the empirical model was then formed by taking the log-transform of the above equation, in which t_{crit}, C_0, and C_1 are unknown and will be defined by the results of the test.

$$\log t_{crit} = \log\left(\frac{\pi}{8}\frac{k^2}{\alpha}T_{crit}^2\right) - C_0 \log q_1 - C_1 \log(q_o - q_1)$$

Based on this theory, the tests could be designed to evaluate the ignition plane for thermoset and thermoplastic cables. Figure 2-2 shows an example ignition plane that was developed for both thermoset and thermoplastic jacket types. The red dot on the plane is where the data from the Phase 0b tests would fall relative to the ignition plane.

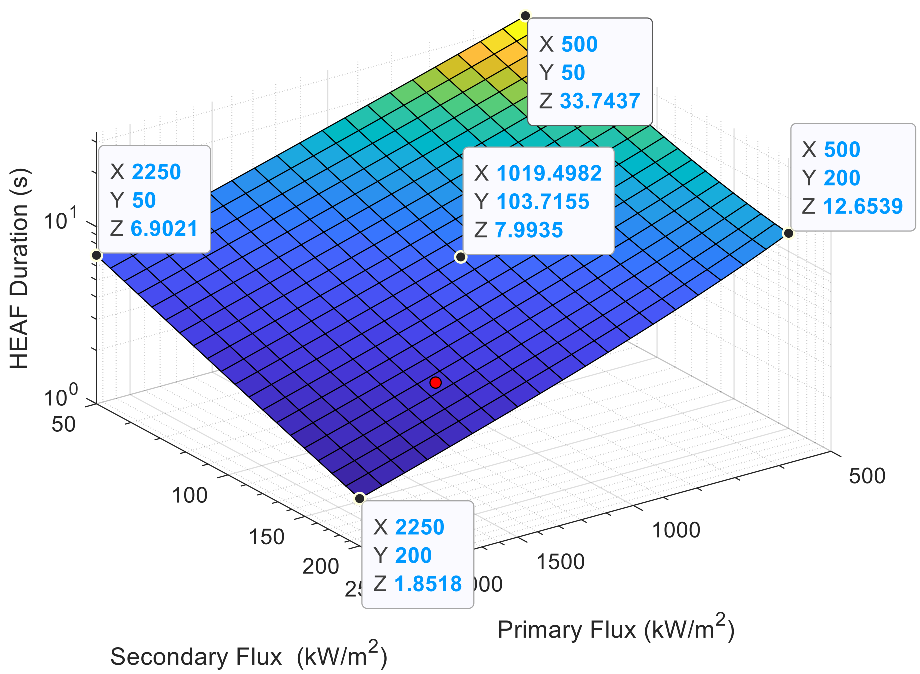


Figure 2-2: Example Ignition Plane

To develop the semi-empirical sustained ignition plane, several datapoints were evaluated. Figure 2-3 shows a test plan based on the theory for each of the different jacket materials. The grey space in the figure is the design space for the primary and secondary flux magnitudes, which is non-uniform because of unknown, poorly characterized experimental limitations (orange lines). These orange lines represent design space limitations such as a case in which the maximum primary and secondary heat flux are sufficiently high so that the primary heat flux duration cannot be reduced enough to find the ignition threshold. Also, there is a threshold in which the primary heat flux is so low that spontaneous ignition would not occur, let alone sustained ignition. To gather relevant data for the semi-empirical model, the range at which testing will occur needs to be easily resolvable. Therefore, the maximum bounds of the design space should not be evaluated. Instead, the points of the plane to be evaluated need to span a reasonable range so that the primary flux duration is resolvable.

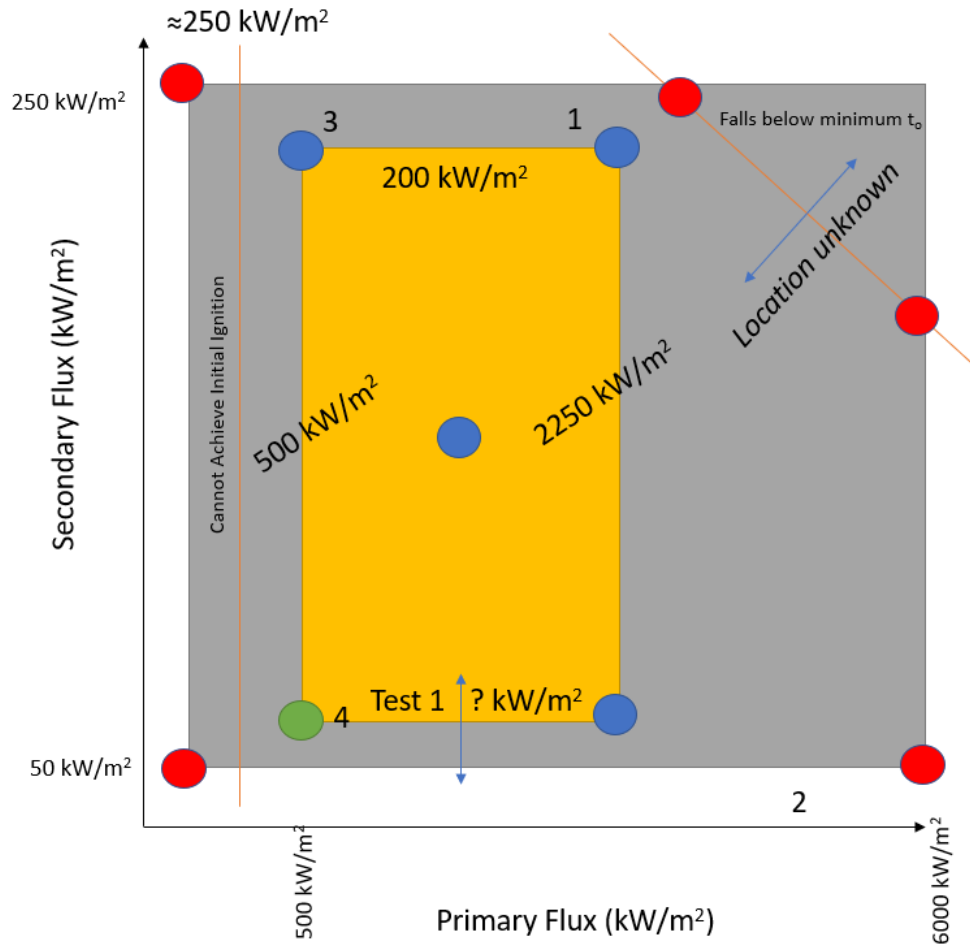


Figure 2-3: Test Plan to resolve Semi-empirical Model

A total of five different primary/secondary flux combinations could be tested to provide enough data to resolve the semi-empirical model. At each combination, a series of 4-5 "up/down" tests could be run to evaluate the primary duration variable. The center point (1 MW/m^2 primary flux, 100 kW/m^2 secondary flux) could be tested first to get preliminary data on the t_{crit} value for a given jacket type. This information could be used to approximate (in terms of primary flux duration) the corner points. Through these tests (4-5 up/down tests at each flux combination), the magnitude and shape of the sustained ignition plane could be defined. Also, since ignition results are typically stochastic, the uncertainty in the plane could be defined.

2.2. Simplification and Implementation

The semi-empirical model, as defined in Section 2.1, is a fairly complicated model that requires evaluation of three independent variables. Prior to the beginning of the Phase 1 test program, an effort was taken to simplify the model so there were only two independent variables. To do this, a modified exposure profile was developed that accounted for heat feedback in a consistent manner as a function of the primary heat flux magnitude. The resulting heat flux profile is shown in Figure 2-4. This profile is informed by the HEAF exposure seen by the instrumentation in the 2018 full-scale tests at KEMA. This exposure does not account for any buoyant drive heating term from a post-HEAF enclosure fire.

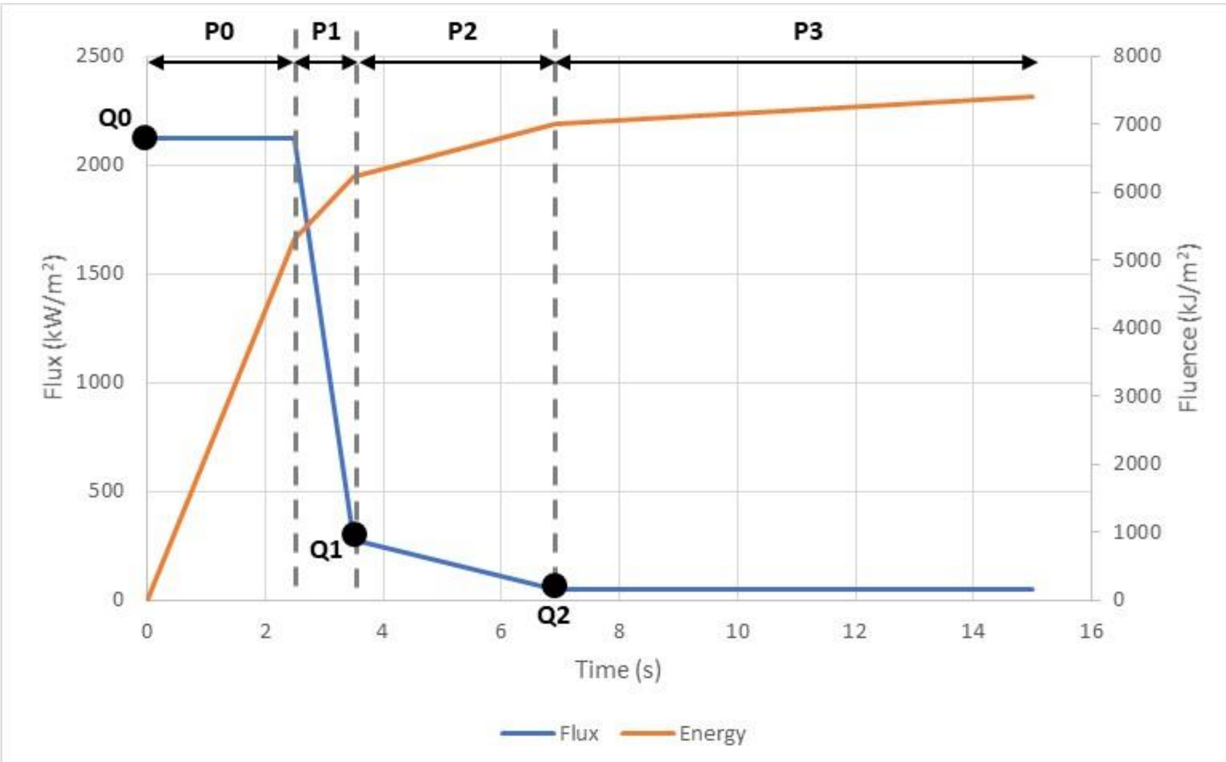


Figure 2-4: Phase 1 Exposure Profile

Where:

Q0 =	Primary heat flux magnitude
P0 =	Primary heat flux duration
Q1 =	Secondary heat flux magnitude (22% of Q0)
P1 =	Ramp duration to secondary flux
Q2 =	Long-term steady state flux (50 kW/m^2)
P2 =	Duration of secondary flux ramp down to Q2 (4 seconds)
P3 =	Duration of steady state flux

With this simplified profile, the test matrix could be simplified to only evaluate the primary heat flux magnitude and the primary heat flux duration (since Q1 is a function of Q0, and Q2 is constant). Table 2-1 shows the preliminary test matrix that was used for each jacket type. The primary duration would be alternated up and down until the sustained ignition time could be reasonably bracketed. Note, that because the Phase 0b tests showed that sustained ignition is possible with the single cable as well as the cable bundle, single cables were used for simplicity.

Table 2-1: Phase 1 Test Matrix

Primary Heat Flux (kW/m^2)	Primary Duration
3,000	4-5 Tests
2,000	4-5 Tests
1,000	4-5 Tests
500	4-5 Tests
250	4-5 Tests

2.3. Modification During Testing

The test matrix outlined in the previous section represented the initial plan going into the Phase 1 test program. However, sustained ignition events were not seen after the first six tests were executed. These first six tests were performed with thermoplastic and thermoset cables at a primary heat flux of 3 MW/m^2 with durations ranging from 2 to 10 seconds. Daily meetings were held with an NRC/EPRI working group to discuss the results from the previous day and any modifications that needed to be made to the test plan based on the results. During these meetings, the test plan was modified to probe different failure modes than sustained ignition, including electrical failure, sub-jacket temperature, and jacket damage. Additionally, a three-cable bundle was introduced for some of the later tests. Each of the tests that were conducted during Phase 1 are documented in Section 3, including the test setup, purpose, and exposure profile.

2.4. Instrumentation

Based on previous heat flux tests at the solar furnace, the following typical instrumentation was used:

- Cameras (60 FPS filtered, adjusted for resolving the flames)
- Record of current time/temperature/humidity
- Pre- and post-test weight of the samples
- Pre-and post-test flux
- Pre- and post-test photographs of the samples
- A device for flame detection
- Thermocouples mounted to the test object
- Electrical monitoring circuit

2.5. Test Procedure

The following procedures was used for pre- and post-test data collection. Testing proceeded on days and times when the sky was clear and the conditions were repeatable.

1. Record current ambient conditions
2. Sample preparation:
   a. Photograph samples
   b. Pre-weigh samples
3. Mount samples on holder in the low table position
4. Adhere thermocouple/electrical monitoring if used for this test
5. Raise the motorized table in position for the test
6. Start Cameras/Video
7. Verify the test area is clear of personnel
8. Take a pre-test flux reading with the flux gauge
9. Execute the test, record observations
10. Take a post-test flux reading with the flux gauge
11. Stop/pause cameras/video
12. Lower the table with the tested sample
13. Post-test data collection
    a. Photograph samples
    b. Post-weigh samples

2.6. Cable Types

The Phase 1 test series will focus on two different control cables. The cable selection survey conducted in CAROLFIRE [4] was leveraged to determine which thermoset and thermoplastic cables will be investigated. The cross-linked polyethylene (XLPE) insulation, chlorosulfonated polyethylene (CSPE) jacket Rockbestos Firewall III control cable was chosen as the representative thermoset cable for the Phase 1 tests (Cable Number 10 in CAROLFIRE). These cables are fully qualified for NPP applications and are one of the most common insulation/jacket combinations found in the U.S. nuclear power industry [4].

The polyvinyl chloride (PVC) insulation, PVC jacket BICC-Brand cable was chosen as the representative thermoplastic cable for the Phase 1 tests. Note, this cable included a metallic shield beneath the jacket. It is similar to Cable Number 1 in CAROLFIRE. This cable is an industrial grade cable that is widely used in general commercial and nuclear applications. Note that PVC is the most common thermoplastic jacket material used in U.S. NPPs. Both cable types are 7-conductor (7C), 12 AWG cables, which is the most common control cable configuration [4].

2.7. Electrical Monitoring

The Phase 1 tests used the Surrogate Circuit Diagnostic Unit (SCDU) to monitor electrical performance, which was also used in the CAROLFIRE test program [4]. The test voltage applied to the cable sample was 600 V. The SCDU was used to monitor the cables for short circuits between conductors within the cable. Three pairs of conductors were identified for each of the 7-conductor cables, and adjacent conductors were energized/grounded based on the SCDU set-up. The monitoring allowed for identification of a short circuit failure in each of the three pairs of adjacent conductors. Note, that six conductors were connected to the SCDU (three energized, three grounded) and the seventh (center) cable was not connected.

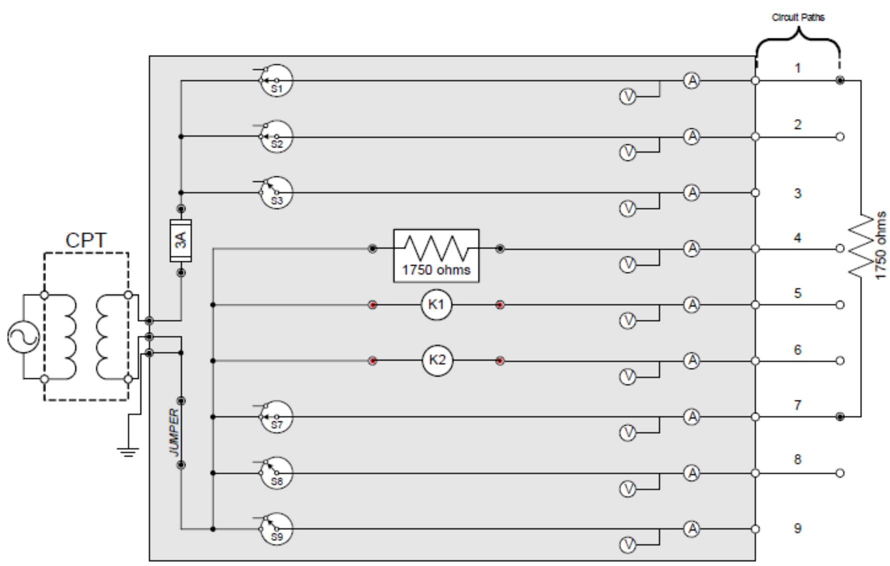


Figure 2-5: SCDU Circuit Configuration for MOV Representation

2.8. Thermal Monitoring

The cable temperature response was measured using a thermocouple inserted below the cable's outer jacket. This technique has been used in several prior test programs and has been shown to provide good correlation between cable temperature and electrical failure behaviors (e.g., see NUREG/CR-6931 [5]). Insertion of a thermocouple may compromise a cable's electrical integrity, so temperature response samples were not monitored for electrical performance. The thermocouples are Omega, type K (part number KMQIN-040U-18) and were placed below the cable jacket. These thermocouples have a 0.04" diameter and stainless-steel immersion probe.

3. PHASE 1 TEST RESULTS

The results from each of the tests are documented in this section. The exposure profile is documented for each of the tests. This profile was derived from the data output from each test and the calibration curves for each test is documented in Appendix C.

Note the post-test photos of the cable samples were used to determine the damage state of the cable. The damage of the cables was subjectively categorized as follows:

- Jacket Damage: Surface damage to the jacket was observed but was overall still intact such that no inner components of the cable were exposed.
- Insulation Exposure Imminent: Surface damage to the jacket was observed and no inner components of the cable were exposed. However, there were damage characteristics on the jacket, such as “pinholes” or “deep cracks” that suggest exposure of insulation was imminent.
- Insulation Exposure: The jacket was sufficiently damaged so that there was clear exposure of the inner shielding and/or insulated wires of the cable.
- Wire Exposure: The jacket and insulation of the wires were damaged sufficiently such that the copper wire of a conductor was exposed.

3.1. Test 1-01

Test 1-01 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 2 seconds. As described in the notes below, this test did not yield usable data, so the test parameters were re-evaluated in Test 1-02.

Table 3-1: Test 1-01 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-01	3	2	0.66	0.05	396.05	395.45	TS

- Purpose: Examine sustained ignition with dynamic profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 1-27-21

Note:

- High heat flux gage was used for calibration of the Q0, Q1, and Q2 points. Note, the high heat flux gage is less accurate for the lower heat flux point of Q2. The high heat flux gage calibration resulted in an attenuator position of 0.55% open for the 0.05 MW value. Later in day, when the radiometer was used for calibration in Test 2, an attenuator position of 1.75% open was used for the 0.05 MW value. Therefore, Q2 for Test 1 was likely ~0.02 MW.
- Also, data file was not saved correctly, so no data for profile shape, total energy, or electrical monitoring
- Camera was not set-up correctly, so no photos were taken
- No usable data from this test, but a lot of the test execution errors were worked out for the subsequent tests.

3.2. Test 1-02

Test 1-02 evaluated a thermoset cable with a primary flux of 3 MW/m² for a duration of 2 seconds.

Table 3-2: Test 1-02 Test Summary Data

Test Number	Q0 (MW/m²)	T0 (s)	Q1 (MW/m²)	Q2 (MW/m²)	Pre-weight (g)	Post-weight (g)	Cable Type
1-02	3	2	0.66	0.05	389.96	388.19	TS

- Purpose: Examine sustained ignition with dynamic profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 1-27-21

3.2.1. Profile/Energy

Figure 3-1 and Figure 3-2 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux profile remained at the primary heat flux for a lesser duration when compared to the planned profile. The cable target was exposed to a total of approximately 14 MJ/m².

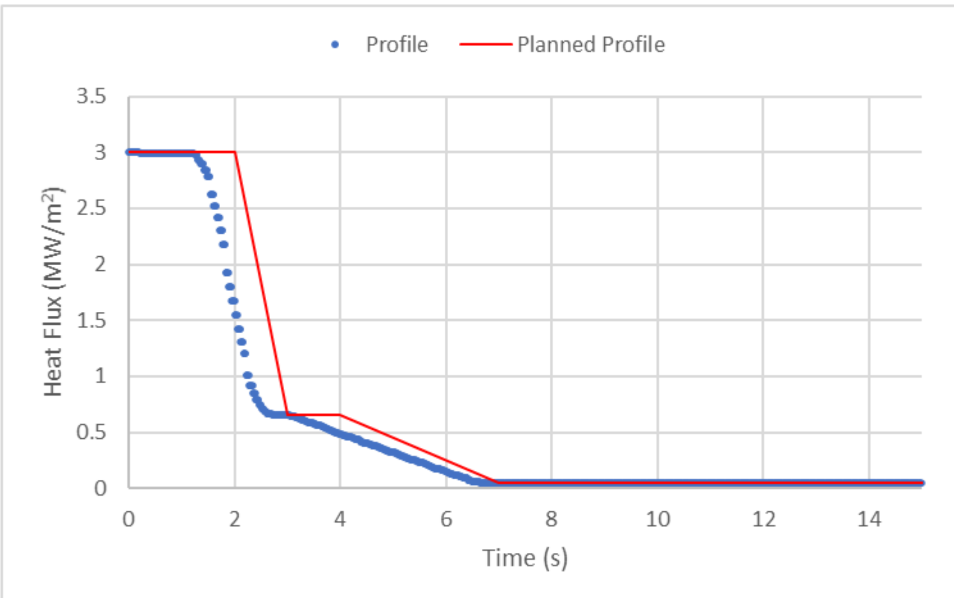


Figure 3-1: Test 1-02 Heat Flux Profile

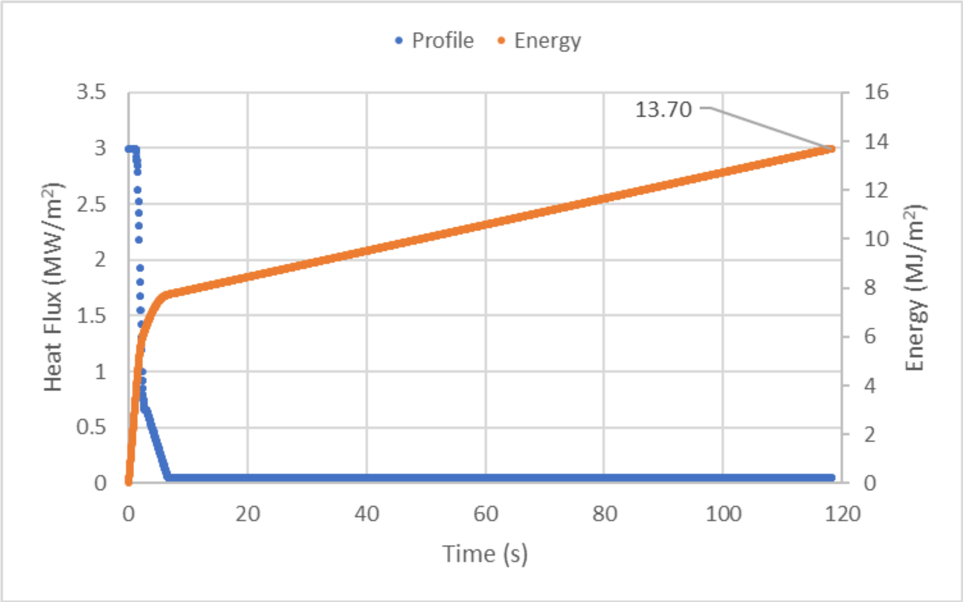


Figure 3-2: Test 1-02 Total Energy

3.2.2. *Electrical/Thermal Monitoring*

Figure 3-3 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

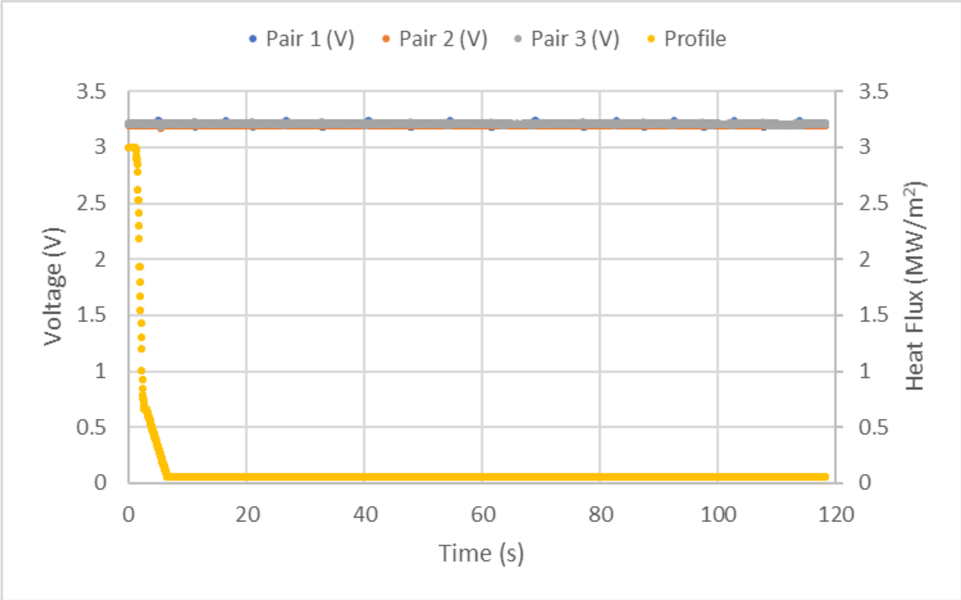


Figure 3-3: Test 1-02 Electrical Monitoring

3.2.3. Photos

Figure 3-4 shows the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-4: Test 1-02 Post-test Photo

3.2.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.5 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 5.97 seconds after the shutter was fully open. Figure 3-5 shows the time at which the ignition extinguished as a function of total energy and heat flux.

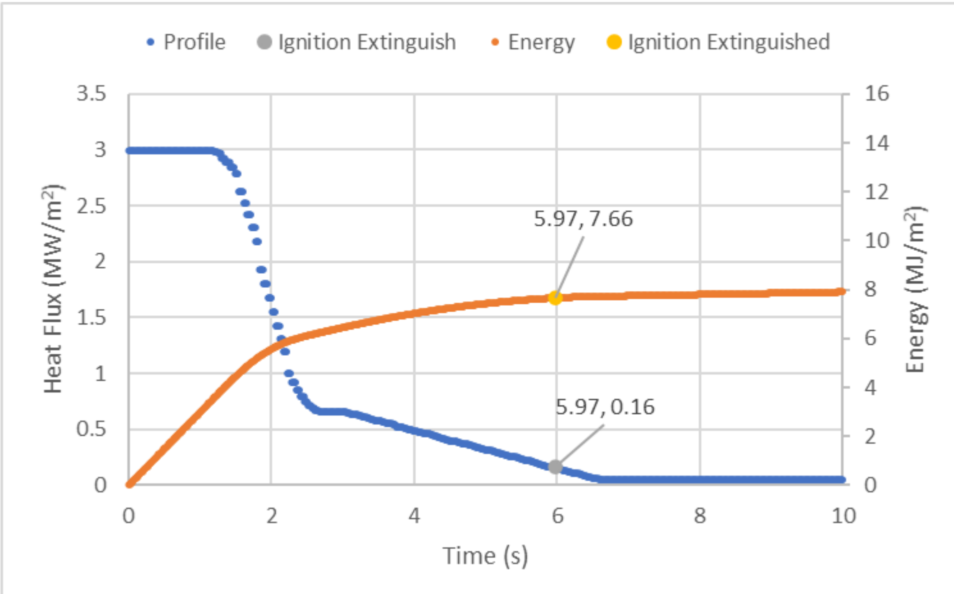


Figure 3-5: Test 1-02 Sustained Ignition as a Function of Heat Flux and Time

3.3. Test 1-03

Test 1-03 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 10 seconds.

Table 3-3: Test 1-03 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-03	3	10	0.66	0.05	393.38	390.08	TS

- Purpose: Examine sustained ignition with dynamic profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 1-27-21

3.3.1. Profile/Energy

Figure 3-6 and Figure 3-7 show the heat flux profile and total energy for which the cable target was exposed. As shown, the primary flux magnitude is slightly less than the planned 3 MW/m^2. Also, the profile data from the data acquisition system (DAQ) at the solar furnace is a little choppy. The cable target was exposed to a total of approximately 37 MJ/m^2.

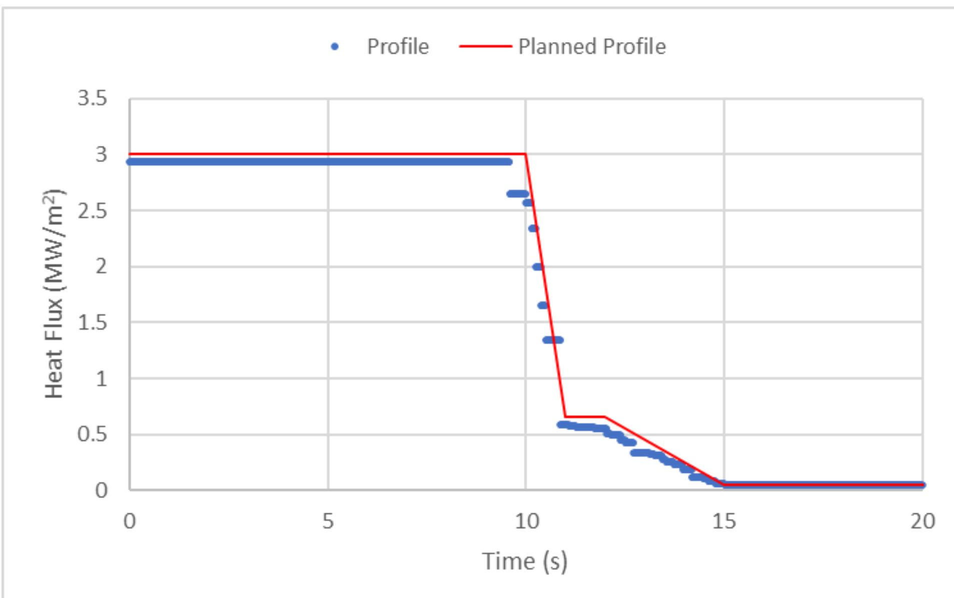


Figure 3-6: Test 1-03 Heat Flux Profile

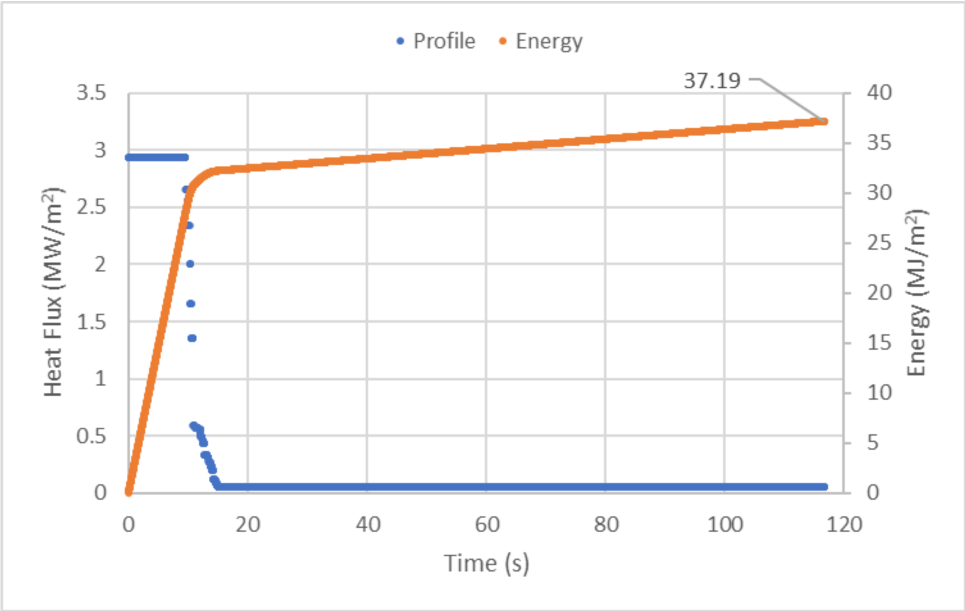


Figure 3-7: Test 1-03 Total Energy

3.3.2. *Electrical/Thermal Monitoring*

Figure 3-8 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

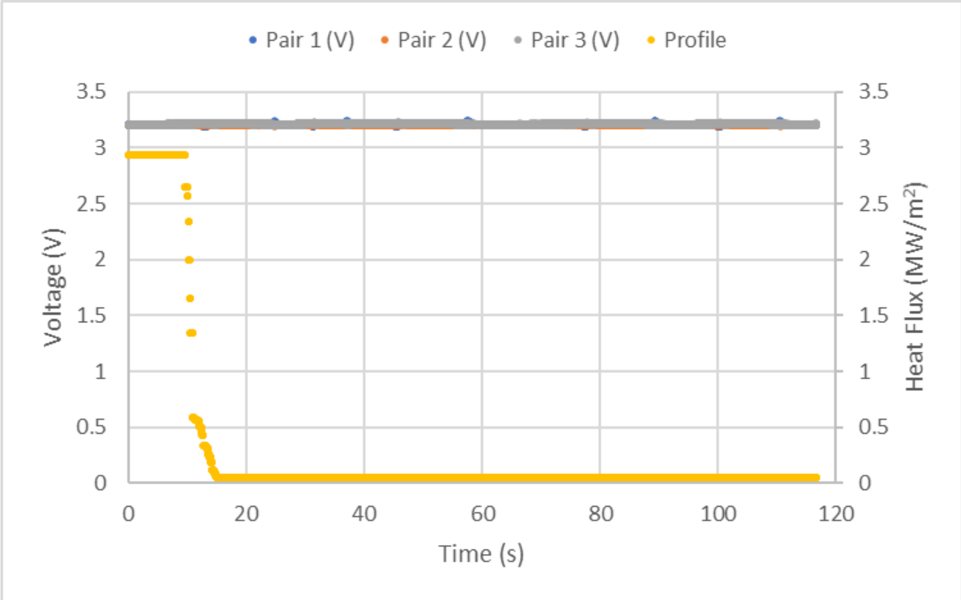


Figure 3-8: Test 1-03 Electrical Monitoring

3.3.3. Photos

Figure 3-9 and Figure 3-10 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-9: Test 1-03 Post-test Photo (1)

Figure 3-10: Test 1-03 Post-test Photo (2)

3.3.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.37 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 14.30 seconds after the shutter was fully open. Figure 3-11 shows the time at which the ignition extinguished as a function of total energy and heat flux.

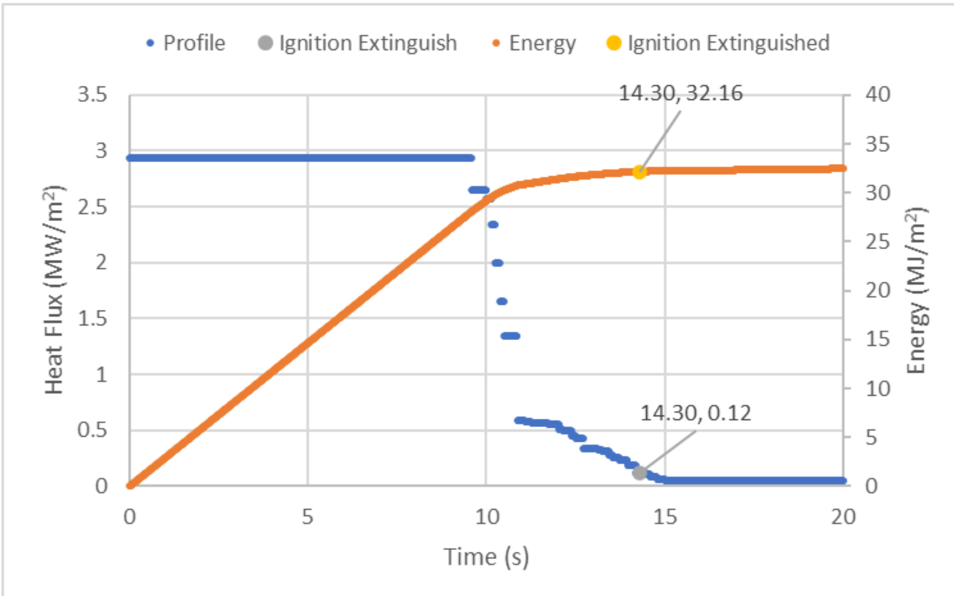


Figure 3-11: Test 1-03 Sustained Ignition as a Function of Heat Flux and Time

3.4. Test 1-04

Test Not Performed.

3.5. Test 1-05

Test 1-05 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 2 seconds.

Table 3-4: Test 1-05 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-05	3	2	0.66	0.05	334.3	332.72	TP

- Purpose: Examine sustained ignition with dynamic profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-4-21

3.5.1. Profile/Energy

Figure 3-12 and Figure 3-13 show the heat flux profile and total energy for which the cable target was exposed. As shown, the profile is fairly accurate. However, due to operator error, the secondary flux applied to the cable was stopped for approximately 20 seconds, and then restarted. The cable target was exposed to a total of approximately 14 MJ/m^2.

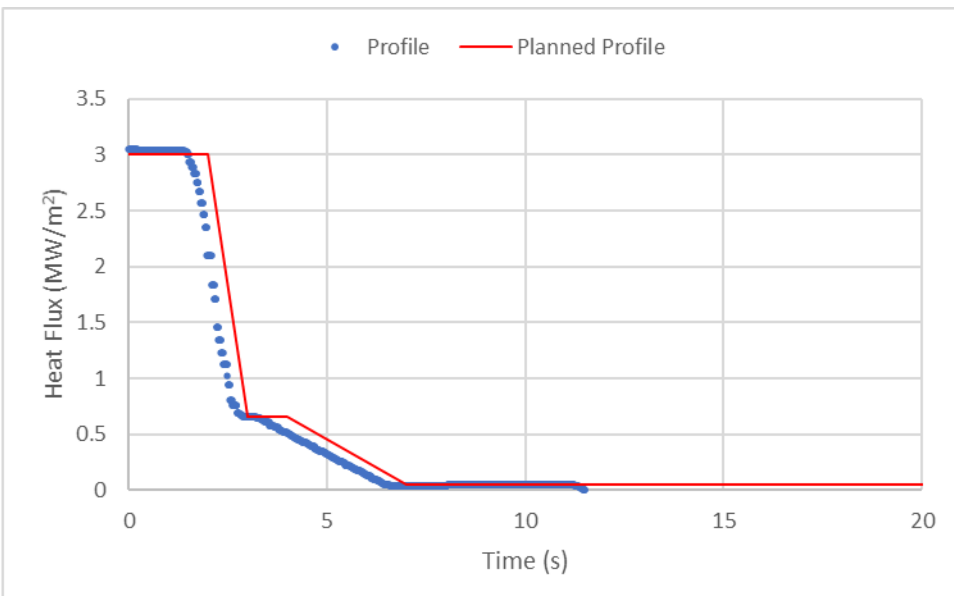


Figure 3-12: Test 1-05 Heat Flux Profile

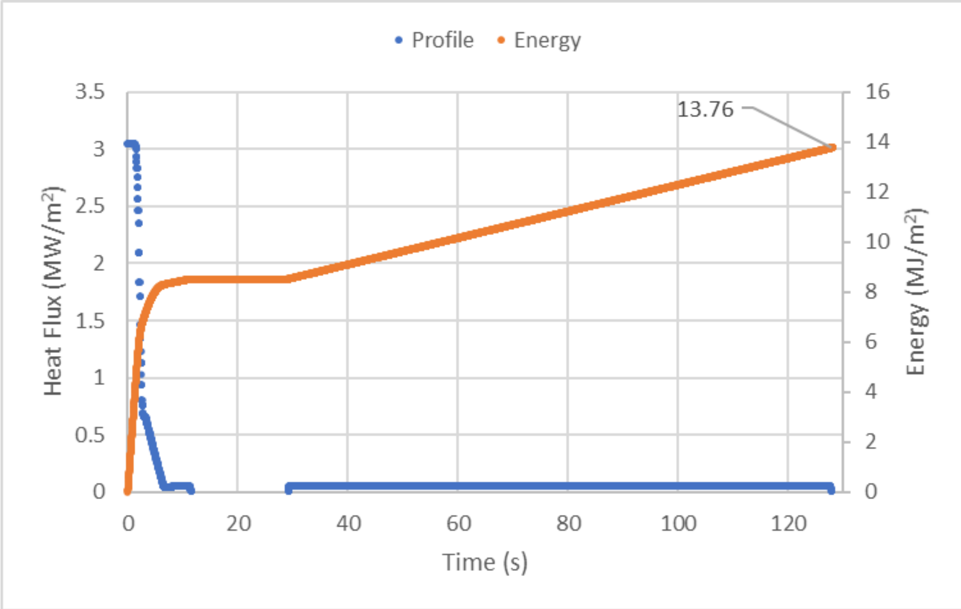


Figure 3-13: Test 1-05 Total Energy

3.5.2. *Electrical/Thermal Monitoring*

Figure 3-14 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

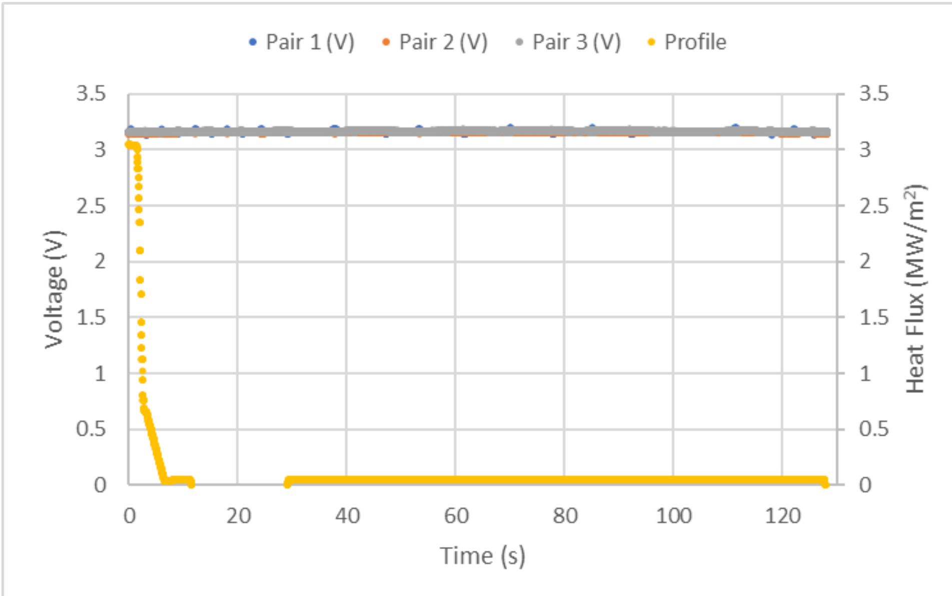


Figure 3-14: Test 1-05 Electrical Monitoring

3.5.3. Photos

Figure 3-15 shows the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-15: Test 1-05 Post-test Photo

3.5.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.4 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 5.90 seconds after the shutter was fully open. Figure 3-16 shows the time at which the ignition extinguished as a function of total energy and heat flux.

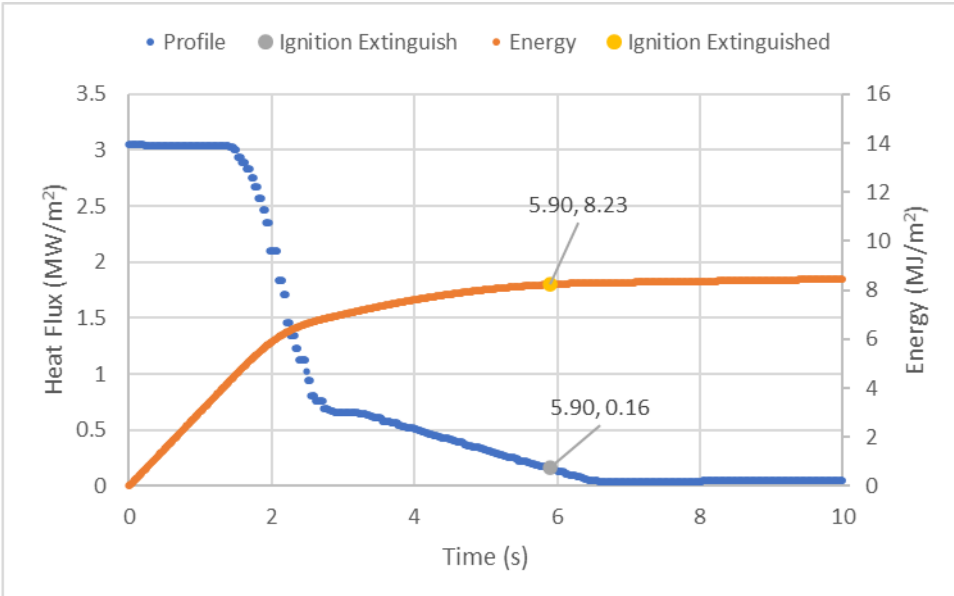


Figure 3-16: Test 1-05 Sustained Ignition as a Function of Heat Flux and Time

3.6. Test 1-06

Test 1-06 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 10 seconds.

Table 3-5: Test 1-06 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-06	3	10	0.66	0.05	341.06	337.84	TP

- Purpose: Examine sustained ignition with dynamic profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-4-21

3.6.1. *Profile/Energy*

Figure 3-17 and Figure 3-18 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile is fairly accurate compared to the planned profile. The cable target was exposed to a total of approximately 40 MJ/m^2.

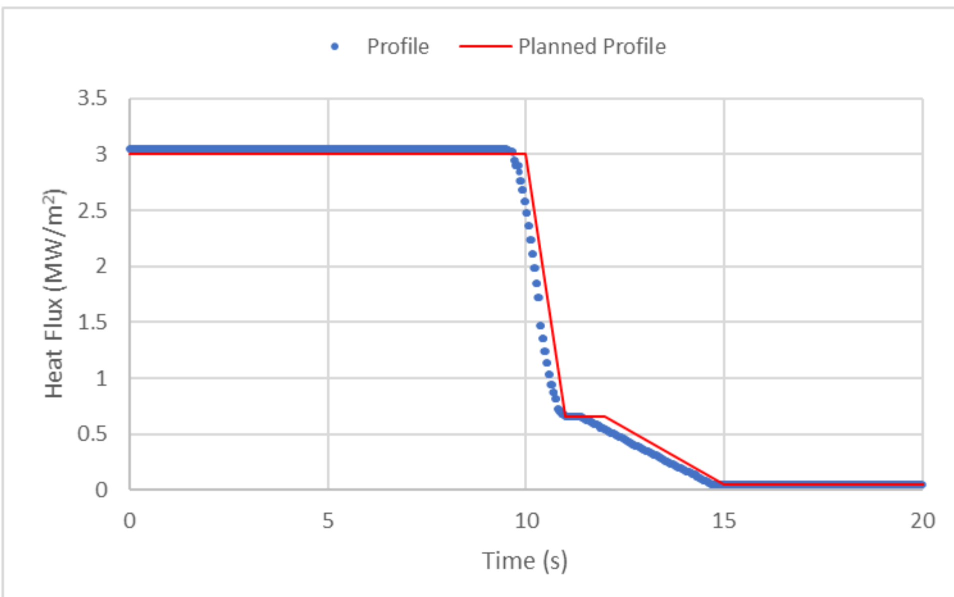


Figure 3-17: Test 1-06 Heat Flux Profile

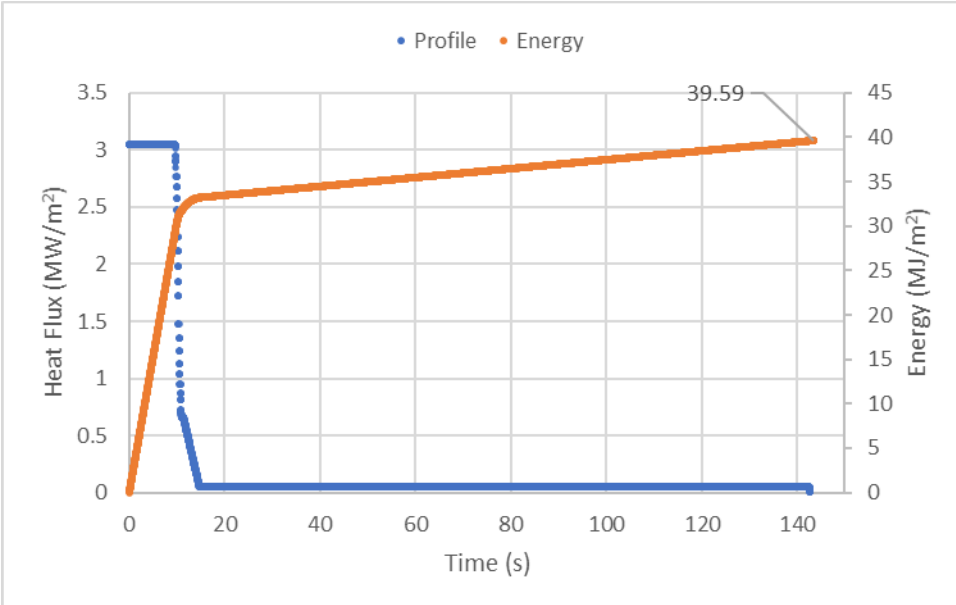


Figure 3-18: Test 1-06 Total Energy

3.6.2. Electrical/Thermal Monitoring

Figure 3-19 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

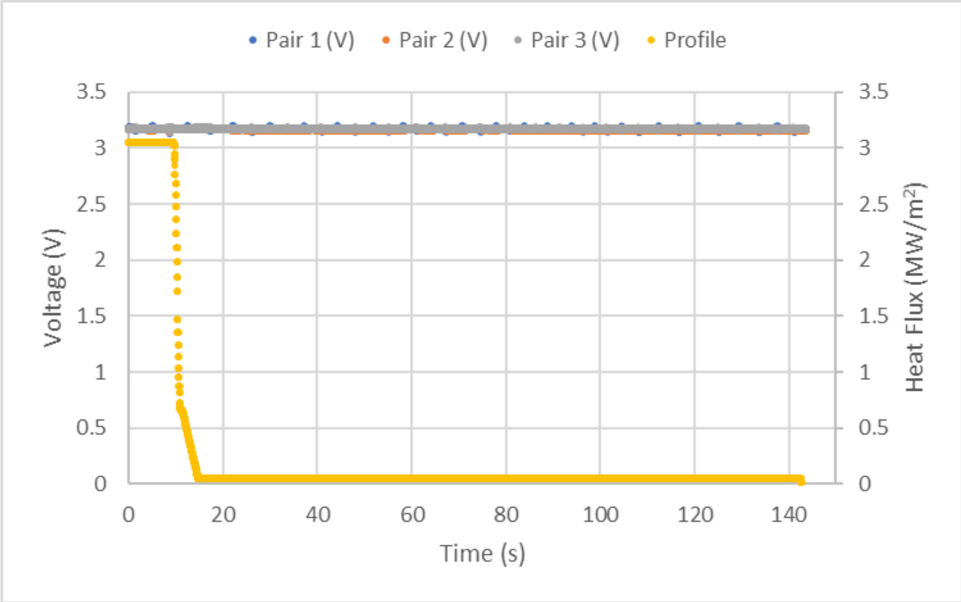


Figure 3-19: Test 1-06 Electrical Monitoring

3.6.3. Photos

Figure 3-20 shows the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test. Also, there is damage to the insulation, exposing bare wire.

Figure 3-20: Test 1-06 Post-test Photo

3.6.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.37 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 14.03 seconds after the shutter was fully open. Figure 3-21 shows the time at which the ignition extinguished as a function of total energy and heat flux.

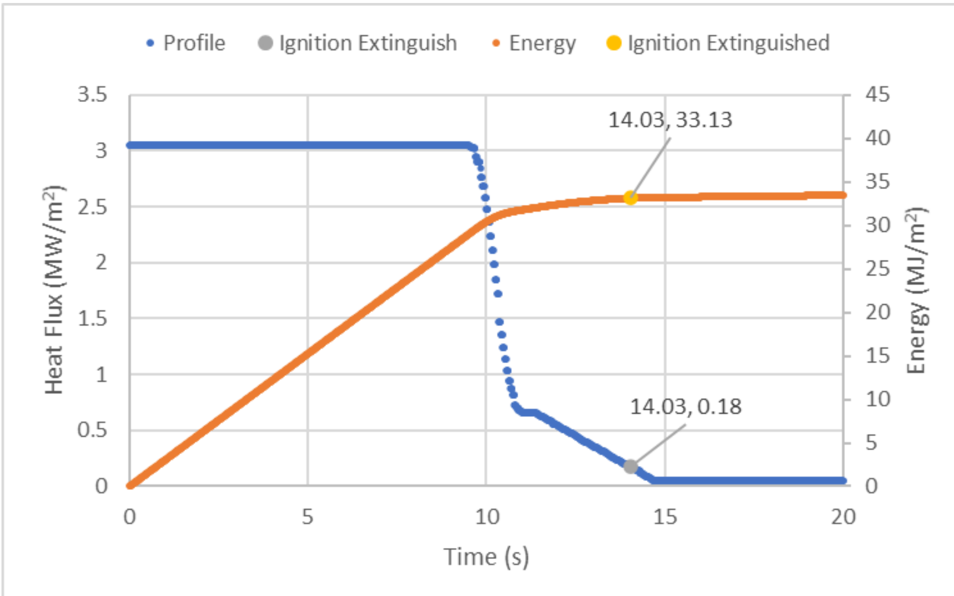


Figure 3-21: Test 1-06 Sustained Ignition as a Function of Heat Flux and Time

3.7. Test 1-07

Test 1-07 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 4 seconds. Note that a long ramp was performed after Q1 to evaluate the flux at which ignition extinguished.

Table 3-6: Test 1-07 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-07	3	4	0.66	0.05	341.36	339.02	TP

- Purpose: Examine sustained ignition with long ramp profile.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-4-21

3.7.1. *Profile/Energy*

Figure 3-22 and Figure 3-23 show the heat flux profile and total energy for which the cable target was exposed. As shown, a long ramp was used for this test to get better resolution to the heat flux at which ignition extinguished. The cable target was exposed to a total of approximately 24 MJ/m^2.

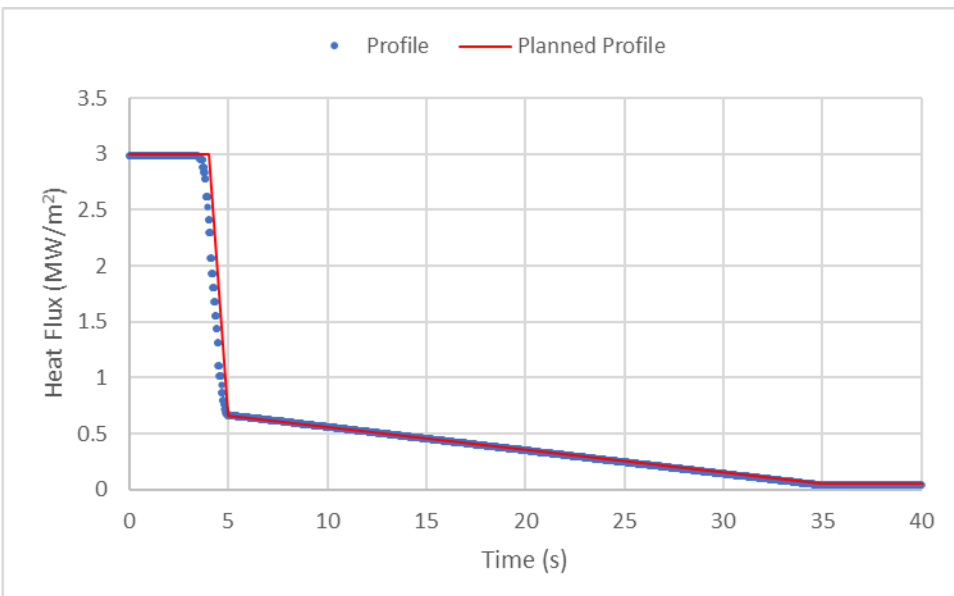


Figure 3-22: Test 1-07 Heat Flux Profile

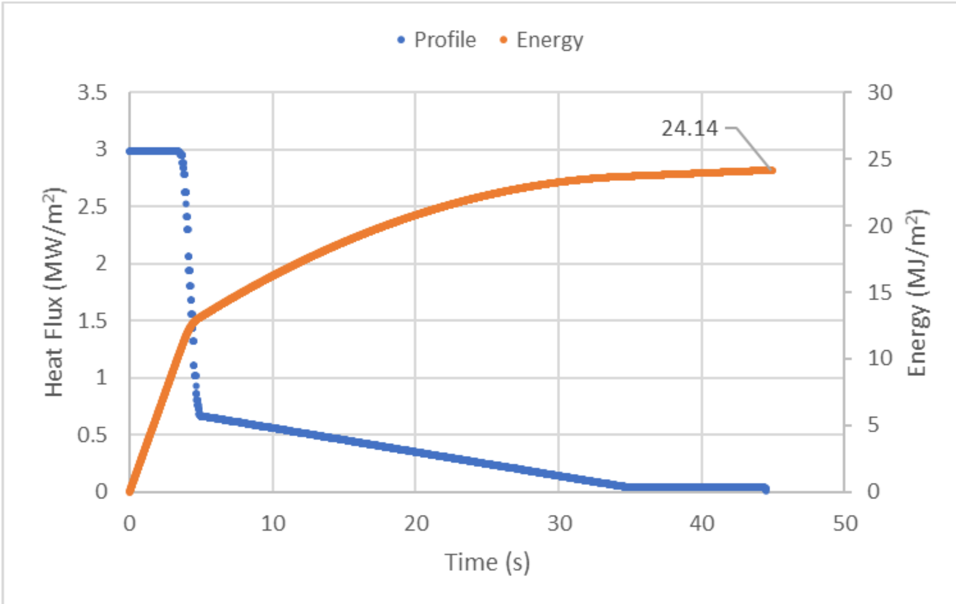


Figure 3-23: Test 1-07 Total Energy

3.7.2. Electrical/Thermal Monitoring

Figure 3-24 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

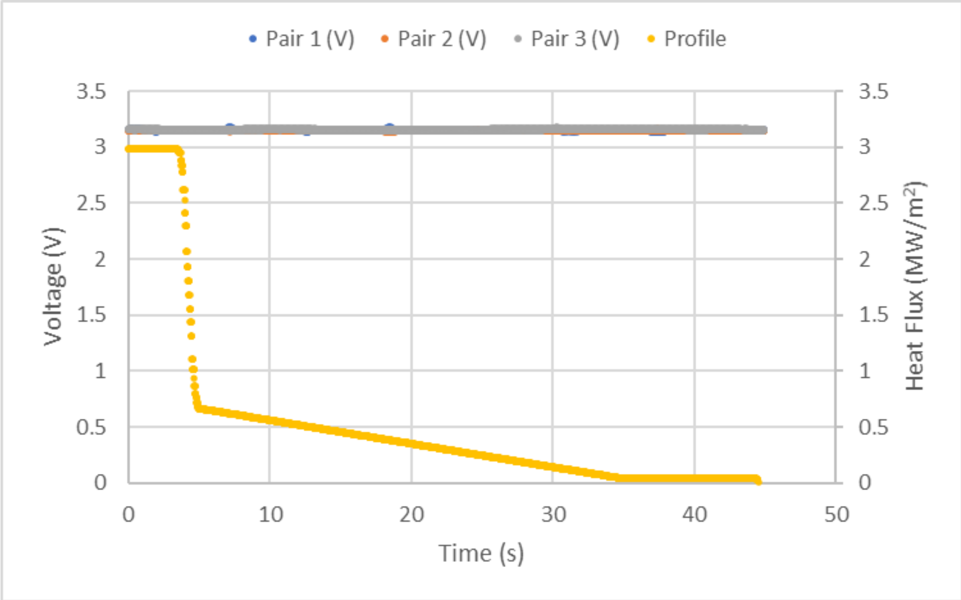


Figure 3-24: Test 1-07 Electrical Monitoring

3.7.3. Photos

Figure 3-25 Figure 3-26 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-25: Test 1-07 Post-test Photo (1)

Figure 3-26: Test 1-07 Post-test Photo (2)

3.7.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.33 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 29.30 seconds after the shutter was fully open. Figure 3-27 shows the time at which the ignition extinguished as a function of total energy and heat flux.

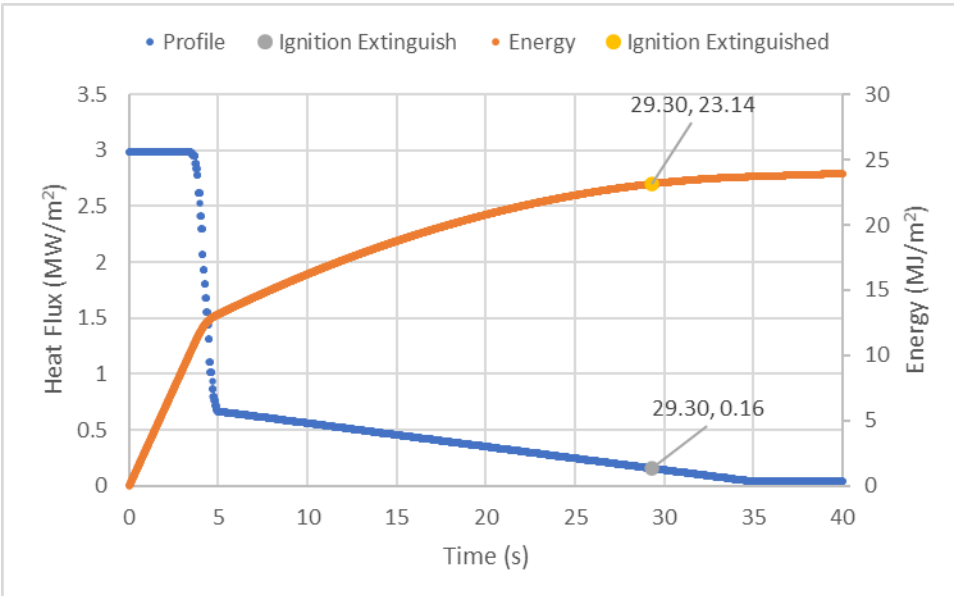


Figure 3-27: Test 1-07 Sustained Ignition as a Function of Heat Flux and Time

3.8. Test 1-08

Test 1-08 evaluated a thermoplastic cable with a primary flux of 1 MW/m^2 for a duration sufficient to experience electrical failure of the cable.

Table 3-7: Test 1-08 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-08	1	N/A	N/A	N/A	339.67	326.43	TP

- Purpose: Examine electrical failure with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-5-21

3.8.1. *Profile/Energy*

Figure 3-28 and Figure 3-29 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 1 MW/m^2 was applied for a longer duration to evaluate electrical failure of the cable. The cable target was exposed to a total of approximately 144 MJ/m^2.

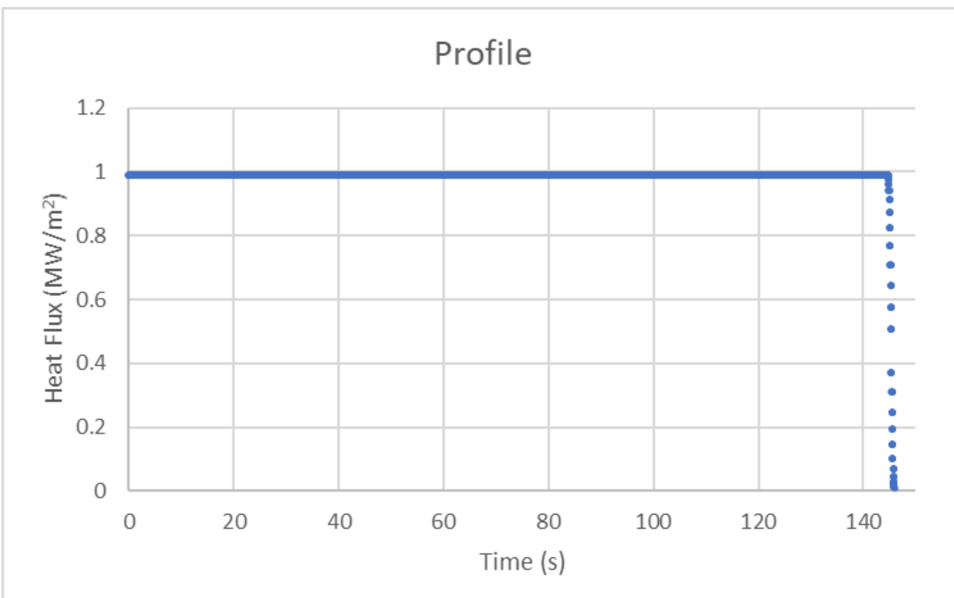


Figure 3-28: Test 1-08 Heat Flux Profile

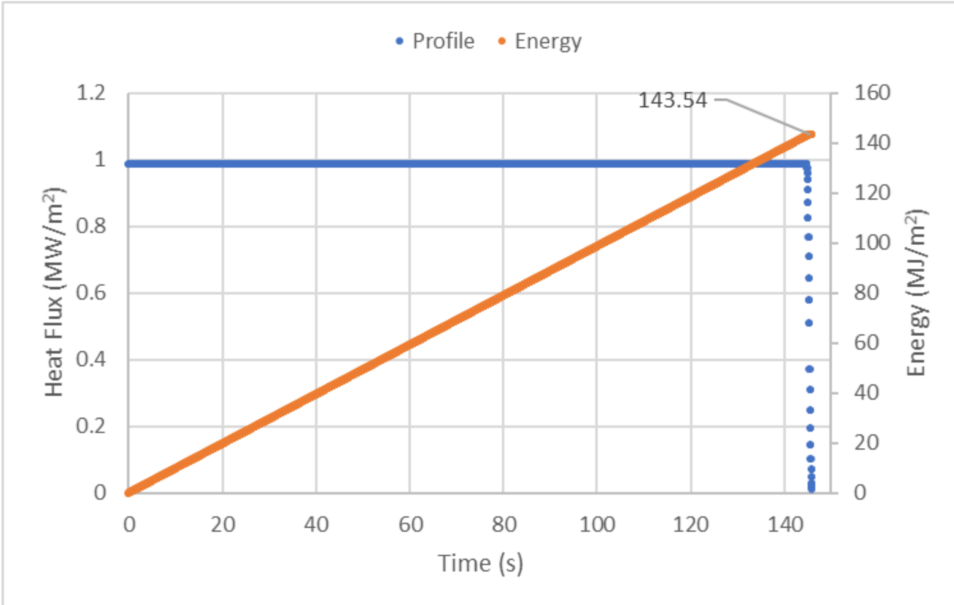


Figure 3-29: Test 1-08 Total Energy

3.8.2. Electrical/Thermal Monitoring

Figure 3-30 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was observed for each pair, the first of which occurred at 72 seconds into the test. The total energy at 72 seconds was approximately 69 MJ/m^2.

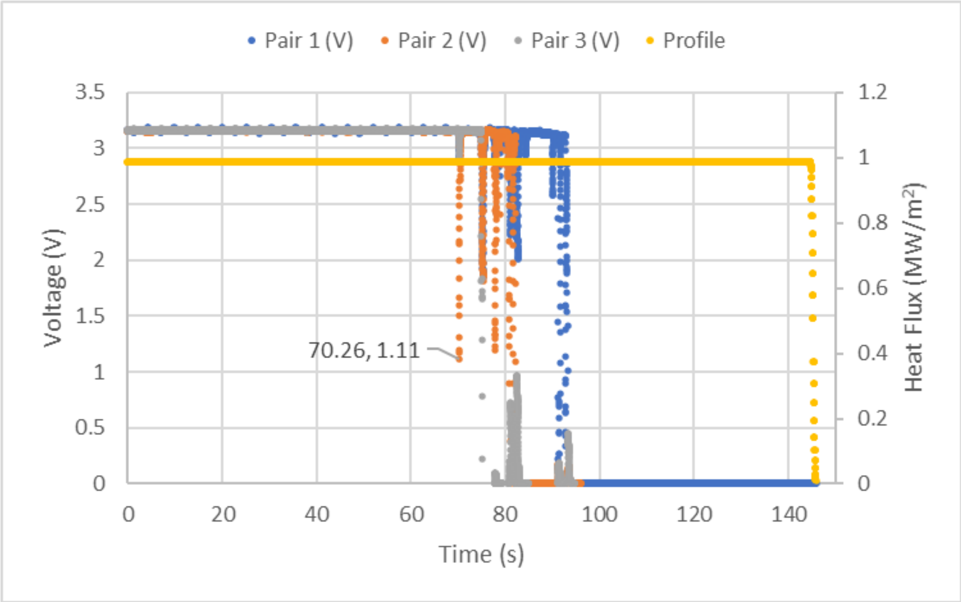


Figure 3-30: Test 1-08 Electrical Monitoring

3.8.3. Photos

Figure 3-31 and Figure 3-32 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test. Also, there is damage to the insulation, exposing bare wire.

Figure 3-31: Test 1-08 Post-test Photo (1)

Figure 3-32: Test 1-08 Post-test Photo (2)

3.8.4. Ignition

The shutters were fully open at 1.50 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.9. Test 1-09

Test 1-09 evaluated a thermoplastic cable with a primary flux of 1 MW/m^2. Note that this test is meant to be paired with Test 1-08 to evaluate the sub-jacket temperature of the cable.

Table 3-8: Test 1-09 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-09	1	N/A	N/A	N/A	334.21	319.08	TP

- Purpose: Examine sub-jacket temperature with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-5-21

3.9.1. Profile/Energy

Figure 3-33 and Figure 3-34 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 1 MW/m^2 was applied for a longer duration to evaluate the sub-jacket temperature of the cable. The cable target was exposed to a total of approximately 206 MJ/m^2.

Figure 3-33: Test 1-09 Heat Flux Profile

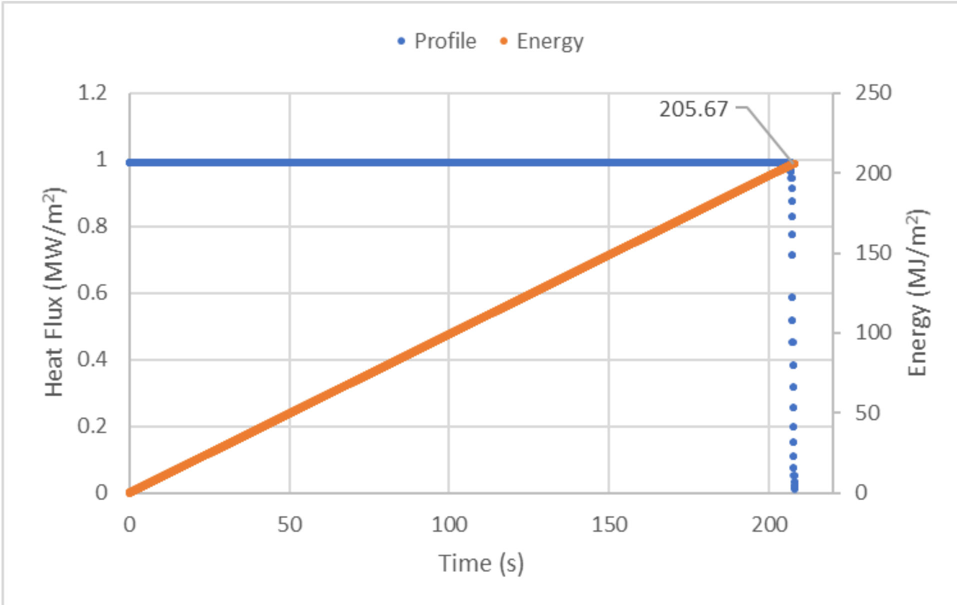


Figure 3-34: Test 1-09 Total Energy

3.9.2. *Electrical/Thermal Monitoring*

Figure 3-35 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 7.5 cm from the center of the target exposure, and the thermocouple was inserted under the jacket.

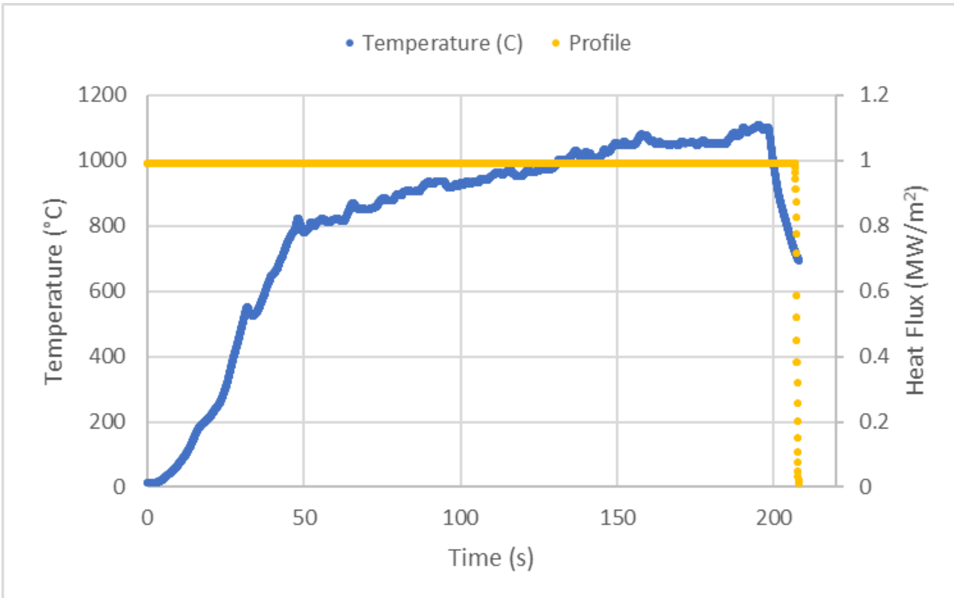


Figure 3-35: Test 1-09 Thermal Monitoring

3.9.3. Photos

Figure 3-36 and Figure 3-37 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test. Also, it appears that there is damage to the insulation, exposing bare wire.

Figure 3-36: Test 1-09 Post-test Photo (1)

Figure 3-37: Test 1-09 Post-test Photo (2)

3.9.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.10. Test 1-10

Test 1-10 evaluated a thermoset cable with a primary flux of 1 MW/m^2 for a duration sufficient to experience electrical failure of the cable.

Table 3-9: Test 1-10 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-10	1	N/A	N/A	N/A	408.38	390.7	TS

- Purpose: Examine electrical failure with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-5-21

3.10.1. Profile/Energy

Figure 3-38 and Figure 3-39 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 1 MW/m^2 was applied for a longer duration to evaluate electrical failure of the cable. The cable target was exposed to a total of approximately 202 MJ/m^2.

Figure 3-38: Test 1-10 Heat Flux Profile

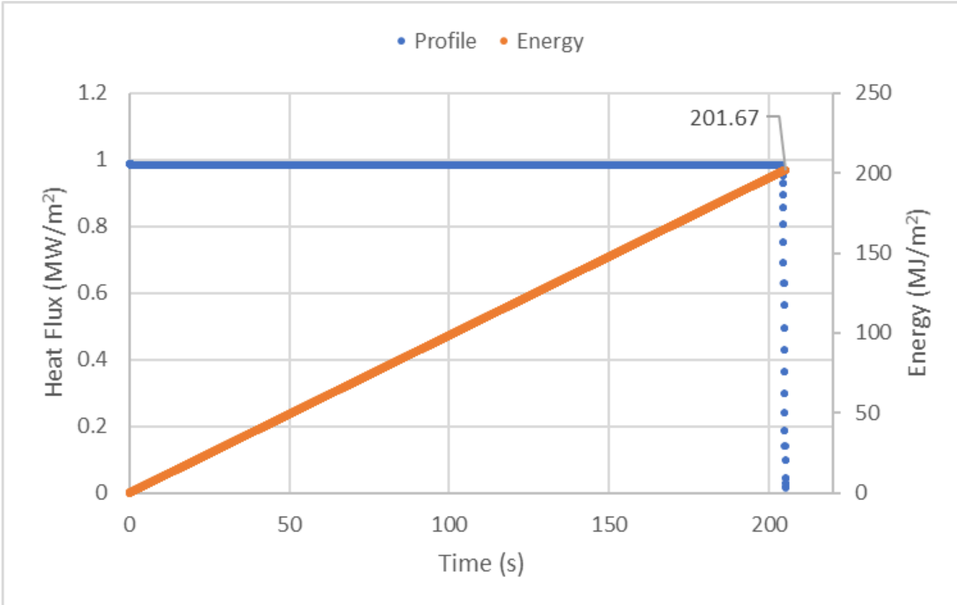


Figure 3-39: Test 1-10 Total Energy

3.10.2. *Electrical/Thermal Monitoring*

Figure 3-40 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was observed for each pair, the first of which occurred at 75 seconds into the test. The total energy at 75 seconds was approximately 74 MJ/m^2.

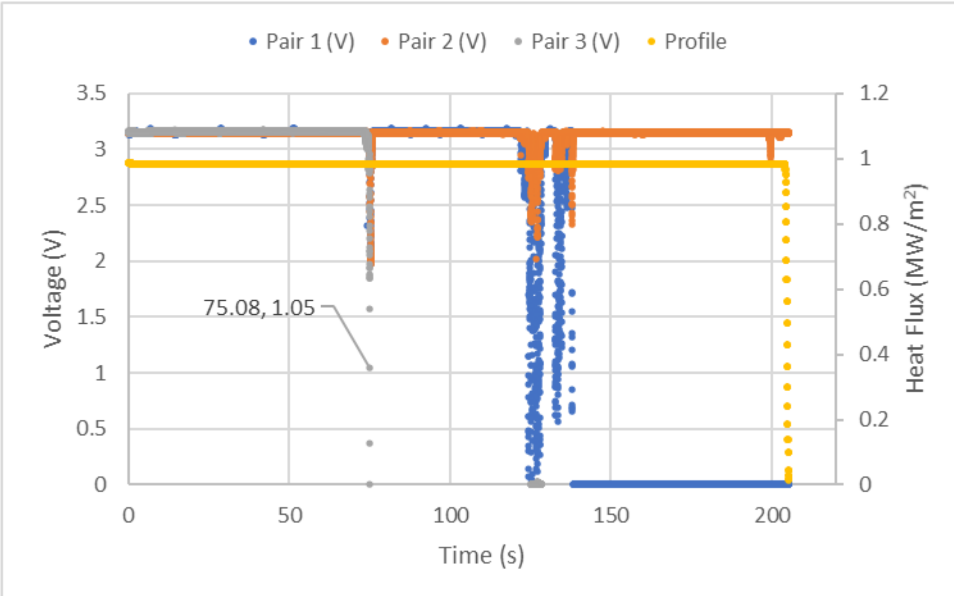


Figure 3-40: Test 1-10 Electrical Monitoring

3.10.3. Photos

Figure 3-41 and Figure 3-42 show the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated.

Figure 3-41: Test 1-10 Post-test Photo (1)

Figure 3-42: Test 1-10 Post-test Photo (2)

3.10.4. Ignition

The shutters were fully open at 0.40 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.11. Test 1-11

Test 1-11 evaluated a thermoset cable with a primary flux of 1 MW/m^2. Note that this test is meant to be paired with Test 1-10 to evaluate the sub-jacket temperature of the cable.

Table 3-10: Test 1-11 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-11	1	N/A	N/A	N/A	395.38	374.20	TS

- Purpose: Examine sub-jacket temperature with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-5-21

3.11.1. Profile/Energy

Figure 3-43 and Figure 3-44 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 1 MW/m^2 was applied for a longer duration to evaluate the sub-jacket temperature of the cable. The cable target was exposed to a total of approximately 208 MJ/m^2.

Figure 3-43: Test 1-11 Heat Flux Profile

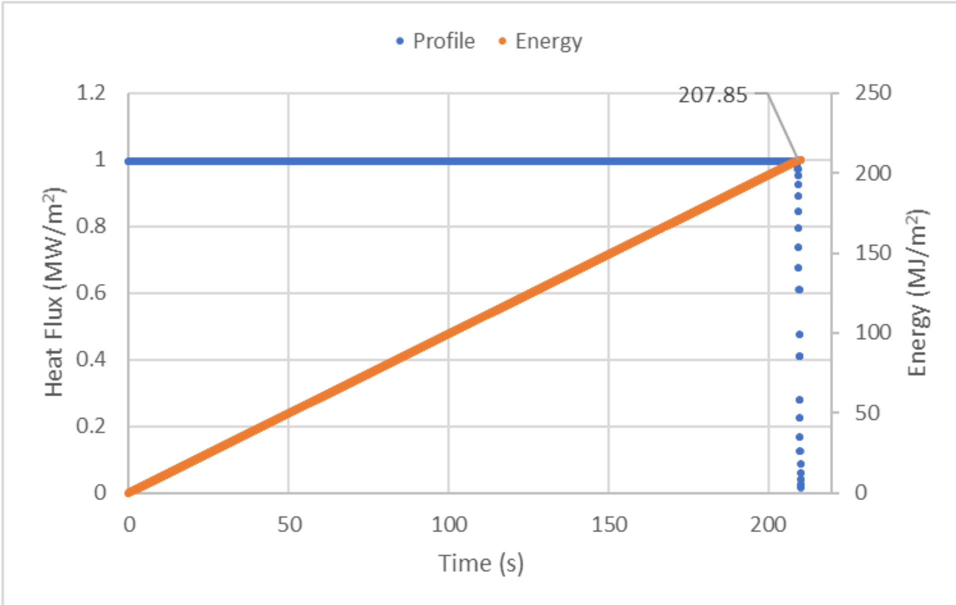


Figure 3-44: Test 1-11 Total Energy

3.11.2. *Electrical/Thermal Monitoring*

Figure 3-45 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 7.5 cm from the center of the target exposure, and the thermocouple was inserted under the jacket.

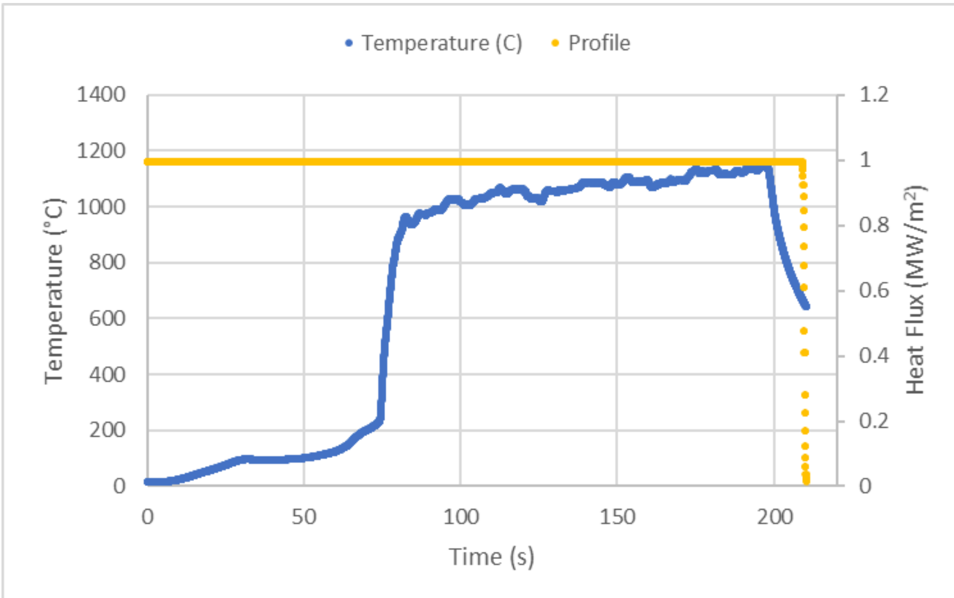


Figure 3-45: Test 1-11 Thermal Monitoring

3.11.3. Photos

Figure 3-46 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated.

Figure 3-46: Test 1-11 Post-test Photo

3.11.4. Ignition

The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.12. Test 1-12

Test 1-12 evaluated a thermoset cable with a primary flux of 4 MW/m² for a duration sufficient to experience electrical failure of the cable.

Table 3-11: Test 1-12 Test Summary Data

Test Number	Q0 (MW/m²)	T0 (s)	Q1 (MW/m²)	Q2 (MW/m²)	Pre-weight (g)	Post-weight (g)	Cable Type
1-12	4	N/A	N/A	N/A	399.58	355.35	TS

- Purpose: Examine electrical failure with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-8-21

3.12.1. *Profile/Energy*

Figure 3-47 and Figure 3-48 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 4 MW/m² was applied for a longer duration to evaluate electrical failure of the cable. The cable target was exposed to a total of approximately 790 MJ/m².

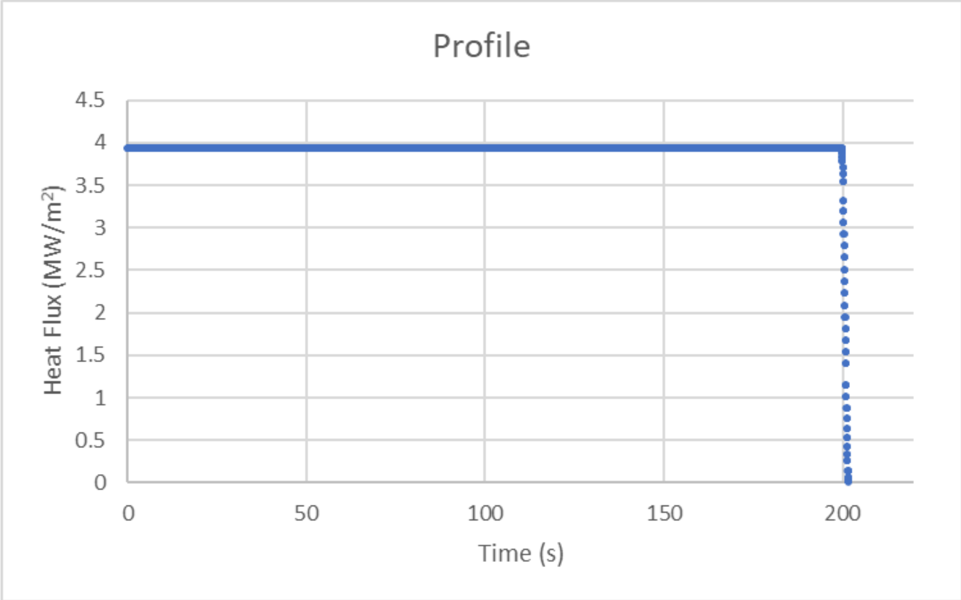


Figure 3-47: Test 1-12 Heat Flux Profile

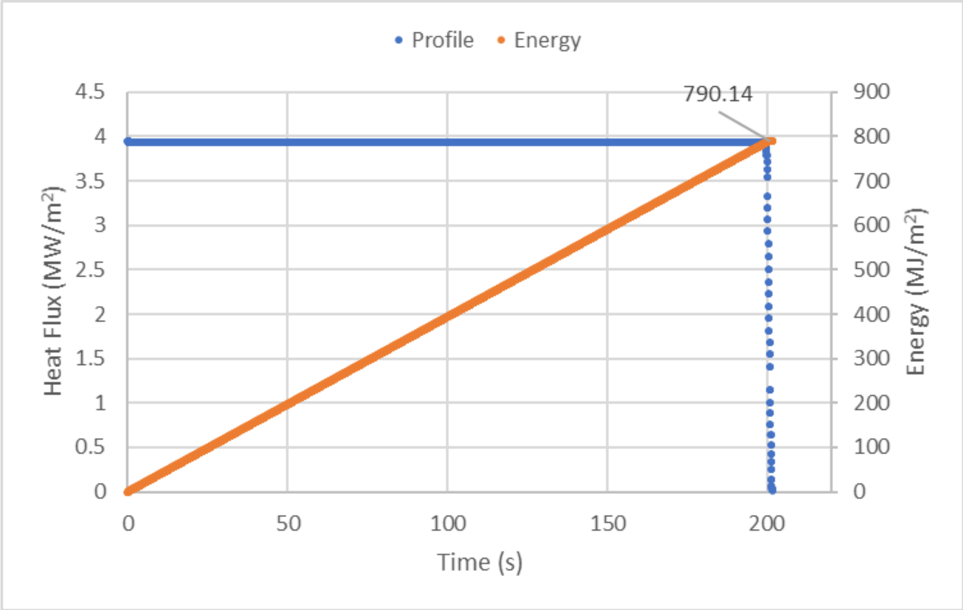


Figure 3-48: Test 1-12 Total Energy

3.12.2. *Electrical/Thermal Monitoring*

Figure 3-49 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was observed for each pair, the first of which occurred at 54 seconds into the test. The total energy at 54 seconds was approximately 212 MJ/m^2.

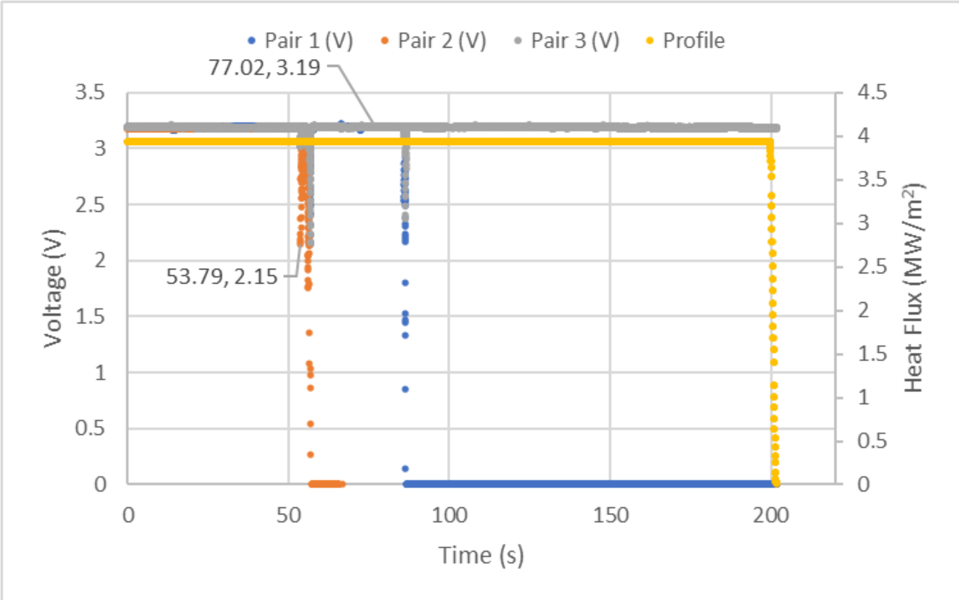


Figure 3-49: Test 1-12 Electrical Monitoring

3.12.3. Photos

Figure 3-50 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated, and the inner wires were separated. The cables were severed during the test exposure. Note, the exposure for this photo is dark because the background light was not turned on.

Figure 3-50: Test 1-12 Post-test Photo

3.12.4. Ignition

The shutters were fully open at 0.23 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.13. Test 1-13

Test 1-13 evaluated a thermoset cable with a primary flux of 4 MW/m^2. Note that this test is meant to be paired with Test 1-12 to evaluate the sub-jacket temperature of the cable.

Table 3-12: Test 1-13 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-13	4	N/A	N/A	N/A	400.96	377.00	TS

- Purpose: Examine sub-jacket temperature with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-8-21

3.13.1. *Profile/Energy*

Figure 3-51 and Figure 3-52 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 4 MW/m^2 was applied for a longer duration to evaluate the sub-jacket temperature of the cable. The cable target was exposed to a total of approximately 487 MJ/m^2.

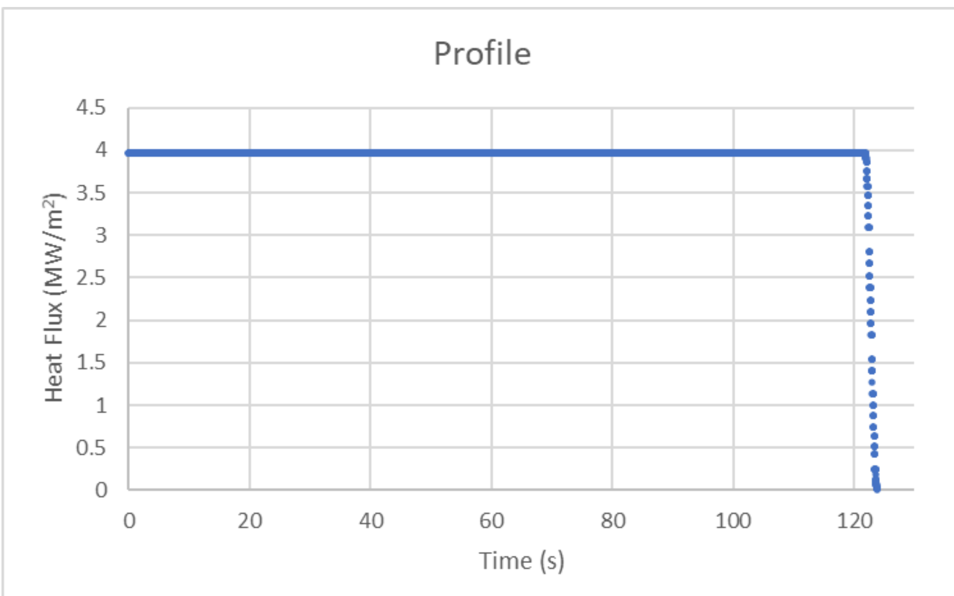


Figure 3-51: Test 1-13 Heat Flux Profile

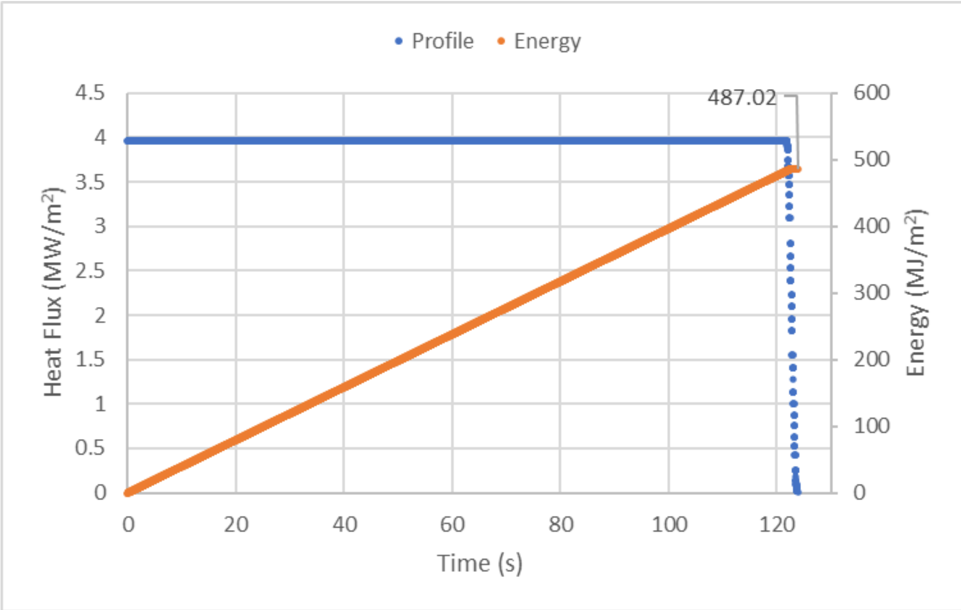


Figure 3-52: Test 1-13 Total Energy

3.13.2. Electrical/Thermal Monitoring

Figure 3-53 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 3 inches from the center of the target exposure, and the thermocouple was inserted under the jacket.

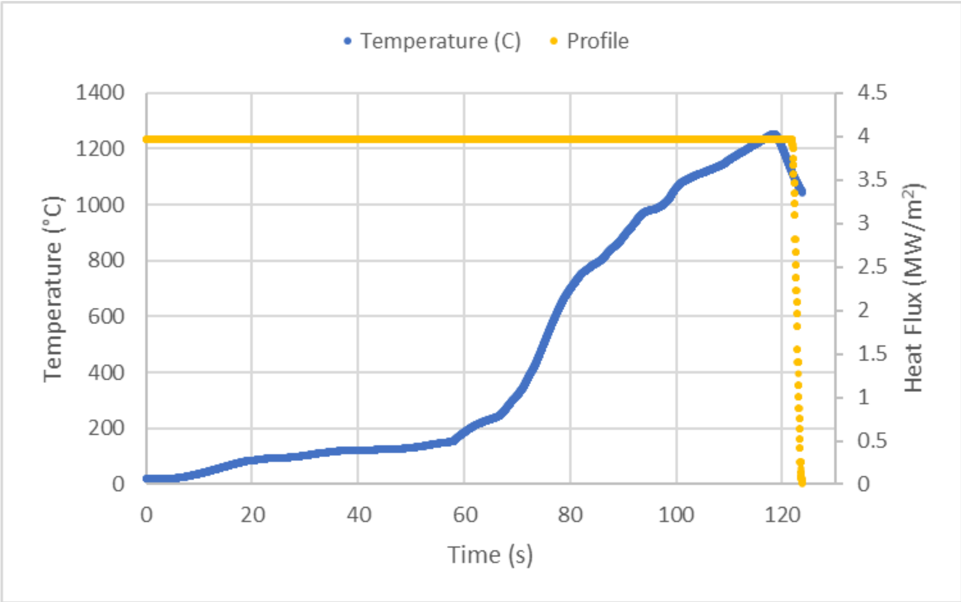


Figure 3-53: Test 1-13 Thermal Monitoring

3.13.3. Photos

Figure 3-54 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated, and the inner wires were separated.

Figure 3-54: Test 1-13 Post-test Photo

3.13.4. Ignition

The shutters were fully open at 0.37 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.14. Test 1-14

Test 1-14 evaluated a thermoplastic cable with a primary flux of 4 MW/m^2 for a duration sufficient to experience electrical failure of the cable.

Table 3-13: Test 1-14 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-14	4	N/A	N/A	N/A	334.16	305.15	TP

- Purpose: Examine electrical failure with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-8-21

3.14.1. Profile/Energy

Figure 3-55 and Figure 3-56 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 4 MW/m^2 was applied for a longer duration to evaluate electrical failure of the cable. The cable target was exposed to a total of approximately 492 MJ/m^2.

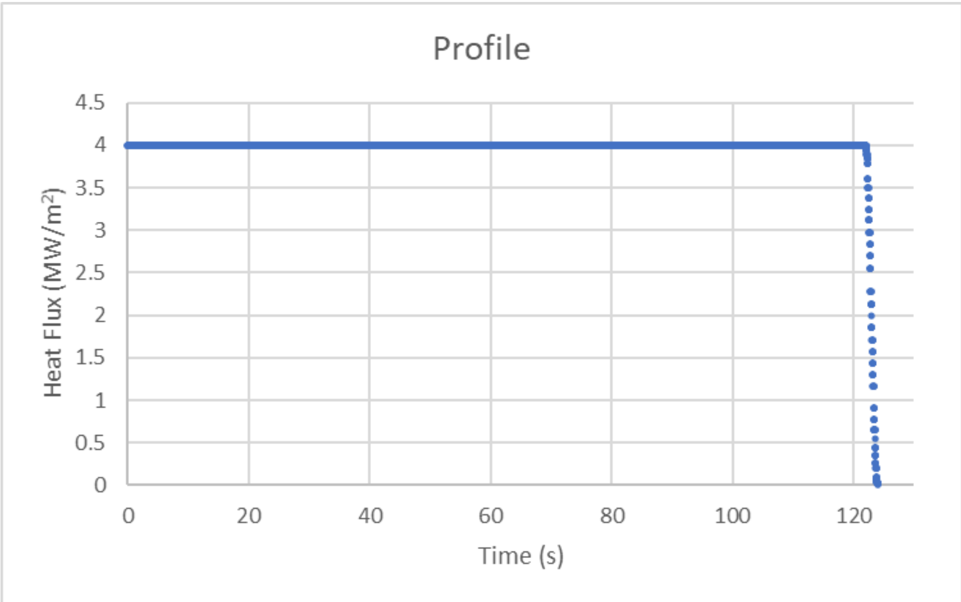


Figure 3-55: Test 1-14 Heat Flux Profile

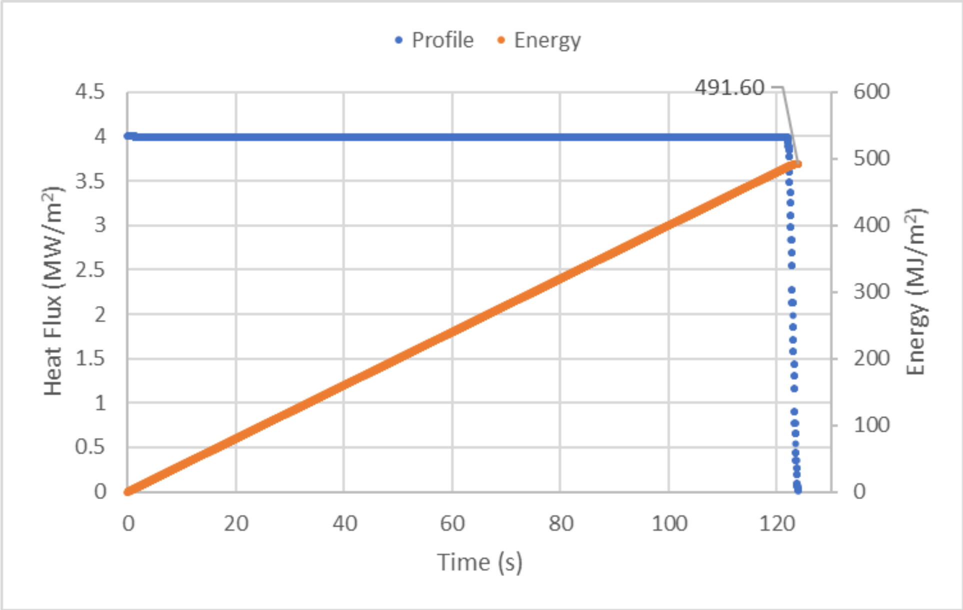


Figure 3-56: Test 1-14 Total Energy

3.14.2. Electrical/Thermal Monitoring

Figure 3-57 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was observed for each pair, the first of which occurred at 20 seconds into the test. The total energy at 20 seconds was approximately 77 MJ/m^2.

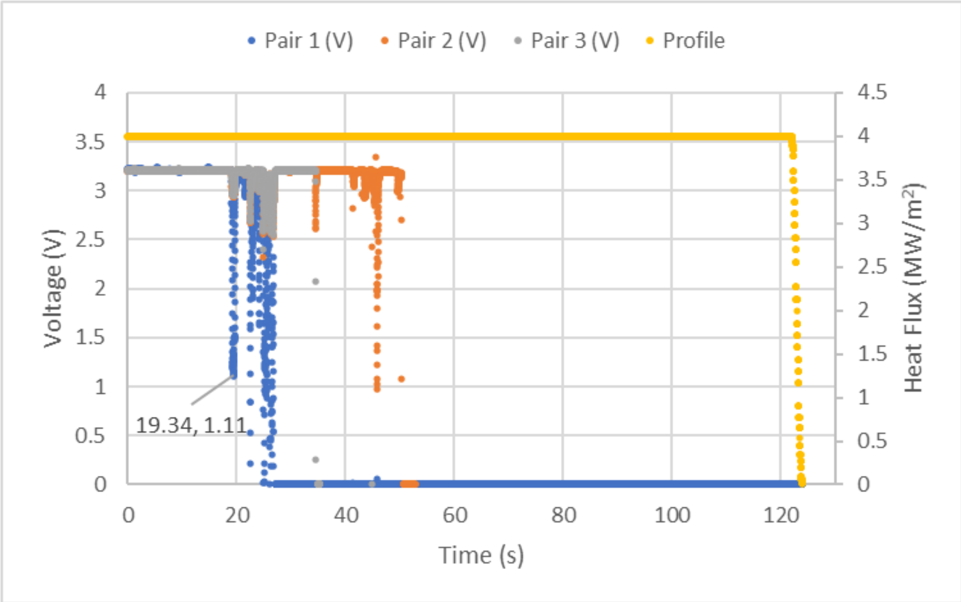


Figure 3-57: Test 1-14 Electrical Monitoring

3.14.3. Photos

Figure 3-58 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated, and the inner wires were separated. The cables were severed during the test exposure.

Figure 3-58: Test 1-14 Post-test Photo

3.14.4. Ignition

The shutters were fully open at 0.33 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.15. Test 1-15

Test 1-15 evaluated a thermoplastic cable with a primary flux of 4 MW/m^2. Note that this test is meant to be paired with Test 1-14 to evaluate the sub-jacket temperature of the cable.

Table 3-14: Test 1-15 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-15	4	N/A	N/A	N/A	351.68	321.01	TP

- Purpose: Examine sub-jacket temperature with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-8-21

3.15.1. Profile/Energy

Figure 3-59 and Figure 3-60 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 4 MW/m^2 was applied for a longer duration to evaluate the sub-jacket temperature of the cable. The cable target was exposed to a total of approximately 502 MJ/m^2.

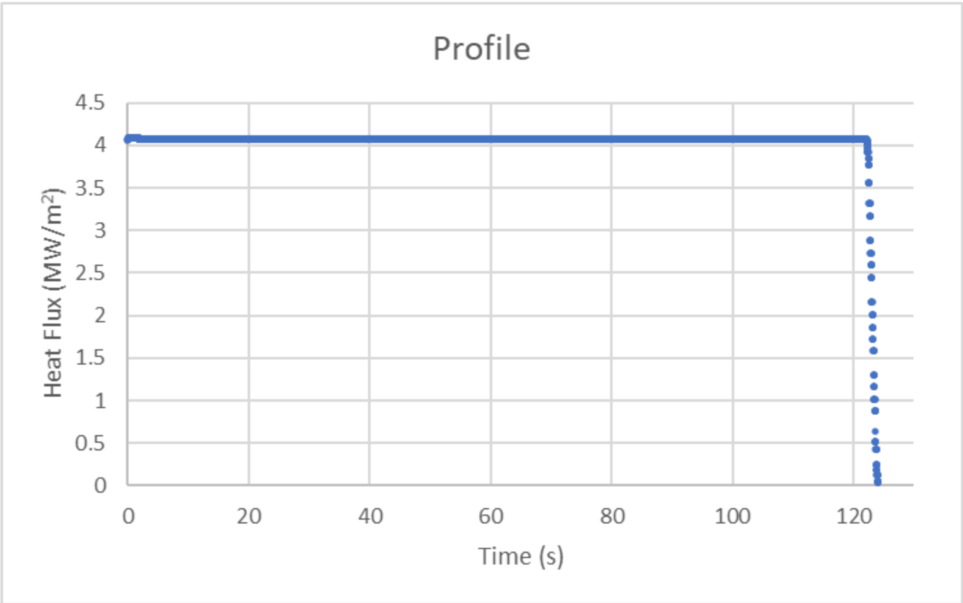


Figure 3-59: Test 1-15 Heat Flux Profile

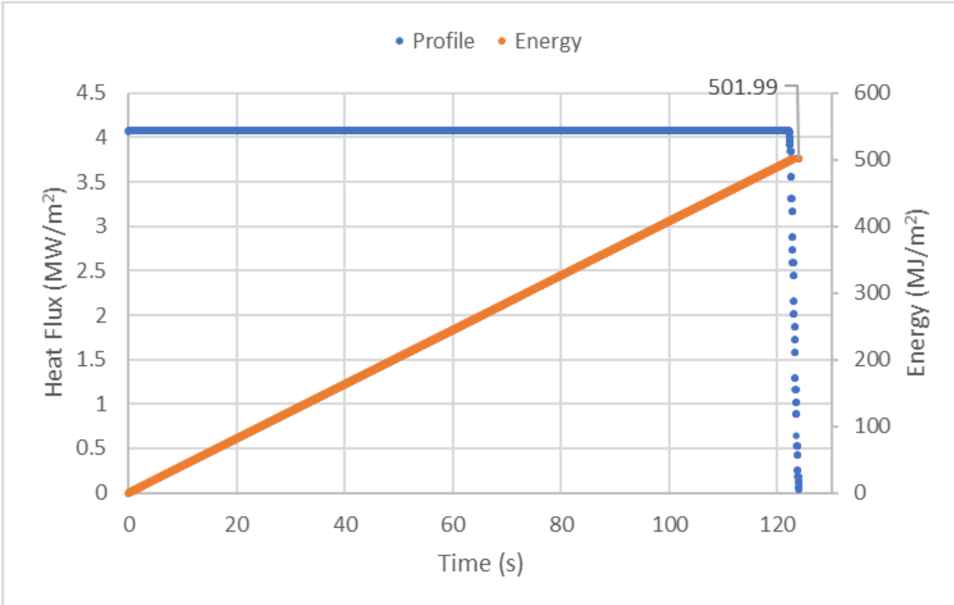


Figure 3-60: Test 1-15 Total Energy

3.15.2. *Electrical/Thermal Monitoring*

Figure 3-61 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 7.5 cm from the center of the target exposure, and the thermocouple was inserted under the jacket.

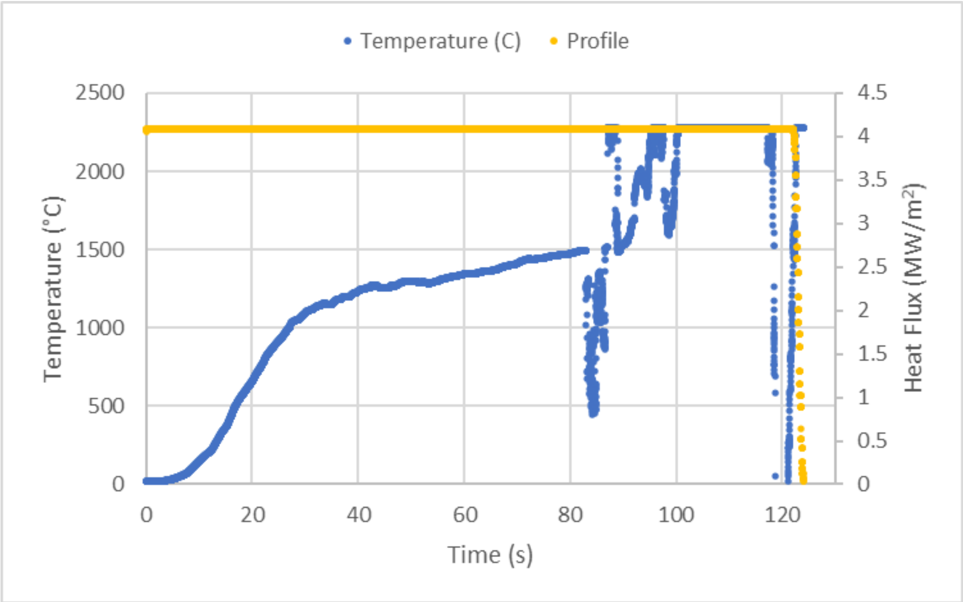


Figure 3-61: Test 1-15 Thermal Monitoring

3.15.3. Photos

Figure 3-62 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated, and the inner wires were separated. The cables were severed during the test exposure.

Figure 3-62: Test 1-15 Post-test Photo

3.15.4. Ignition

The shutters were fully open at 0.33 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.16. Test 1-16

Test 1-16 evaluated a thermoset cable with a primary flux of 2 MW/m^2 for a duration sufficient to experience electrical failure of the cable. Note that the subsequent paired test with sub-jacket thermal monitoring was not performed.

Table 3-15: Test 1-16 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-16	2	N/A	N/A	N/A	395.05	371.78	TS

- Purpose: Examine electrical failure with long duration test at constant heat flux.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-8-21

3.16.1. Profile/Energy

Figure 3-63 and Figure 3-64 show the heat flux profile and total energy for which the cable target was exposed. As shown, a constant heat flux of 2 MW/m^2 was applied for a longer duration to evaluate electrical failure of the cable. The cable target was exposed to a total of approximately 300 MJ/m^2.

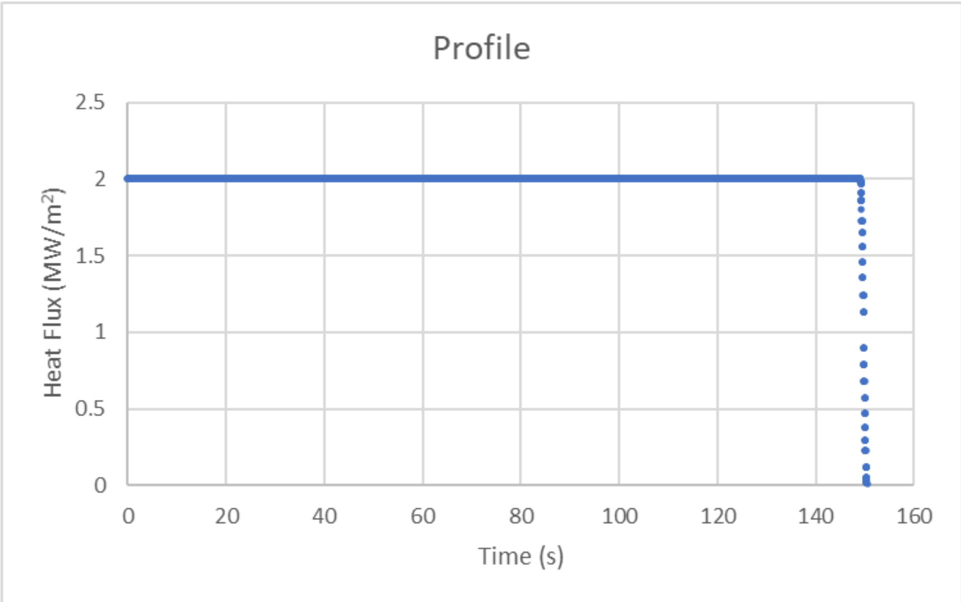


Figure 3-63: Test 1-16 Heat Flux Profile

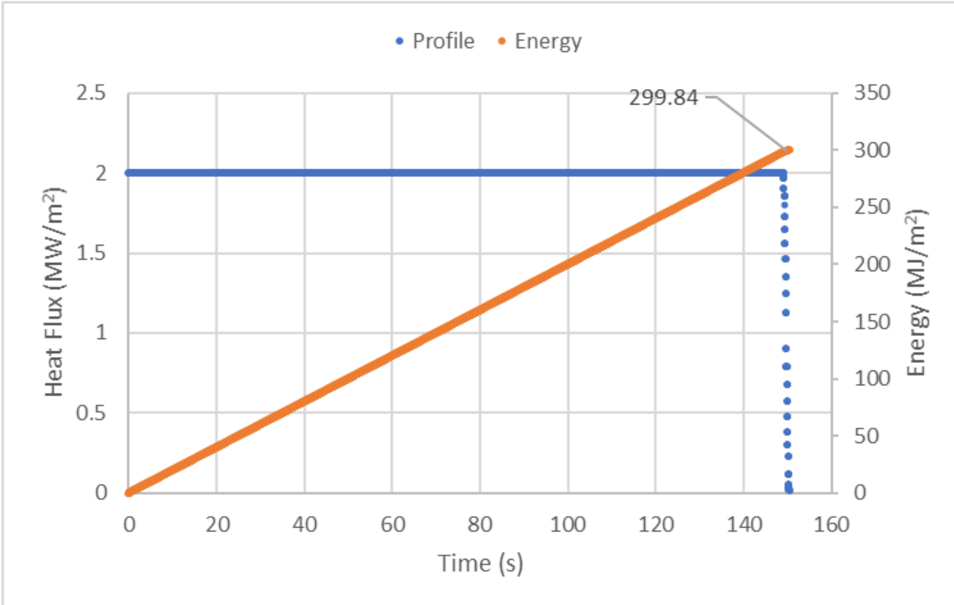


Figure 3-64: Test 1-16 Total Energy

3.16.2. *Electrical/Thermal Monitoring*

Figure 3-65 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was observed for each pair, the first of which occurred at 52 seconds into the test. The total energy at 52 seconds was approximately 103 MJ/m^2.

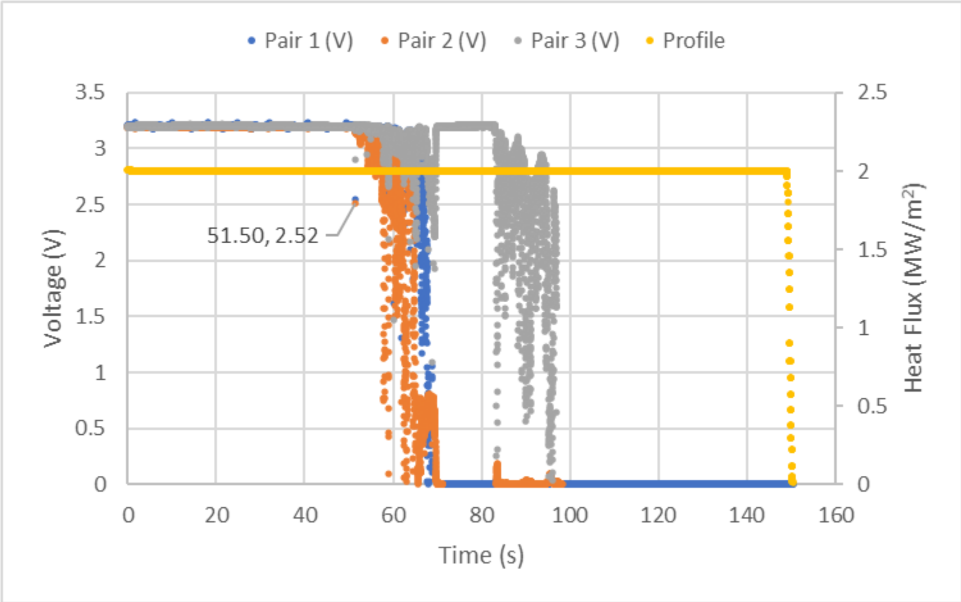


Figure 3-65: Test 1-16 Electrical Monitoring

3.16.3. Photos

Figure 3-66 shows the target cable after the exposure profile. As shown, the jacket and insulation are completely ablated.

Figure 3-66: Test 1-16 Post-test Photo

3.16.4. Ignition

The shutters were fully open at 0.33 seconds. This delay is reflected in all figures in this section and the total energy calculation. Due to the purpose of this test, information about when the flame extinguished was not gathered. The shutters closed at the end of the test prior to the flame extinguishing.

3.17. Test 1-17

Test 1-17 evaluated a thermoset cable with a primary flux of 0.05 MW/m^2. This is a long-duration test with the sub-jacket temperature monitored. Note that this test is meant to be paired with the electrically monitored Test 1-20.

Table 3-16: Test 1-17 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-17	0.05	N/A	N/A	N/A	392.11	390.06	TS

- Purpose: Low-flux test to examine heat transfer through the jacket and compare to THIEF/Penlight tests. Thermally monitored.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-11-21

3.17.1. Profile/Energy

Figure 3-67 and Figure 3-68 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual heat flux magnitude applied to the cable is slightly lower than 0.05 MW/m^2. The cable target was exposed to a total of approximately 33 MJ/m^2.

Figure 3-67: Test 1-17 Heat Flux Profile

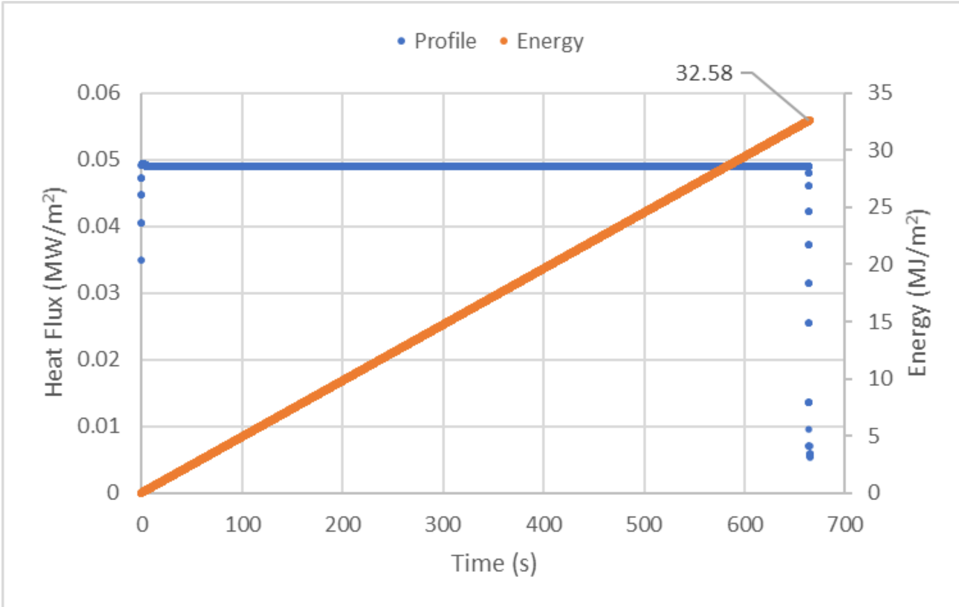


Figure 3-68: Test 1-17 Total Energy

3.17.2. *Electrical/Thermal Monitoring*

Figure 3-69 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 7.5 cm from the center of the target exposure from the top and bottom, and the thermocouples were inserted under the jacket.

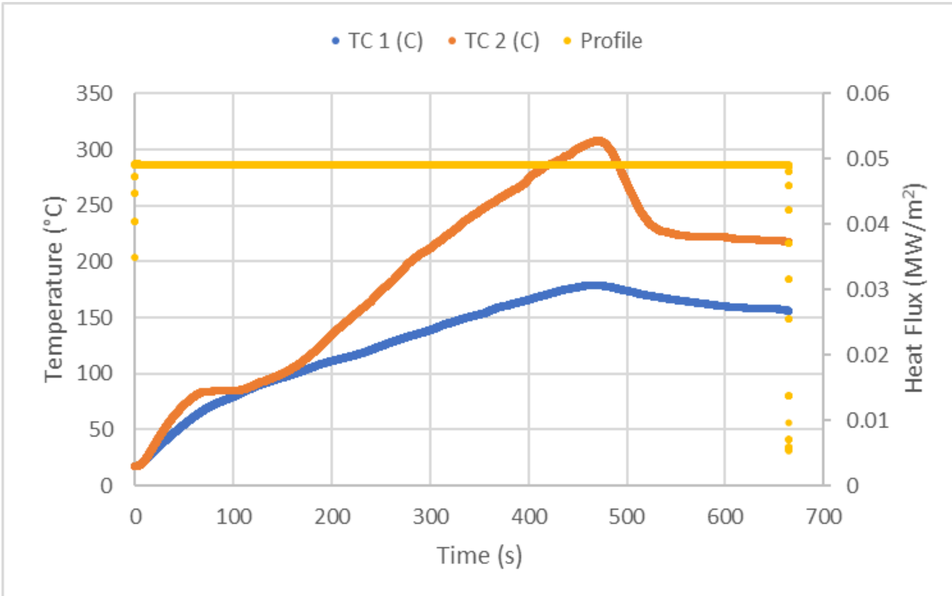


Figure 3-69: Test 1-17 Thermal Monitoring

3.17.3. Photos

Figure 3-70 and Figure 3-71 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-70: Test 1-17 Post-test Photo (1)

Figure 3-71: Test 1-17 Post-test Photo (2)

3.17.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.18. Test 1-18

Test 1-18 evaluated a thermoplastic cable with a primary flux of 0.05 MW/m^2. This is a long-duration test with the cable monitored for electrical failure. Note that this test is meant to be paired with the thermally monitored Test 1-19.

Table 3-17: Test 1-18 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-18	0.05	N/A	N/A	N/A	334.33	332.59	TP

- Purpose: Low-flux test to examine heat transfer through the jacket and compare to THIEF/Penlight tests. Electrically monitored.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-11-21

3.18.1. Profile/Energy

Figure 3-72 and Figure 3-73 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux magnitude applied to the cable is approximately 0.05 MW/m^2. The cable target was exposed to a total of approximately 89 MJ/m^2.

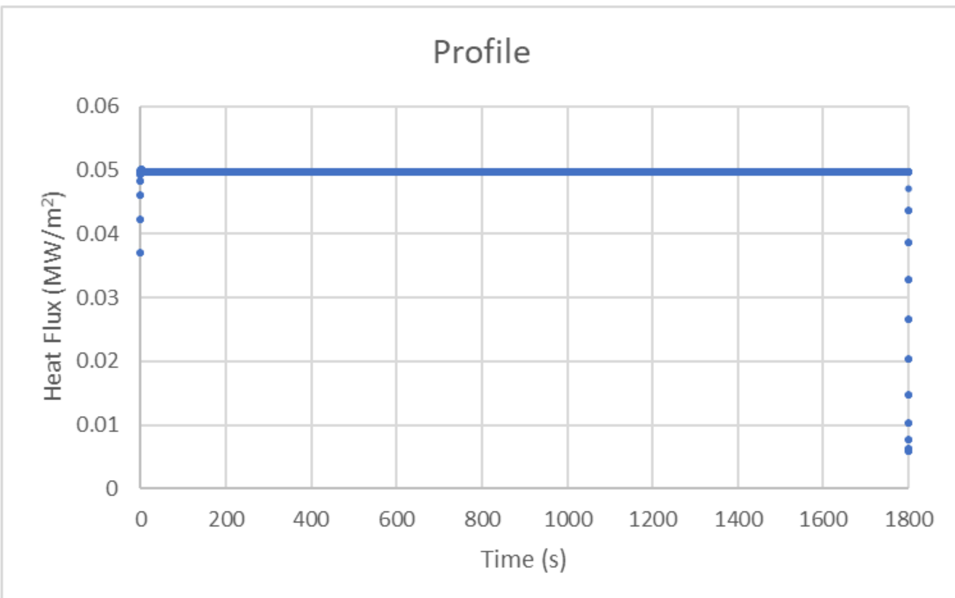


Figure 3-72: Test 1-18 Heat Flux Profile

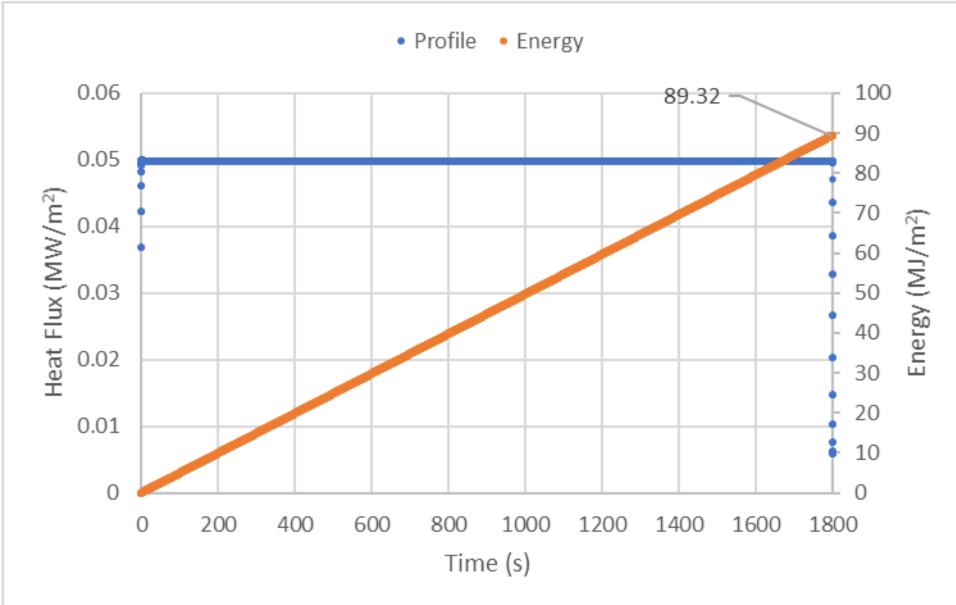


Figure 3-73: Test 1-18 Total Energy

3.18.2. Electrical/Thermal Monitoring

Figure 3-74 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

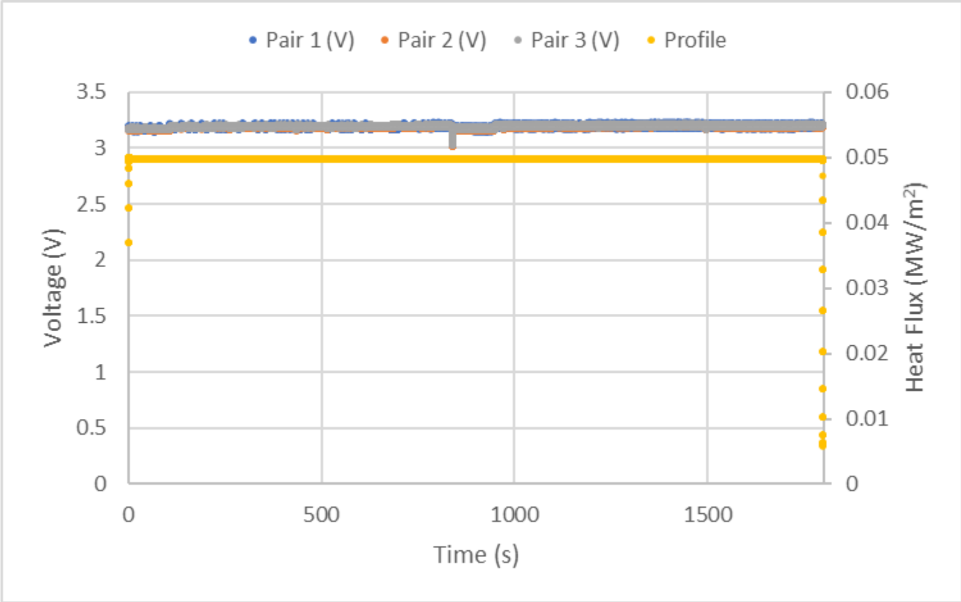


Figure 3-74: Test 1-18 Electrical Monitoring

3.18.3. Photos

Figure 3-75, Figure 3-76, and Figure 3-77 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test. Note that the photos for this test were mislabeled as Test 1-20.

Figure 3-75: Test 1-18 Post-test Photo (1)

Figure 3-76: Test 1-18 Post-test Photo (2)

Figure 3-77: Test 1-18 Post-test Photo (3)

3.18.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.19. Test 1-19

Test 1-19 evaluated a thermoplastic cable with a primary flux of 0.05 MW/m^2. This is a long-duration test with the sub-jacket temperature monitored. Note that this test is meant to be paired with the electrically monitored Test 1-18.

Table 3-18: Test 1-19 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-19	0.05	N/A	N/A	N/A	343.43	341.94	TP

- Purpose: Low-flux test to examine heat transfer through the jacket and compare to THIEF/Penlight tests. Thermally monitored.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-11-21

3.19.1. *Profile/Energy*

Figure 3-78 and Figure 3-79 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual heat flux magnitude applied to the cable is slightly lower than 0.05 MW/m^2. The cable target was exposed to a total of approximately 52 MJ/m^2.

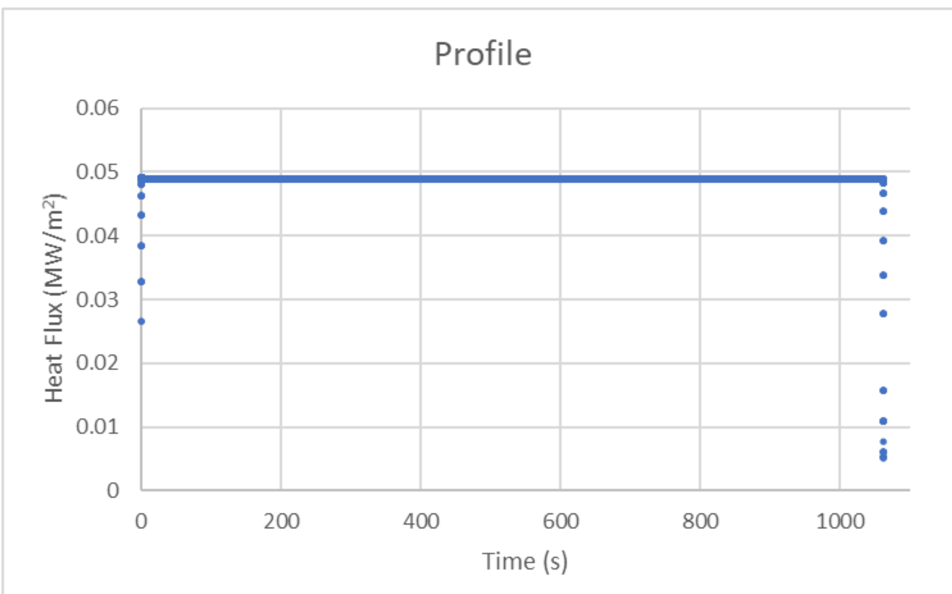


Figure 3-78: Test 1-19 Heat Flux Profile

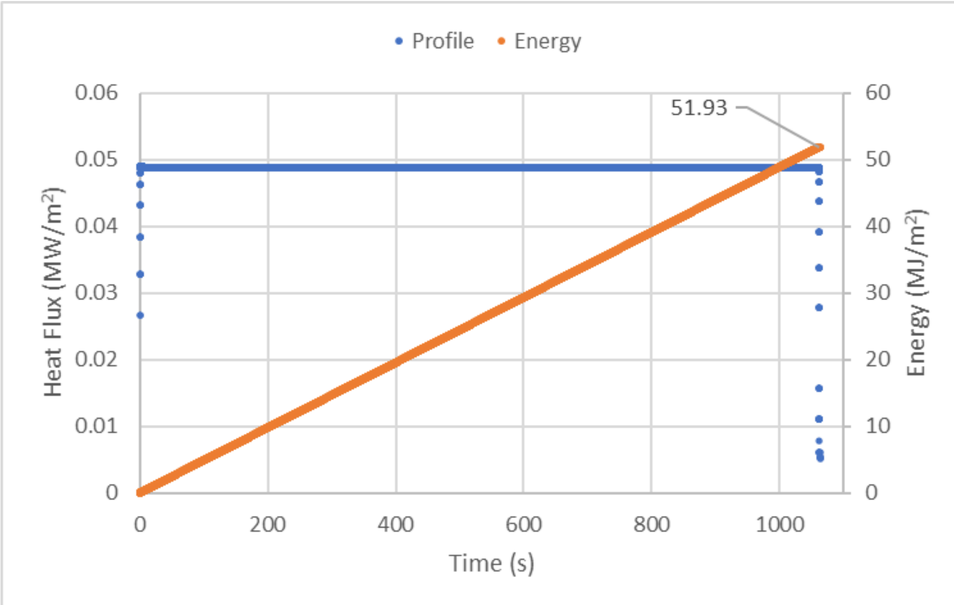


Figure 3-79: Test 1-19 Total Energy

3.19.2. Electrical/Thermal Monitoring

Figure 3-80 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket to monitor the sub-jacket temperature. Note, a slit in the jacket was made approximately 7.5 cm from the center of the target exposure from the top and bottom, and the thermocouples were inserted under the jacket.

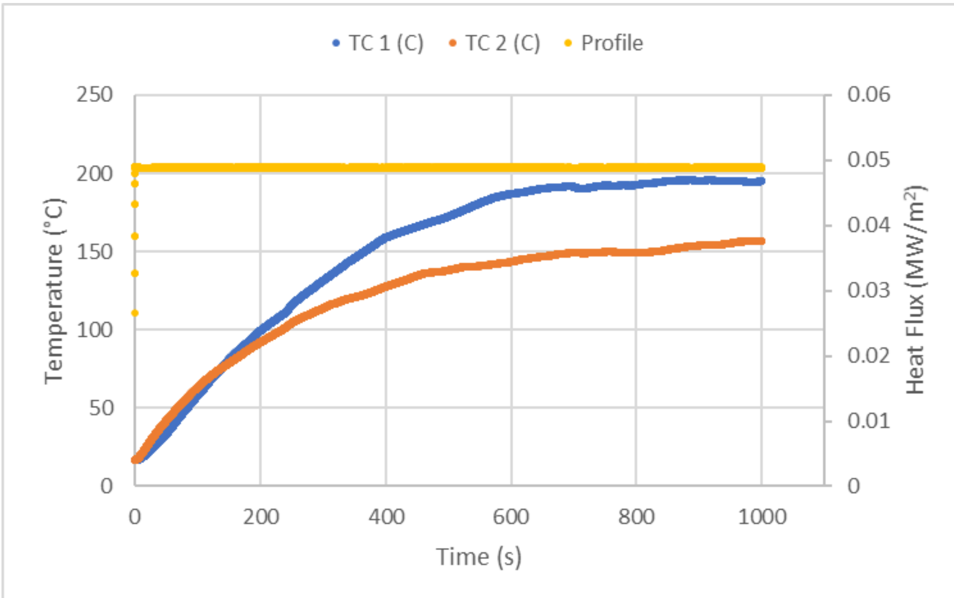


Figure 3-80: Test 1-19 Thermal Monitoring

3.19.3. Photos

Figure 3-81 and Figure 3-82 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-81: Test 1-19 Post-test Photo (1)

Figure 3-82: Test 1-19 Post-test Photo (2)

3.19.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.20. Test 1-20

Test 1-20 evaluated a thermoset cable with a primary flux of 0.05 MW/m^2. This is a long-duration test with the cable monitored for electrical failure. Note that this test is meant to be paired with the thermally monitored Test 1-17.

Table 3-19: Test 1-20 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-20	0.05	N/A	N/A	N/A	398.73	395.24	TS

- Purpose: Low-flux test to examine heat transfer through the jacket and compare to THIEF/Penlight tests. Electrically monitored.
- Target: Single Cable, approximately 1 m length
- Test Date: 2-11-21

3.20.1. Profile/Energy

Figure 3-83 and Figure 3-84 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual heat flux magnitude applied to the cable is lower than 0.05 MW/m^2 (see Appendix C for the calibration curve). The cable target was exposed to a total of approximately 85 MJ/m^2.

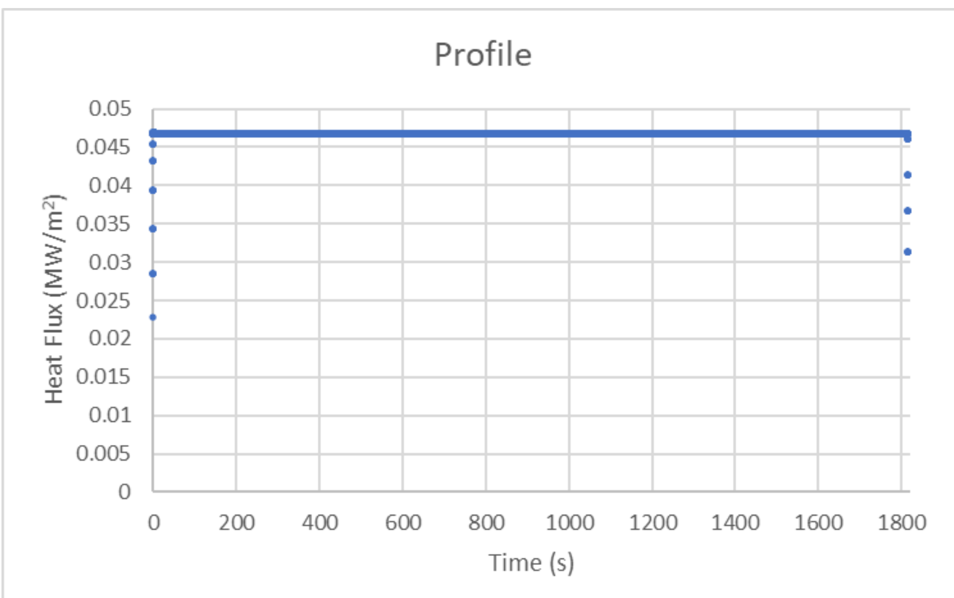


Figure 3-83: Test 1-20 Heat Flux Profile

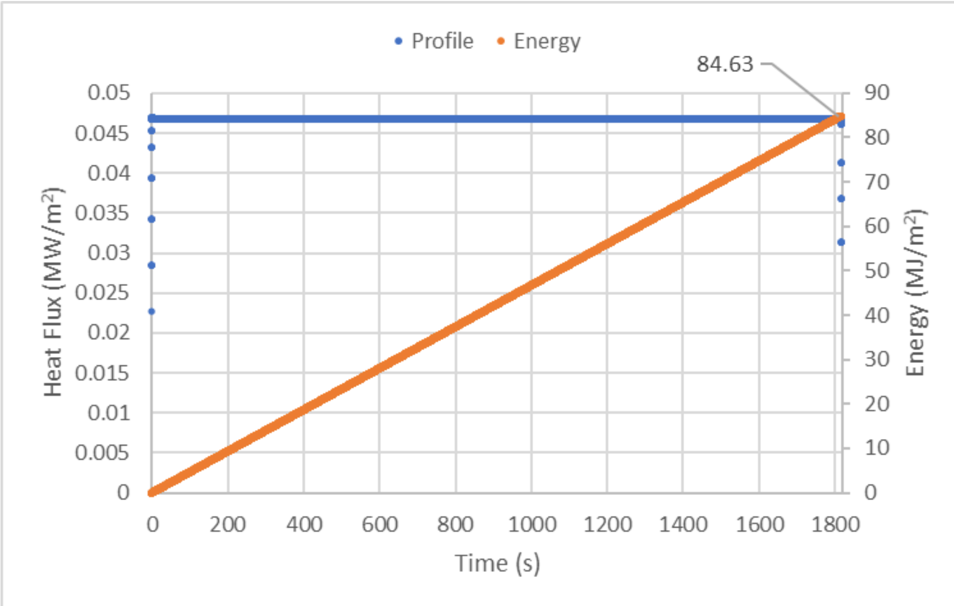


Figure 3-84: Test 1-20 Total Energy

3.20.2. Electrical/Thermal Monitoring

Figure 3-85 shows the electrical results from the test. Three pairs were monitored in the 7C cable for short circuit failure. As shown, electrical failure was not observed.

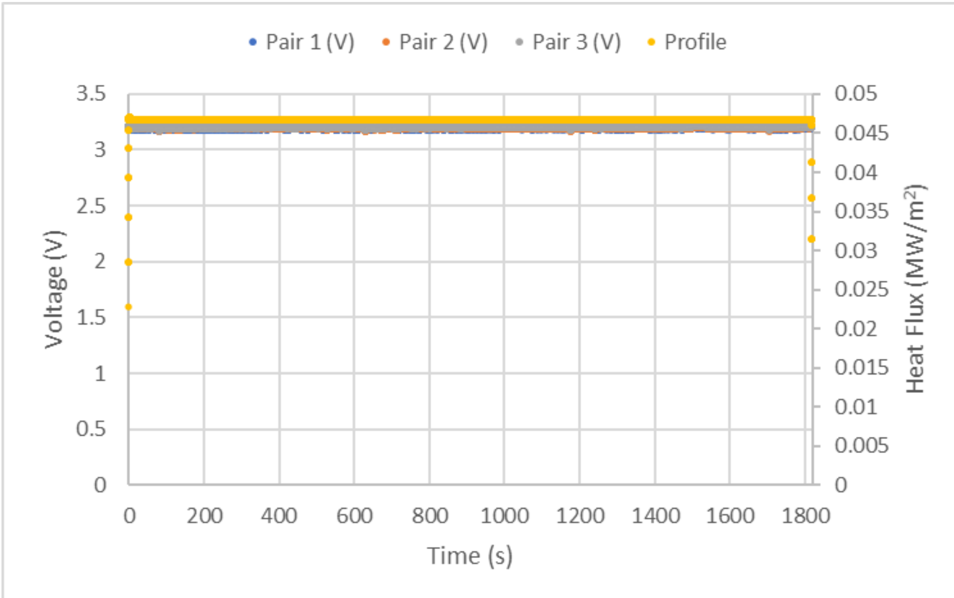


Figure 3-85: Test 1-20 Electrical Monitoring

3.20.3. Photos

Figure 3-86 and Figure 3-87 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-86: Test 1-20 Post-test Photo (1)

Figure 3-87: Test 1-20 Post-test Photo (2)

3.20.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.21. Test 1-21

Test 1-21 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 25 seconds. Note that this test was meant to be held for 2 seconds but was input into the control system incorrectly. The two second test was subsequently evaluated in Test 1-23.

Table 3-20: Test 1-21 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-21	3	25	N/A	N/A	131.5	125.56	TS

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.21.1. Profile/Energy

Figure 3-88 and Figure 3-89 show the heat flux profile and total energy for which the cable target was exposed. As shown, due to an input error in the control system, the test was not terminated at 2 seconds. Also, the actual heat flux magnitude applied to the cable is slightly higher than 3 MW/m^2. The cable target was exposed to a total of approximately 82 MJ/m^2.

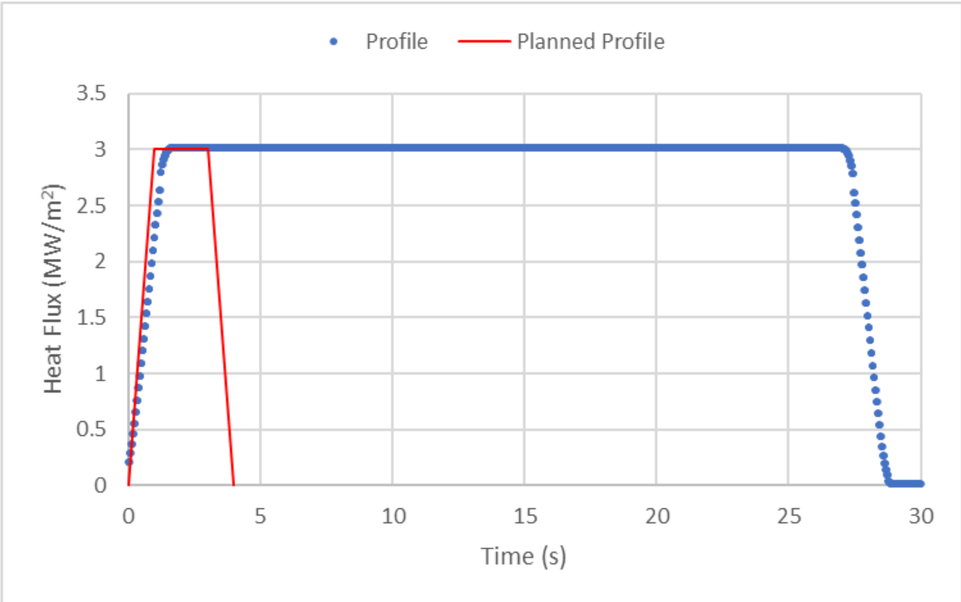


Figure 3-88: Test 1-21 Heat Flux Profile

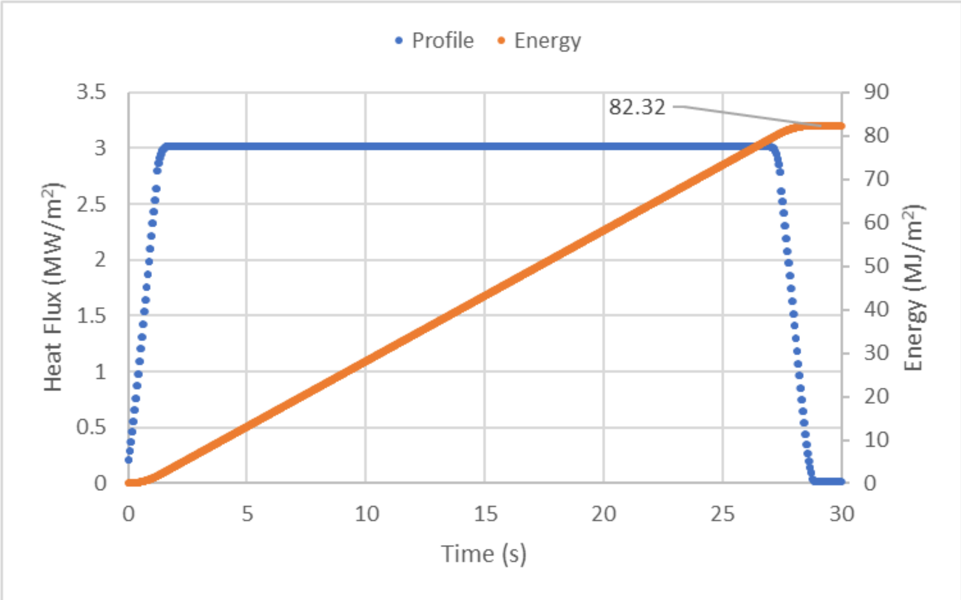


Figure 3-89: Test 1-21 Total Energy

3.21.2. *Electrical/Thermal Monitoring*

Figure 3-90 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

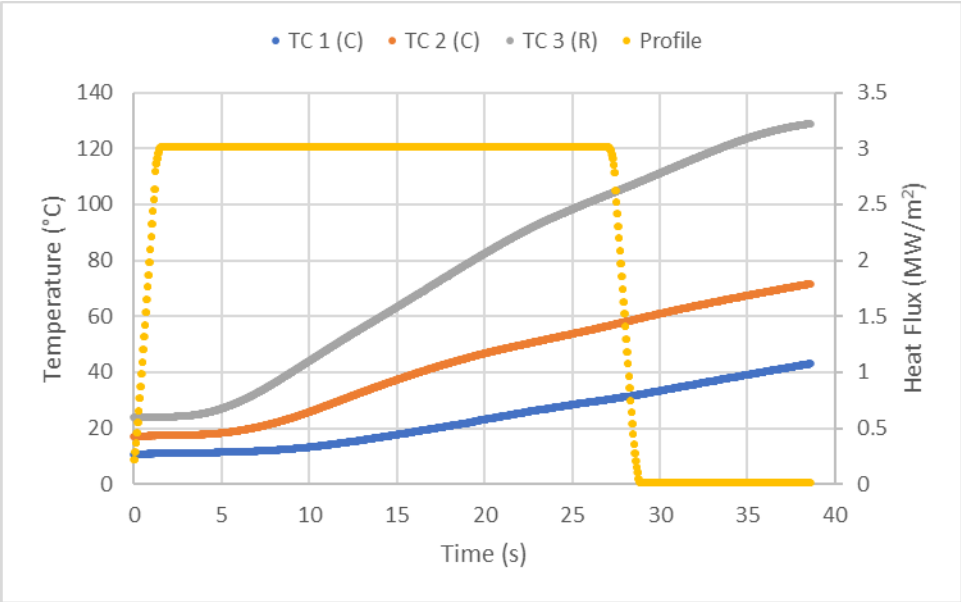


Figure 3-90: Test 1-21 Thermal Monitoring

3.21.3. *Photos*

Figure 3-91 and Figure 3-92 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-91: Test 1-21 Post-test Photo (1)

Figure 3-92: Test 1-21 Post-test Photo (2)

3.21.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.22. Test 1-22

Test 1-22 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 2 seconds.

Table 3-21: Test 1-22 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-22	3	2	N/A	N/A	107.53	106.54	TP

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.22.1. *Profile/Energy*

Figure 3-93 and Figure 3-94 show the heat flux profile and total energy for which the cable target was exposed. As shown, the profile is fairly accurate. The cable target was exposed to a total of approximately 7 MJ/m^2.

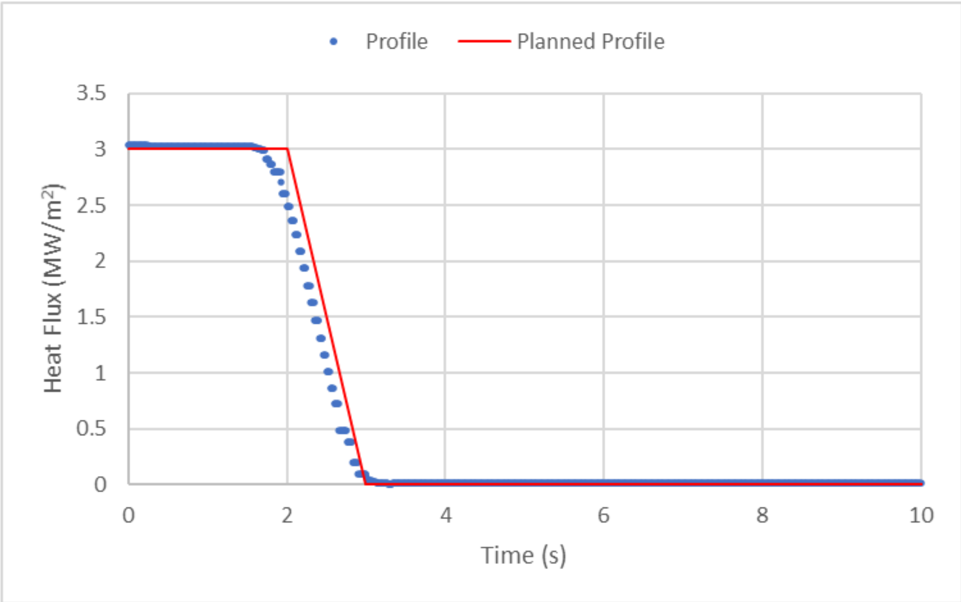


Figure 3-93: Test 1-22 Heat Flux Profile

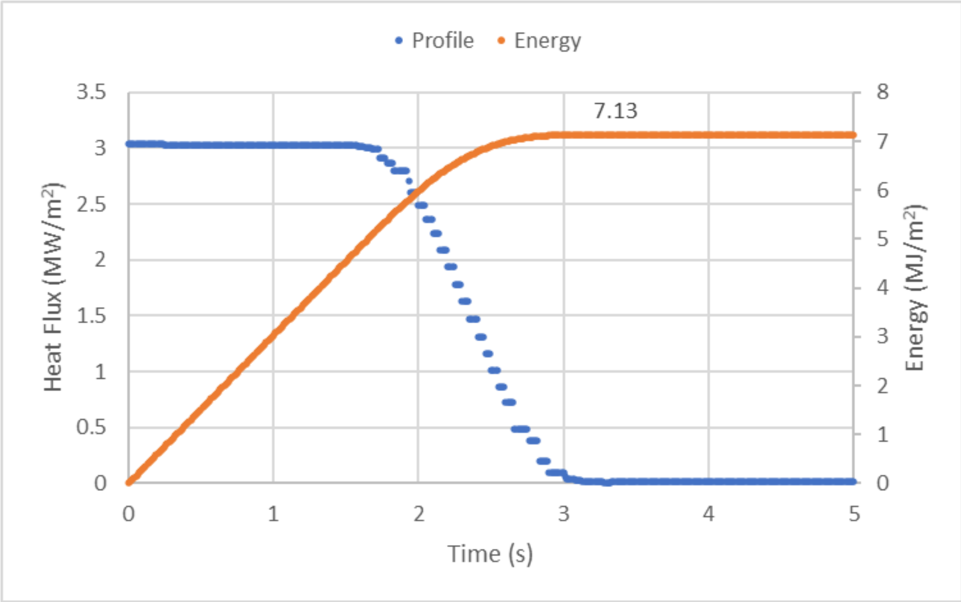


Figure 3-94: Test 1-22 Total Energy

3.22.2. Electrical/Thermal Monitoring

Figure 3-95 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

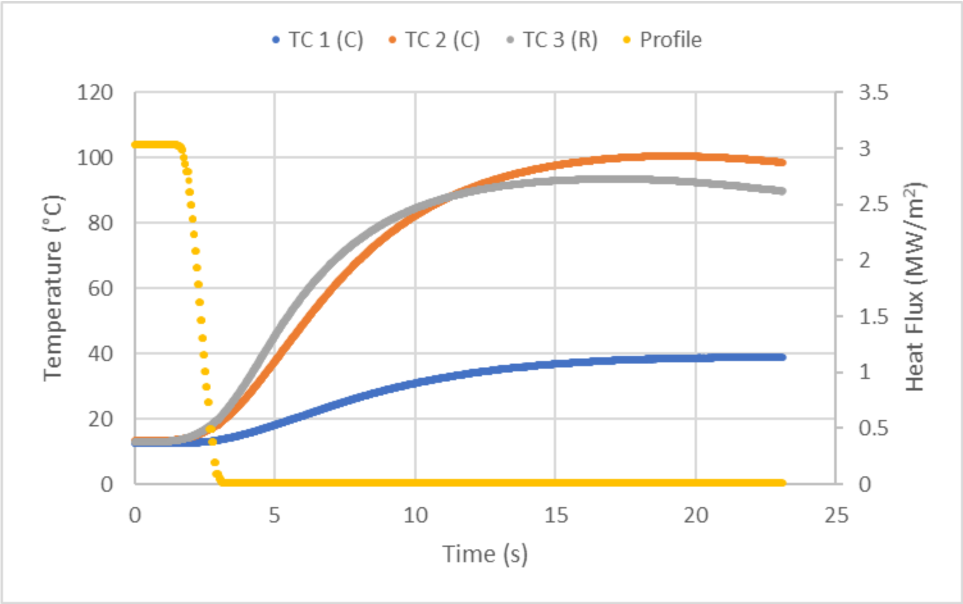


Figure 3-95: Test 1-22 Thermal Monitoring

3.22.3. Photos

Figure 3-96 and Figure 3-97 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-96: Test 1-22 Post-test Photo (1)

Figure 3-97: Test 1-22 Post-test Photo (2)

3.22.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 2.56 seconds after the shutter was fully open. Figure 3-98 shows the time at which the ignition extinguished as a function of total energy and heat flux.

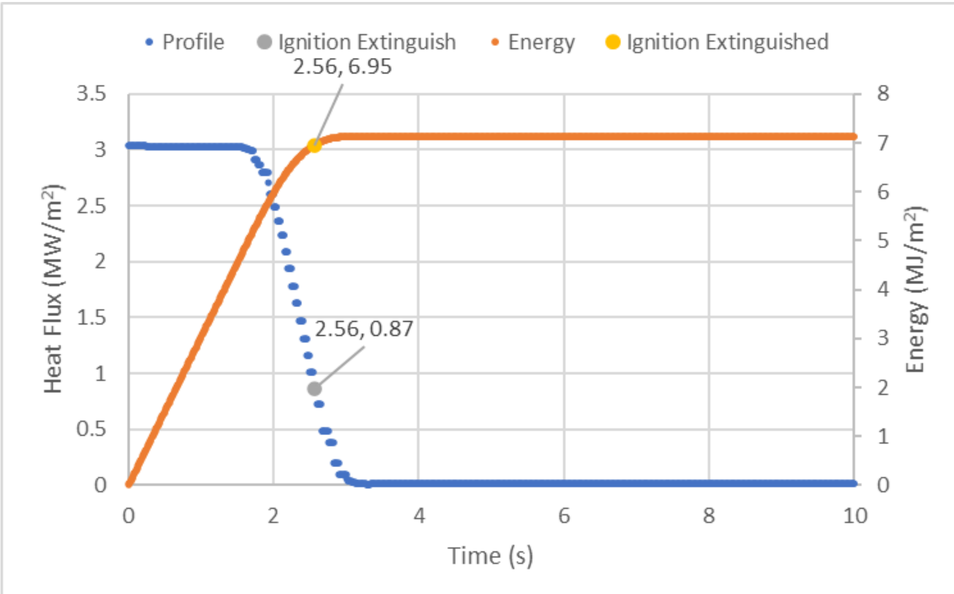


Figure 3-98: Test 1-22 Sustained Ignition as a Function of Heat Flux and Time

3.23. Test 1-23

Test 1-23 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 2 seconds.

Table 3-22: Test 1-23 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-23	3	2	N/A	N/A	131.21	130.62	TS

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.23.1. *Profile/Energy*

Figure 3-99 and Figure 3-100 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux profile remained at the primary heat flux for a lesser duration when compared to the planned profile. The cable target was exposed to a total of approximately 7 MJ/m^2.

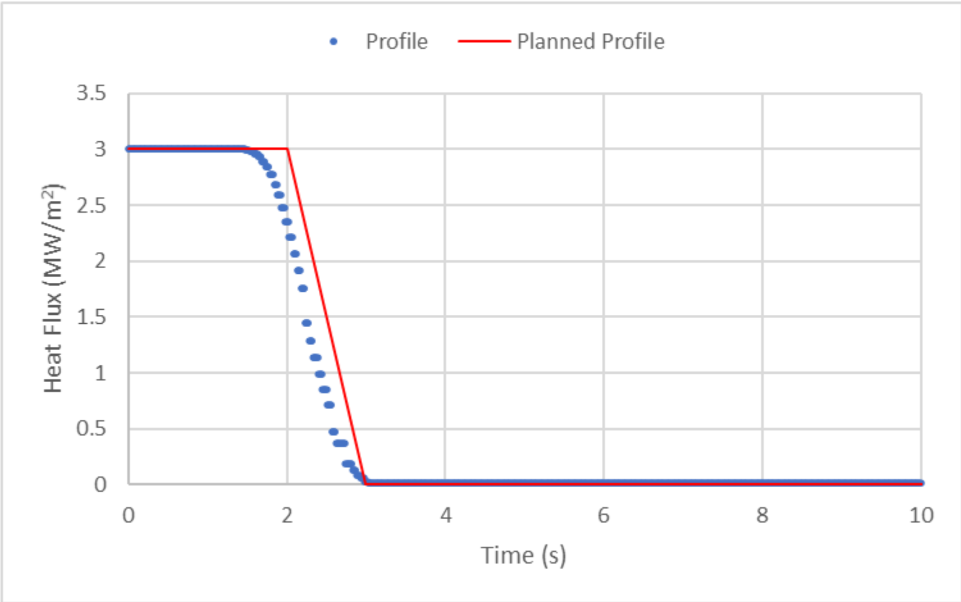


Figure 3-99: Test 1-23 Heat Flux Profile

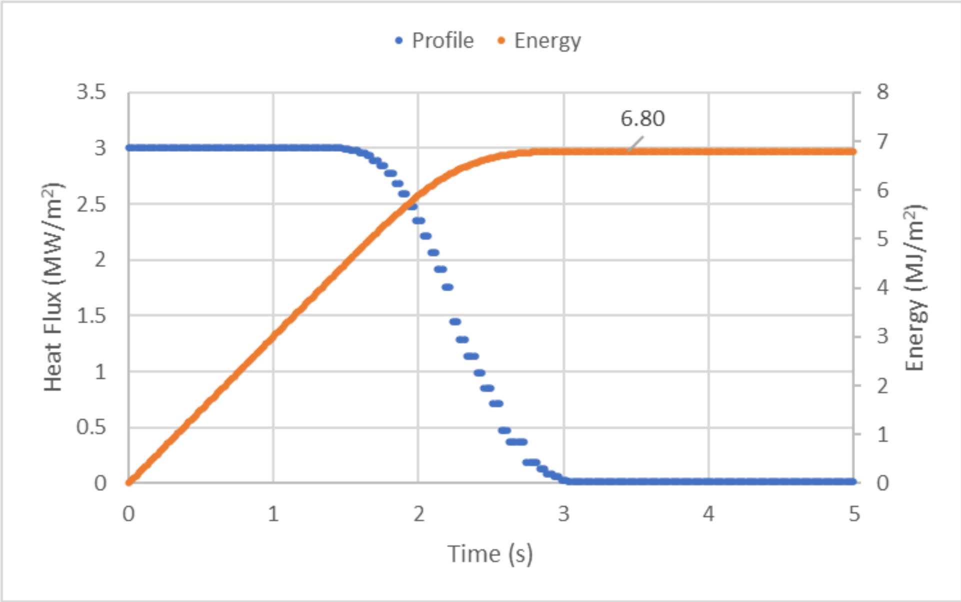


Figure 3-100: Test 1-23 Total Energy

3.23.2. *Electrical/Thermal Monitoring*

Figure 3-101 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

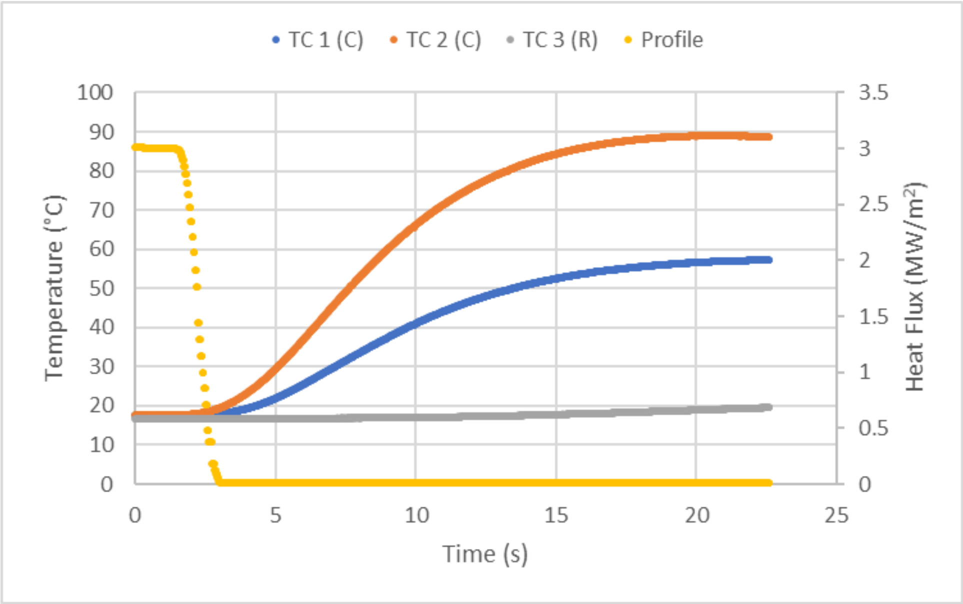


Figure 3-101: Test 1-23 Thermal Monitoring

3.23.3. Photos

Figure 3-102 and Figure 3-103 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-102: Test 1-23 Post-test Photo (1)

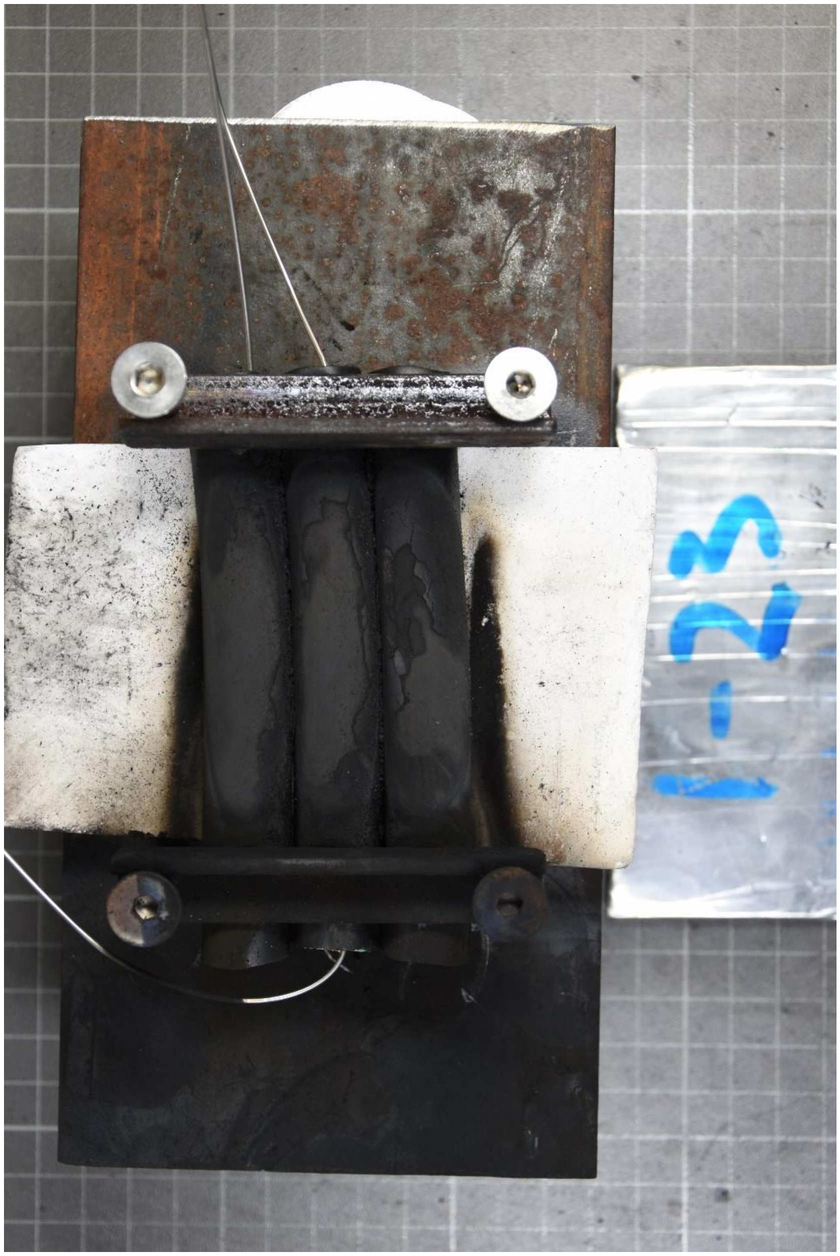


Figure 3-103: Test 1-23 Post-test Photo (2)

3.23.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.33 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 2.67 seconds after the shutter was fully open. Figure 3-104 shows the time at which the ignition extinguished as a function of total energy and heat flux.

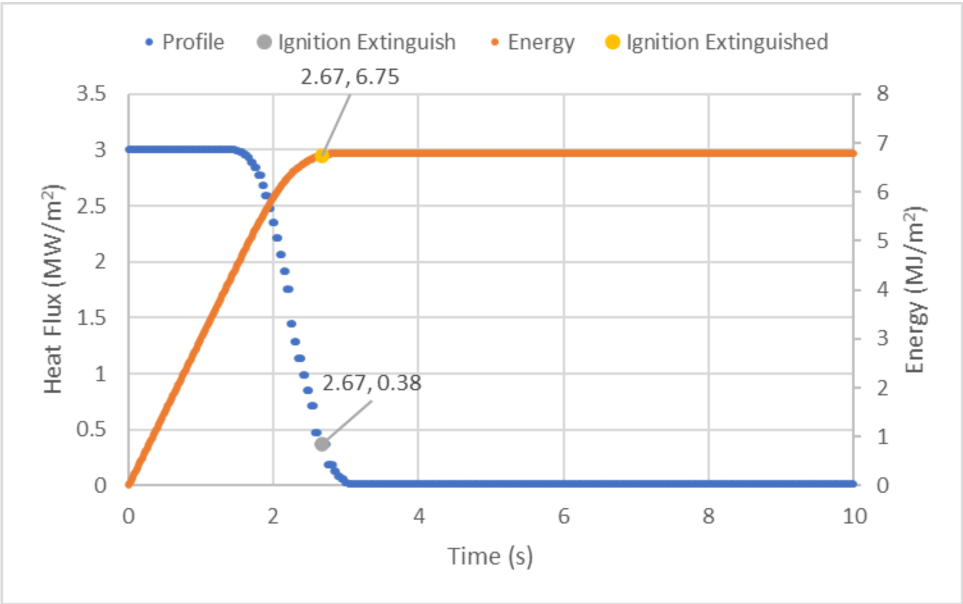


Figure 3-104: Test 1-23 Sustained Ignition as a Function of Heat Flux and Time

3.24. Test 1-24

Test 1-24 evaluated a thermoplastic cable with a primary flux of 4.6 MW/m^2 for a duration of 2 seconds.

Table 3-23: Test 1-24 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-24	4.6	2	N/A	N/A	109.51	107.87	TP

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.24.1. Profile/Energy

Figure 3-105 and Figure 3-106 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile delivered more energy to the cable than planned. The cable target was exposed to a total of approximately 15 MJ/m^2.

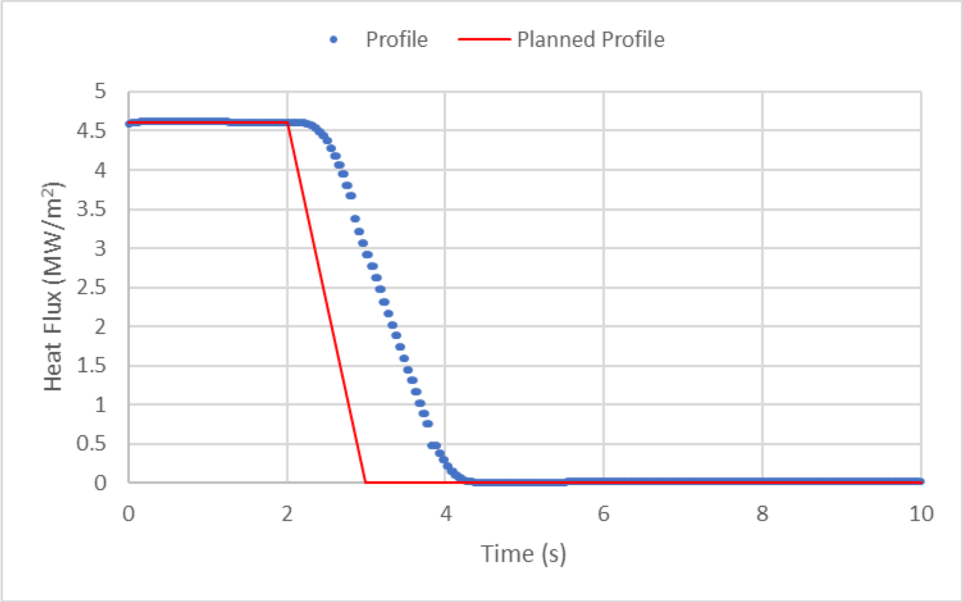


Figure 3-105: Test 1-24 Heat Flux Profile

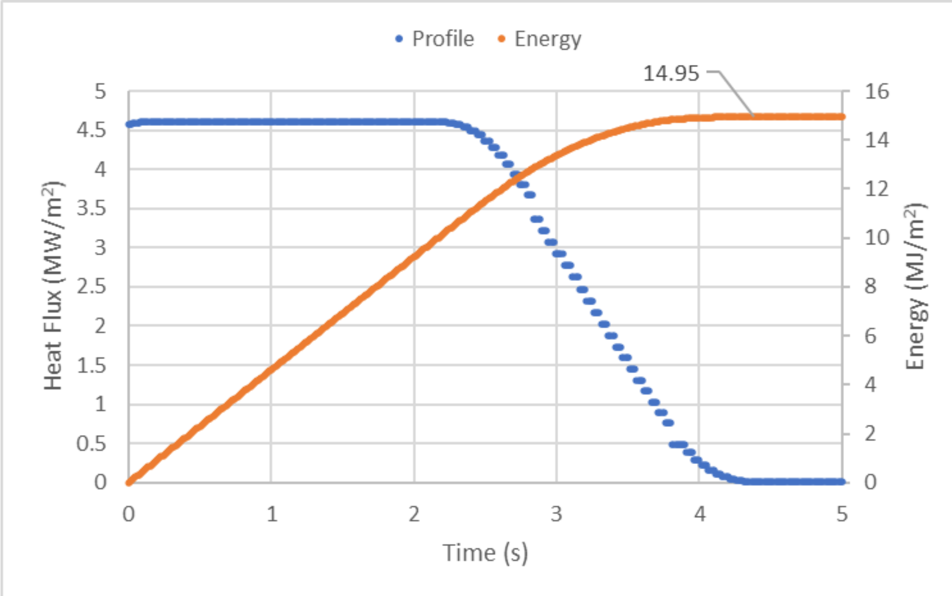


Figure 3-106: Test 1-24 Total Energy

3.24.2. Electrical/Thermal Monitoring

Figure 3-107 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

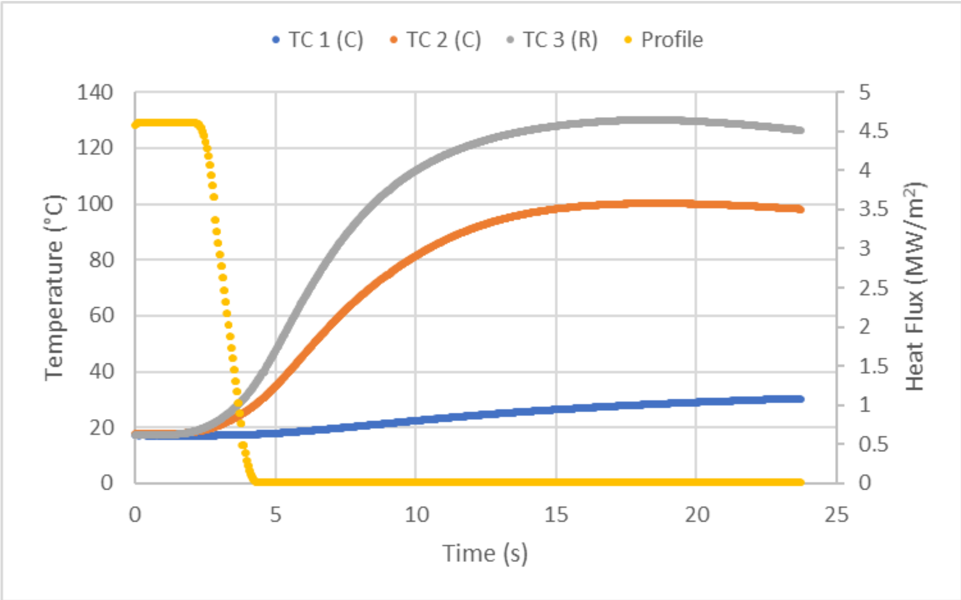


Figure 3-107: Test 1-24 Thermal Monitoring

3.24.3. Photos

Figure 3-108 and Figure 3-109 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-108: Test 1-24 Post-test Photo (1)

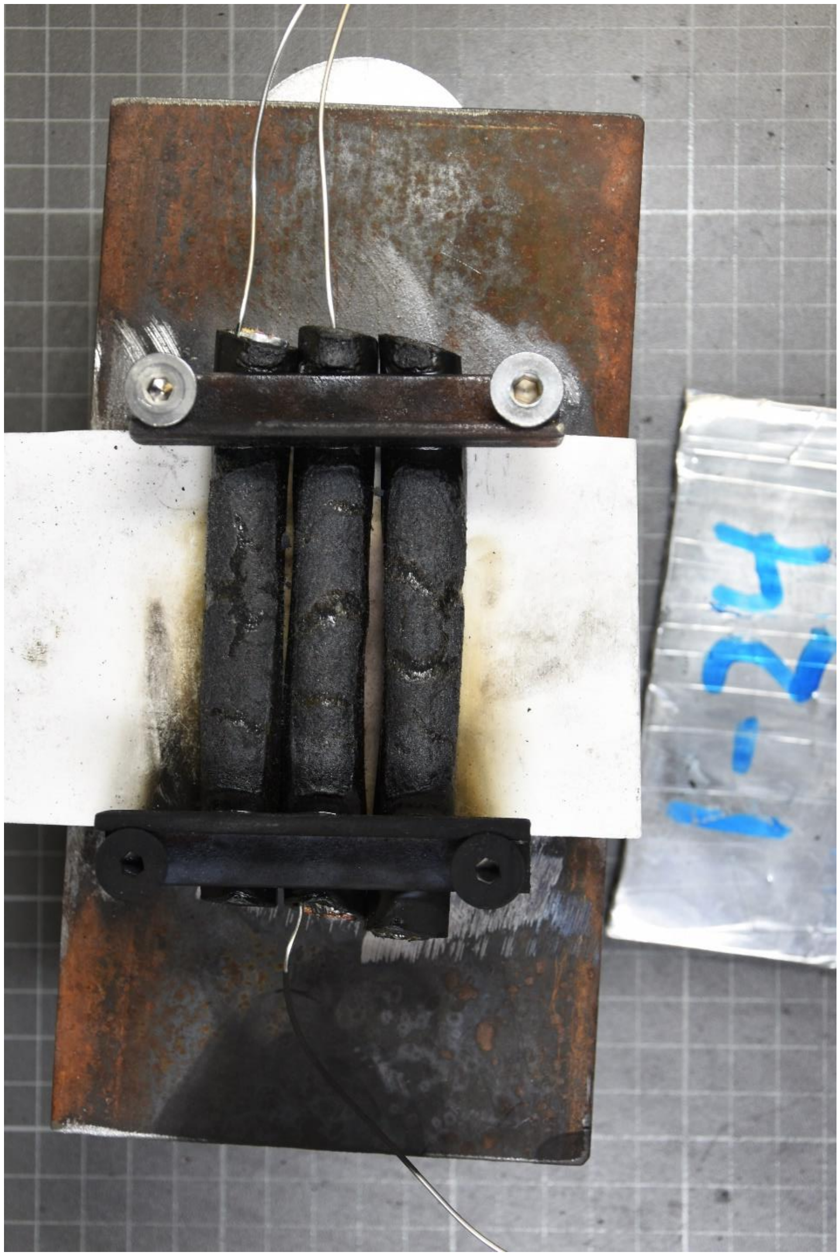


Figure 3-109: Test 1-24 Post-test Photo (2)

3.24.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.23 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 3.93 seconds after the shutter was fully open. Figure 3-110 shows the time at which the ignition extinguished as a function of total energy and heat flux.

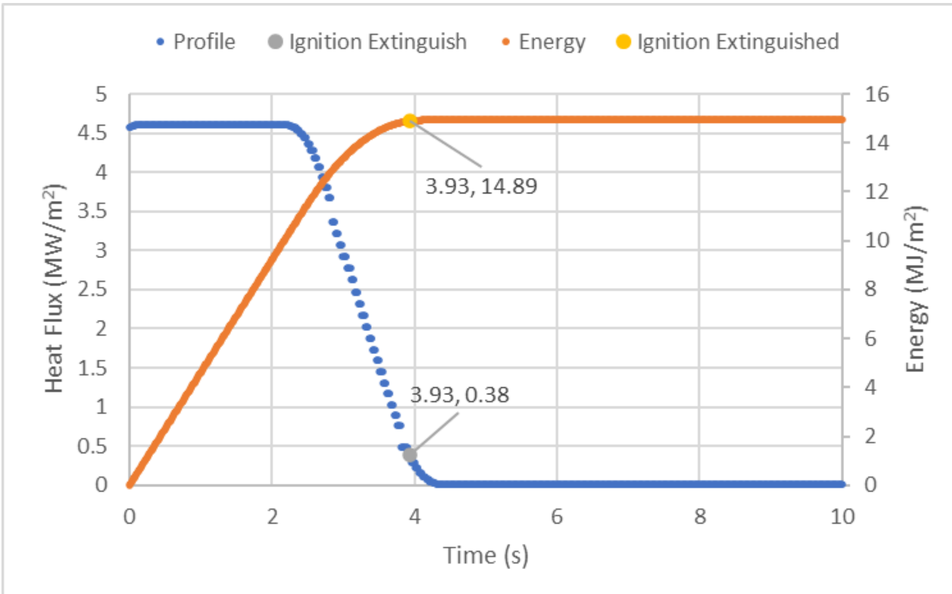


Figure 3-110: Test 1-24 Sustained Ignition as a Function of Heat Flux and Time

3.25. Test 1-25

Test 1-25 evaluated a thermoset cable with a primary flux of 4.6 MW/m^2 for a duration of 2 seconds.

Table 3-24: Test 1-25 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-25	4.6	2	N/A	N/A	130.9	129.74	TS

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.25.1. Profile/Energy

Figure 3-111 and Figure 3-112 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile delivered more energy to the cable than planned. This is because the flux was still rising at the time the high-speed shutter was opened. However, the actual heat flux magnitude was slightly lower than 4.6 MW/m^2. The cable target was exposed to a total of approximately 15 MJ/m^2.

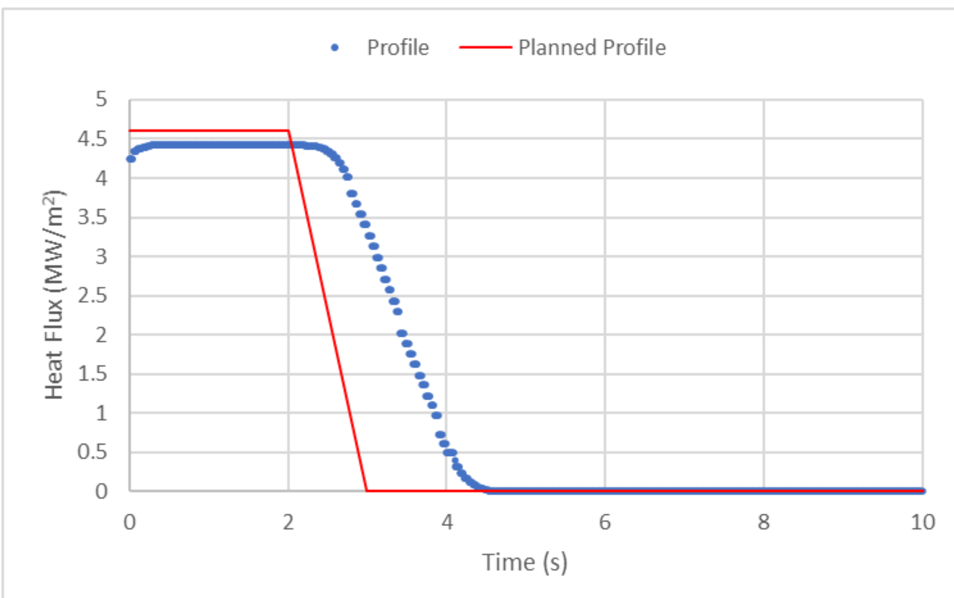


Figure 3-111: Test 1-25 Heat Flux Profile

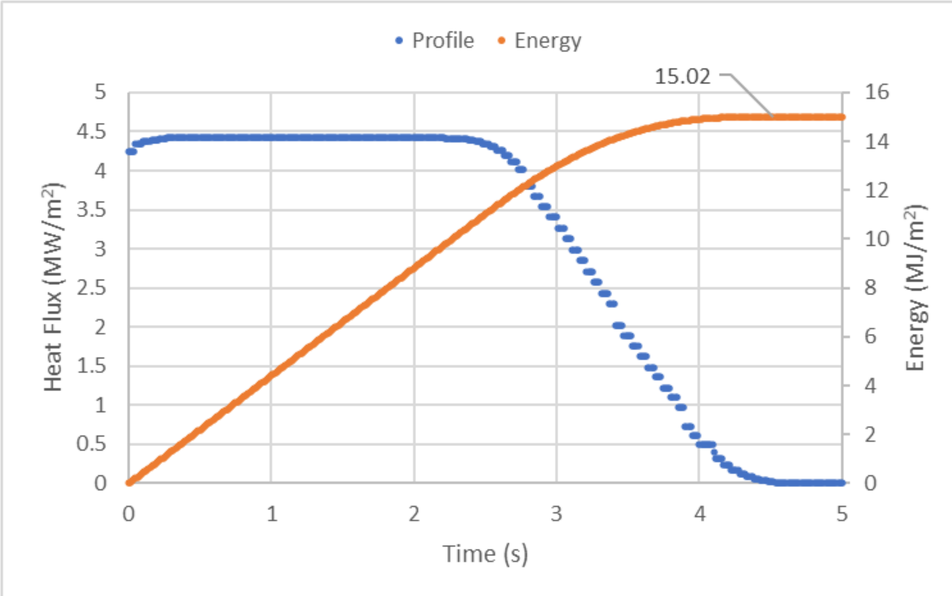


Figure 3-112: Test 1-25 Total Energy

3.25.2. Electrical/Thermal Monitoring

Figure 3-113 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

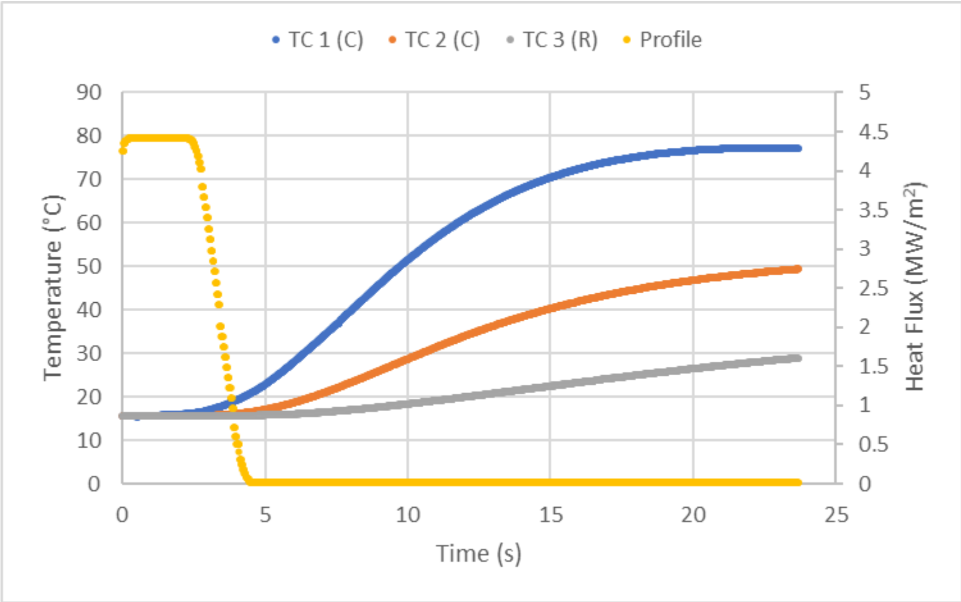


Figure 3-113: Test 1-25 Thermal Monitoring

3.25.3. Photos

Figure 3-114 and Figure 3-115 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-114: Test 1-25 Post-test Photo (1)

Figure 3-115: Test 1-25 Post-test Photo (2)

3.25.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 4.43 seconds after the shutter was fully open. Figure 3-116 shows the time at which the ignition extinguished as a function of total energy and heat flux.

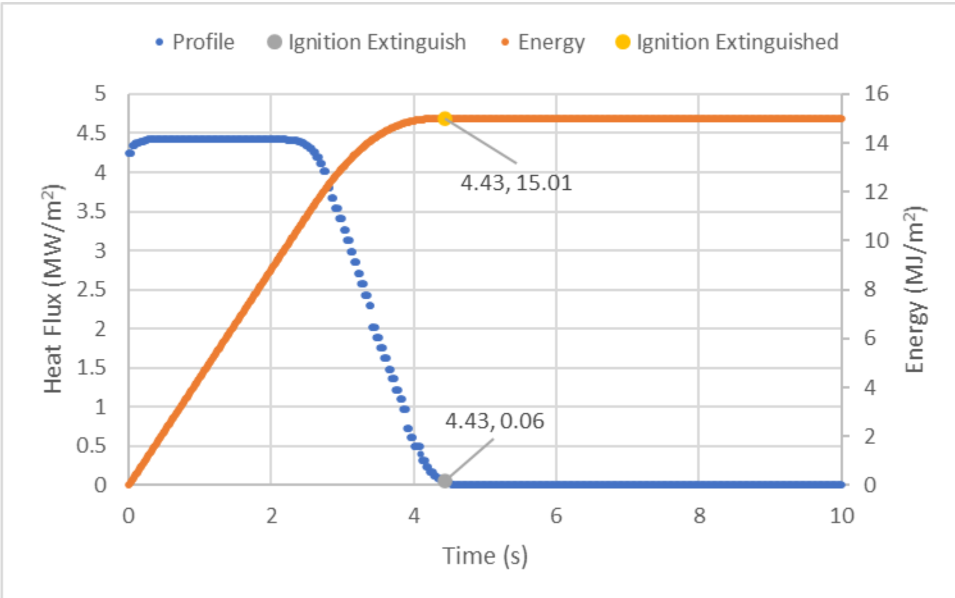


Figure 3-116: Test 1-25 Sustained Ignition as a Function of Heat Flux and Time

3.26. Test 1-26

Test 1-26 evaluated a thermoplastic cable with a primary flux of 6 MW/m^2 for a duration of 4 seconds.

Table 3-25: Test 1-26 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-26	6	4	N/A	N/A	109.58	105.9	TP

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.26.1. Profile/Energy

Figure 3-117 and Figure 3-118 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile delivered more energy to the cable than planned. This is because the flux was still rising at the time the high-speed shutter was opened. The cable target was exposed to a total of approximately 36 MJ/m^2.

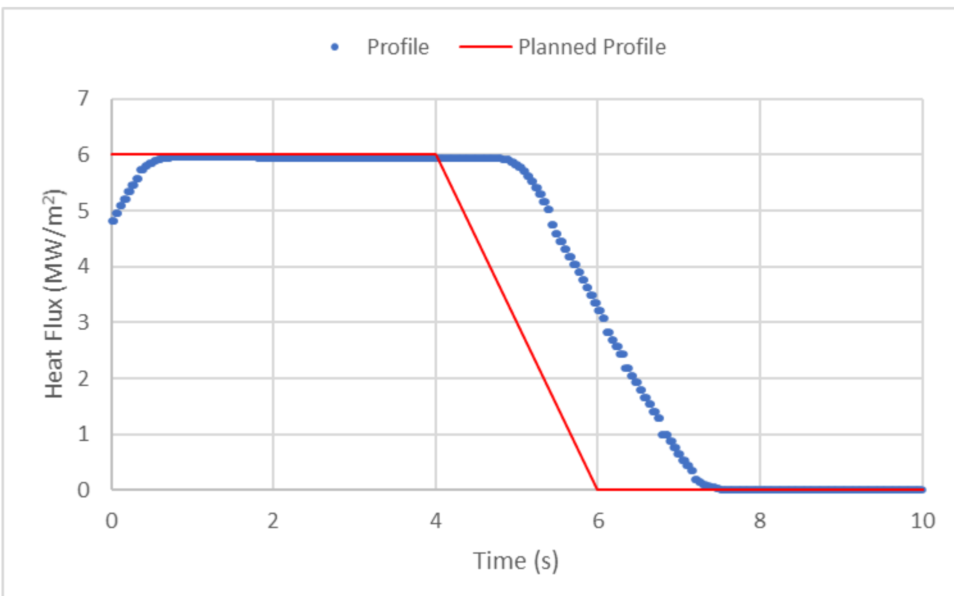


Figure 3-117: Test 1-26 Heat Flux Profile

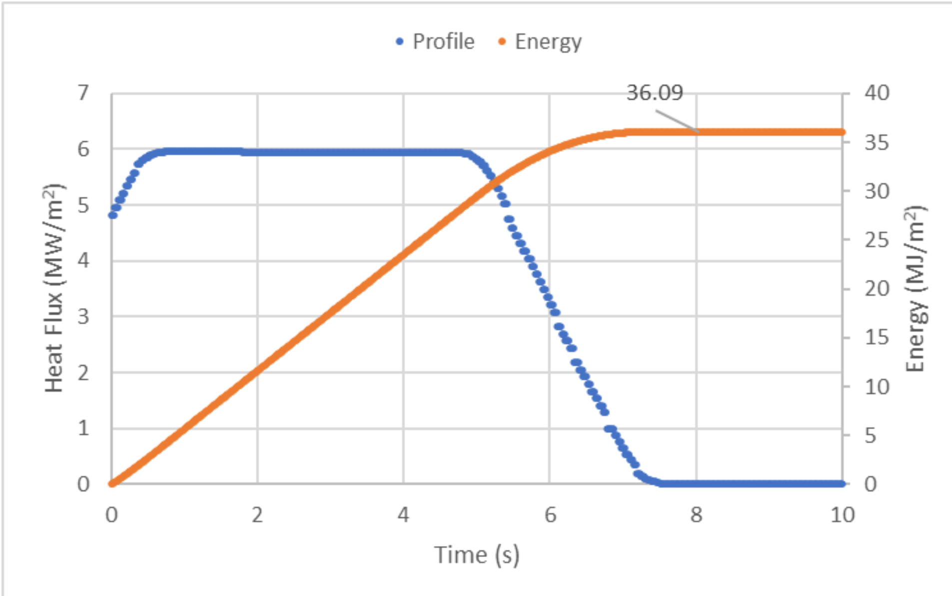


Figure 3-118: Test 1-26 Total Energy

3.26.2. Electrical/Thermal Monitoring

Figure 3-119 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

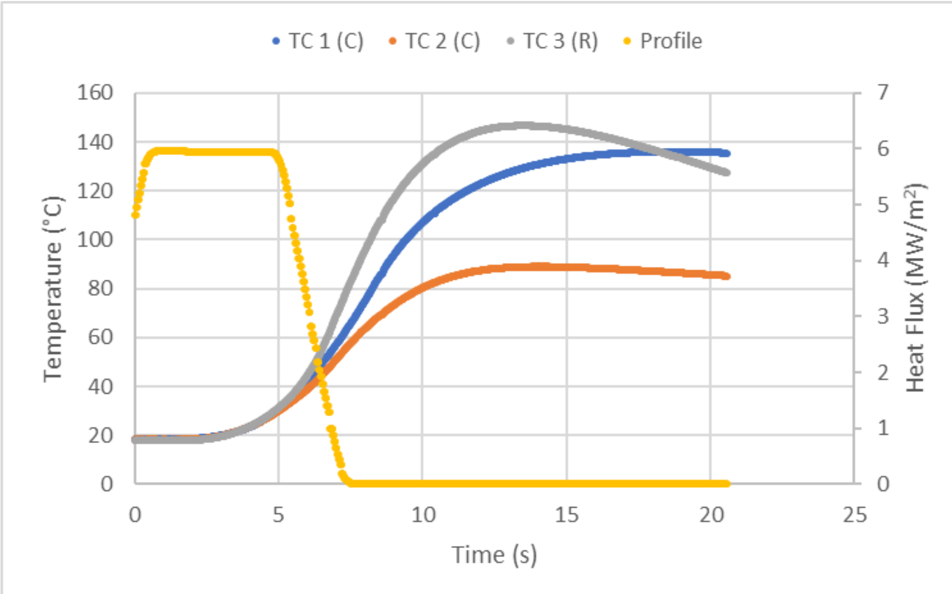


Figure 3-119: Test 1-26 Thermal Monitoring

3.26.3. Photos

Figure 3-120 and Figure 3-121 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-120: Test 1-26 Post-test Photo (1)

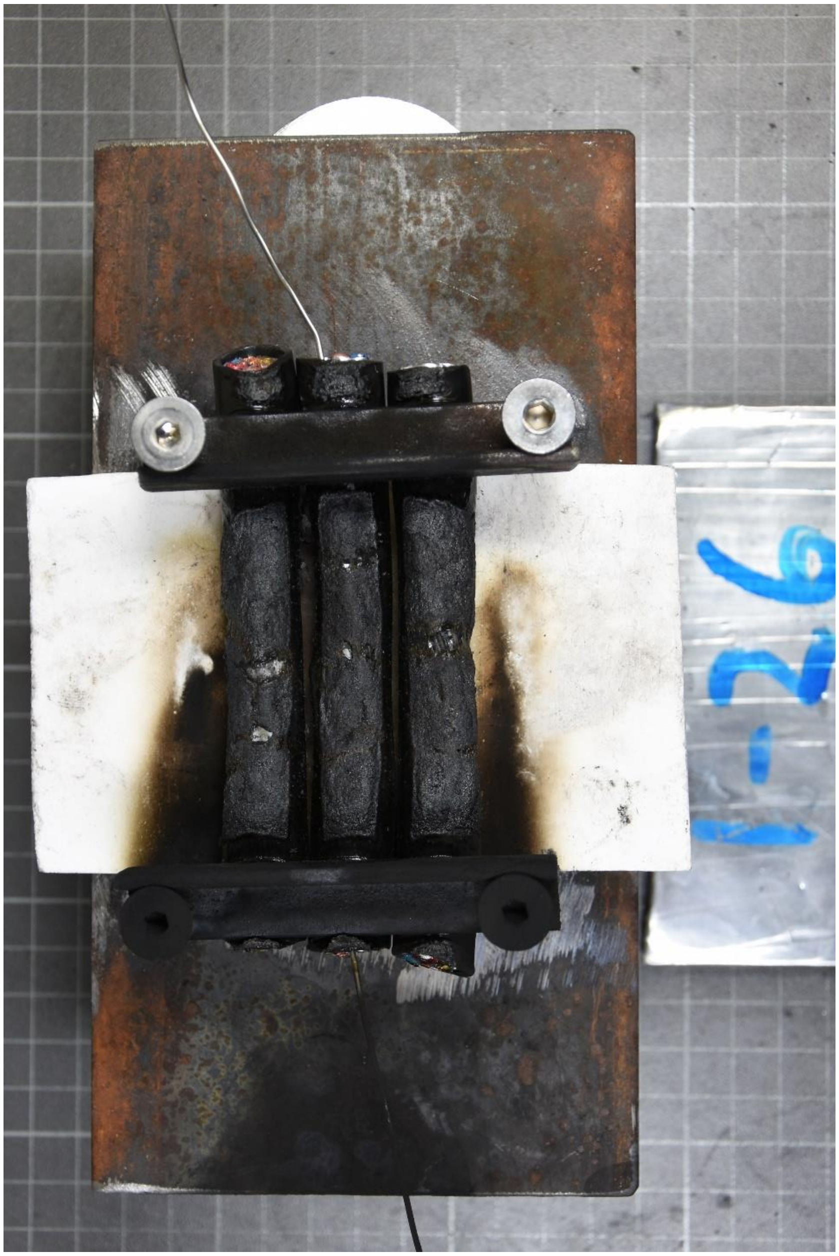


Figure 3-121: Test 1-26 Post-test Photo (2)

3.26.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 7.50 seconds after the shutter was fully open. Figure 3-122 shows the time at which the ignition extinguished as a function of total energy and heat flux.

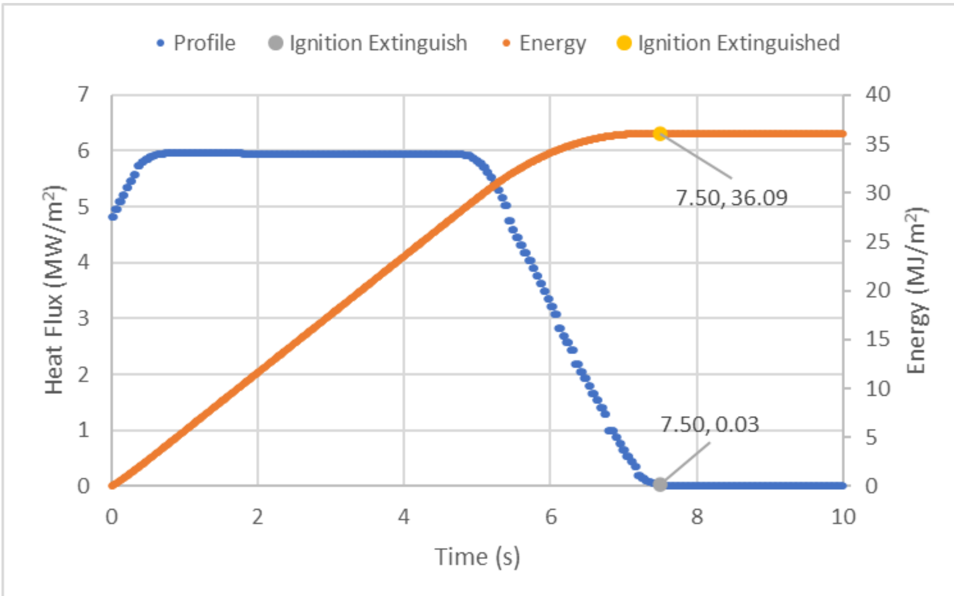


Figure 3-122: Test 1-26 Sustained Ignition as a Function of Heat Flux and Time

3.27. Test 1-27

Test 1-27 evaluated a thermoset cable with a primary flux of 6 MW/m^2 for a duration of 4 seconds.

Table 3-26: Test 1-27 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-27	6	4	N/A	N/A	131.13	128.16	TS

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.27.1. *Profile/Energy*

Figure 3-123 and Figure 3-124 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile delivered more energy to the cable than planned. This is because the flux was still rising at the time the high-speed shutter was opened. The cable target was exposed to a total of approximately 38 MJ/m^2.

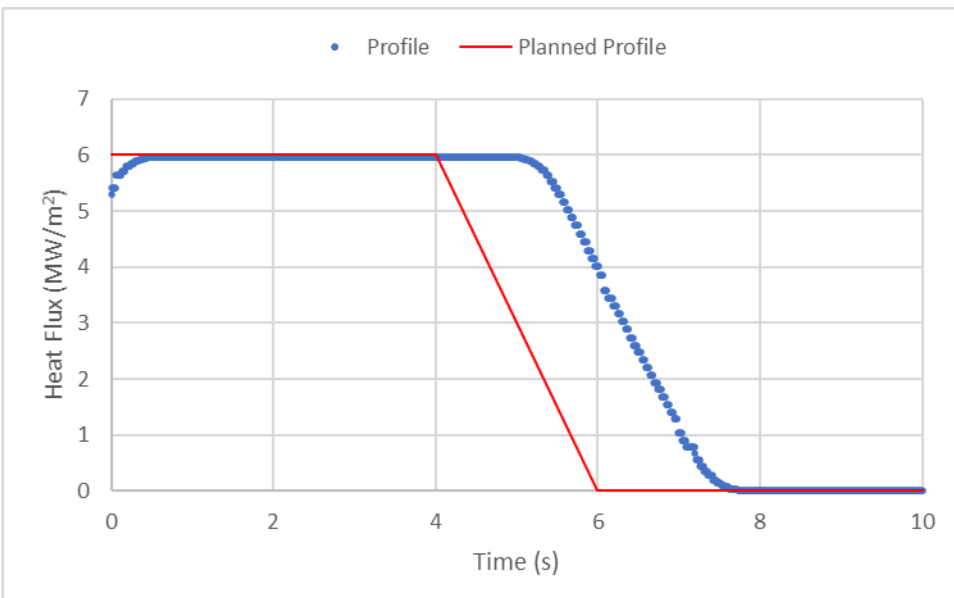


Figure 3-123: Test 1-27 Heat Flux Profile

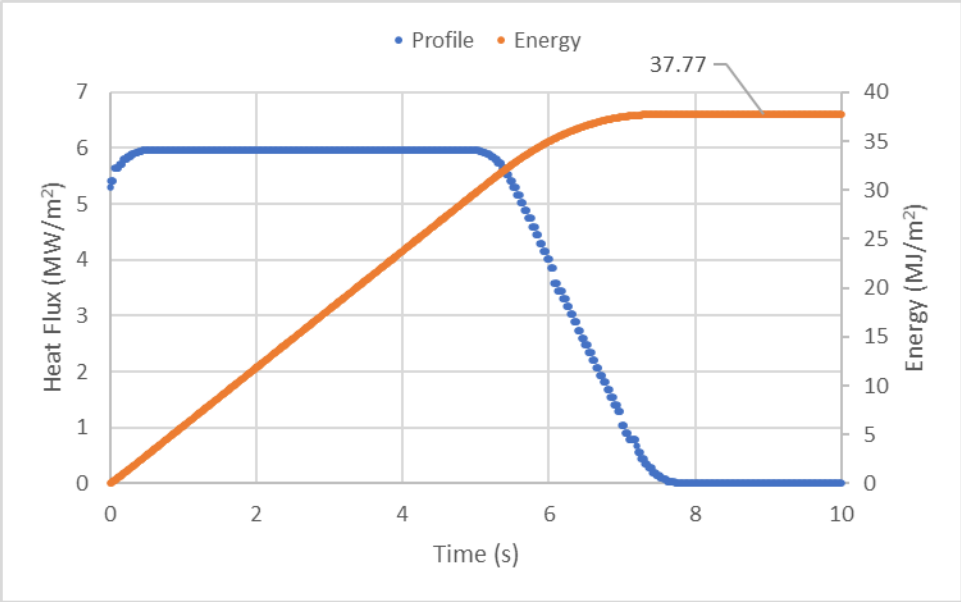


Figure 3-124: Test 1-27 Total Energy

3.27.2. Electrical/Thermal Monitoring

Figure 3-125 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

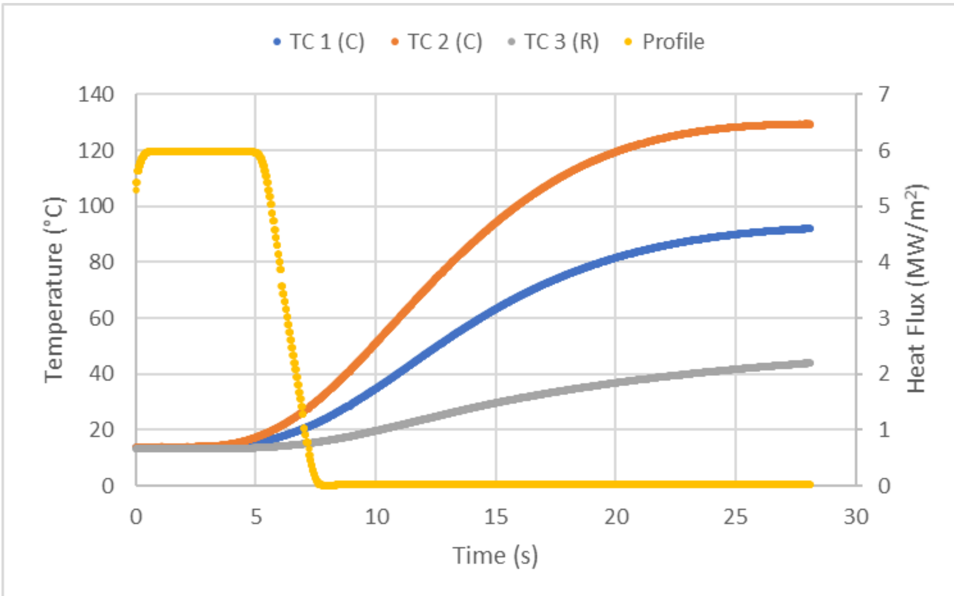


Figure 3-125: Test 1-27 Thermal Monitoring

3.27.3. Photos

Figure 3-126 and Figure 3-127 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-126: Test 1-27 Post-test Photo (1)

Figure 3-127: Test 1-27 Post-test Photo (2)

3.27.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 8.27 seconds after the shutter was fully open. Figure 3-128 shows the time at which the ignition extinguished as a function of total energy and heat flux.

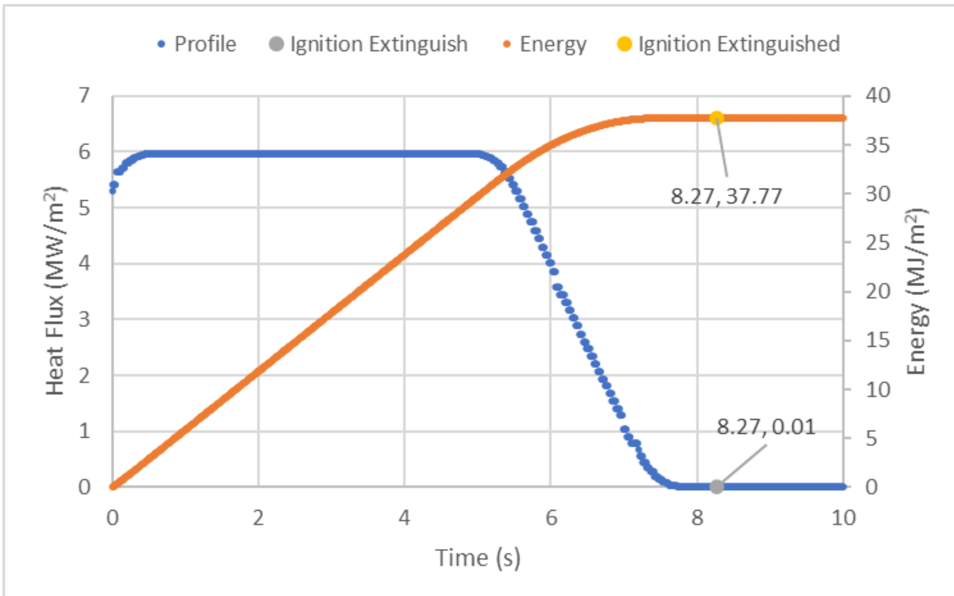


Figure 3-128: Test 1-27 Sustained Ignition as a Function of Heat Flux and Time

3.28. Test 1-28

Test 1-28 evaluated a thermoset cable with a primary flux of 6 MW/m² for a duration of 8 seconds.

Table 3-27: Test 1-28 Test Summary Data

Test Number	Q0 (MW/m²)	T0 (s)	Q1 (MW/m²)	Q2 (MW/m²)	Pre-weight (g)	Post-weight (g)	Cable Type
1-28	6	8	N/A	N/A	131.77	126.82	TS

- Purpose: Examine damage threshold as a function of total energy with constant flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-19-21

3.28.1. Profile/Energy

Figure 3-129 and Figure 3-130 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual profile delivered more energy to the cable than planned. This is because the flux was still rising at the time the high-speed shutter was opened. The cable target was exposed to a total of approximately 63 MJ/m².

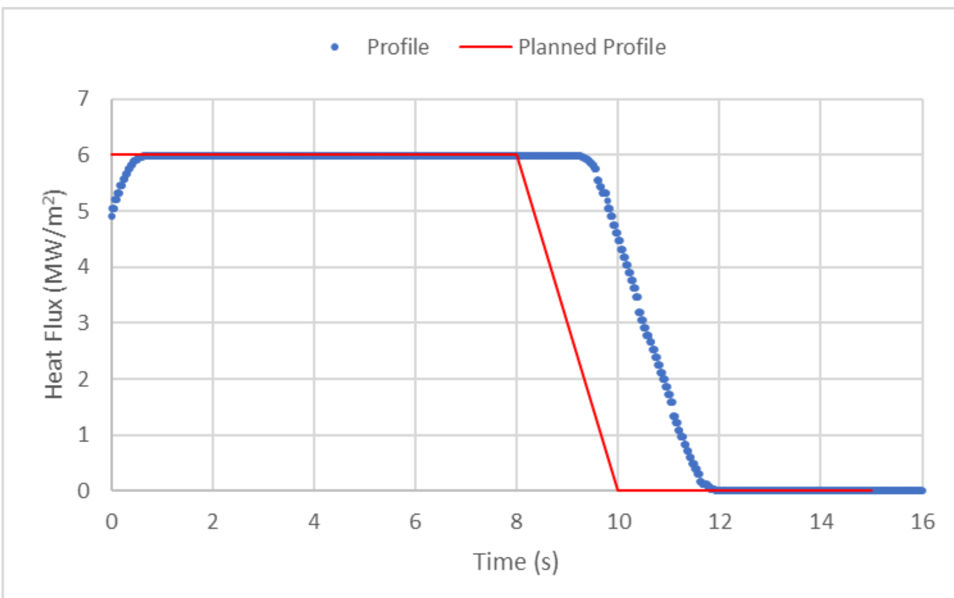


Figure 3-129: Test 1-28 Heat Flux Profile

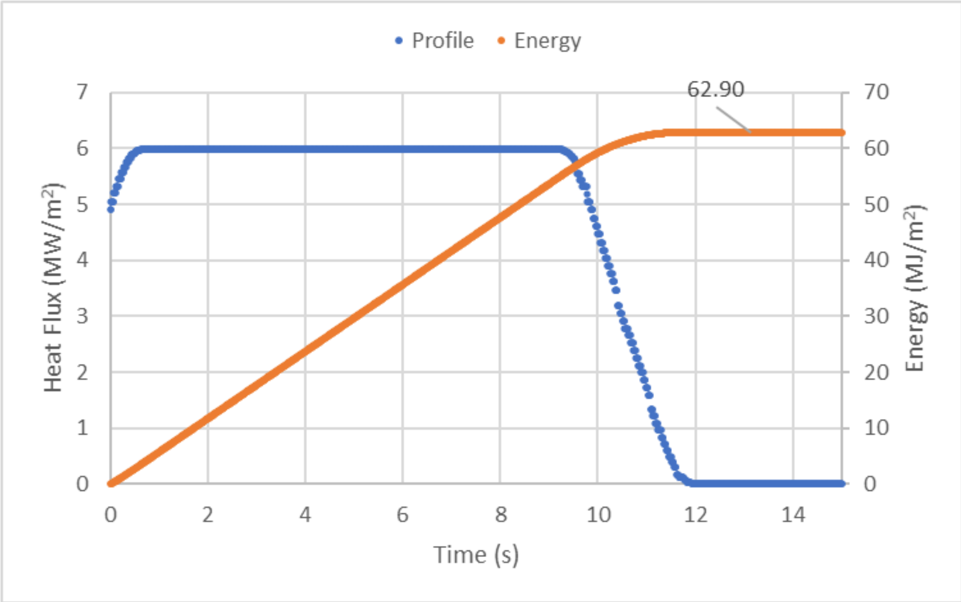


Figure 3-130: Test 1-28 Total Energy

3.28.2. Electrical/Thermal Monitoring

Figure 3-131 shows the thermal monitoring results from the test. Two thermocouples were placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that these TCs were placed directly in the top/bottom end of the cable sample, so no slit in the jacket was necessary. Also, a third thermocouple was placed from the bottom of one of the ancillary cables.

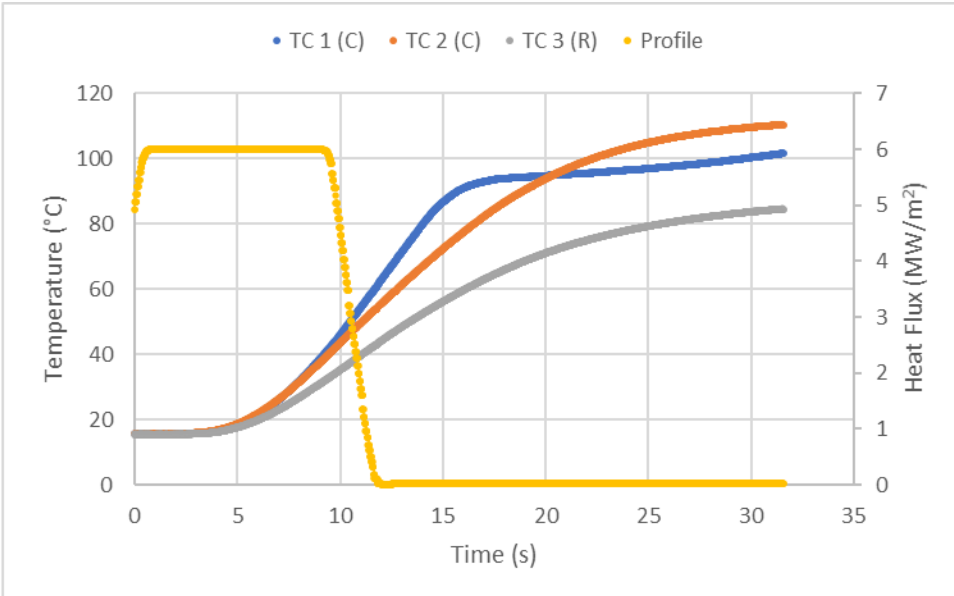


Figure 3-131: Test 1-28 Thermal Monitoring

3.28.3. Photos

Figure 3-132 and Figure 3-133 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test. Note, that there are cracks forming (as shown in Figure 3-133), that indicate that insulation exposure is imminent.

Figure 3-132: Test 1-28 Post-test Photo (1)

Figure 3-133: Test 1-28 Post-test Photo (2)

3.28.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 12.73 seconds after the shutter was fully open. Figure 3-134 shows the time at which the ignition extinguished as a function of total energy and heat flux.

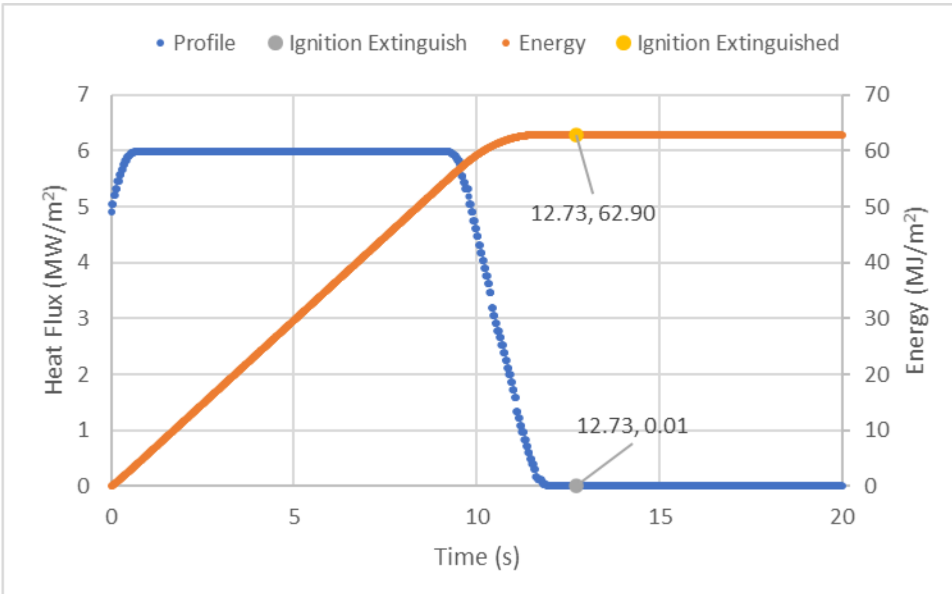


Figure 3-134: Test 1-28 Sustained Ignition as a Function of Heat Flux and Time

3.29. Test 1-29

Test 1-29 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 8 seconds.

Table 3-28: Test 1-29 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-29	3	8	0.66	0.05	133.37	129.19	TS

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-22-21

3.29.1. *Profile/Energy*

Figure 3-135 and Figure 3-136 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. The cable target was exposed to a total of approximately 32 MJ/m^2.

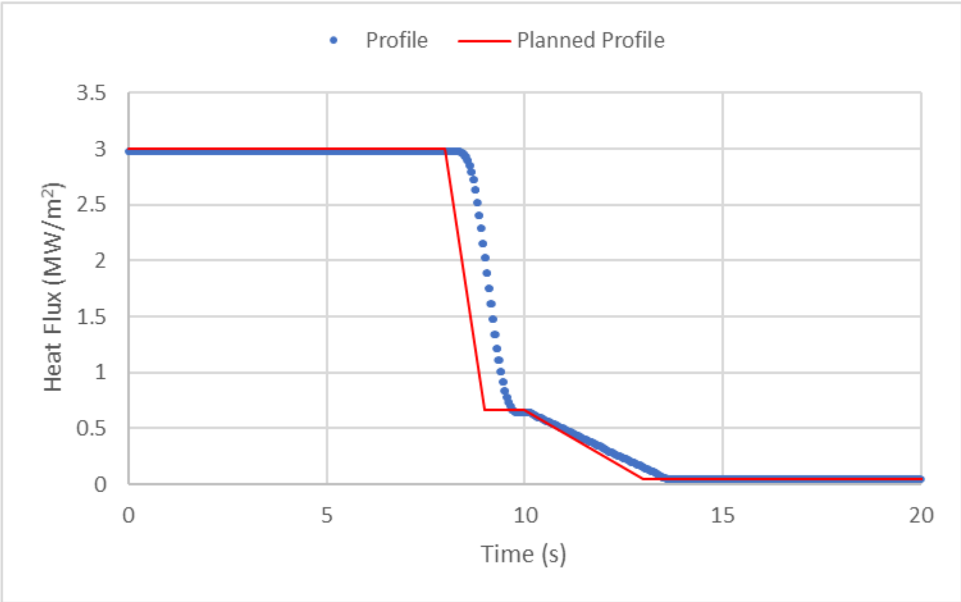


Figure 3-135: Test 1-29 Heat Flux Profile

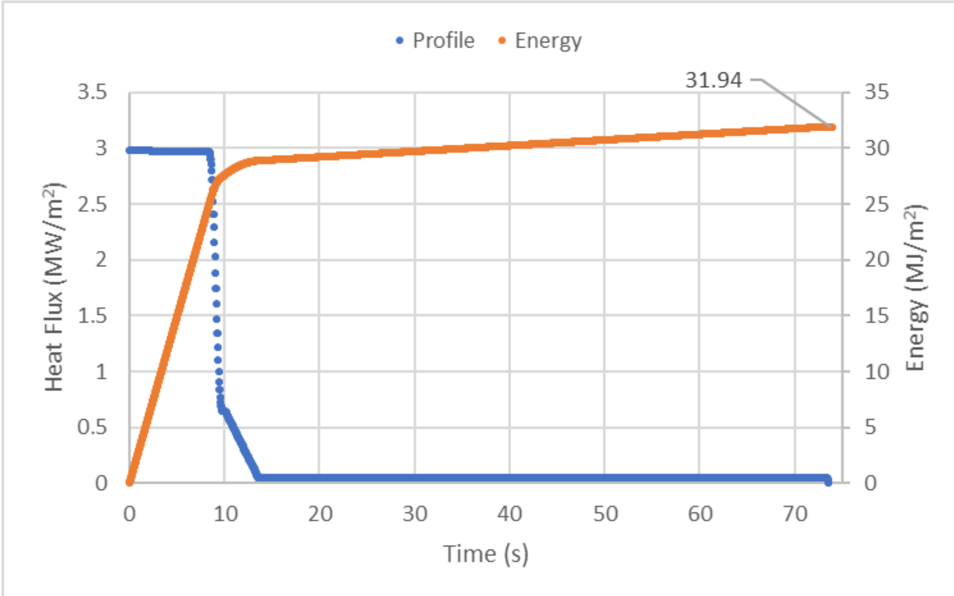


Figure 3-136: Test 1-29 Total Energy

3.29.2. Electrical/Thermal Monitoring

Figure 3-137 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

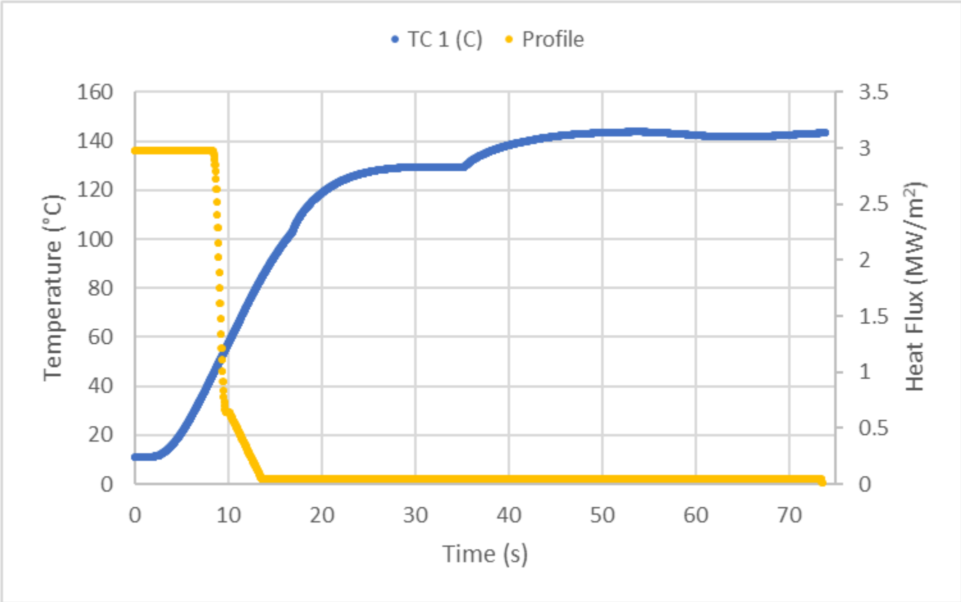


Figure 3-137: Test 1-29 Thermal Monitoring

3.29.3. Photos

Figure 3-138 and Figure 3-139 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test.

Figure 3-138: Test 1-29 Post-test Photo (1)

Figure 3-139: Test 1-29 Post-test Photo (2)

3.29.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 14.47 seconds after the shutter was fully open. Figure 3-140 shows the time at which the ignition extinguished as a function of total energy and heat flux.

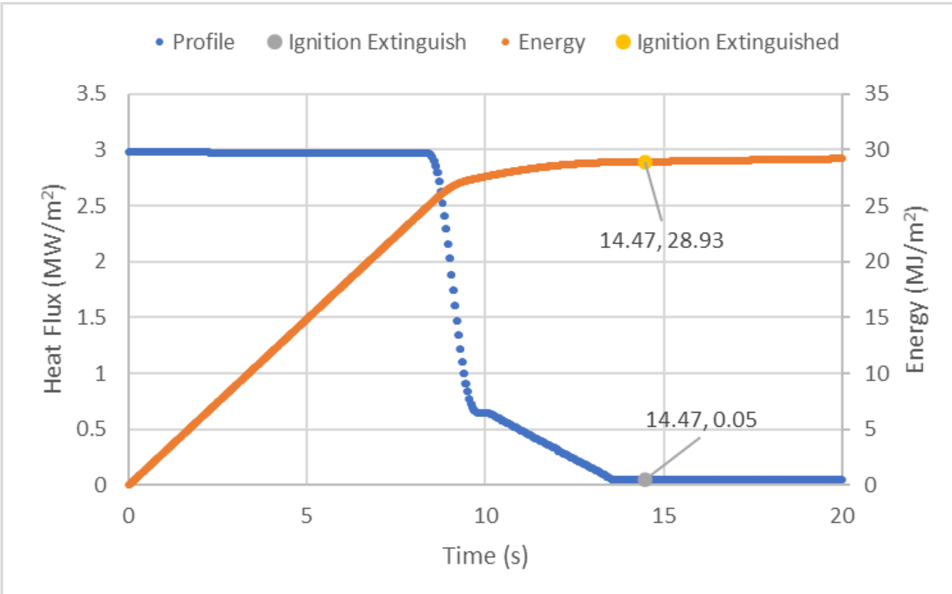


Figure 3-140: Test 1-29 Sustained Ignition as a Function of Heat Flux and Time

3.30. Test 1-30

Test 1-30 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 10 seconds.

Table 3-29: Test 1-30 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-30	3	10	0.66	0.05	131.18	126.85	TS

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-22-21

3.30.1. Profile/Energy

Figure 3-141 and Figure 3-142 show the heat flux profile and total energy for which the cable target was exposed. The profile is fairly accurate. The cable target was exposed to a total of approximately 35 MJ/m^2.

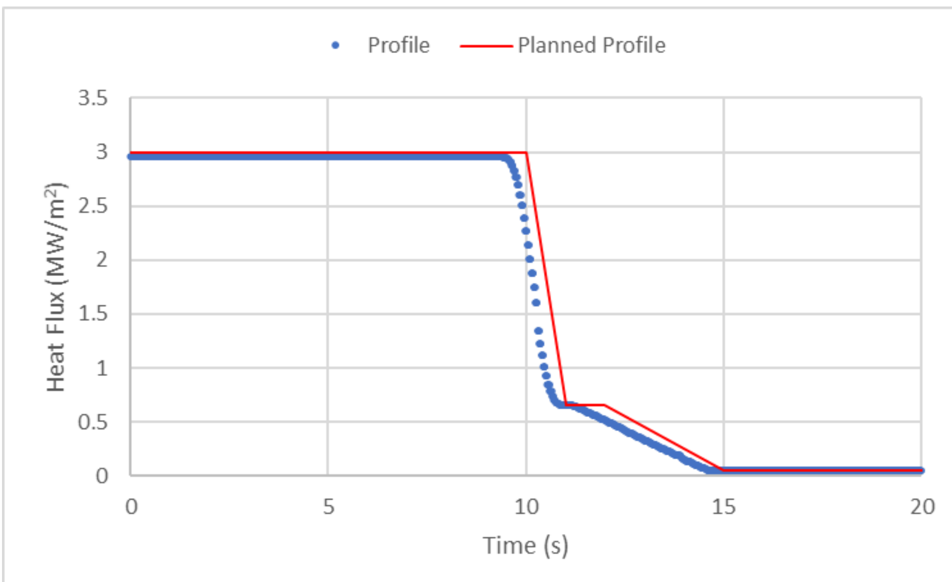


Figure 3-141: Test 1-30 Heat Flux Profile

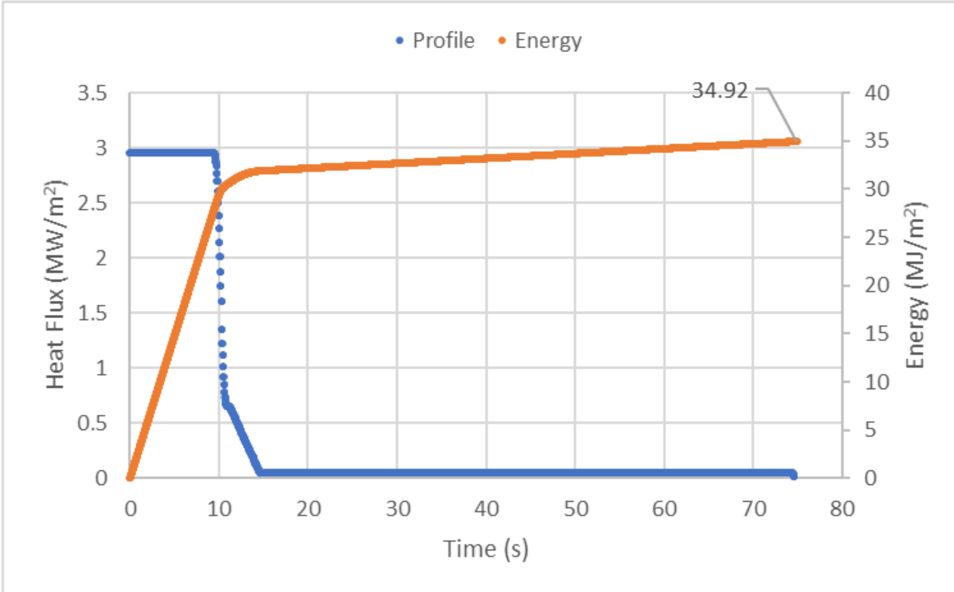


Figure 3-142: Test 1-30 Total Energy

3.30.2. Electrical/Thermal Monitoring

Figure 3-143 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

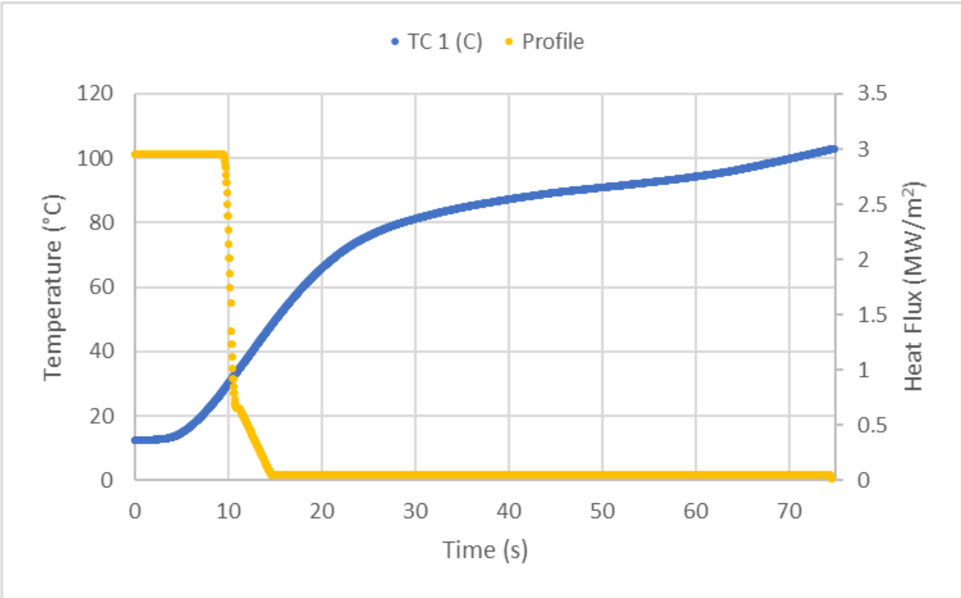


Figure 3-143: Test 1-30 Thermal Monitoring

3.30.3. Photos

Figure 3-144, Figure 3-145, and Figure 3-146 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-144: Test 1-30 Post-test Photo (1)

Figure 3-145: Test 1-30 Post-test Photo (2)

Figure 3-146: Test 1-30 Post-test Photo (3)

3.30.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 14.63 seconds after the shutter was fully open. Figure 3-147 shows the time at which the ignition extinguished as a function of total energy and heat flux.

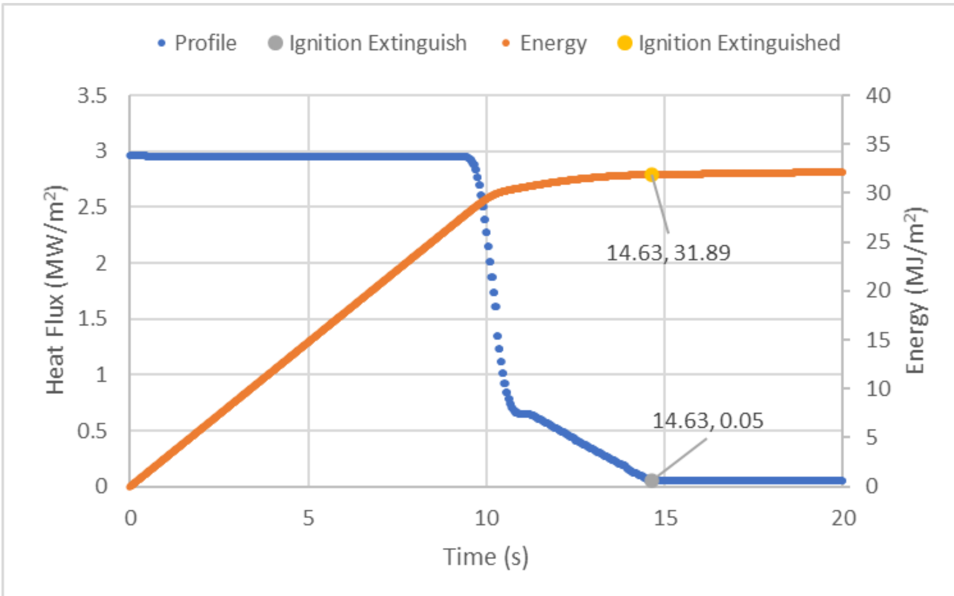


Figure 3-147: Test 1-30 Sustained Ignition as a Function of Heat Flux and Time

3.31. Test 1-31

Test 1-31 evaluated a thermoset cable with a primary flux of 4.5 MW/m^2 for a duration of 6.3 seconds.

Table 3-30: Test 1-31 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-31	4.5	6.3	0.99	0.05	131.47	127.54	TS

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-22-21

3.31.1. Profile/Energy

Figure 3-148 and Figure 3-149 show the heat flux profile and total energy for which the cable target was exposed. As shown, the profile is fairly accurate compared to the planned profile. The cable target was exposed to a total of approximately 37 MJ/m^2.

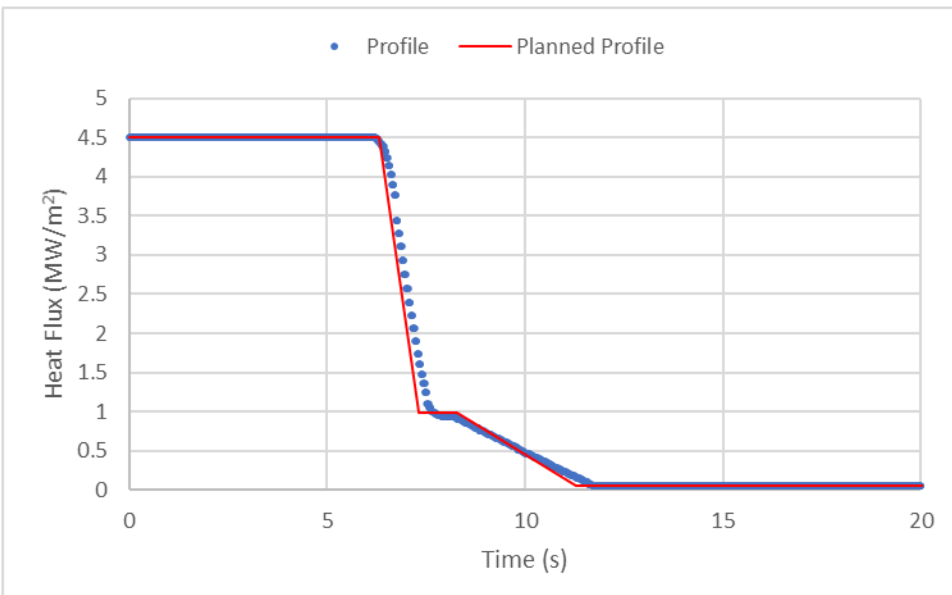


Figure 3-148: Test 1-31 Heat Flux Profile

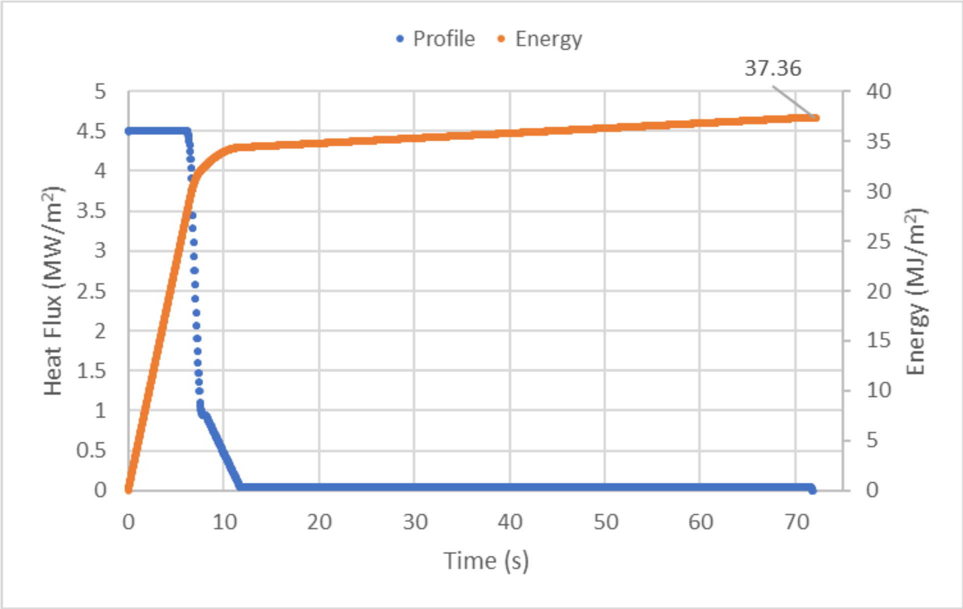


Figure 3-149: Test 1-31 Total Energy

3.31.2. *Electrical/Thermal Monitoring*

Figure 3-150 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

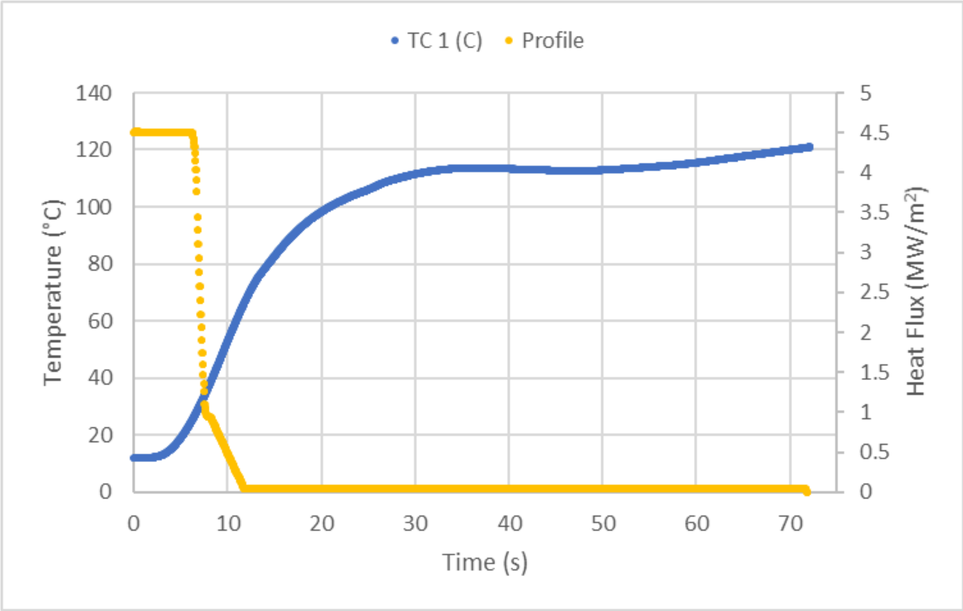


Figure 3-150: Test 1-31 Thermal Monitoring

3.31.3. Photos

Figure 3-151 and Figure 3-152 show the target cable after the exposure profile. As shown, surface damage to the jacket is present. However, the insulated wires were not exposed during this test. Note, that pinholes are formed in the center cable (as shown in Figure 3-152), which indicates that insulation exposure is imminent.

Figure 3-151: Test 1-31 Post-test Photo (1)

Figure 3-152: Test 1-31 Post-test Photo (2)

3.31.4. Ignition

The video for this test is not available for processing. Therefore, no ignition data is available. An assumed shutter delay of 0.36 seconds (the average delay from all available test videos) was applied to this test. This delay is reflected in all figures in this section and the total energy calculation.

3.32. Test 1-32

Test 1-32 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 6 seconds.

Table 3-31: Test 1-32 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-32	3	6	0.66	0.05	110.17	106.94	TP

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-23-21

3.32.1. *Profile/Energy*

Figure 3-153 and Figure 3-154 show the heat flux profile and total energy for which the cable target was exposed. The profile is fairly accurate. The cable target was exposed to a total of approximately 24 MJ/m^2.

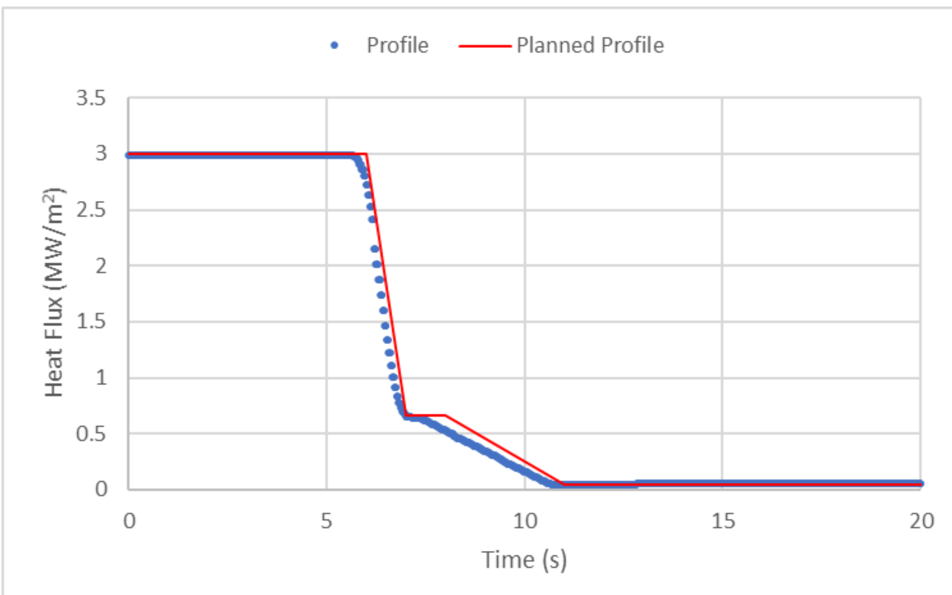


Figure 3-153: Test 1-32 Heat Flux Profile

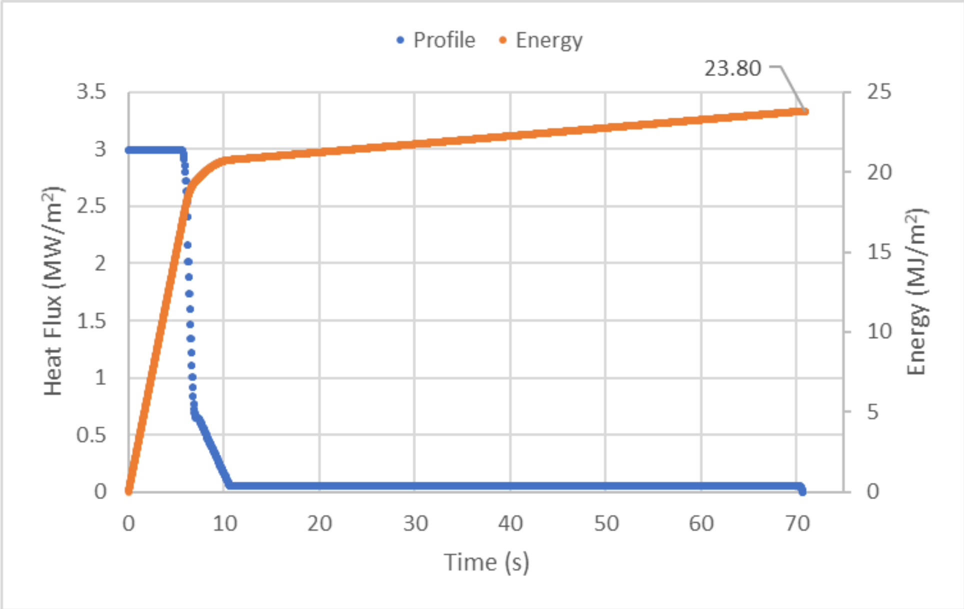


Figure 3-154: Test 1-32 Total Energy

3.32.2. Electrical/Thermal Monitoring

Figure 3-155 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

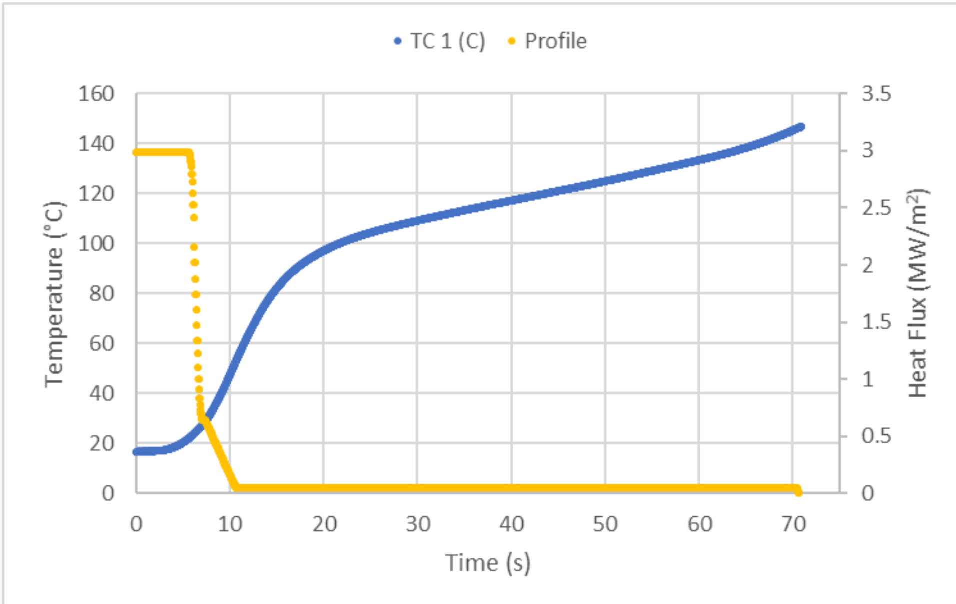


Figure 3-155: Test 1-32 Thermal Monitoring

3.32.3. Photos

Figure 3-156 and Figure 3-157 show the target cable after the exposure profile. As shown, the sub-jacket metallic shielding was exposed during this test.

Figure 3-156: Test 1-31 Post-test Photo (1)

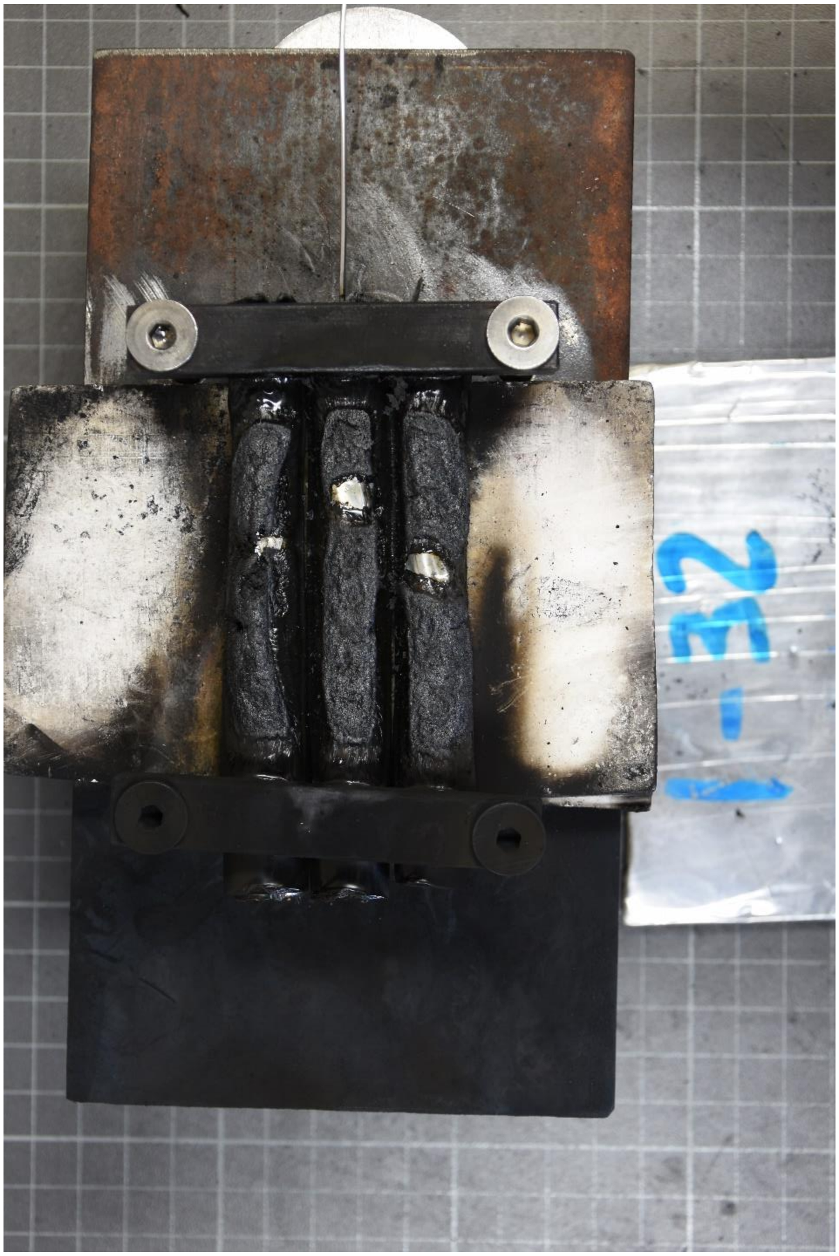


Figure 3-157: Test 1-32 Post-test Photo (2)

3.32.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 11.03 seconds after the shutter was fully open. Figure 3-158 shows the time at which the ignition extinguished as a function of total energy and heat flux.

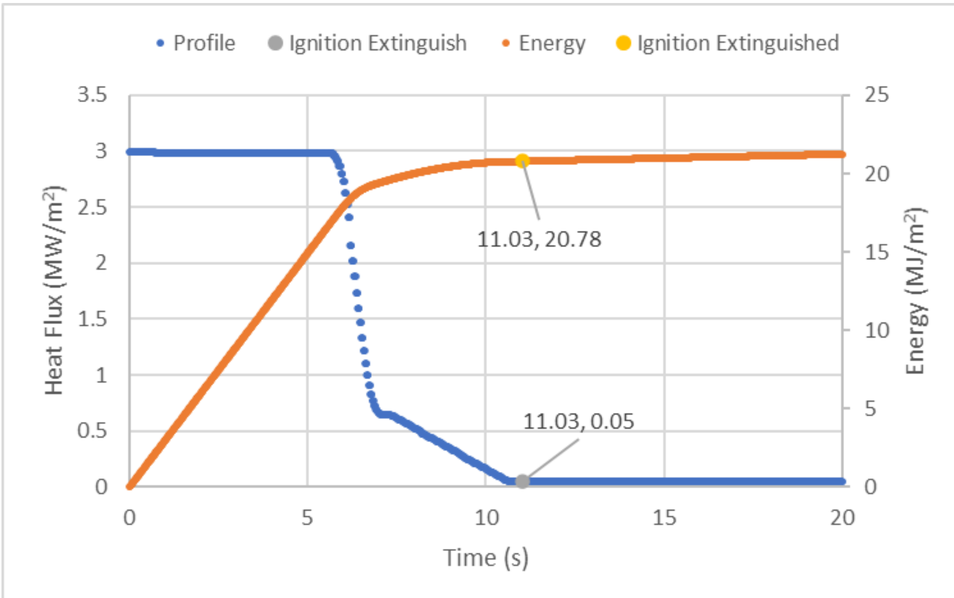


Figure 3-158: Test 1-32 Sustained Ignition as a Function of Heat Flux and Time

3.33. Test 1-33

Test 1-33 evaluated a thermoplastic cable with a primary flux of 3 MW/m^2 for a duration of 4 seconds.

Table 3-32: Test 1-33 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-33	3	4	0.66	0.05	110.48	108.1	TP

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-23-21

3.33.1. *Profile/Energy*

Figure 3-159 and Figure 3-160 show the heat flux profile and total energy for which the cable target was exposed. As shown, the actual heat flux magnitude applied to the cable is lower than 3 MW/m^2 (see Appendix C for the calibration curve). The cable target was exposed to a total of approximately 17 MJ/m^2.

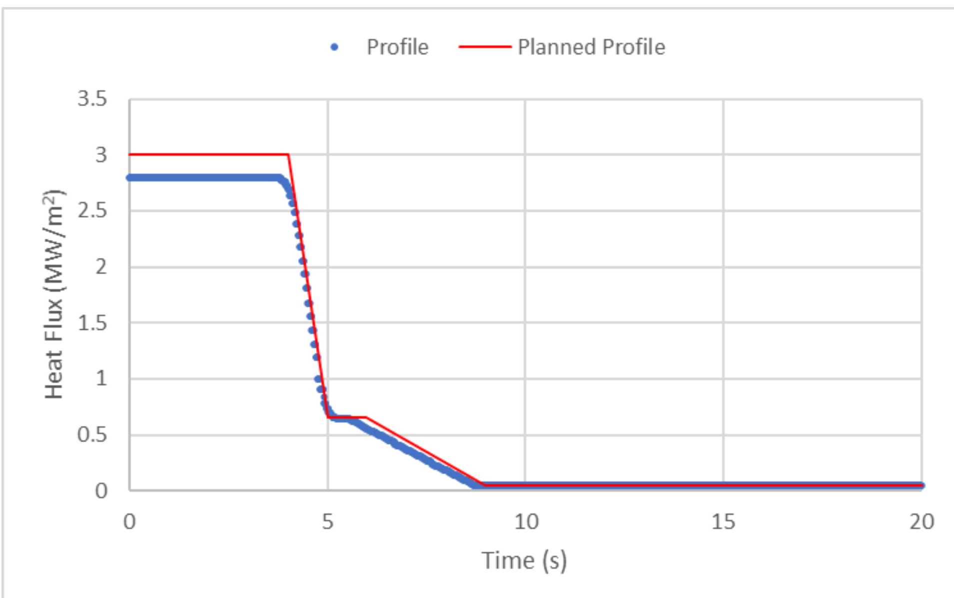


Figure 3-159: Test 1-33 Heat Flux Profile

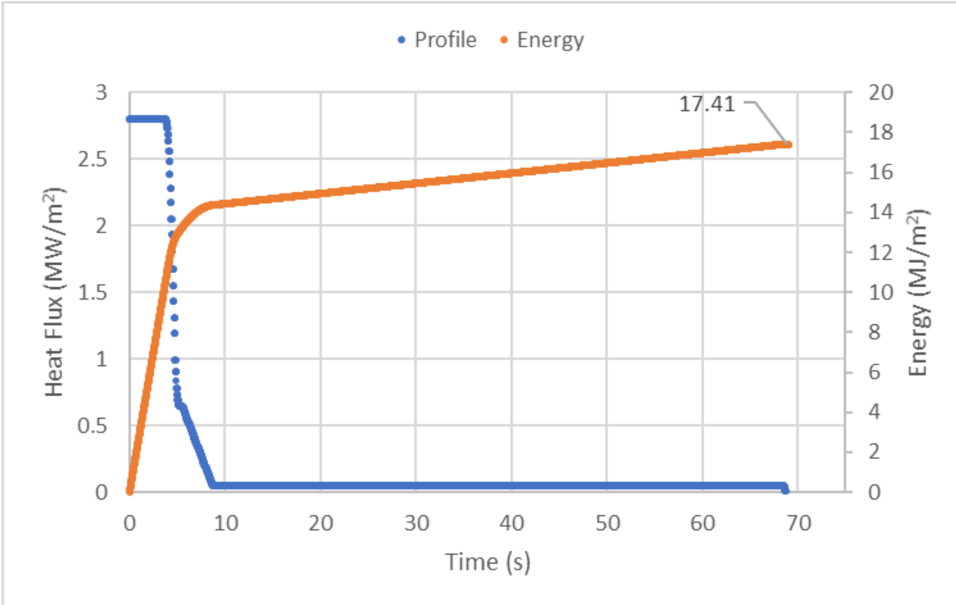


Figure 3-160: Test 1-33 Total Energy

3.33.2. *Electrical/Thermal Monitoring*

Figure 3-161 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

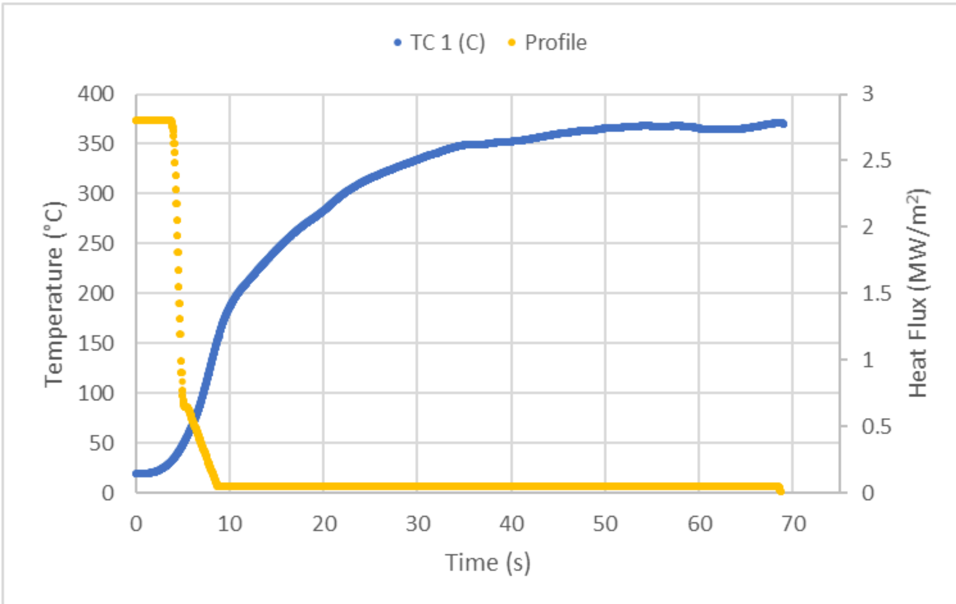


Figure 3-161: Test 1-33 Thermal Monitoring

3.33.3. Photos

Figure 3-162 and Figure 3-163 show the target cable after the exposure profile. As shown, the sub-jacket metallic shielding was exposed during this test.

Figure 3-162: Test 1-33 Post-test Photo (1)

Figure 3-163: Test 1-33 Post-test Photo (2)

3.33.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 8.43 seconds after the shutter was fully open. Figure 3-164 shows the time at which the ignition extinguished as a function of total energy and heat flux.

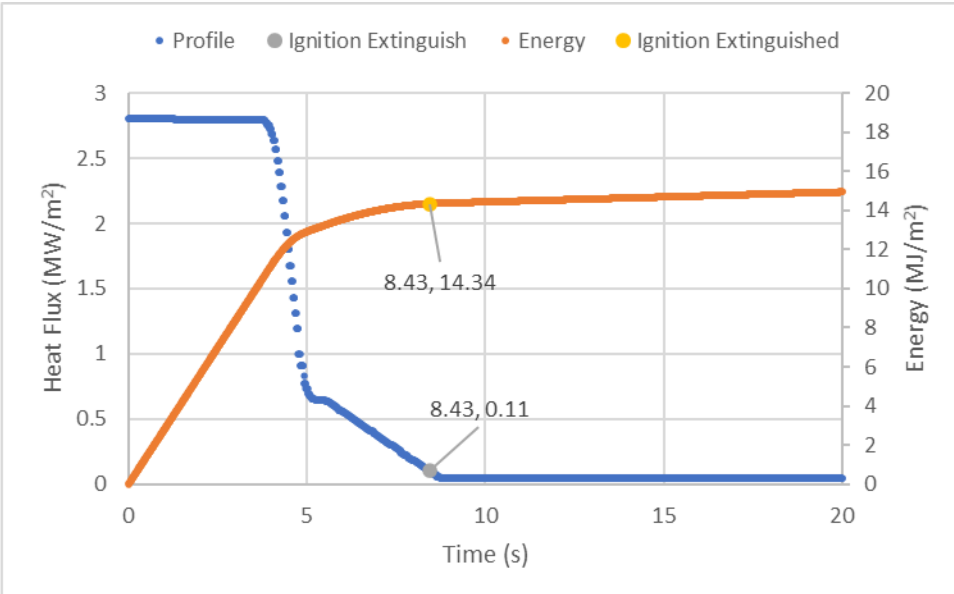


Figure 3-164: Test 1-33 Sustained Ignition as a Function of Heat Flux and Time

3.34. Test 1-34

Test 1-34 evaluated a thermoplastic cable with a primary flux of 4.5 MW/m² for a duration of 2.5 seconds.

Table 3-33: Test 1-34 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-34	4.5	2.5	0.99	0.05	112.216	110.14	TP

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-24-21

3.34.1. *Profile/Energy*

Figure 3-165 and Figure 3-166 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. The cable target was exposed to a total of approximately 25 MJ/m².

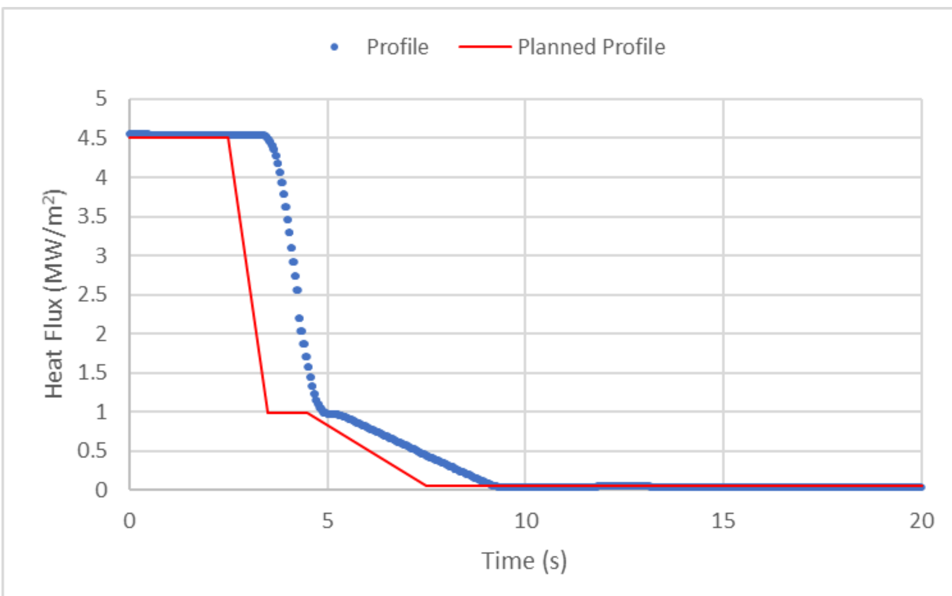


Figure 3-165: Test 1-34 Heat Flux Profile

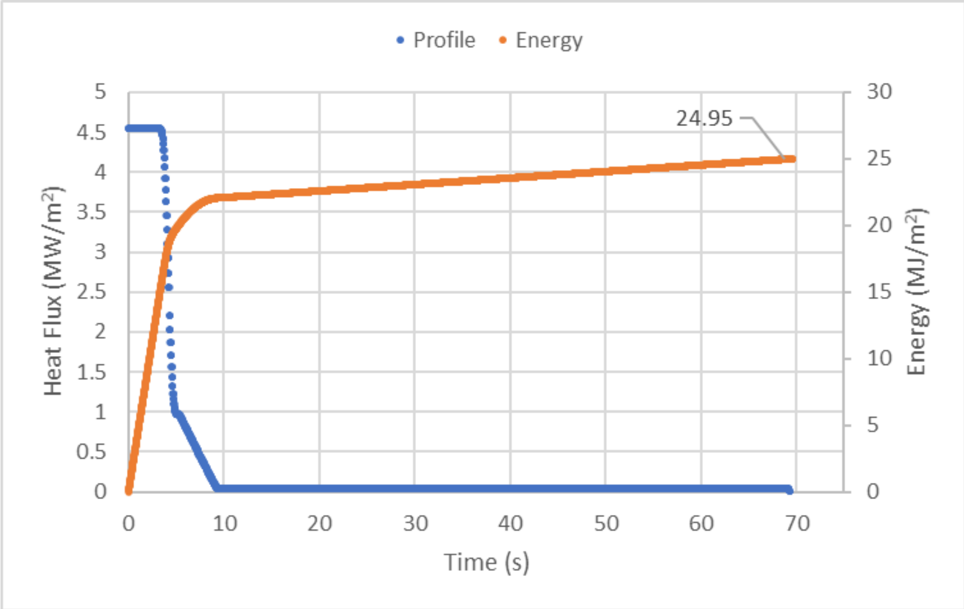


Figure 3-166: Test 1-34 Total Energy

3.34.2. *Electrical/Thermal Monitoring*

Figure 3-167 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

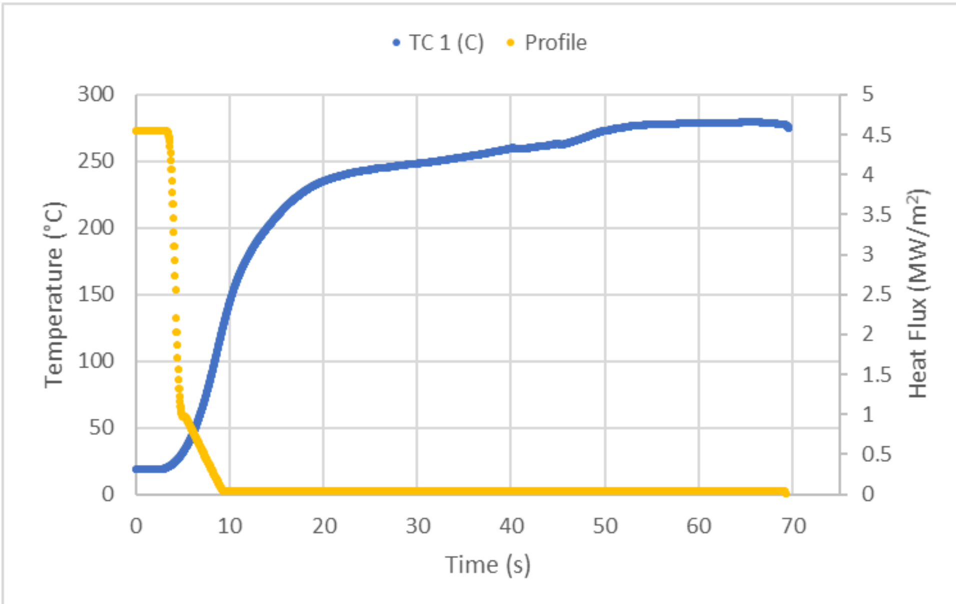


Figure 3-167: Test 1-34 Thermal Monitoring

3.34.3. Photos

Figure 3-168 and Figure 3-169 show the target cable after the exposure profile. As shown, the sub-jacket metallic shielding was exposed during this test.

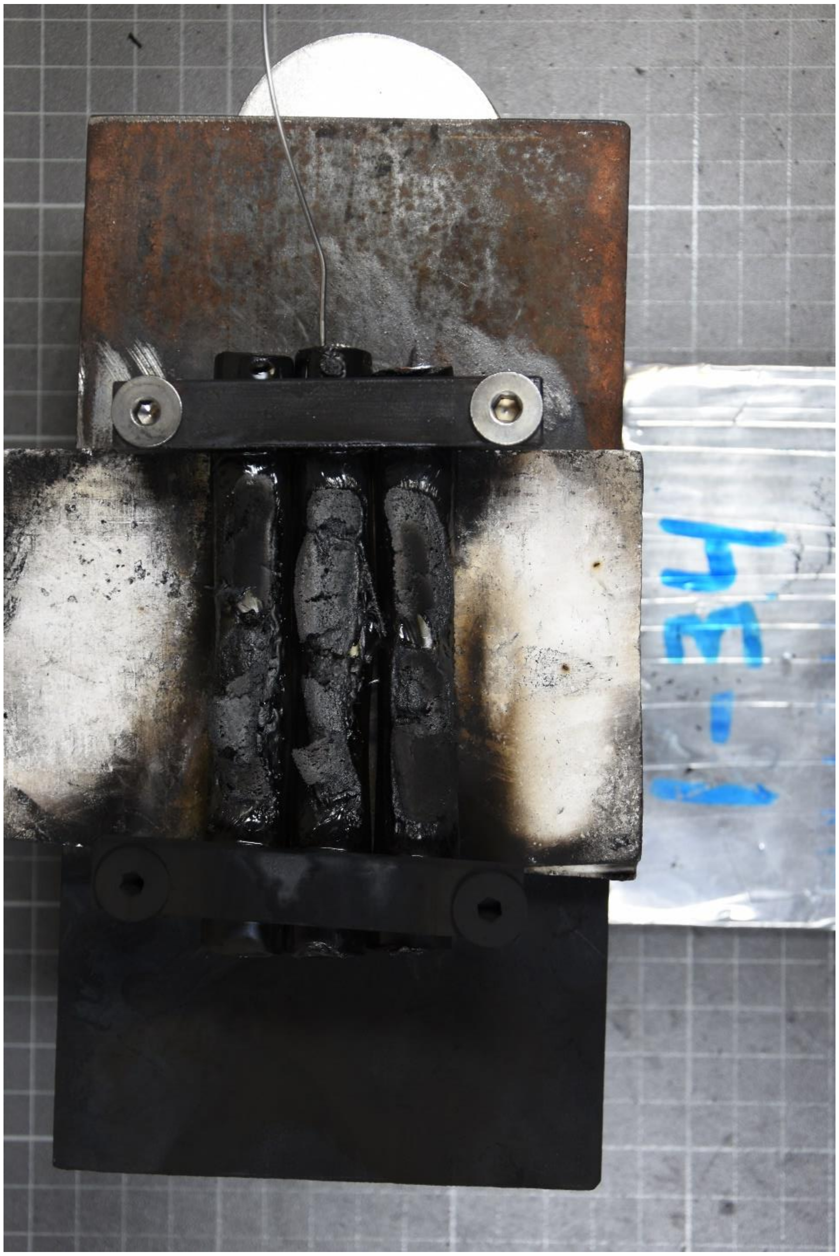


Figure 3-168: Test 1-34 Post-test Photo (1)

Figure 3-169: Test 1-34 Post-test Photo (2)

3.34.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 7.50 seconds after the shutter was fully open. Figure 3-170 shows the time at which the ignition extinguished as a function of total energy and heat flux.

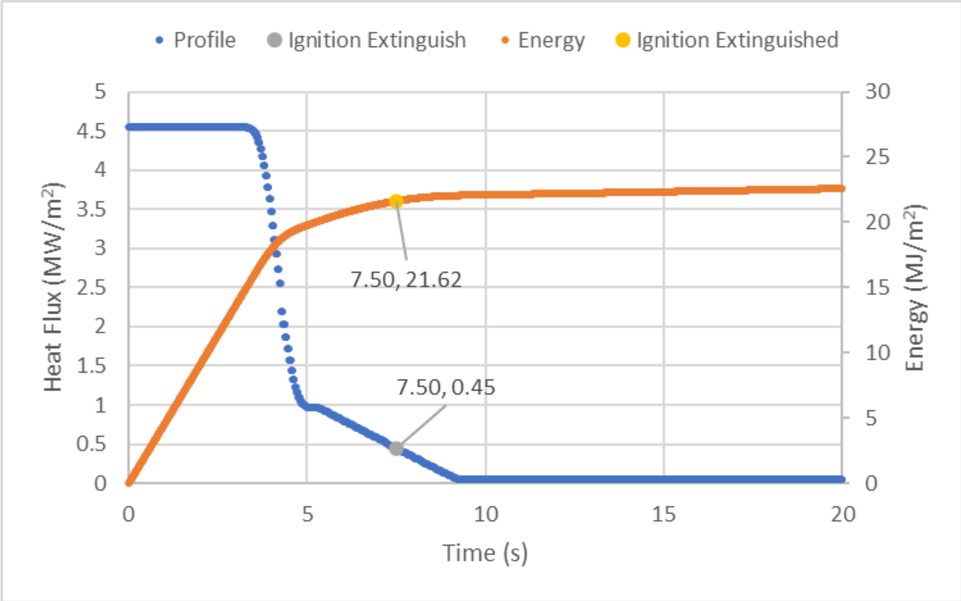


Figure 3-170: Test 1-34 Sustained Ignition as a Function of Heat Flux and Time

3.35. Test 1-35

Test 1-35 evaluated a thermoplastic cable with a primary flux of 2 MW/m^2 for a duration of 7 seconds.

Table 3-34: Test 1-35 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-35	2	7	0.44	0.05	112.68	109.74	TP

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-24-21

3.35.1. Profile/Energy

Figure 3-171 and Figure 3-172 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. Also, the transition flux was input into the control system incorrectly, so the actual dynamic profile shape differs slightly from the planned profile. The cable target was exposed to a total of approximately 21 MJ/m^2.

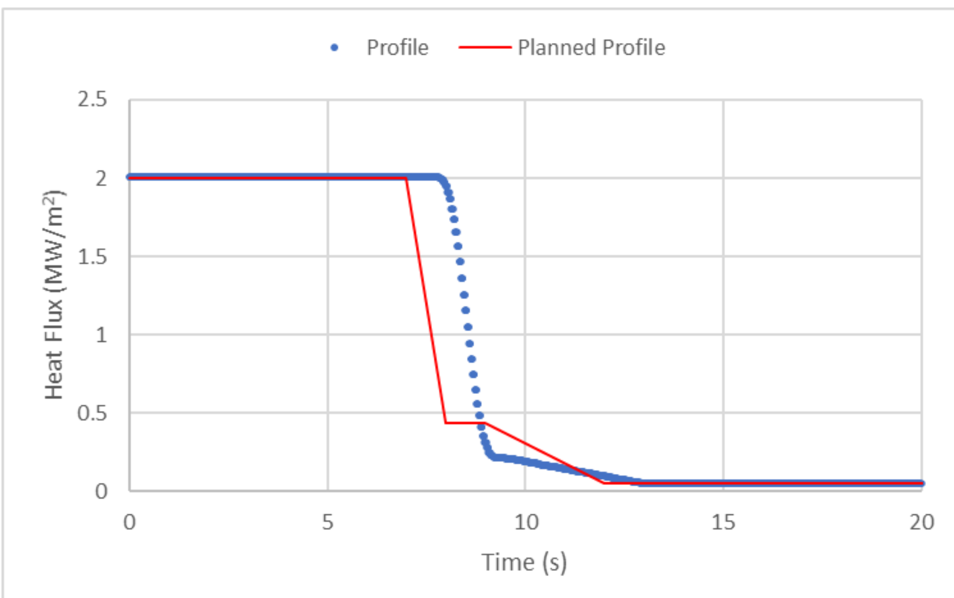


Figure 3-171: Test 1-35 Heat Flux Profile

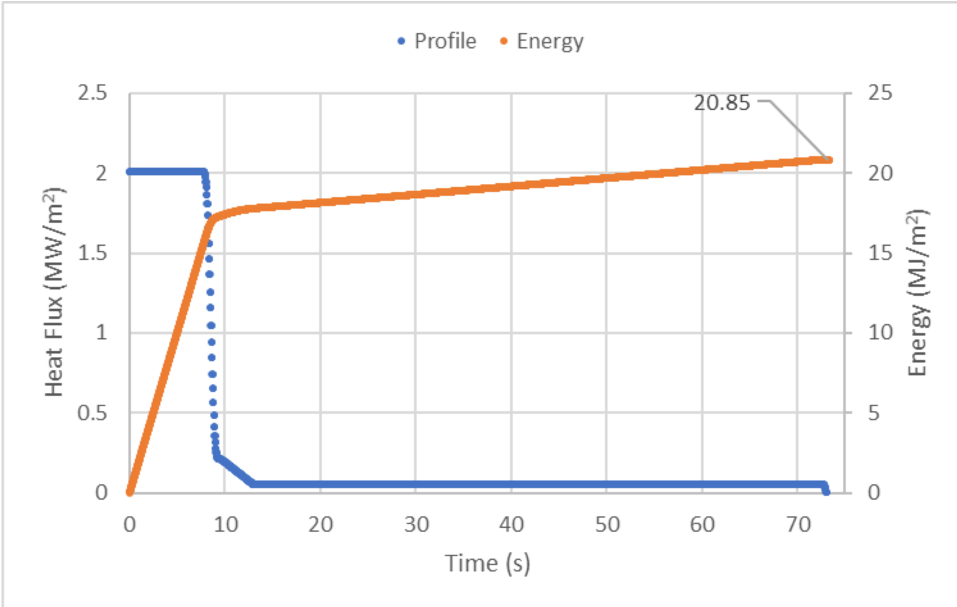


Figure 3-172: Test 1-35 Total Energy

3.35.2. Electrical/Thermal Monitoring

Figure 3-173 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

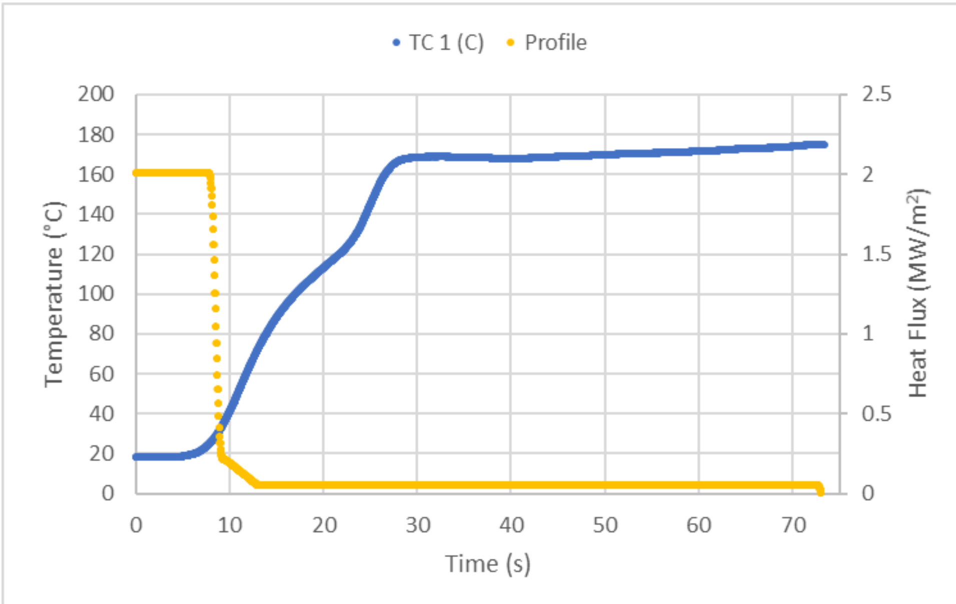


Figure 3-173: Test 1-35 Thermal Monitoring

3.35.3. Photos

Figure 3-174 and Figure 3-175 show the target cable after the exposure profile. As shown, the sub-jacket metallic shielding was exposed during this test.

Figure 3-174: Test 1-35 Post-test Photo (1)

Figure 3-175: Test 1-35 Post-test Photo (2)

3.35.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.27 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 10.56 seconds after the shutter was fully open. Figure 3-176 shows the time at which the ignition extinguished as a function of total energy and heat flux.

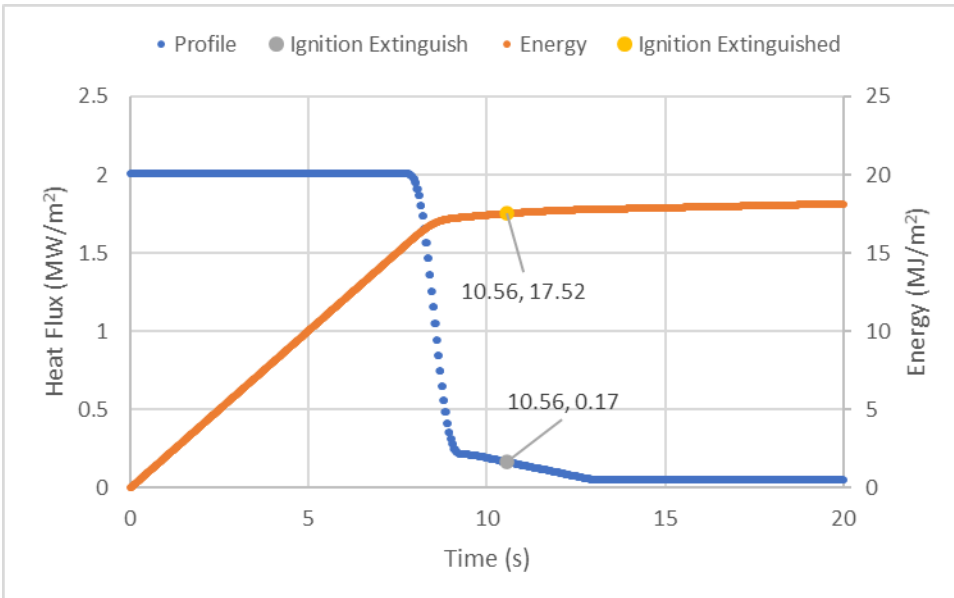


Figure 3-176: Test 1-35 Sustained Ignition as a Function of Heat Flux and Time

3.36. Test 1-36

Test 1-36 evaluated a thermoset cable with a primary flux of 2 MW/m^2 for a duration of 15.5 seconds.

Table 3-35: Test 1-36 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-36	2	15.5	0.44	0.05	130.67	125.23	TS

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-24-21

3.36.1. Profile/Energy

Figure 3-177 and Figure 3-178 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. Also, the transition flux was input into the control system incorrectly, so the actual dynamic profile shape differs slightly from the planned profile. The cable target was exposed to a total of approximately 36 MJ/m^2.

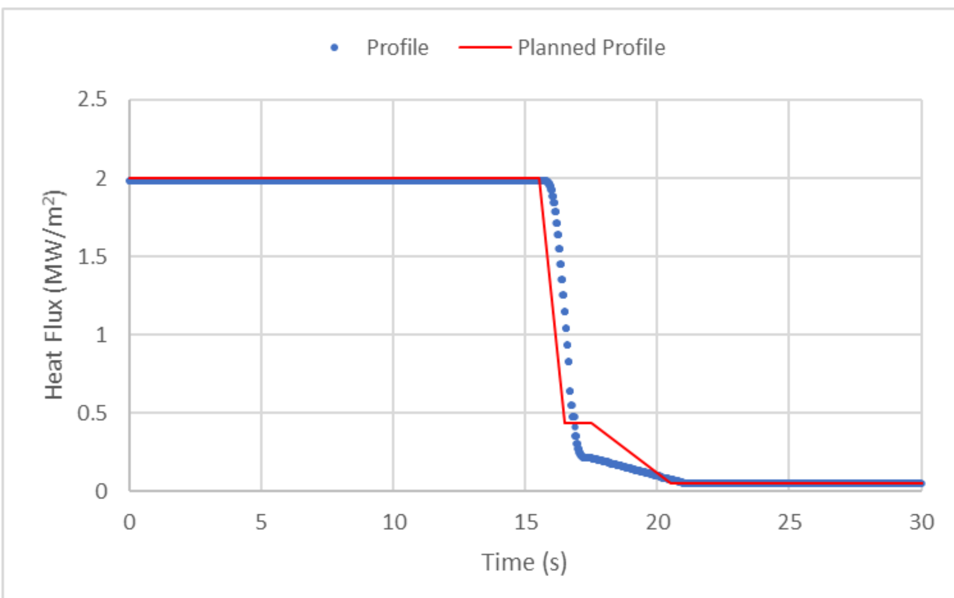


Figure 3-177: Test 1-36 Heat Flux Profile

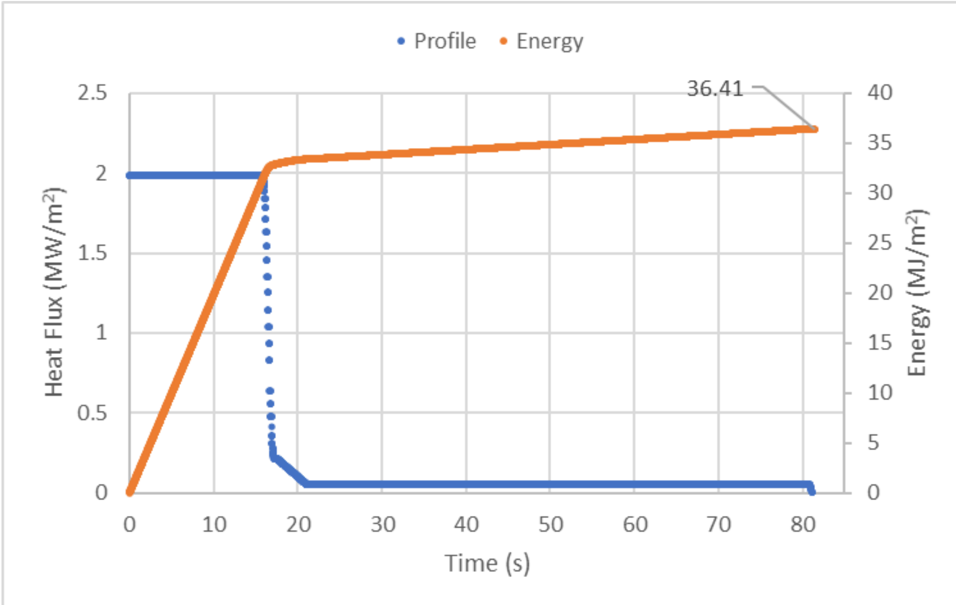


Figure 3-178: Test 1-36 Total Energy

3.36.2. Electrical/Thermal Monitoring

Figure 3-179 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

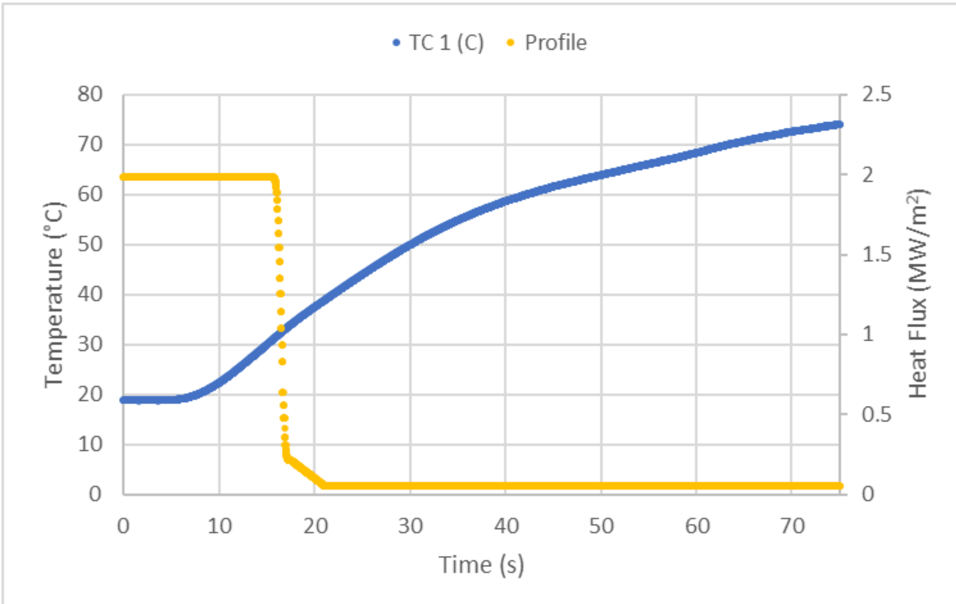


Figure 3-179: Test 1-36 Thermal Monitoring

3.36.3. Photos

Figure 3-180, Figure 3-181, and Figure 3-182 show the target cable after the exposure profile. As shown, deep pinholes formed in the center and left cable targets. Although not visible in these photos, the insulated wires could be seen through the pinhole in the center cable.

Figure 3-180: Test 1-36 Post-test Photo (1)

Figure 3-181: Test 1-36 Post-test Photo (2)

Figure 3-182: Test 1-36 Post-test Photo (3)

3.36.4. *Ignition*

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 19.63 seconds after the shutter was fully open. Figure 3-183 shows the time at which the ignition extinguished as a function of total energy and heat flux.

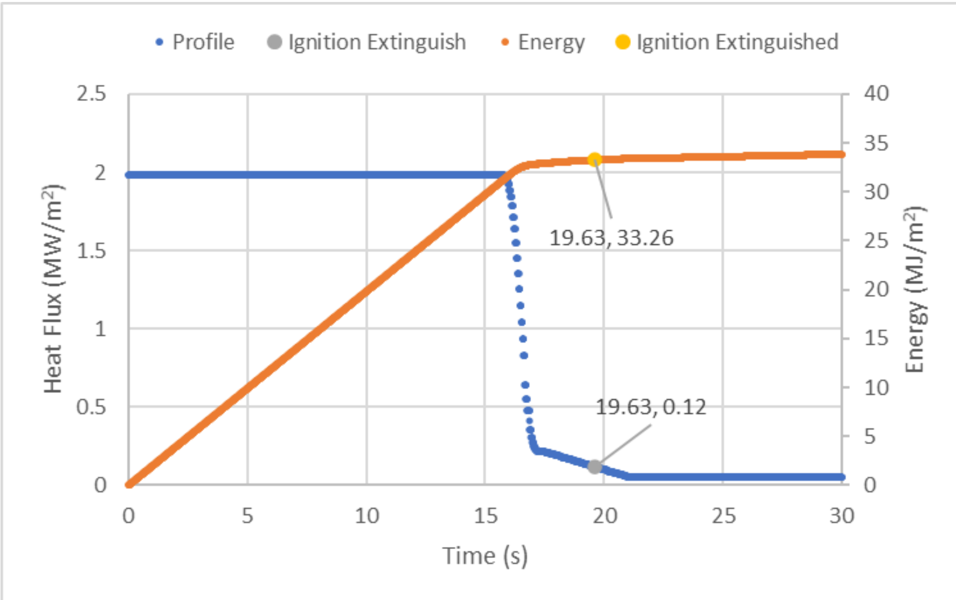


Figure 3-183: Test 1-36 Sustained Ignition as a Function of Heat Flux and Time

3.37. Test 1-37

Test 1-37 evaluated a thermoset cable with a primary flux of 3 MW/m^2 for a duration of 10 seconds.

Table 3-36: Test 1-37 Test Summary Data

Test Number	Q0 (MW/m^2)	T0 (s)	Q1 (MW/m^2)	Q2 (MW/m^2)	Pre-weight (g)	Post-weight (g)	Cable Type
1-37	3	10	0.66	0.05	132.81	128.06	TS

- Purpose: Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-24-21

3.37.1. *Profile/Energy*

Figure 3-184 and Figure 3-185 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. The cable target was exposed to a total of approximately 39 MJ/m^2.

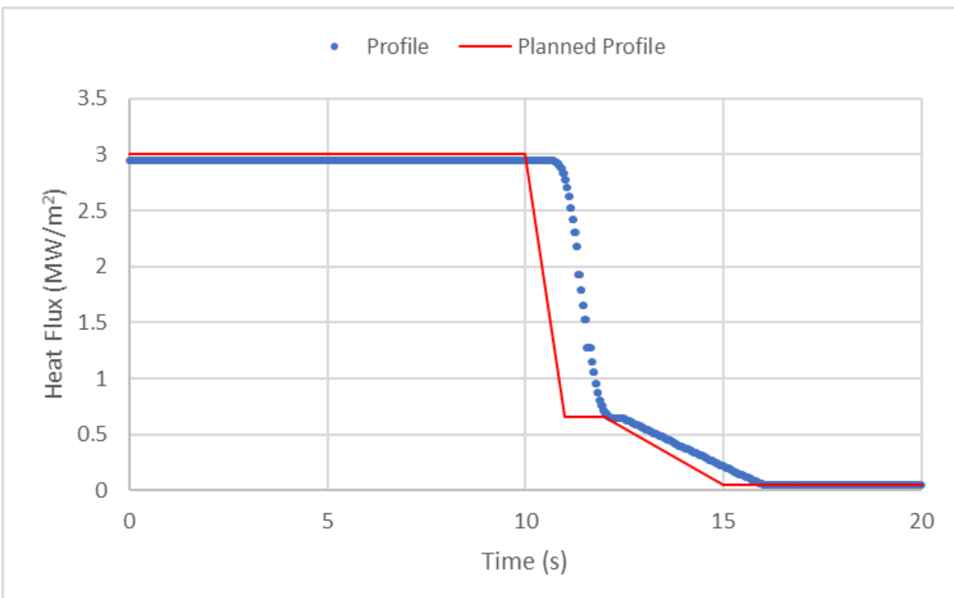


Figure 3-184: Test 1-37 Heat Flux Profile

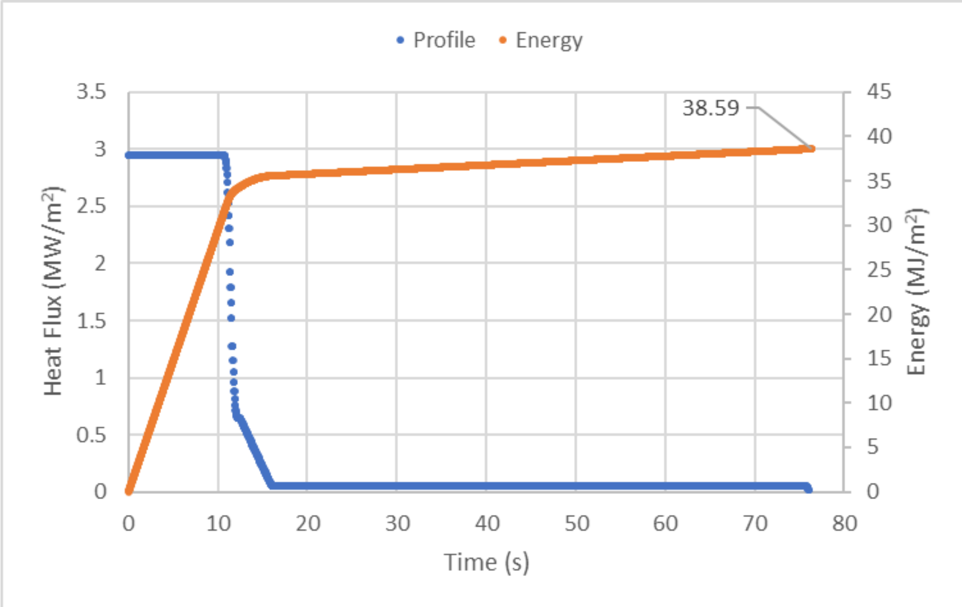


Figure 3-185: Test 1-37 Total Energy

3.37.2. Electrical/Thermal Monitoring

Figure 3-186 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

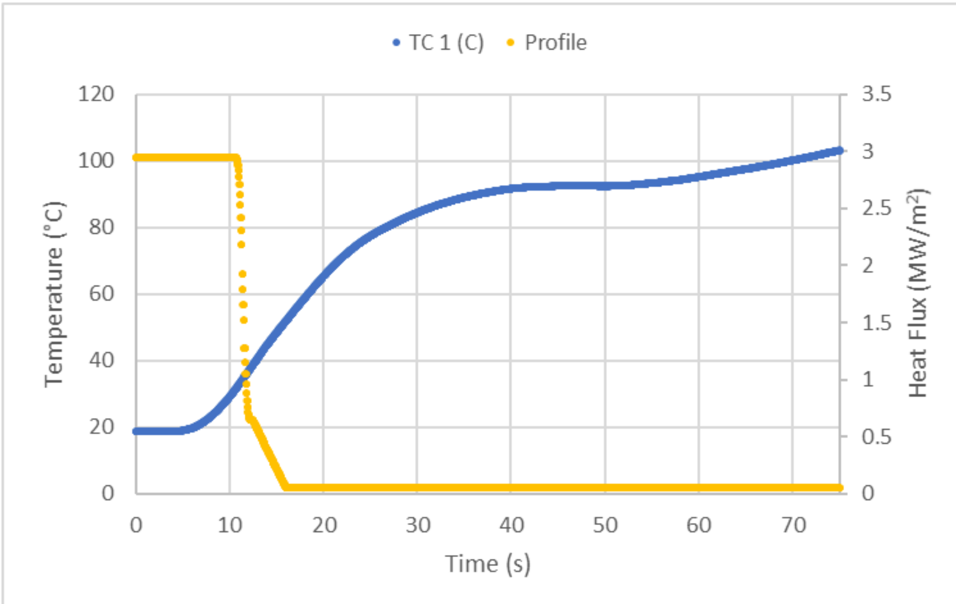


Figure 3-186: Test 1-37 Thermal Monitoring

3.37.3. Photos

Figure 3-187, Figure 3-188, and Figure 3-189 show the target cable after the exposure profile. As shown, the insulated wires under the jacket were exposed during this test.

Figure 3-187: Test 1-37 Post-test Photo (1)

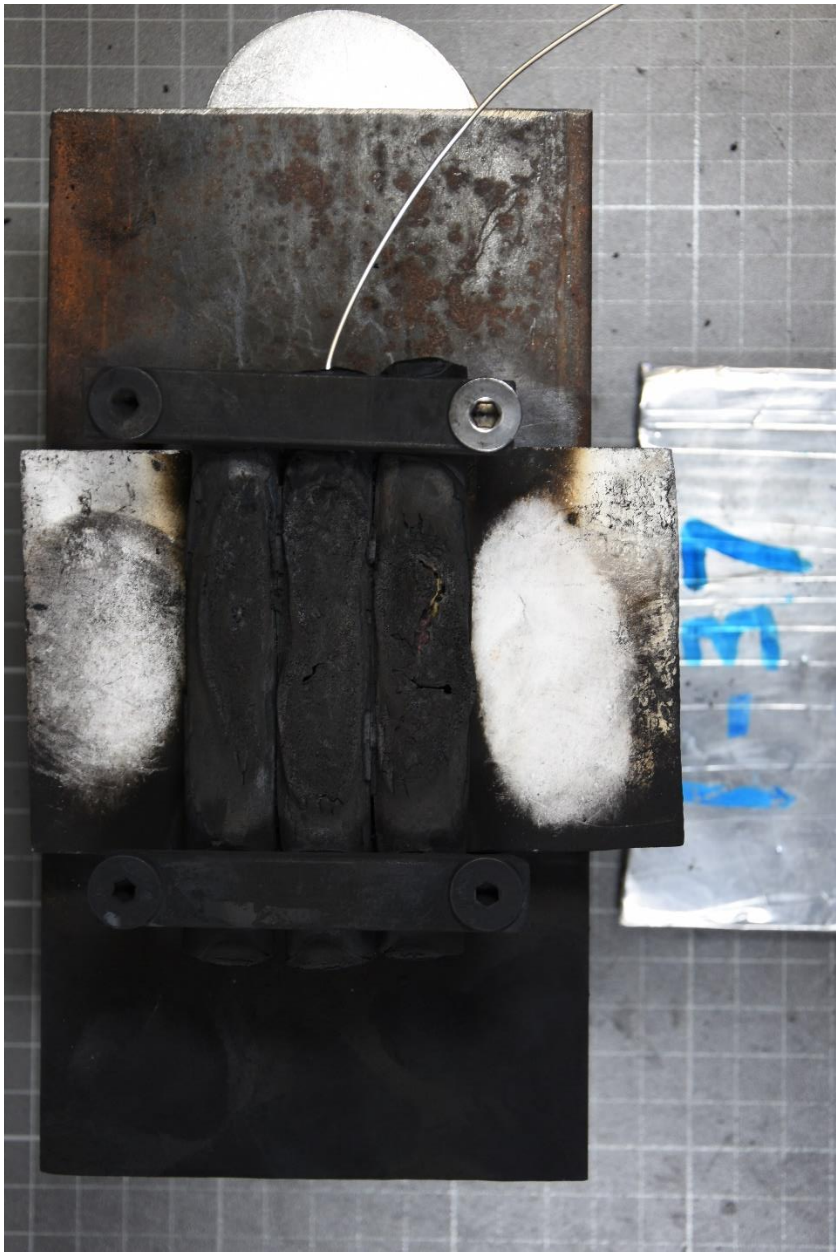


Figure 3-188: Test 1-37 Post-test Photo (2)

Figure 3-189: Test 1-37 Post-test Photo (3)

3.37.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 15.37 seconds after the shutter was fully open. Figure 3-190 shows the time at which the ignition extinguished as a function of total energy and heat flux.

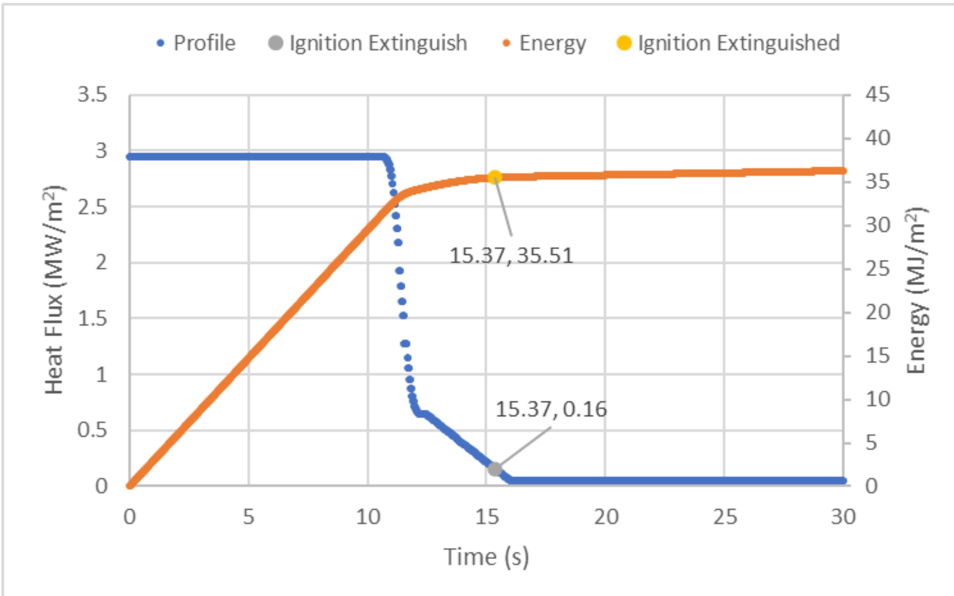


Figure 3-190: Test 1-37 Sustained Ignition as a Function of Heat Flux and Time

3.38. Test 1-38

Test 1-38 evaluated a thermoplastic cable with a primary flux of 3 MW/m² for a duration of 4 seconds.

Table 3-37: Test 1-38 Test Summary Data

Test Number	Q0 (MW/m²)	T0 (s)	Q1 (MW/m²)	Q2 (MW/m²)	Pre-weight (g)	Post-weight (g)	Cable Type
1-38	3	4	0.66	0.05	111.64	109.26	TP

- Purpose; Examine damage threshold as a function of total energy with dynamic flux profile.
- Target: 3 cable bundle, approximately 10 cm samples
- Test Date: 2-24-21

3.38.1. Profile/Energy

Figure 3-191 and Figure 3-192 show the heat flux profile and total energy for which the cable target was exposed. As shown, the heat flux remained at the primary magnitude slightly longer than planned, which resulted in additional energy delivered to the cable. The cable target was exposed to a total of approximately 21 MJ/m².

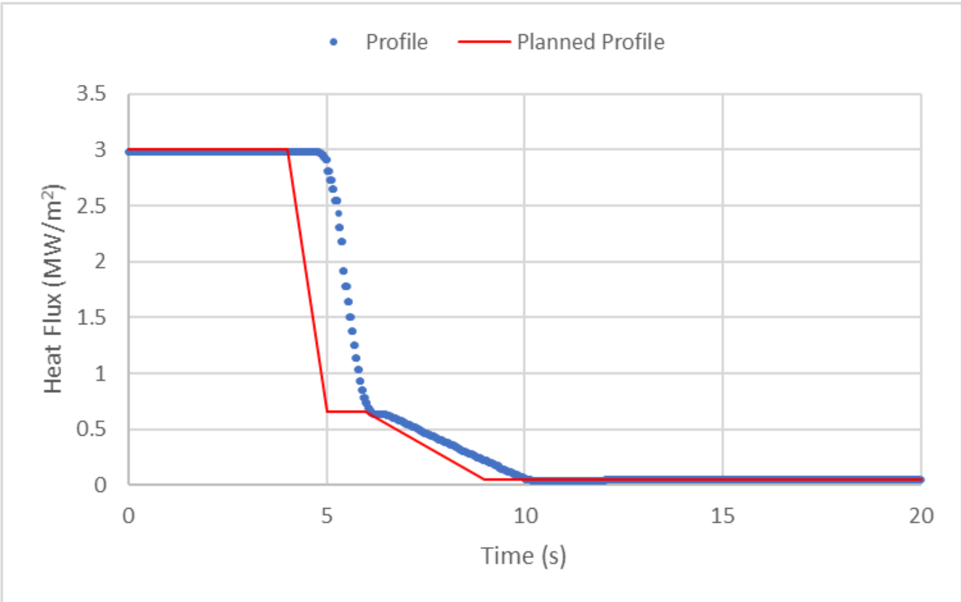


Figure 3-191: Test 1-38 Heat Flux Profile

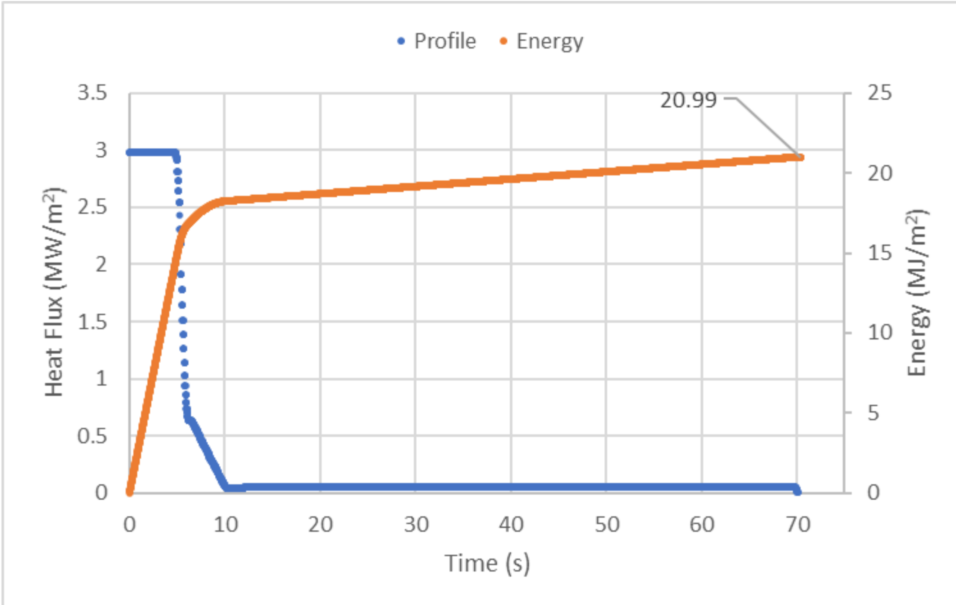


Figure 3-192: Test 1-38 Total Energy

3.38.2. Electrical/Thermal Monitoring

Figure 3-193 shows the thermal monitoring results from the test. A single thermocouple was placed under the jacket of the center cable to monitor the sub-jacket temperature. Note, that this TC was directly in the bottom end of the cable sample, so no slit in the jacket was necessary.

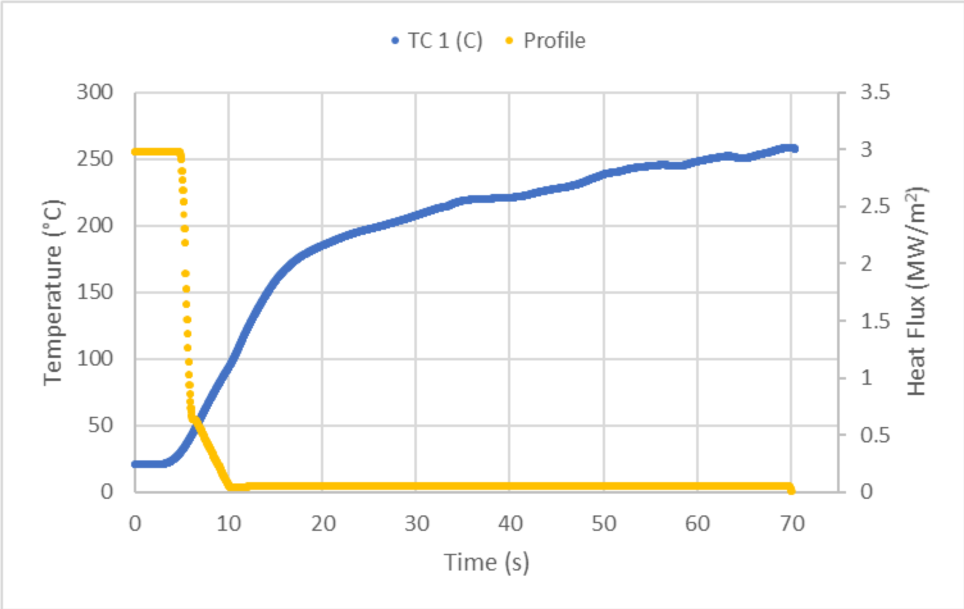


Figure 3-193: Test 1-38 Thermal Monitoring

3.38.3. Photos

Figure 3-194 and Figure 3-195 show the target cable after the exposure profile. As shown, the sub-jacket metallic shielding was exposed during this test.

Figure 3-194: Test 1-38 Post-test Photo (1)

Figure 3-195: Test 1-38 Post-test Photo (2)

3.38.4. Ignition

The video was reviewed to determine the time at which pyrolysis, ignition, and extinguishment occurred during this test. Ignition and pyrolysis happened essentially immediately, prior to the shutters being fully open. The shutters were fully open at 0.30 seconds. This delay is reflected in all figures in this section and the total energy calculation. The ignition extinguished at 8.37 seconds after the shutter was fully open. Figure 3-196 shows the time at which the ignition extinguished as a function of total energy and heat flux.

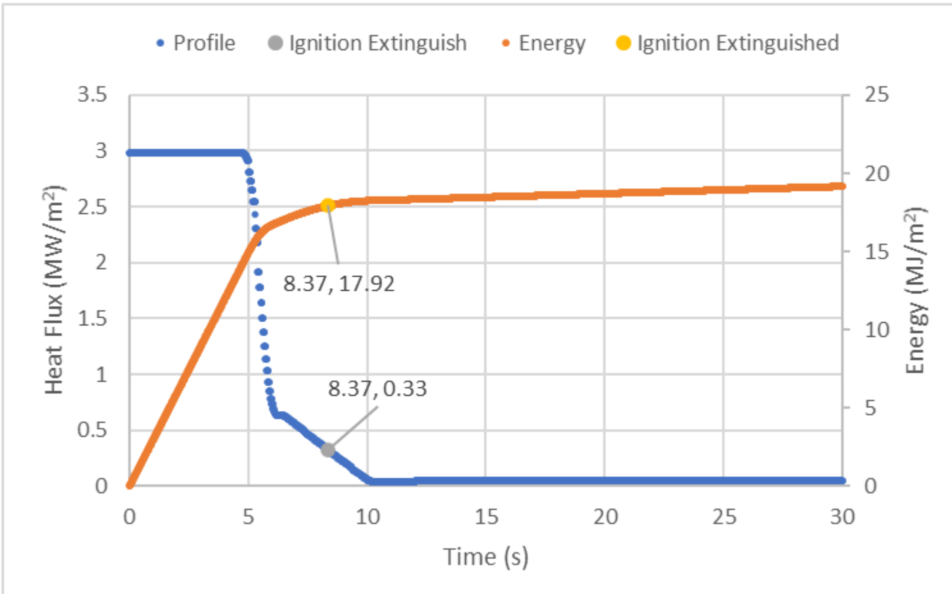


Figure 3-196: Test 1-38 Sustained Ignition as a Function of Heat Flux and Time

4. SUMMARY AND CONCLUSIONS

The Phase 1 test program evaluated the cable target fragility when exposed to a HEAF environment. Several different failure modes were evaluated, including ignition, damage as a function of total energy, electrical failure of cables, and sub-jacket temperature. Initially, this test program was meant to investigate the parameters that lead to sustained ignition of the cable target. However, after the initial several tests, it was apparent that reliable and repeatable data for sustained ignition could not be gathered through these tests at the small scale. Therefore, additional failure modes were probed. Investigation of electrical failure of the cables demonstrated that this failure mode is not likely at the HEAF timescale. Additionally, the traditional failure mode of sub-jacket temperature limit was not an appropriate metric because the physics of heat conduction through a cable jacket were not relevant to the high heat flux/low duration conditions. However, the damage done to the jacket as a function of total energy was a reliable metric in which test data was gathered during the Phase 1 tests. This metric seemed to have reasonably repeatable data for tests conducted with similar total energy but different rates of application.

Table 4-1 summarizes the results from every test in Phase 1. Note, the nominal (planned) values for primary flux and duration are listed. These values differ slightly from the actual values for each test. The actual profile values are shown in detail in the respective test sections.

Table 4-1: Results Summary from Phase 1 Tests

Test Number	Primary Flux (MW/m^2)	Primary Duration (s)	Profile	Weight-loss (g)	Cable Type	Instrumentation	Total Energy (MJ/m^2)	Damage
1-01	3	2	Dynamic	0.6	TS	Electrical	N/A	N/A
1-02	3	2	Dynamic	1.77	TS	Electrical	14	Jacket damage
1-03	3	10	Dynamic	3.3	TS	Electrical	37	Insulation exposure
1-05	3	2	Dynamic	1.58	TP	Electrical	14	Jacket damage
1-06	3	10	Dynamic	3.22	TP	Electrical	40	Wire exposure
1-07	3	4	Long Ramp	2.34	TP	Electrical	24	Insulation exposure
1-08	1	RTF*	Simple	13.24	TP	Electrical	144	Wire exposure
1-09	1	RTF*	Simple	15.13	TP	Thermal	206	Wire exposure
1-10	1	RTF*	Simple	17.68	TS	Electrical	202	Wire exposure
1-11	1	RTF*	Simple	21.18	TS	Thermal	208	Wire exposure
1-12	4	RTF*	Simple	44.23	TS	Electrical	790	Wire separation
1-13	4	RTF*	Simple	23.96	TS	Thermal	487	Wire separation
1-14	4	RTF*	Simple	29.01	TP	Electrical	492	Wire separation
1-15	4	RTF*	Simple	30.67	TP	Thermal	502	Wire separation
1-16	2	RTF*	Simple	23.27	TS	Electrical	300	Wire exposure
1-17	0.05	RTF*	Simple	2.05	TS	Thermal	33	Insulation exposure
1-18	0.05	RTF*	Simple	1.74	TP	Electrical	89	Insulation exposure
1-19	0.05	RTF*	Simple	1.49	TP	Thermal	52	Jacket damage
1-20	0.05	RTF*	Simple	3.49	TS	Electrical	85	Insulation exposure
1-21	3	25	Simple	5.94	TS	Thermal	82	Insulation exposure
1-22	3	2	Simple	0.99	TP	Thermal	7	Jacket damage
1-23	3	2	Simple	0.59	TS	Thermal	7	Jacket damage
1-24	4.6	2	Simple	1.64	TP	Thermal	15	Jacket damage
1-25	4.6	2	Simple	1.16	TS	Thermal	15	Jacket damage
1-26	6	4	Simple	3.68	TP	Thermal	36	Insulation exposure
1-27	6	4	Simple	2.97	TS	Thermal	38	Jacket damage

Test Number	Primary Flux (MW/m^2)	Primary Duration (s)	Profile	Weight-loss (g)	Cable Type	Instrumentation	Total Energy (MJ/m^2)	Damage
1-28	6	8	Simple	4.95	TS	Thermal	63	Insulation exposure imminent
1-29	3	8	Dynamic	4.18	TS	Thermal	32	Jacket damage
1-30	3	10	Dynamic	4.33	TS	Thermal	35	Insulation exposure
1-31	4.5	6.3	Dynamic	3.93	TS	Thermal	37	Insulation exposure imminent
1-32	3	6	Dynamic	3.23	TP	Thermal	24	Insulation exposure
1-33	3	4	Dynamic	2.38	TP	Thermal	17	Insulation exposure
1-34	4.5	2.5	Dynamic	2.076	TP	Thermal	25	Insulation exposure
1-35	2	7	Dynamic	2.94	TP	Thermal	21	Insulation exposure
1-36	2	15.5	Dynamic	5.44	TS	Thermal	36	Insulation exposure
1-37	3	10	Dynamic	4.75	TS	Thermal	39	Insulation exposure
1-38	3	4	Dynamic	2.38	TP	Thermal	21	Insulation exposure

*RTF: Run to Failure

REFERENCES

[1] S. Martin, "Diffusion-controlled ignition of cellulosic materials by intense radiant energy," vol. 10, no. 1, January 1965.

[2] J. Engerer, A. Brown and J. Christian, "Ignition and Damage Thresholds of Materials at Extreme Incident Radiative Heat Flux," Atlanta, Georgia, June 2018.

[3] NUREG/CR-7244, "Response of Nuclear Power Plant Instrumentation Cables Exposed to Fire Conditions".

[4] NUREG/CR-6931, Vol. 1, "Cable Response to Live Fire (CAROLFIRE) Volume 1: Test Descriptions and Analysis of Circuit Response Data," January 2008.

[5] S. Nowloen and J. Brown, "Kerite Analysis in Thermal Environment of FIRE (KATE-Fire): Test Results," 2011.

APPENDIX A. LUMPED CABLE CORE IGNITION ANALYSIS

This appendix derives the semi-empirical model for the ignition of a large-diameter wire or cable. Begin with the following assumptions:

1- Heated region of the cable is broad enough to eliminate 2D effects (1D heat transfer).
2- Incident Heat flux is applied as a square wave and is spatially uniform.
3- The entire cable is inert.
4- Density, conductivity, and specific heat are constant.
5- Cable is initially isothermal.
6- Internal core is approximated as a lumped thermal mass (i.e., the "thin film" model).
7- Approximate jacket as a 1D planar material.

Assumptions 1-5 are shared with Martin's derivation, upon which this work builds. Assumption 6 would work well for a single, jacketed wire, but is perhaps questionable for a multi-wire cable. Assumption 7 seems dubious, but the thermal model is only for the relatively thin jacket of a large-diameter cable (L<<D). The thermal mass thereunder is lumped (Assumption 6).

Overall, these assumptions are not perfectly accurate; however, this model is not claimed to work *a priori* but is proposed as a starting point for analyzing experimental data. Namely, the objective is an empirical model capturing first-order effects. Moreover, the model describes the threshold conditions for the initial ignition event, which is dominated by the physics at early time – before the assumptions break down. In particular, the model eventually demonstrates that (initial) ignition is insensitive to the cable core under HEAF conditions ($q'' > 100$ kW/m^2).

The empirical model is derived using Green's function. The front boundary condition is imposed heat flux (Neumann, Type 2) and the back boundary condition is a thin-film model (Carslaw, Type 4). The appropriate basis function is:

$$G_{X24} = \frac{1/L}{1 + C_2} + \sum_{m=1}^{\infty} \exp\left(-\frac{\beta_m^2 \alpha (t-\tau)}{L^2}\right) \frac{\cos\frac{\beta_m x}{L} \cos\frac{\beta_m x'}{L}}{N_m}$$

where:

$$N_m = \frac{L}{2} \frac{1 + {C^*}^2 \beta_m^2 + C^*}{1 + {C^*}^2 \beta_m^2}$$

And β_m are the sequential solutions to the transcendental equation:

$$\tan\beta_m = -C^* \beta_m; m = 1,2,3 \ldots; \ \beta_m > 0$$

$$C^* = \frac{(\rho c b)_2}{\rho c L}$$

Where $(\rho c b)_2$ is the lumped thermal mass of the second layer (i.e., cable core). ρ, c, L, and α are the density, specific heat, thickness, and thermal diffusivity of the first layer (i.e., cable jacket). x and t are the space and time coordinates, and x' and τ are the space and time integration variables.

The Green's function solution for temperature response to heat flux absorbed by the surface (q_a'') and applied as a step function starting at $t = 0$ is:

$$\Delta T(x,t) = \alpha \int_{\tau=0}^{t} \frac{q_o''}{k} G_{x24}(x,t\,|0,\tau)\, d\tau$$

Stepping through the solution:

$$\Delta T(x,t) = \frac{q_a''\alpha}{k} \int_{\tau=0}^{t} \frac{1/L\, d\tau}{1+C^*} + \int_{\tau=0}^{t} \sum_{m=1}^{\infty} \exp\left(-\frac{\beta_m^2 \alpha (t-\tau)}{L^2}\right) \frac{\cos\frac{\beta_m x}{L} \cos 0}{N_m} d\tau$$

$$\frac{kL\Delta T(x,t)}{q_a''\alpha} = \int_{\tau=0}^{t} \frac{1\, d\tau}{1+C^*} + \int_{\tau=0}^{t} \sum_{m=1}^{\infty} \exp\left(-\frac{\beta_m^2 \alpha (t-\tau)}{L^2}\right) \frac{\cos\frac{\beta_m x}{L}}{N_m/L} d\tau$$

$$\frac{kL\Delta T(x,t)}{q_a''\alpha} = \frac{t}{1+C^*} + \sum_{m=1}^{\infty} \frac{L^2}{\beta_m^2 \alpha}\left[1 - \exp\left(\frac{\beta_m^2 \alpha t}{L^2}\right)\right] \frac{\cos\frac{\beta_m x}{L}}{N_m/L}$$

$$\frac{k\Delta T(x,t)}{Lq_a''} = \frac{\alpha t/L^2}{1+C^*} + \sum_{m=1}^{\infty} \frac{1}{\beta_m^2}\left[1 - \exp\left(\frac{\beta_m^2 \alpha t}{L^2}\right)\right] \frac{\cos\frac{\beta_m x}{L}}{N_m/L}$$

$$\frac{k\Delta T(x,t)}{Lq_a''} = \frac{Fo}{1+C^*} + \sum_{m=1}^{\infty} \frac{1}{\beta_m^2}\left[1 - \exp\left(\beta_m^2 Fo\right)\right] \frac{\cos\frac{\beta_m x}{L}}{N_m/L}$$

where $Fo = \alpha t/L^2$ is the Fourier number.

Replicating the ignition model of Martin, we require surface temperatures ($x = 0$) and will leverage normalized threshold flux ($q^* = q_a'' L/k$) and normalized threshold fluence ($Q^* = Q''/\rho c L$). The threshold is defined by the surface temperature reaching the critical temperature rise (ΔT_{th}):

$$\frac{\Delta T_{th}}{q_{th}^*} = \frac{Fo_{th}}{1+C^*} + \sum_{m=1}^{\infty} \frac{1}{\beta_m^2}\left[1 - \exp\left(\beta_m^2 Fo_{th}\right)\right] \frac{\cos 0}{N_m/L}$$

Solving for q_{th}^* yields:

$$q_{th}^* = \frac{\Delta T_{th}}{\frac{Fo_{th}}{1+C^*} + \sum_{m=1}^{\infty} \frac{1}{\beta_m^2}\left[1 - \exp\left(\beta_m^2 Fo_{th}\right)\right] \frac{1}{N_m/L}}$$

By definition:

$$Q_{th}^* = q_{th}^* Fo_{th}$$

Yielding:

$$Q_{th}^{*} = \frac{Fo_{th}\Delta T_{th}}{\frac{Fo_{th}}{1 + C^{*}} + \sum_{m=1}^{\infty} \frac{1}{\beta_m^2} [1 - \exp{(\beta_m^2 Fo_{th})}] \frac{1}{N_m/L}}$$

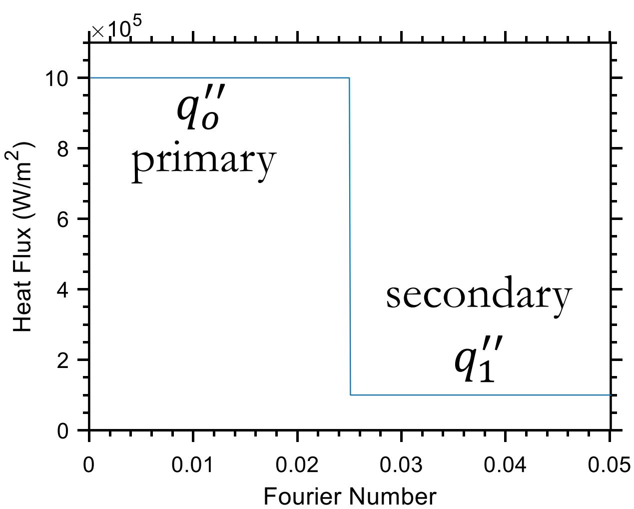
Leveraging a numerical solver, solutions to the transcendental equation (β_m) are obtained and the first 100 terms of the infinite series are computed. This calculation yields the results in the main report. These results collapse onto the traditional ignition threshold proposed by Martin when (1) Fourier number is small ($Fo \ll 1$) and when the cable core has negligible mass ($C^* \ll 1$).
If the model proves effective, the derivation could be further refined. Rederiving these relations under cylindrical coordinates is certainly worth considering. A directional heat flux might also be considered (heat flux is spatially uniform in this case). These considerations were not incorporated here because our experimental conditions rarely diverged to conditions where the cable core was expected to significantly impact initial ignition (q''<100 kW/m^2).

APPENDIX B. SUSTAINED IGNITION MODEL

This appendix attempts to adapt the existing surface-temperature approach for initial ignition to derive a model for sustained ignition. This derivation is for an unproven approximation of first-order effects and was intended as a starting point for defining an experimental parameter space for testing. Following the assumptions of the classical models for surface-temperature driven ignition, we must assume:

1- Heated region of the cable is broad enough to eliminate 2D effects (1D heat transfer).
2- Incident Heat flux is applied as two-step square wave and is spatially uniform.
3- The entire cable is inert.
4- Density, conductivity, and specific heat are constant.
5- Cable is initially isothermal.

Traditionally, the ignitable material is treated as having finite-thickness (L) with a perfectly insulated back face. However, for the extreme heat fluxes considered in our experimental study, critical temperatures are exceeded and maintained at low Fourier number – before heat has reached the back surface. Therefore, we rely on the equations for semi-finite heat-transfer, although the derivation is fully compatible with alternate selections for the rear-face boundary condition.
In traditional analyses, heat-flux is applied as a step function with an undefined endpoint. Here, we consider a two-stage heat source: an initial extreme heat flux from the HEAF event and a secondary heat flux from an unspecified source. This secondary heat flux sources might include hot-surroundings or the flame sheath surrounding the burning cable jacket. This heat flux profile is visualized below:



This profile is considered based on prior testing of materials in extreme heat-flux environments. At extreme heat flux, materials tend to ignite quickly, but thermal penetration is limited. As a result, the material cools down rapidly when the exposure ends due to heat conduction further into the material. Classically, this explains the existence of the transient ignition regime past the branch point in the cellulose-paper ignition maps. An empirically derived sustained ignition threshold was determined in these experiments but was sensitive to factors such as the exposure profile (historically, square-wave or nuclear-weapon profiles). Ignition was significantly easier to sustain when the exposure heat flux was gradually reduced. At Sandia, we have seen similar behavior at the

Solar Furnace facility – flat/planar materials rarely remain ignited at the small-scale facility unless the material is pyrolyzed/ablated through its entire thickness.

Thus, we apply a secondary heat source and evaluate the theoretical material response, looking for conditions to fall below some critical value. While a more elaborate model (e.g., pyrolyzate efflux) could be considered here, we rely on a simple model with historical precedence: a critical surface temperature. Recall, this model is intended for experimental planning and first-order effects. The data may demonstrate cause to modify or completely discard this model.

The heat-flux in Figure A.1 can be represented using the Heaviside step function:

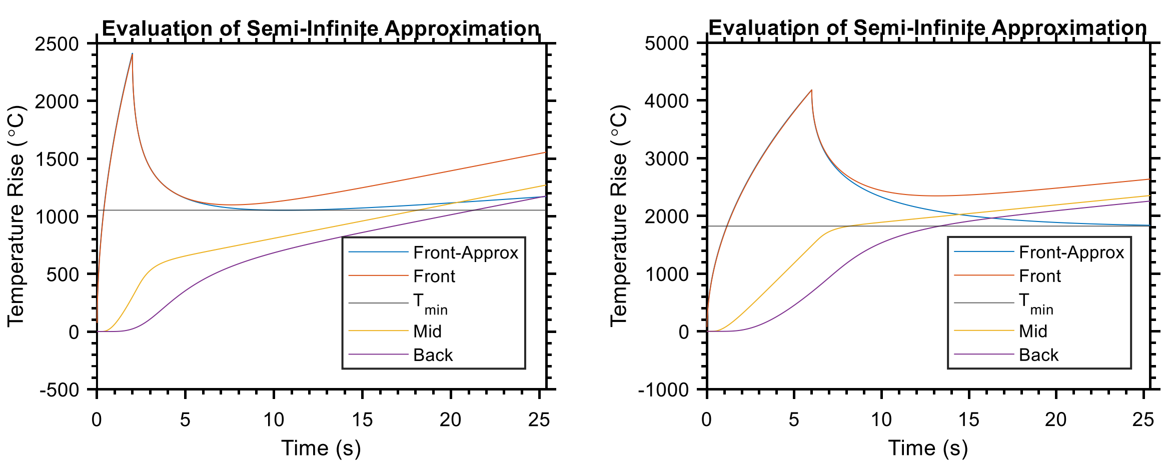
$$q''(t) = q_o''H(t) - (q_o'' - q_1'')H(t - t_o)$$

where q_o'' and q_1'' are the primary and secondary heat flux intensity and t_o is the duration of the primary heat flux.

The surface temperature rise from this heat flux is the summation of the responses to the individual stimuli:

$$\Delta T(x = 0, t) = \frac{2q_o''}{k}\sqrt{\frac{\alpha t}{\pi}} - \frac{2(q_o'' - q_1'')}{k}\sqrt{\frac{\alpha(t - t_o)}{\pi}}H(t - t_o)$$

To verify this solution is adequate for the model herein, this solution is compared to a finite thickness material with an adiabatic back surface. The assumed properties of the jacket are: thickness $L = 1.52$ mm, conductivity $k = 0.2$ W/mK, specific heat $c_p = 1500$ J/kgK, and density $\rho = 1457$ kg/m^3. The primary heat flux is 1 MW/m^2 and the secondary heat flux is 100 kW/m^2. In the figure below, primary heat flux duration is either 2 seconds (left) or 6 seconds (right).
The approximate solution (i.e., semi-infinite solid) in the equation above is provided in blue. Front, mid-point, and back-surface temperatures from the full analytical solution are also provided for comparison. Heat penetration is predicted within roughly 3—4 seconds ($Fo \approx 0.15$). The semi-infinite solution remains approximately valid until roughly 10 seconds ($Fo \approx 0.4$), but quickly degrades thereafter.



The existence of a minimum temperature is representative of the post-HEAF surface cooling that may quench flaming ignition. The semi-infinite approximation predicts the value of this minimum reasonably well for low exposure durations, but is less accurate for longer exposures. However, the model assumptions are increasingly dubious as HEAF duration becomes progressively longer (e.g., charring/fracturing of cable jacket, reradiation, inert cable). For example, temperatures are fictitiously high, revealing the models lack relevant physics (e.g., surface ablation, pyrolysis, reradiation), but similar issues arise in the classical ignition models, where the empirical threshold ($\approx 1200\ °\mathrm{C}$) is much higher than actual ignition temperatures ($\approx 600 - 800\ °\mathrm{C}$).

Regardless, the model is adopted to predict first-order effects for previously unexplored physics regime to assist experimental planning. To this end, the time when the temperature minimum is reached is computed from the semi-infinite approximation for $t > t_o$:

$$\frac{d(\Delta T)}{dt} = \frac{q_o''}{k}\sqrt{\frac{\alpha}{\pi t}} - \frac{(q_o'' - q_1'')}{k}\sqrt{\frac{\alpha}{\pi(t - t_o)}} = 0$$

$$\frac{q_o''}{\sqrt{t}} = \frac{(q_o'' - q_1'')}{\sqrt{t - t_o}}$$

$$\frac{t}{t_o} = \frac{1}{1 - \chi^2}$$

where $\chi = \frac{q_o'' - q_1''}{q_o''}$. Evaluating the semi-infinite solution at this time yields:

$$\frac{kT_{min}}{q_o''\sqrt{\alpha t_o}} = \frac{2}{\sqrt{\pi}}\sqrt{1 - \chi^2}$$

Using this relationship, we can evaluate the minimum temperature associated with a given set of conditions (q_o'', q_1'', t_o). This value can be compared to an experimentally established threshold, T_{crit}. Conditions that cause T_{min} to fall below T_{crit} yield transient (unsustained) ignition.
The formulation above is convenient for some applications, but hides many of the experimental variables we need to design the study. The equation is evaluated for the threshold quantities and rearranged to the form:

$$t_o = \left(\frac{\pi}{8}\frac{k^2}{\alpha}T_{crit}^2\right) q_1^{-1}\left(q_o - \frac{q_1}{2}\right)^{-1}$$

The form above gives us an initial guess for how the threshold might vary across the experimental design space. This is leveraged for the statistical design of experiments in the main body of the report.

APPENDIX C. CALIBRATION CURVES

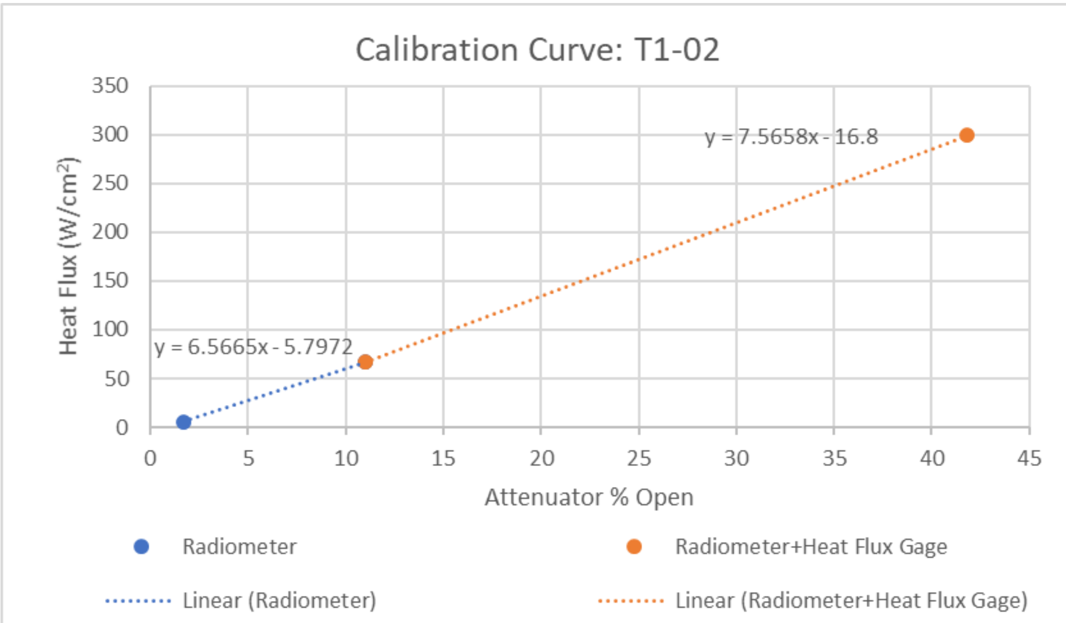
This appendix contains the calibration curves from each that allows the translation between attenuator position and heat flux. During the test, since the exposure beam is targeted at the cable, only attenuator position is known. To address this, calibration points of the heat flux are taken before and after the test as a function of attenuator position. For heat flux magnitudes lower than 250 W/cm^2 (2.5 MW/m^2), the radiometer was used. For magnitudes in excess of 250 W/cm^2, the heat flux gage was used. Note, that the radiometer is generally more accurate than the heat flux gage, so it is the preferred measurement device.

For the dynamic profile, three calibration fluxes were chosen: the primary flux magnitude, the transition flux magnitude, and the secondary flux magnitude. For simple flux profiles, only the primary flux magnitude was calibrated. These points were calibrated prior to the test, and then again after the test to determine how much the flux changed during the test. Note that for some tests, data for either the pre- or post-test calibration is missing. For these tests, it was assumed that the available data is correct (e.g., if only pre-test calibration is available, then it was assumed that it remained constant for the post-test calibration).

For each calibration flux, time-averaged data (of at least 5 seconds) from the raw data output was used to determine an average attenuator position and corresponding heat flux. Based on operator's experience, the curve between calibrated points is linear. Therefore, for the dynamic profile, a line was fit between the two lower points (transition and secondary magnitudes, both taken on the radiometer) and another line was fit between the two higher points (primary magnitude from the heat flux gage or radiometer, and the transition point from the radiometer). This resulted in a piece-wise calibration curve for these tests. For the simple flux profiles, a line was fit through the calibrated point and (0, 0). The pre- and post-test calibration points were each used during the linear fit.

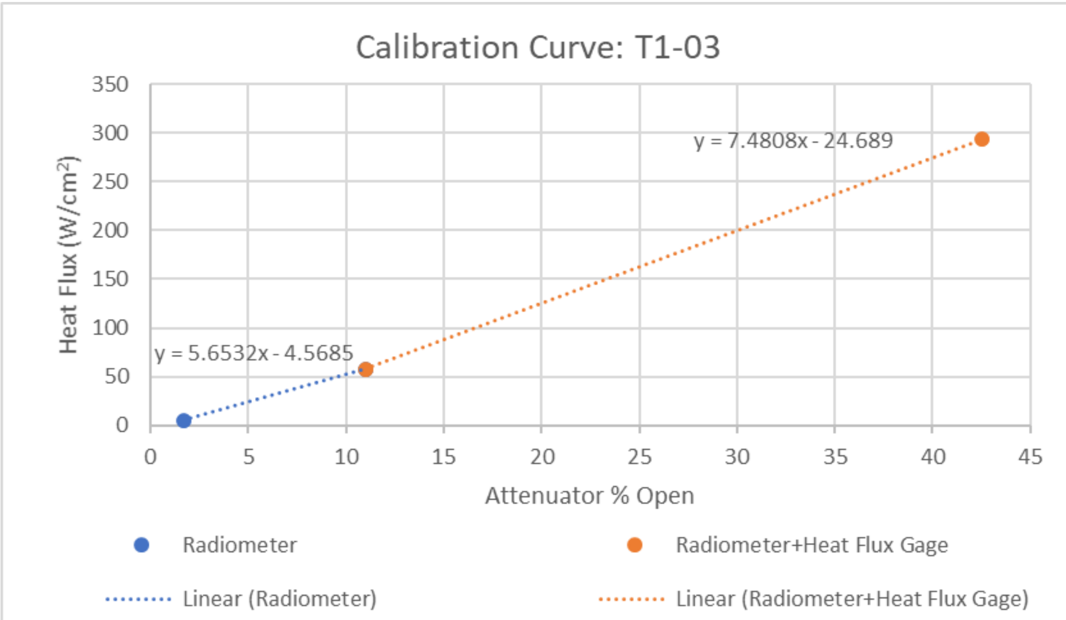
Test 1-02

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.698356	5.355045	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	11.01059	66.50387	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	41.80352	299.4757	Heat Flux Gage
Post-test	N/A	N/A	N/A



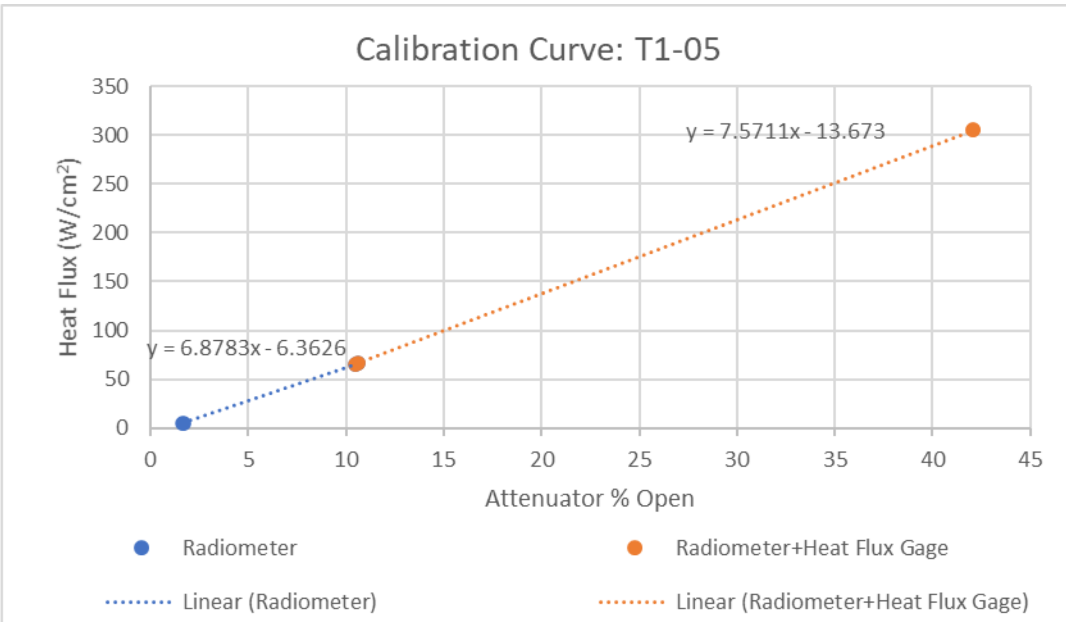
Test 1-03

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	N/A	N/A	N/A
Post-test	1.697907	5.030238	Radiometer
Pre-test	N/A	N/A	N/A
Post-test	11.00913	57.66889	Radiometer
Pre-test	N/A	N/A	N/A
Post-test	42.50097	293.2539	Heat Flux Gage



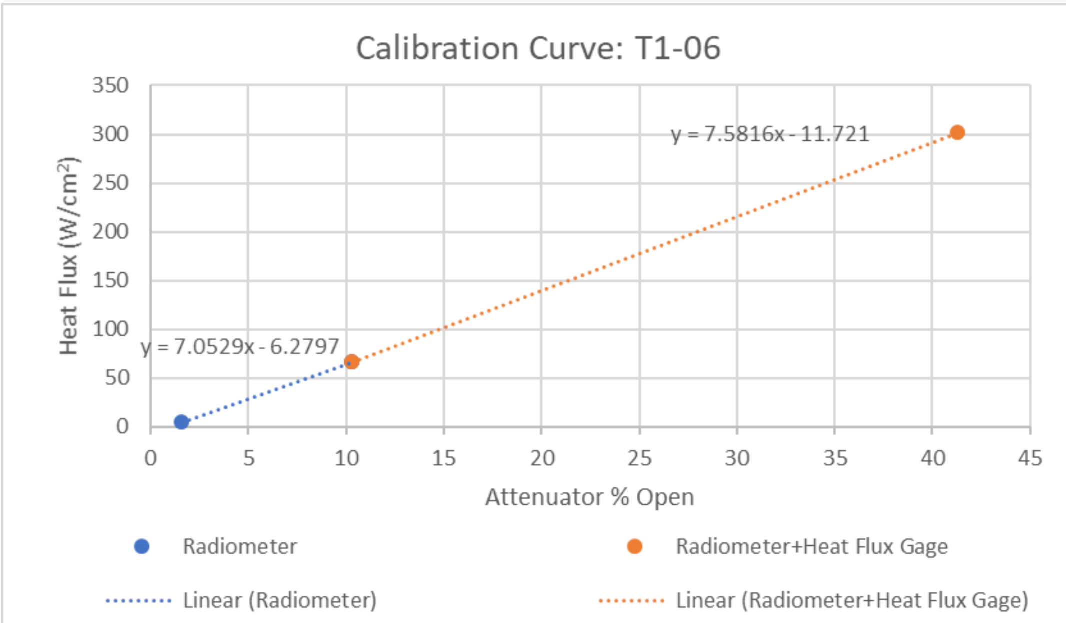
Test 1-05

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.658038	5.113008	Radiometer
Post-test	1.698173	5.250849	Radiometer
Pre-test	10.59915	66.9217	Radiometer
Post-test	10.49597	65.44668	Radiometer
Pre-test	42.09697	305.048	Heat Flux Gage
Post-test	N/A	N/A	N/A



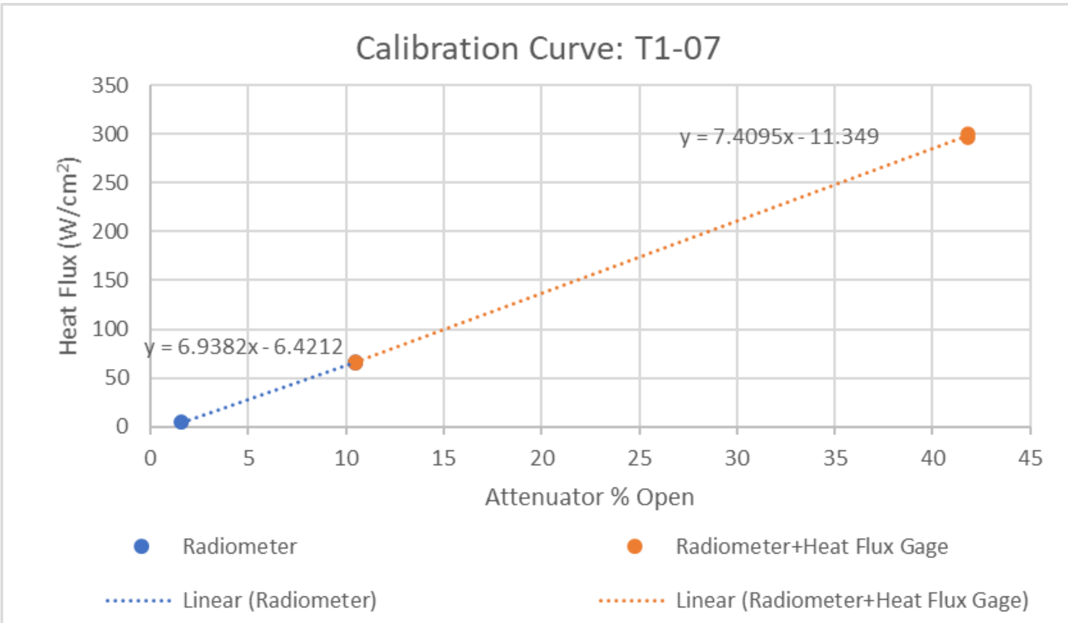
Test 1-06

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.598215	4.992354	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	10.29126	66.30327	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	41.30766	301.4585	Heat Flux Gage
Post-test	N/A	N/A	N/A



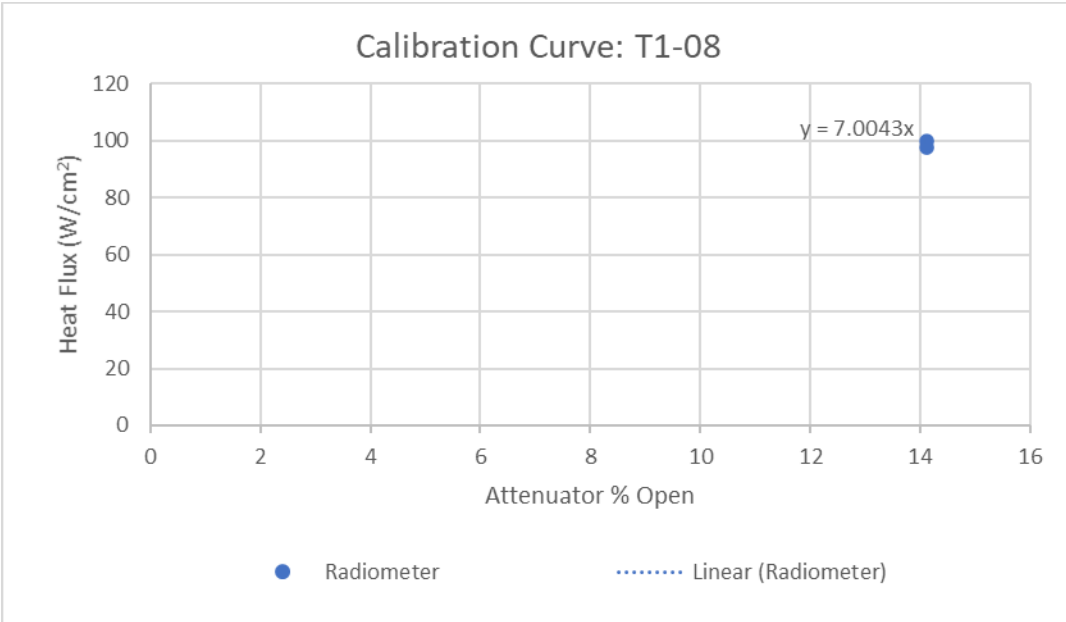
Test 1-07

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.597936	4.983383	Radiometer
Post-test	1.597998	4.348242	Radiometer
Pre-test	10.45523	66.42903	Radiometer
Post-test	10.45545	65.81124	Radiometer
Pre-test	41.80244	300.3441	Heat Flux Gage
Post-test	41.80204	296.4257	Heat Flux Gage



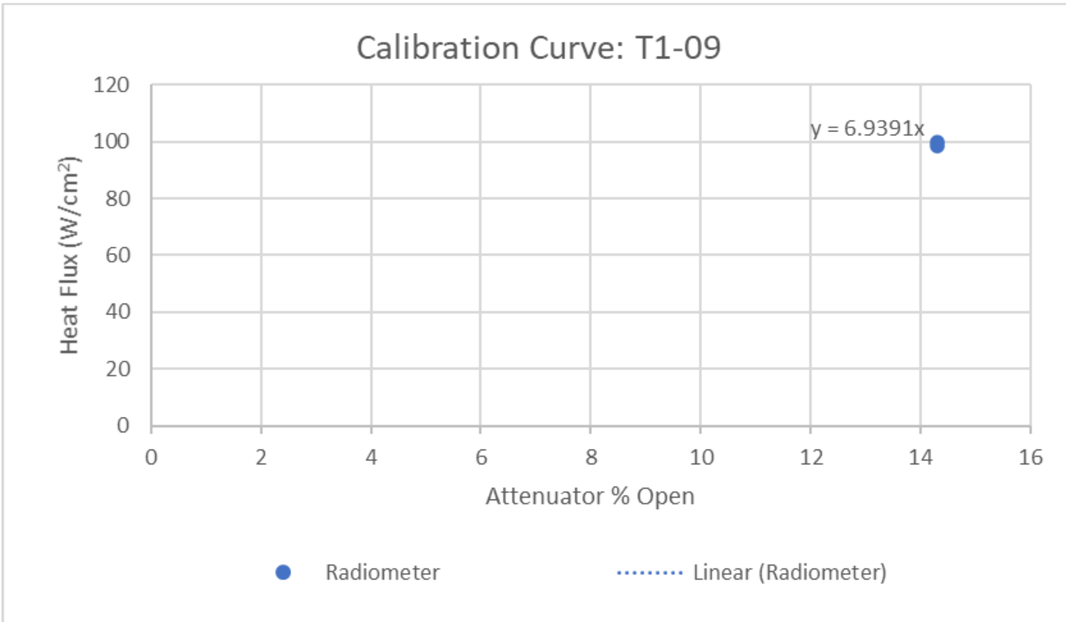
Test 1-08

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	14.10644	100.1118	Radiometer
Post-test	14.10634	97.49965	Radiometer



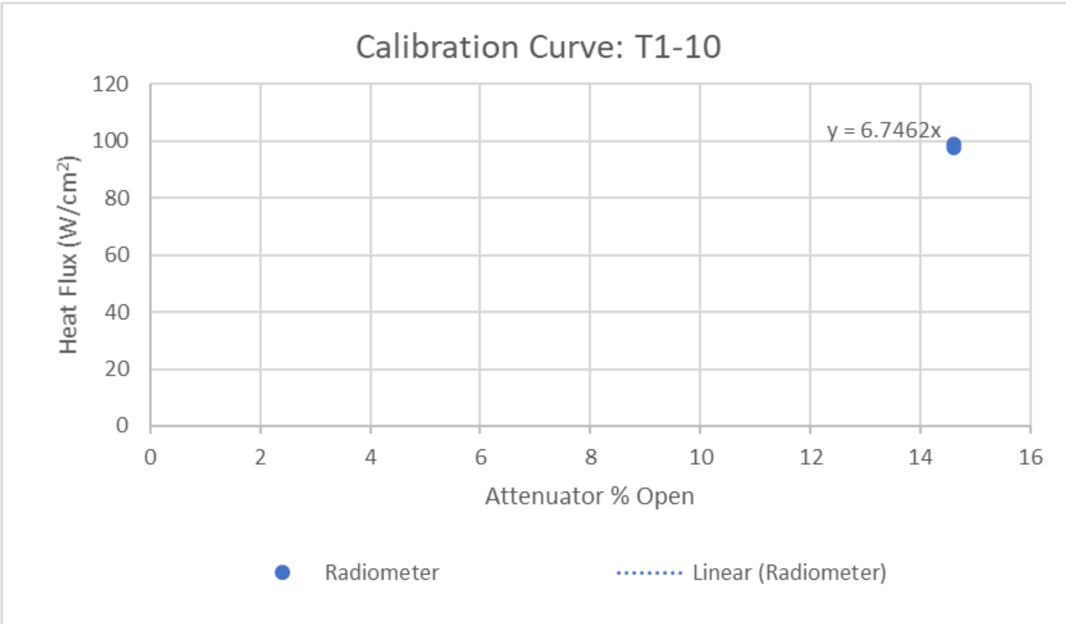
Test 1-09

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	14.293	99.97526	Radiometer
Post-test	14.29304	98.38522	Radiometer



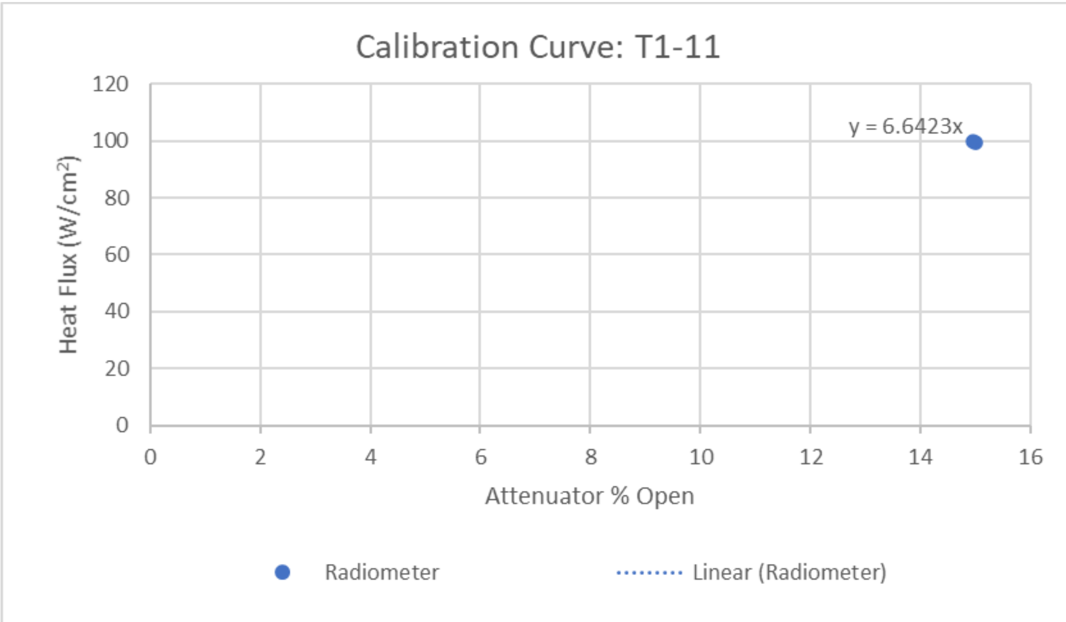
Test 1-10

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	14.60431	99.14489	Radiometer
Post-test	14.60444	97.90344	Radiometer



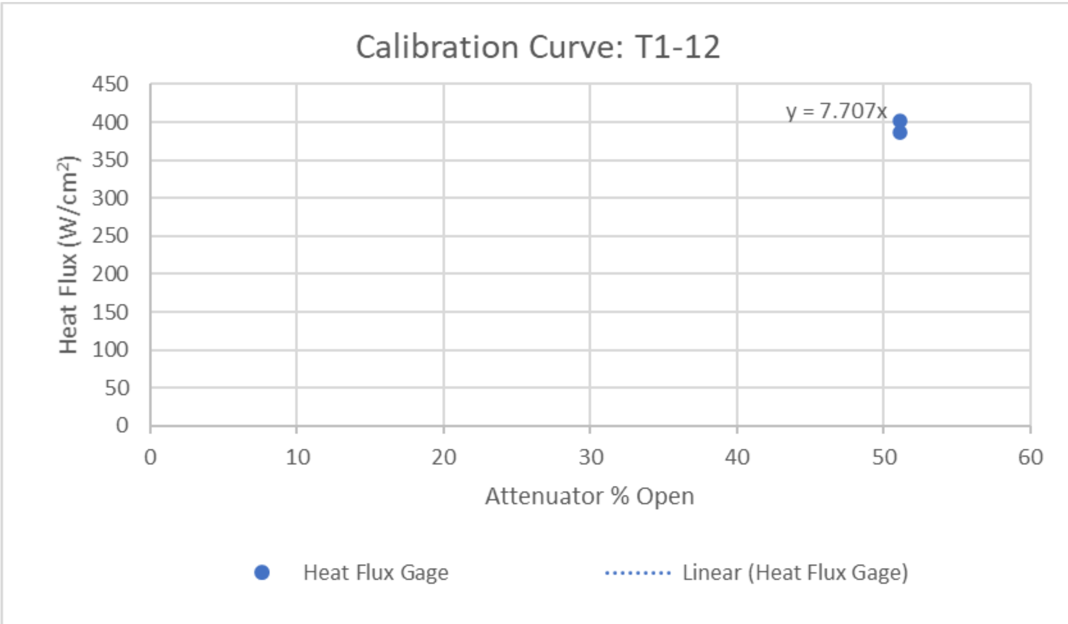
Test 1-11

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	14.99901	99.18843	Radiometer
Post-test	14.95766	99.79399	Radiometer



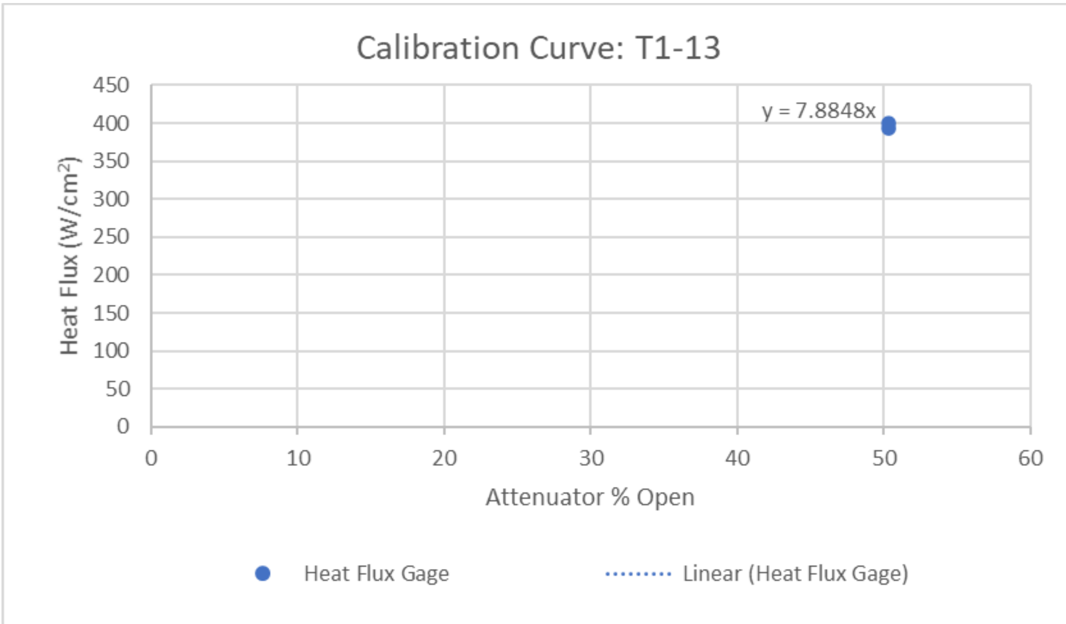
Test 1-12

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	51.09823	401.1078	Heat Flux Gage
Post-test	51.09839	386.517	Heat Flux Gage



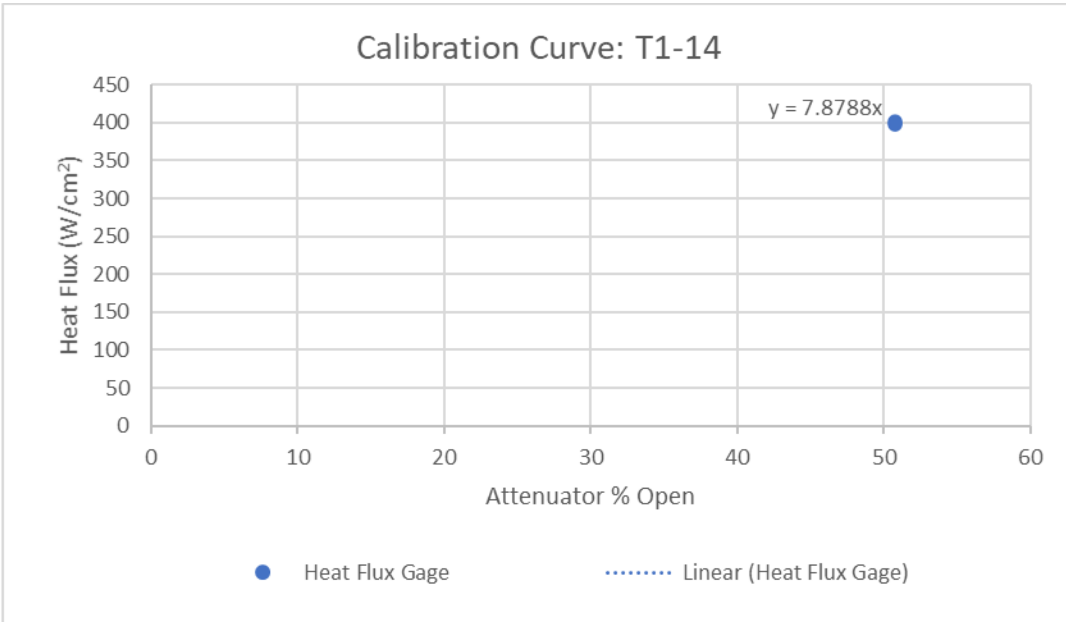
Test 1-13

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	50.31246	400.034	Heat Flux Gage
Post-test	50.31122	393.3615	Heat Flux Gage



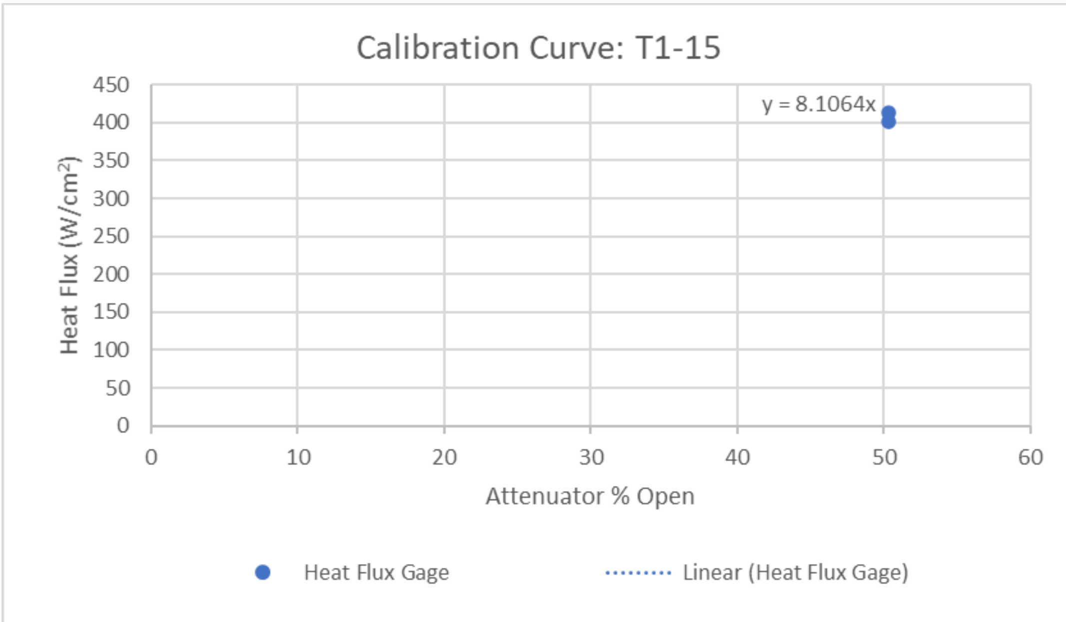
Test 1-14

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	50.74891	401.0137	Heat Flux Gage
Post-test	50.75051	398.6805	Heat Flux Gage



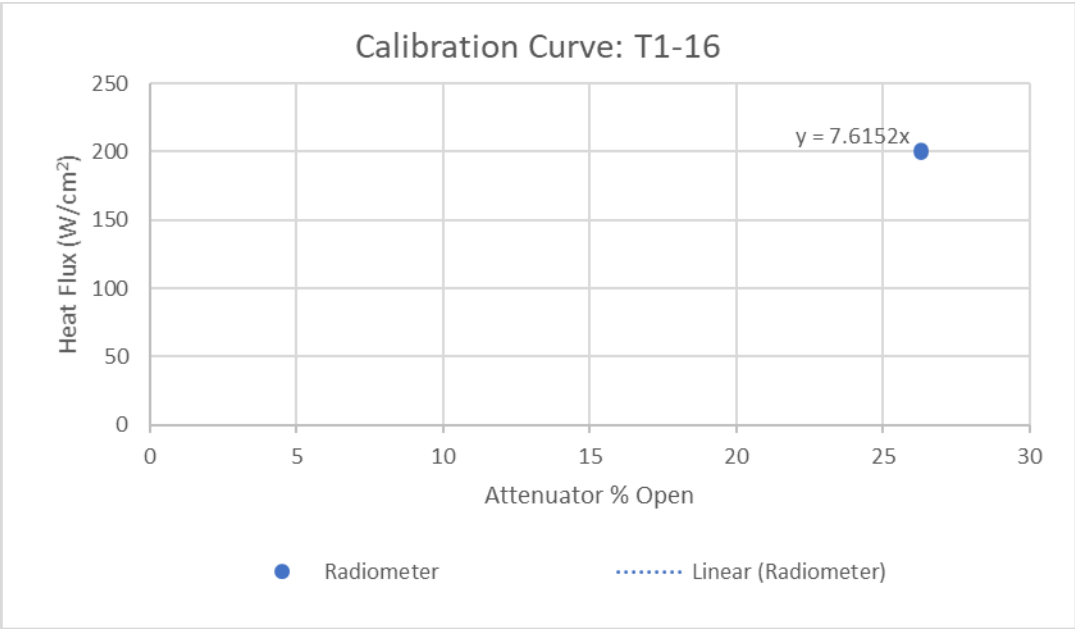
<u>Test 1-15</u>

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	50.31364	402.0644	Heat Flux Gage
Post-test	50.31078	413.634	Heat Flux Gage



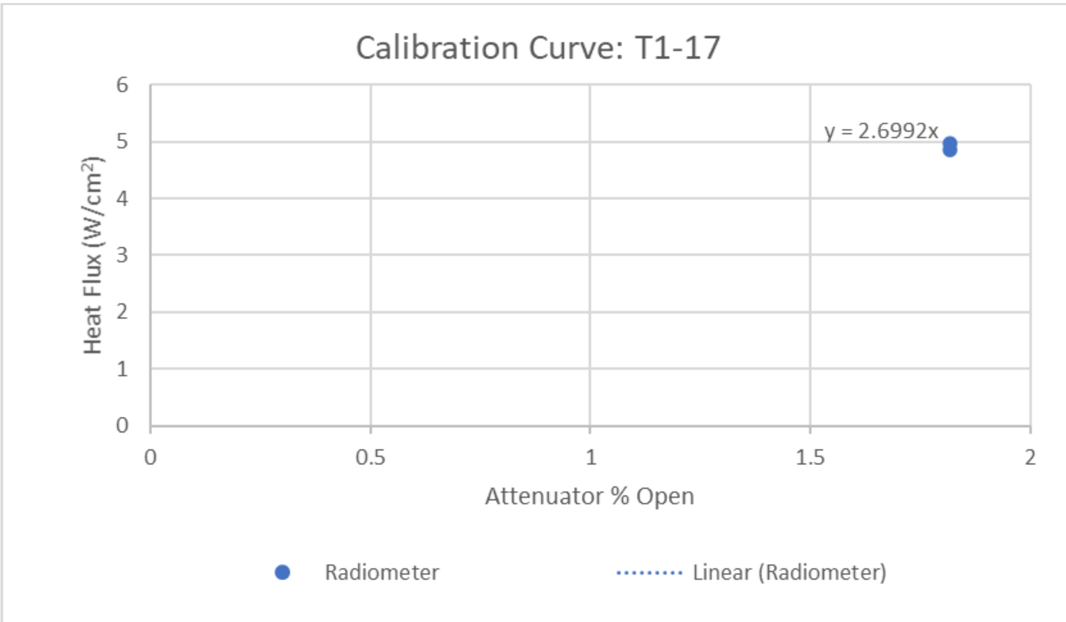
Test 1-16

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	26.30244	201.5155	Radiometer
Post-test	26.30323	199.0885	Radiometer



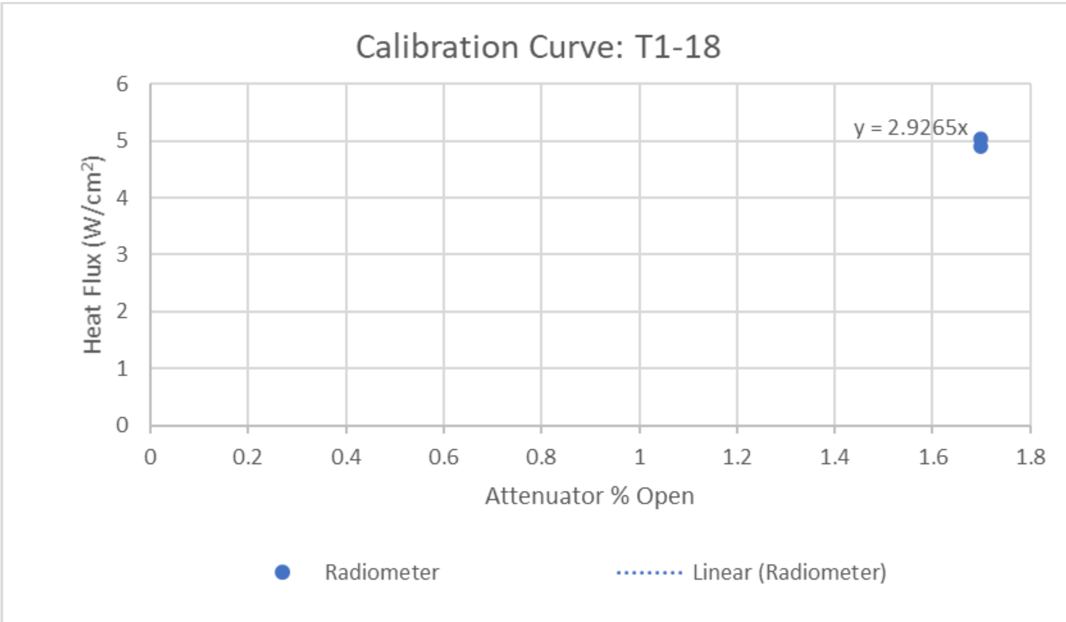
Test 1-17

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.818523	4.968243	Radiometer
Post-test	1.818395	4.848419	Radiometer



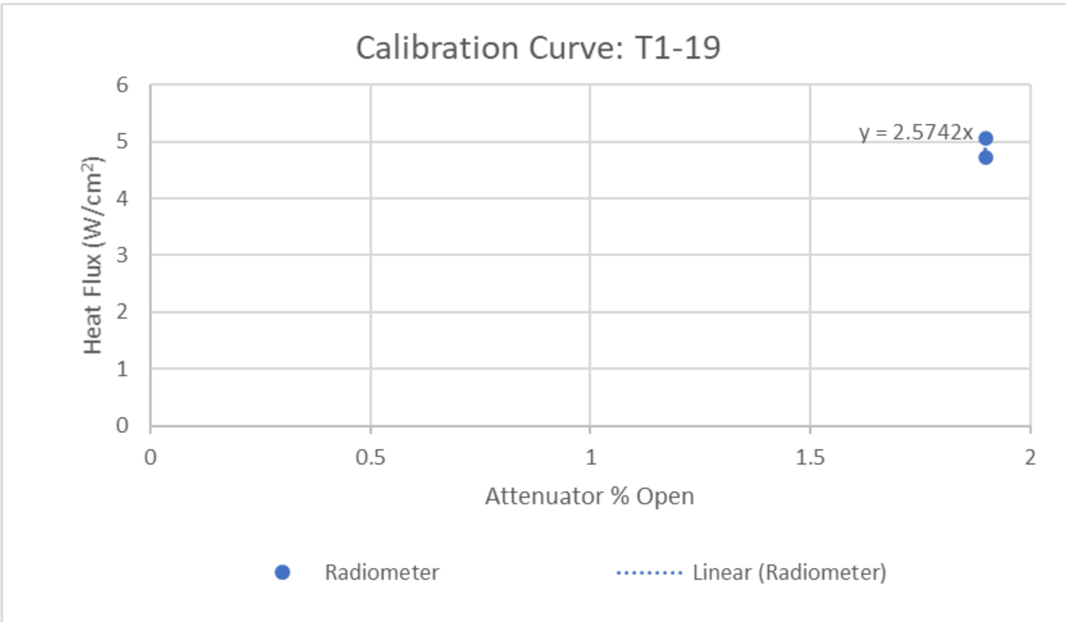
Test 1-18

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.698326	5.029824	Radiometer
Post-test	1.698209	4.909997	Radiometer



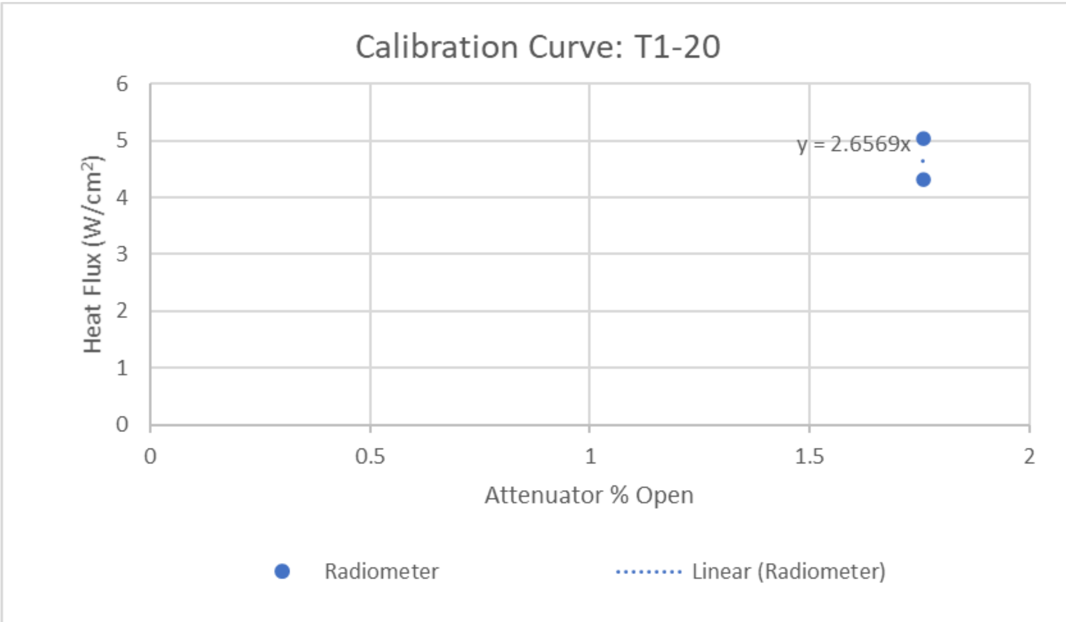
Test 1-19

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.898589	5.053811	Radiometer
Post-test	1.898609	4.721124	Radiometer



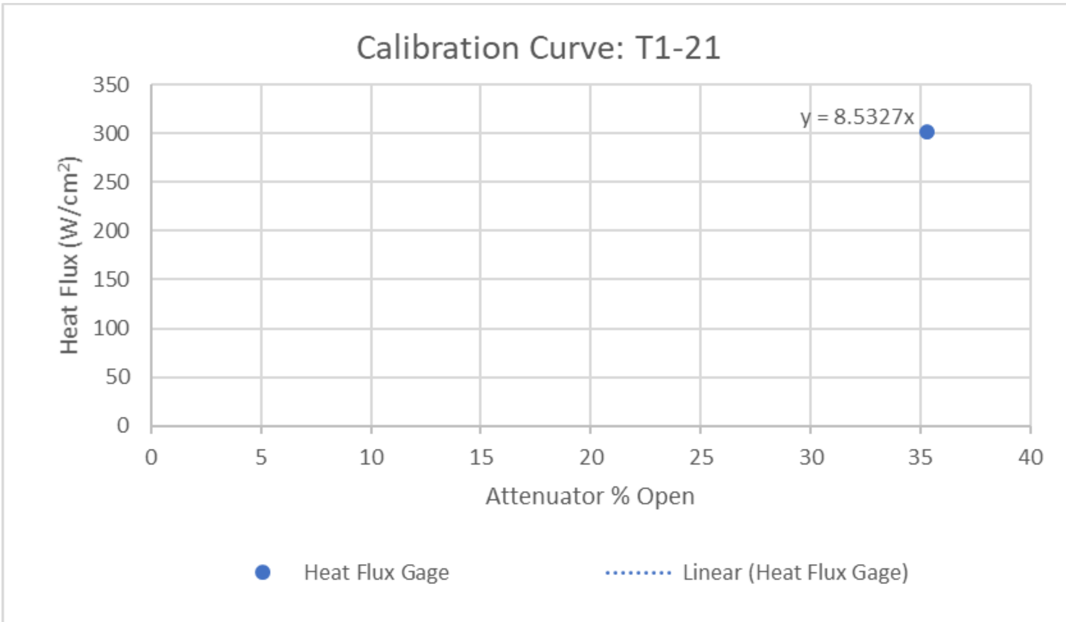
Test 1-20

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.75836	5.032449	Radiometer
Post-test	1.758365	4.311288	Radiometer



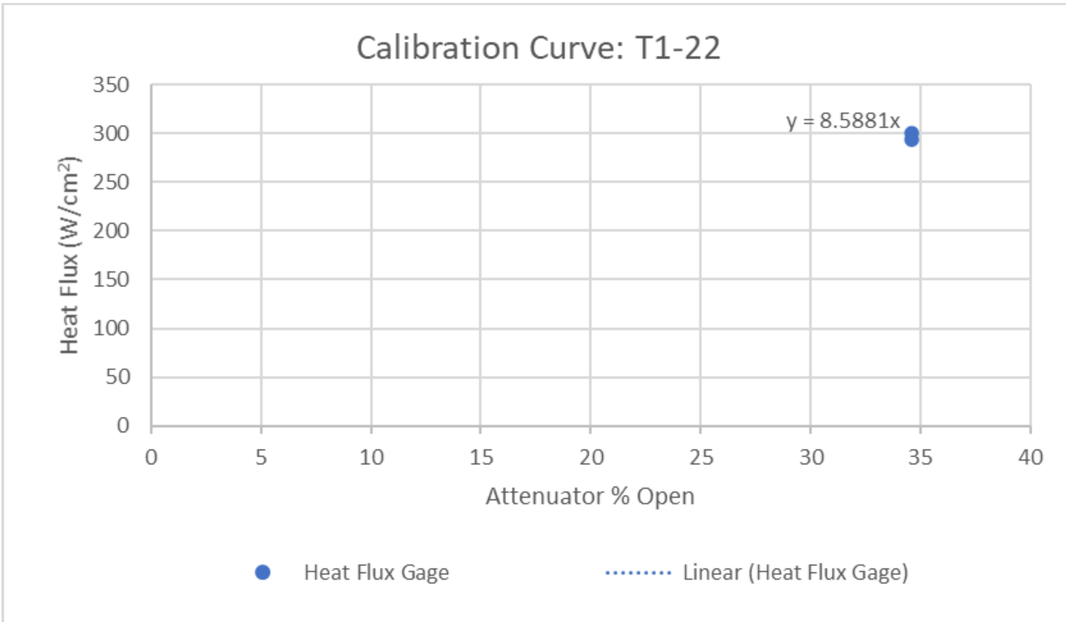
Test 1-21

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	35.29342	301.1473	Heat Flux Gage
Post-test	N/A	N/A	N/A



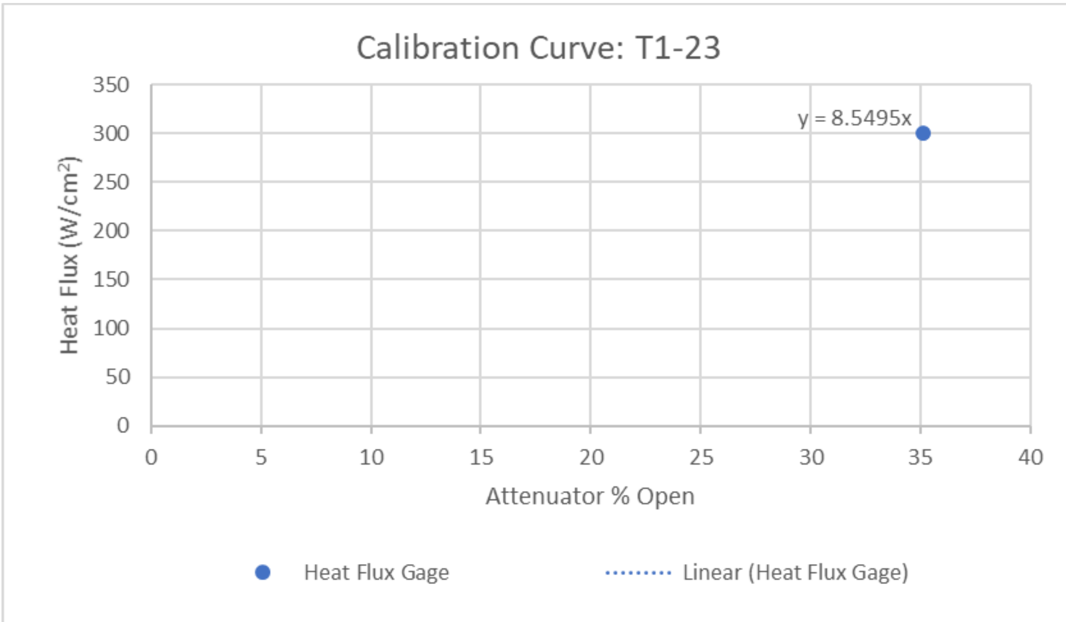
Test 1-22

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	34.61076	300.506	Heat Flux Gage
Post-test	34.61118	293.9756	Heat Flux Gage



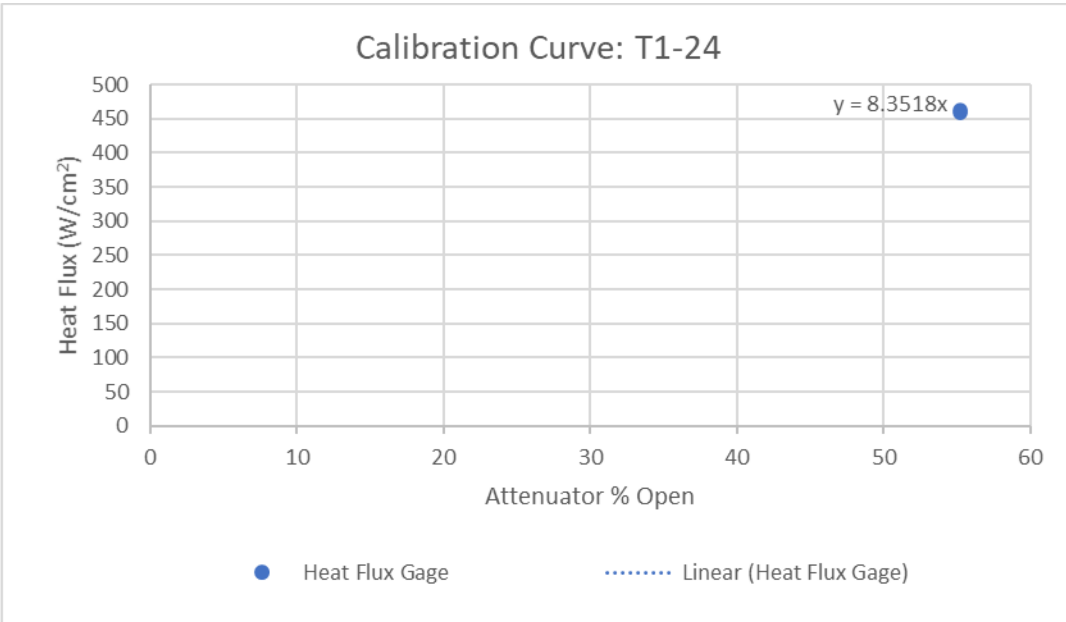
<u>**Test 1-23**</u>

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	35.14048	300.3166	Heat Flux Gage
Post-test	35.13991	300.5476	Heat Flux Gage



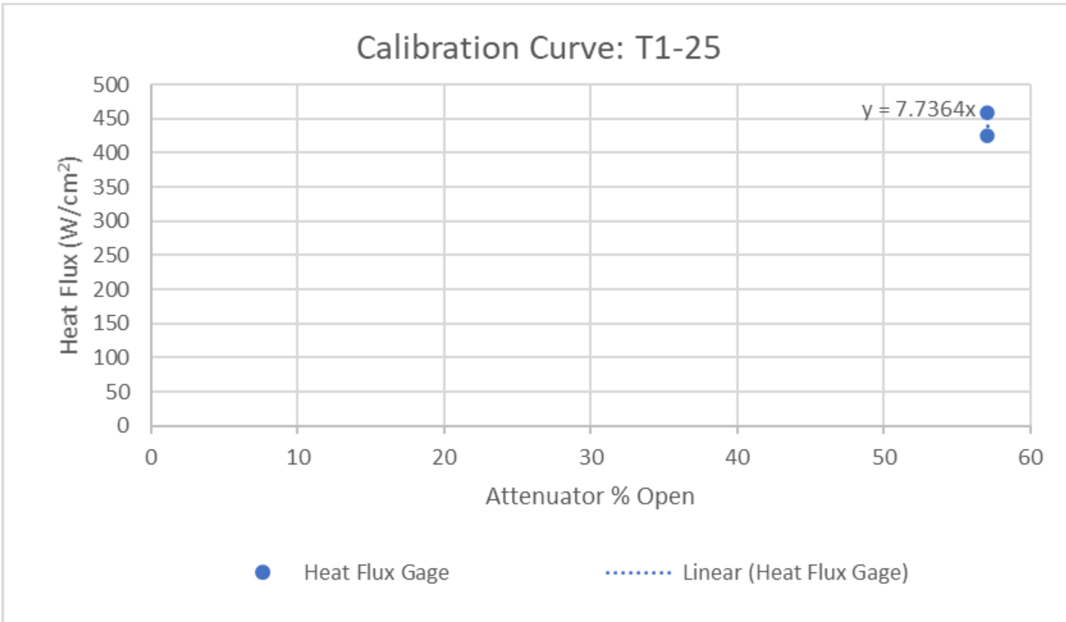
Test 1-24

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	55.20464	459.1149	Heat Flux Gage
Post-test	55.2042	462.9999	Heat Flux Gage



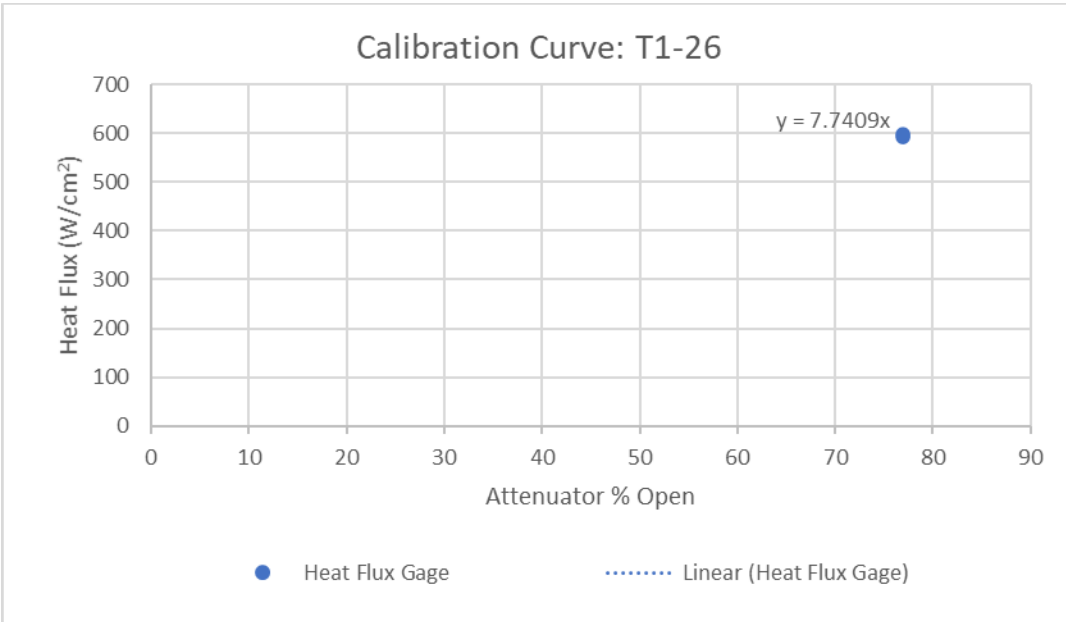
Test 1-25

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	57.08899	458.7802	Heat Flux Gage
Post-test	57.08674	424.5292	Heat Flux Gage



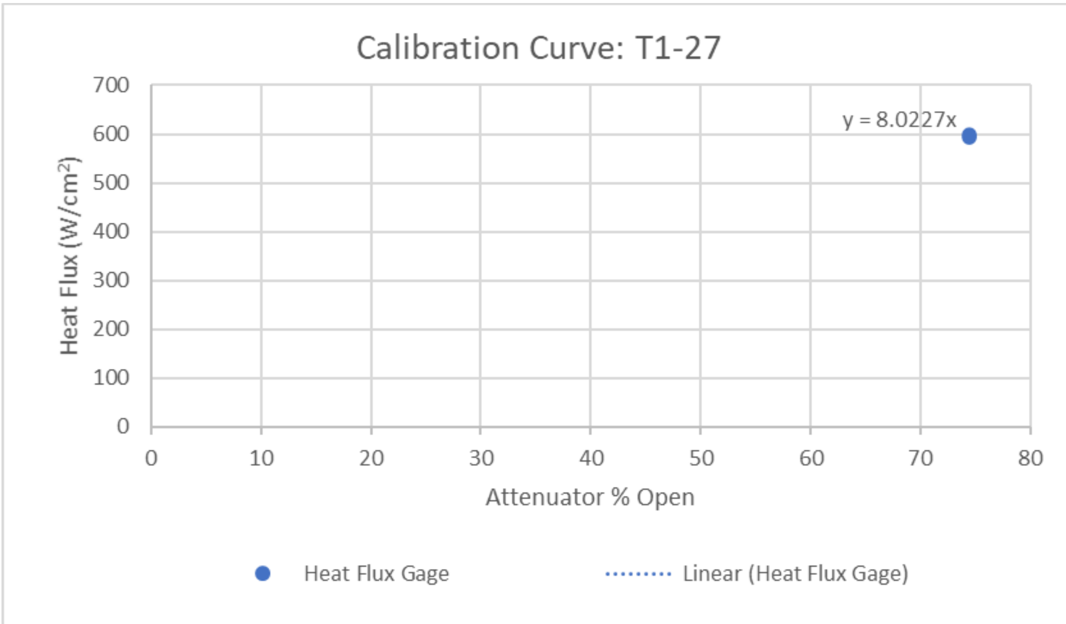
<u>**Test 1-26**</u>

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	76.88885	598.6394	Heat Flux Gage
Post-test	76.88749	591.7306	Heat Flux Gage



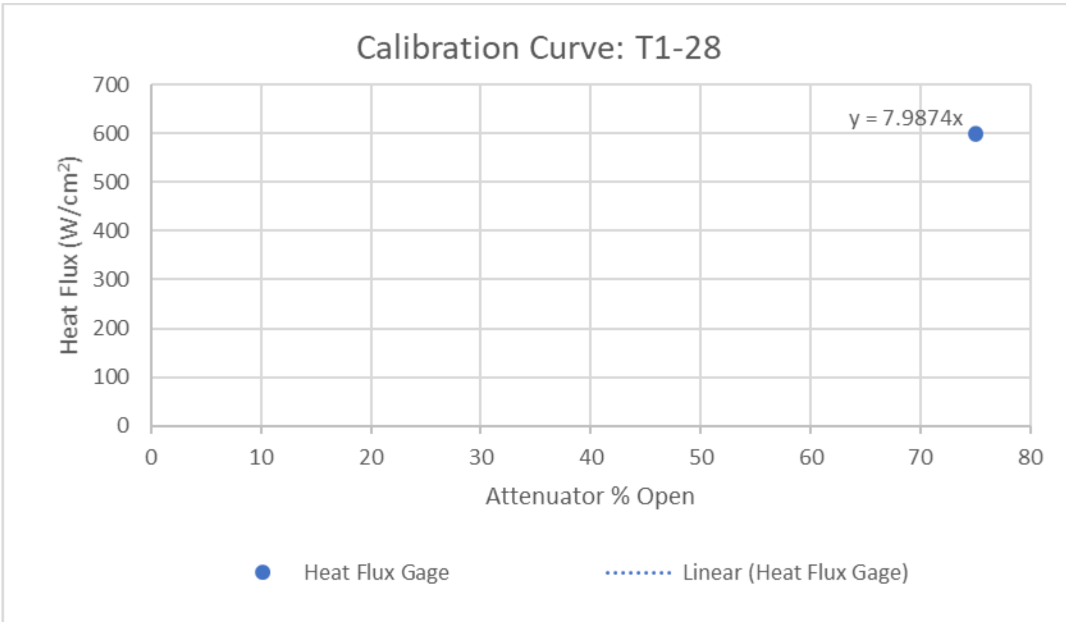
Test 1-27

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	74.40077	599.5894	Heat Flux Gage
Post-test	74.39766	594.1779	Heat Flux Gage



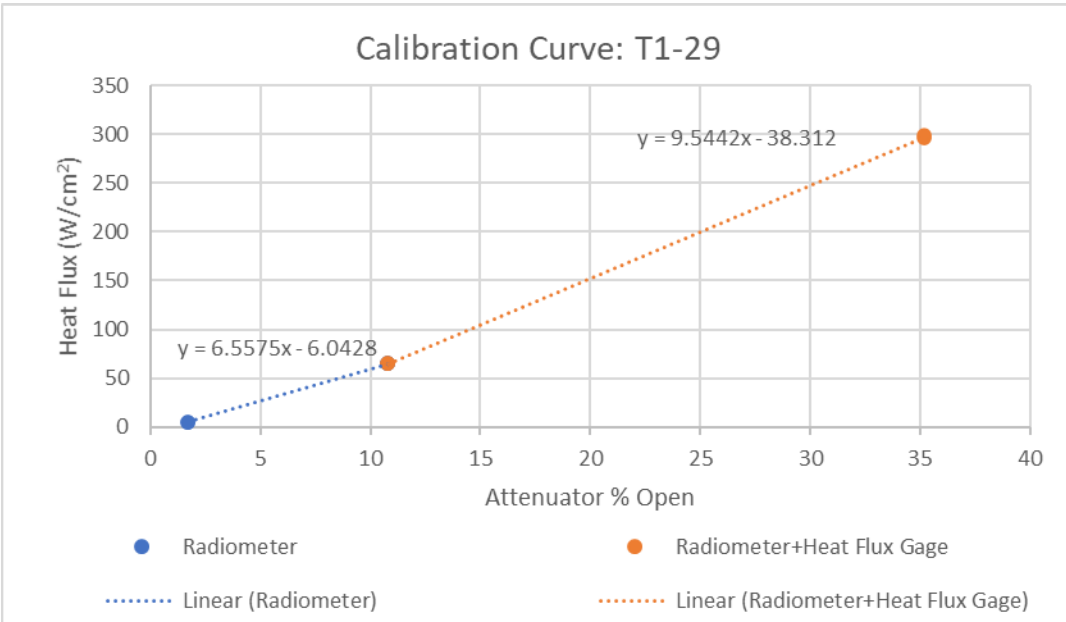
Test 1-27

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	75.0012	600.1413	Heat Flux Gage
Post-test	75.00056	597.9894	Heat Flux Gage



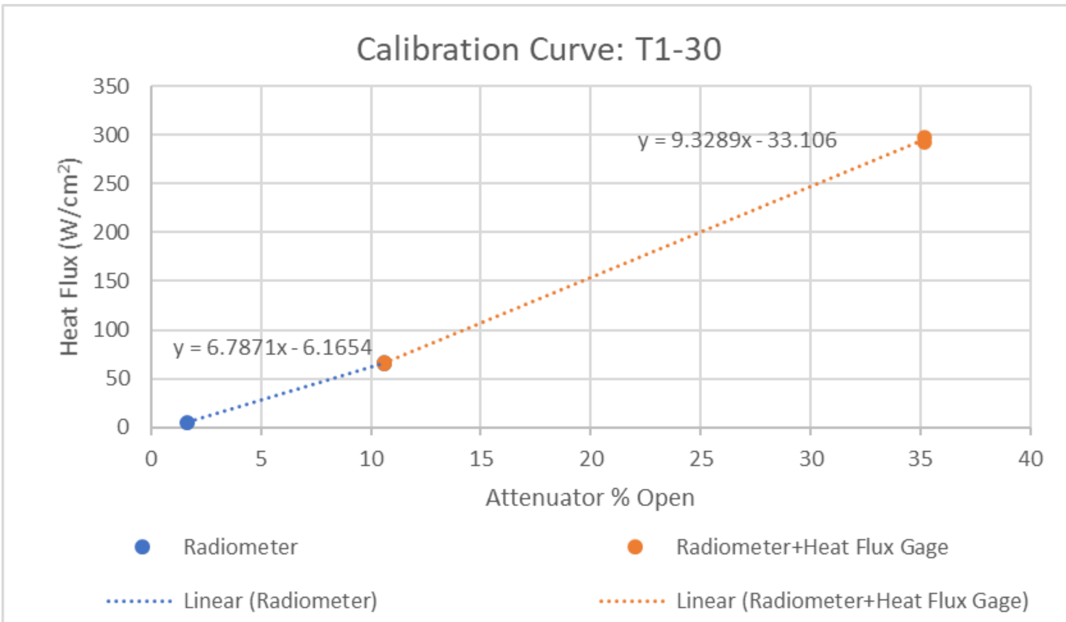
Test 1-29

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.698156	5.092841	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	10.80475	64.84277	Radiometer
Post-test	10.80351	64.7672	Radiometer
Pre-test	35.20613	296.7318	Heat Flux Gage
Post-test	35.20558	298.6702	Heat Flux Gage



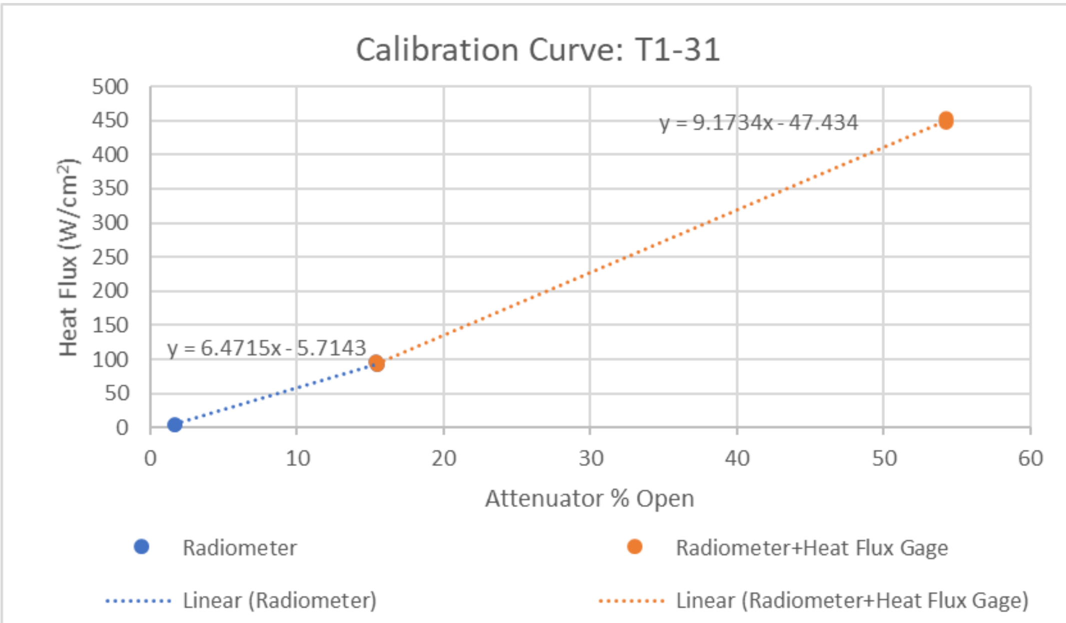
Test 1-30

Phase	Attenuator Position (% open)	Heat Flux (W/cm²)	Instrumentation
Pre-test	1.658027	5.011331	Radiometer
Post-test	1.658115	5.164669	Radiometer
Pre-test	10.59904	66.44518	Radiometer
Post-test	10.59884	65.09523	Radiometer
Pre-test	35.20603	292.2894	Heat Flux Gage
Post-test	35.20506	298.3574	Heat Flux Gage



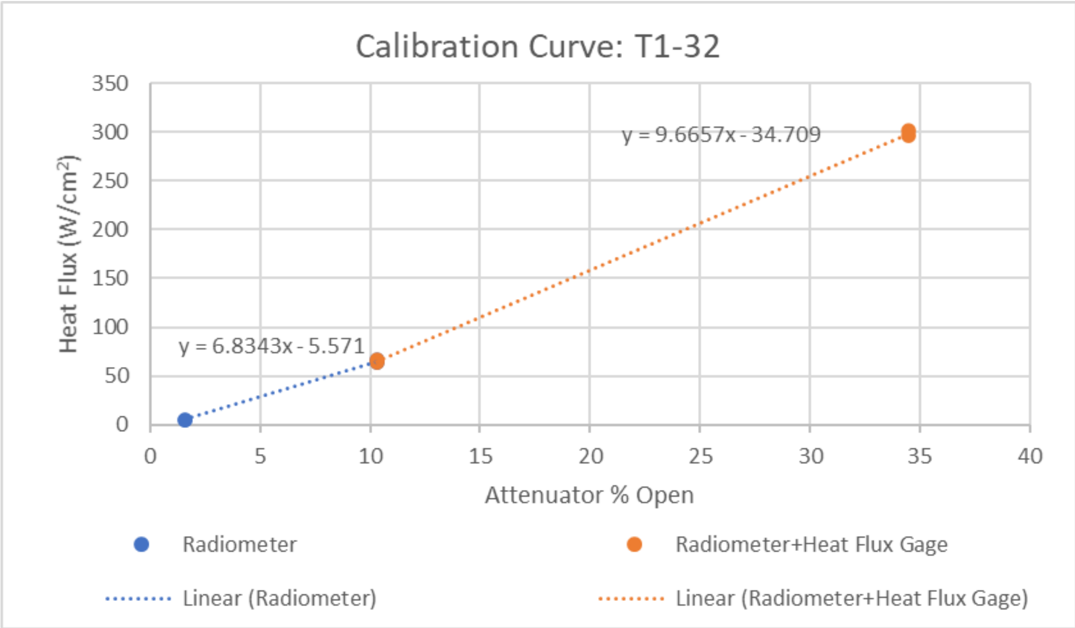
Test 1-31

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.658182	5.011614	Radiometer
Post-test	1.658389	5.005088	Radiometer
Pre-test	15.3941	96.29982	Radiometer
Post-test	15.49762	92.2056	Radiometer
Pre-test	54.28824	453.4362	Heat Flux Gage
Post-test	54.28885	447.7183	Heat Flux Gage



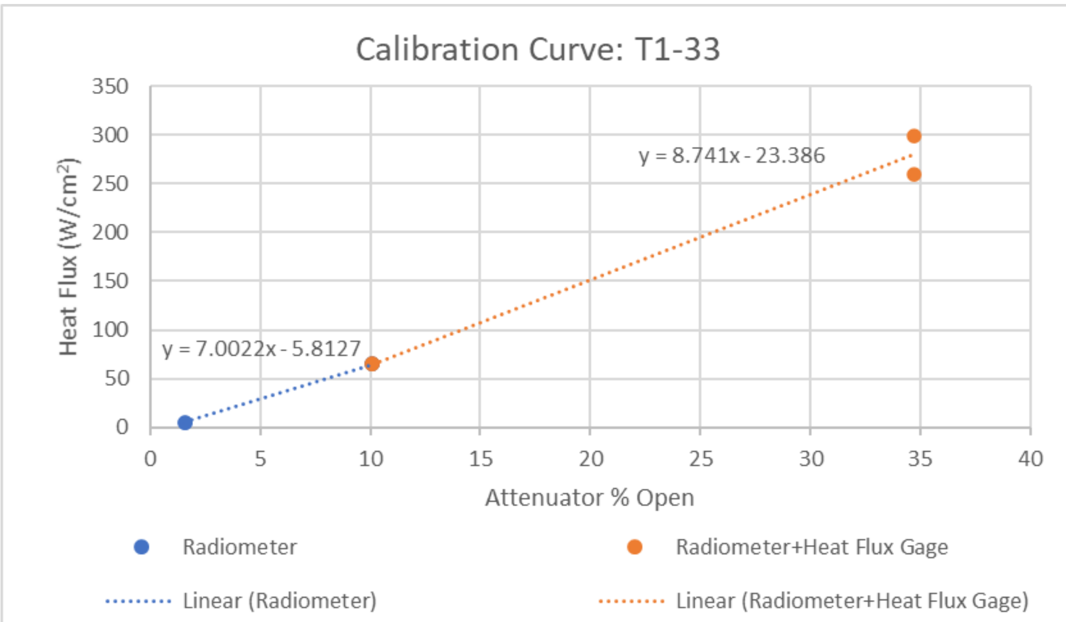
Test 1-32

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.557975	5.157226	Radiometer
Post-test	1.55791	4.995653	Radiometer
Pre-test	10.29089	66.08342	Radiometer
Post-test	10.2909	63.43613	Radiometer
Pre-test	34.50067	301.0984	Heat Flux Gage
Post-test	34.50009	296.4236	Heat Flux Gage



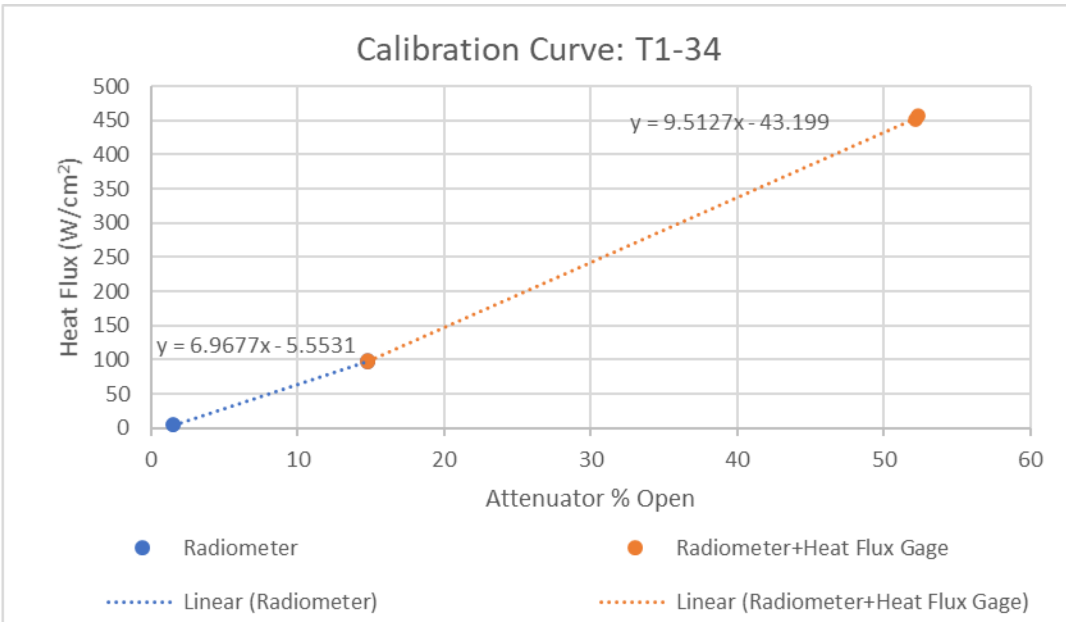
Test 1-33

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.558053	5.097151	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	10.10663	64.95617	Radiometer
Post-test	N/A	N/A	N/A
Pre-test	34.69899	299.5554	Heat Flux Gage
Post-test	34.69795	260.2689	Heat Flux Gage



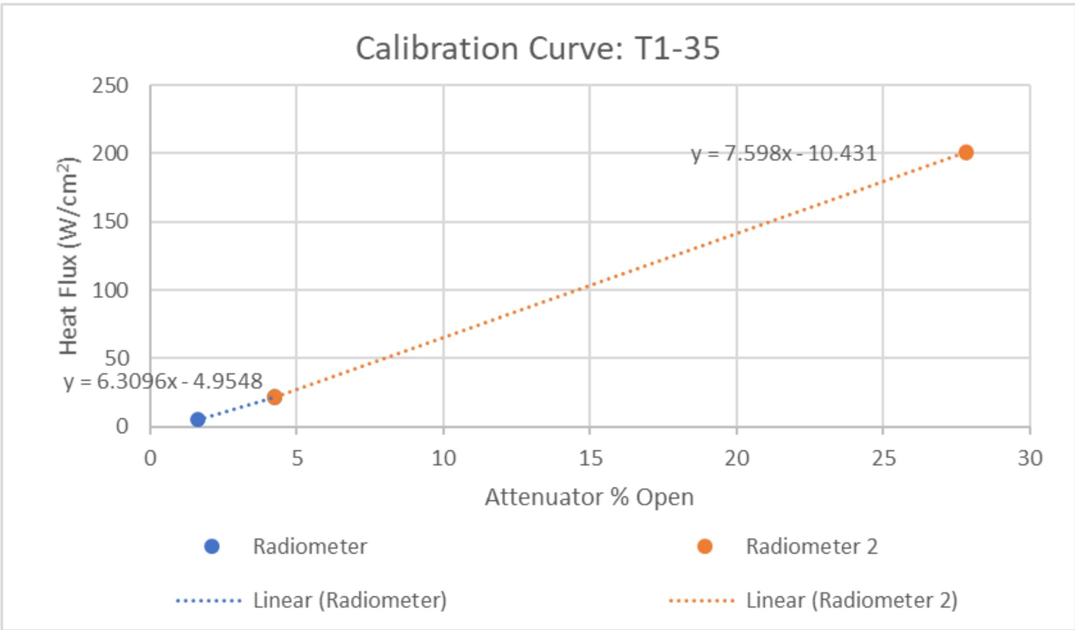
Test 1-34

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.498024	4.845177	Radiometer
Post-test	1.497897	4.923368	Radiometer
Pre-test	14.79129	98.57549	Radiometer
Post-test	14.79009	96.43265	Radiometer
Pre-test	52.18968	450.9348	Heat Flux Gage
Post-test	52.30603	456.6966	Heat Flux Gage



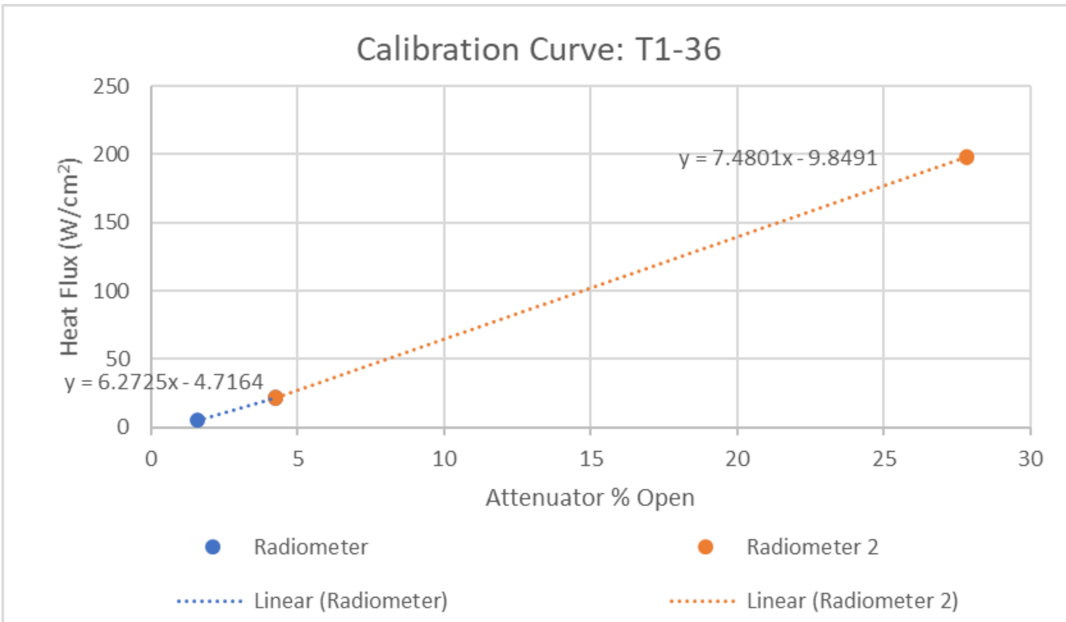
Test 1-35

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.598086	5.13229	Radiometer
Post-test	1.598095	5.124728	Radiometer
Pre-test	4.250441	22.03193	Radiometer
Post-test	4.250293	21.69478	Radiometer
Pre-test	27.81012	200.4494	Radiometer
Post-test	27.81006	201.2914	Radiometer



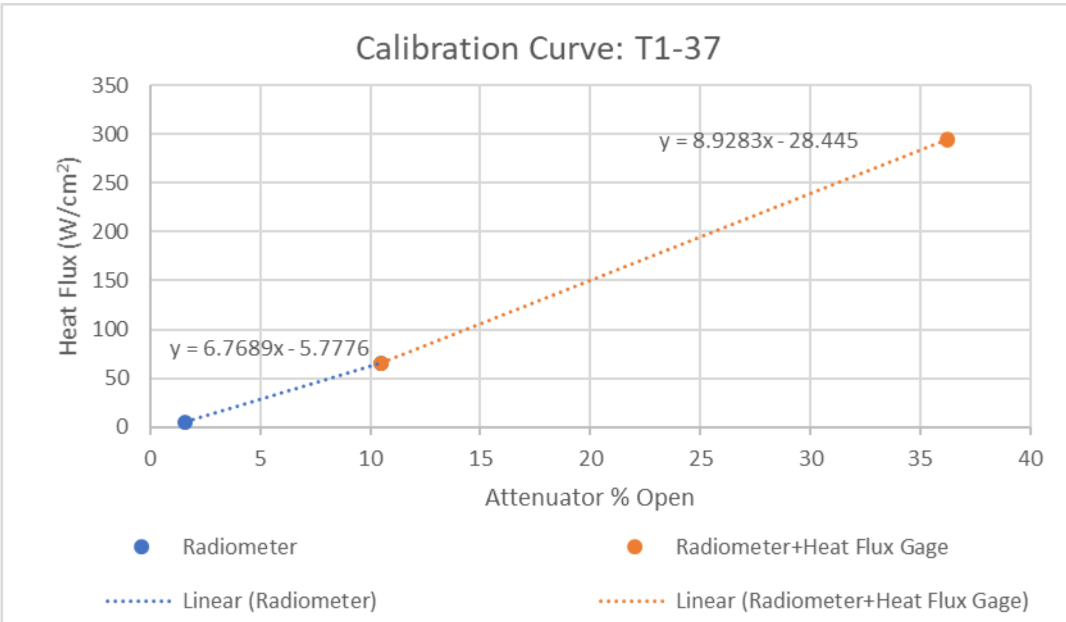
<u>**Test 1-36**</u>

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.557567	5.091885	Radiometer
Post-test	1.55837	5.020188	Radiometer
Pre-test	4.250497	22.44991	Radiometer
Post-test	4.249955	21.43652	Radiometer
Pre-test	27.81022	198.9948	Radiometer
Post-test	27.80978	197.3521	Radiometer



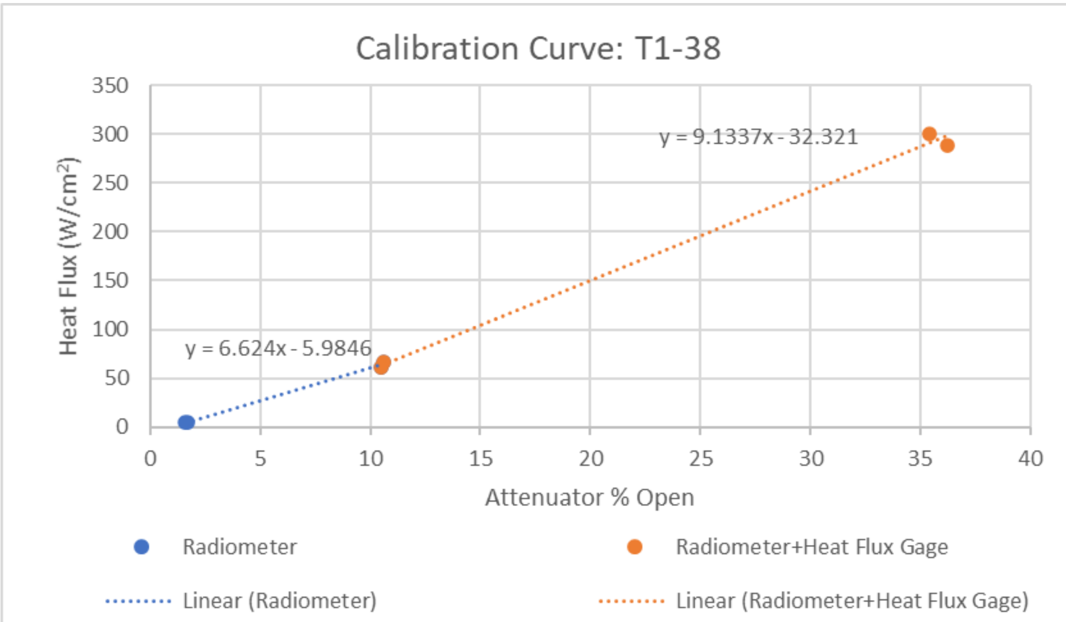
Test 1-37

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.598184	4.954998	Radiometer
Post-test	1.5981	5.125097	Radiometer
Pre-test	10.49711	65.7972	Radiometer
Post-test	10.49654	64.75132	Radiometer
Pre-test	36.20007	293.9793	Heat Flux Gage
Post-test	36.1999	295.5402	Heat Flux Gage



Test 1-38

Phase	Attenuator Position (% open)	Heat Flux (W/cm^2)	Instrumentation
Pre-test	1.698245	5.13624	Radiometer
Post-test	1.598098	4.748306	Radiometer
Pre-test	10.59986	65.98444	Radiometer
Post-test	10.49655	61.76914	Radiometer
Pre-test	35.40368	300.649	Heat Flux Gage
Post-test	36.19958	289.0009	Heat Flux Gage



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