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High Energy Arcing Fault (HEAF) Sandia National Laboratories 2023 Report

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ABSTRACT

High Energy Arcing Faults (HEAFs) are hazardous events in which an electrical arc leads to the rapid release of energy in the form of heat, vaporized metal, and mechanical force. In Nuclear Power Plants (NPPs), these events are often accompanied by loss of essential power and complicated shutdowns. To confirm the probabilistic risk analysis (PRA) methodology in NUREG/CR-6850, which was formulated based on limited observational data, the NRC led an international experimental campaign from 2014 to 2016. The results of these experiments uncovered an unexpected hazard posed by aluminum components in or near electrical equipment and the potential for unanalyzed equipment failures. Sandia National Laboratories (SNL), in support of the NRC work, collaborated with NIST, BSI, KEMA, and NRC to support the full-scale HEAF test campaign in 2023. SNL provided high speed and real time from visible and infrared video/data of tests that collected data from copper and aluminum busses from switchgears and bus-ducts. Part of SNL work was to place cameras with high-speed data collection capability at different vantage points that provide the NRC a more complete and granular view of the test events.

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CONTENTS

Abstract....3

Acknowledgements....4

Executive Summary....13

Acronyms and Terms....14

1. Testing Settings and Conditions....15
   - 1.1. Tests Description....17
   - 1.2. Cameras Used....17
2. Medium-voltage Bus Ducts....19
   - 2.1. Test 2-40 (4.16kV – 30kA – Target 4 Seconds – Copper Bus – Aluminum Enclosure) – Bus Duct Configuration – August 7, 2023....20
   - 2.2. Test 2-41 (4.16kV – 30kA – Target 4 Seconds – Aluminum Bus – Aluminum Enclosure) – Bus Duct Configuration – August 8, 2023....26
3. Medium-voltage Electrical Enclosures....31
   - 3.1. Test 2-35 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration – August 9, 2023....31
   - 3.2. Test 2-37 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration – August 10, 2023....37
   - 3.3. Test 2-36 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 11, 2023....44
   - 3.4. Test 2-38 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Cross-Aisle Configuration - August 14, 2023....51
   - 3.5. Test 2-39 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Back-to-Back Configuration - August 15, 2023....59
4. Low-voltage Electrical Enclosures....69
   - 4.1. Test 2-33A (600V – 15kA – Target 8 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 16, 2023....69
   - 4.2. Test 2-33B (480V – 15kA – Target 8 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 17, 2023....75
   - 4.3. Test 2-34A (480V – 8kA – Target 17.5 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 18, 2023....80
5. Thermal Behavior....87
   - 5.1. Temperature Behavior After Testing....87
   - 5.2. Maximum Radiance and Angles for Bus Duct Testing....87
     - 5.2.1. Test 2-40 – Aluminum Enclosure – Copper Bus Bar – 4 Seconds Test 4.16kV – 30kA....88
     - 5.2.2. Test 2-41 – Aluminum Enclosure – Aluminum Bus Bar – 4 Seconds Test 4.16kV – 30kA....92
6. Conclusion....97

References....98

Distribution....99

LIST OF FIGURES

Figure 1-1 Aerial view of the test facility with placement of the tent covering the external cameras for the medium and low-voltage tests – Google Maps 15
Figure 1-2 Isometric view of Test Cell 9 (top) and Test Cell 7 (bottom) with respect to KEMA facility test bay locations – (KEMA Source). 16
Figure 2-1: Bus duct experiments (Test 2-40 & Test 2-41) cameras locations. 19
Figure 2-2: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background from the burning of the Cu bus...20
Figure 2-3: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice that there is no visibility of the test as the enclosure is being consumed by the arc/fire 3 seconds into the test..21
Figure 2-4: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice that a dark cloud envelope the test bay 4 seconds even if the arc is still going. 21
Figure 2-5: From top left (clockwise): v1310 at southwest side showing the enclosure being consumed by the arc; v7 elevated from the northeast showing the initial breach; GoPro outside southeast; GoPro inside floor northeast. 22
Figure 2-6: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm^2 sr) synchronized with a visible color camera at the end of the test...22
Figure 2-7: Sample frames from synchronized video of 4k and LWIR cameras 4 seconds into the test. 23
Figure 2-8: Fit to measured AlO spectrum from a solid rocket experiment – Gill et al. [1]. The curve indicates the spectral location of AlO emission. Expected temperatures for burning Aluminum should be in the range of 2800K to 3300K [2]. 24
Figure 2-9: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm^2 sr) synchronized with a visible color camera...24
Figure 2-10: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice the white fireball (burning the Al bus). Compared to Test 2-40 where the fireball has more brown and orange colors from burning the Cu bus. 26
Figure 2-11: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice that there is no visibility of the test as the enclosure is being consumed by the arc/fire 2 seconds into the test..27
Figure 2-12: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice that a dark cloud envelopes the test bay 4 seconds at the end of the test, but the cloud is not as dark as in Test 2-40 due to the high flux from the arc and the aluminum from the bus and the enclosure being burned. 27
Figure 2-13: From top left (clockwise): v1310 at southwest side; v7 elevated from the northeast of the test; GoPro outside southeast; GoPro inside floor southwest..28
Figure 2-14: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm^2 sr) synchronized with a visible color camera early in the test, similar time as Figure 2-9. Notice that the visible video background is extremelly bright and that it tends to reduce contrast on the half transparent IR data. 28
Figure 2-15: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm2 sr) synchronized with a visible color camera at the end of the test. 29
Figure 2-16: Sample frames from synchronized video of 4k and LWIR cameras 3 seconds into the test...29
Figure 3-1: Electrical Enclosure (Test 2-35) cameras locations (top) with switchgear enclosure configuration (bottom)...31

Figure 3-2: Test 2-35 imaged through 4k camera – camera imaging at 1000 fps. 32
Figure 3-3: Test 2-35 imaged through 4k camera – notice enlcosure door blown open and venting on top – camera imaging at 1000 fps. 33
Figure 3-4: Test 2-35 imaged through 4k camera – notice fireball venting from adjacent enclosure and burning particulate ejection – camera imaging at 1000 fps. 33
Figure 3-5: From top left (clockwise): v1310 while the door is being blown open; v7 elevated from the northeast of the test while the east side enclosure vents; GoPro outside southwest; GoPro outside floor southeast while molten material is dumped out of the east enclosure. 34
Figure 3-6: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.8 seconds into the test. 34
Figure 3-7: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 3 seconds into the test. Notice that the higher fire activity is occurring on the adjacent enclosure. 35
Figure 3-8: Sample frames from synchronized video of 4k and LWIR cameras 3 seconds into the test. Notice that the IR doesn't show the metal spray to the right of the second enclosure. The spray of metal particulate that probably emitting light in the visible in a narrow band instead of the continuum from a Planck curve profile. 35
Figure 3-9: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Notice enclosure in the foreground shows highest temperature on the top after the test. Arc is induced in the background enclosure. Temperature range from 31 to 660 °C. 36
Figure 3-10: Electrical Enclosure (Test 2-36 & Test 2-37) cameras locations (top) with switchgear enclosure configuration (bottom). Main difference to Test 2-35 is the shorter focal length for the 1310 VEO giving it a wider view. 37
Figure 3-11: Test 2-37 imaged through 4k camera first millisecond into the test – camera imaging at 1000 fps – showing a v-shape object being ejected on the top. 38
Figure 3-12: Test 2-37 imaged through 4k camera 1 second into the test – camera imaging at 1000 fps – where the instrument stand is falling after being pushed by the ejected door from the enclosure where the arc is initiated. 39
Figure 3-13: Test 2-37 imaged through 4k camera 3 second into the test – camera imaging at 1000 fps – where the arc is affecting the second enclosure (mostly in the back). Notice the instrument stand on the ground by this time. 39
Figure 3-14: Test 2-37 imaged through 4k camera 3.5 seconds into the test – camera imaging at 1000 fps – The second enclosure ejecting a large fireball in side pointing north (this has been going on for half a second), while the first enclosure is consumed by the fire and ejecting sprays of burning metal particulate to the south. 40
Figure 3-15: From top left (clockwise): v1310 while there isventing in the adjacent enclosure; v7 elevated from the northeast of the test while the west side enclosure vents in the back; GoPro outside southwest while access door is being ejected; GoPro ouside floor southeast view of the same event. Notice instrument stand is being pushed by the ejected door. 41
Figure 3-16: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 2 seconds into the test. 41
Figure 3-17: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image almost 4 seconds into the test showing the ejection of a panel of the adjacent enclosure. 42
Figure 3-18: Sample frames from synchronized video of 4k and LWIR cameras close to 4 seconds into the test. Notice that the IR shows panel being ejected on the right side. 42

Figure 3-19: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc was induced in the background enclosure. Temperature range from 31 to 300 °C. 43
Figure 3-20: Electrical Enclosure (Test 2-36) camera locations (top) with switchgear enclosure configuration (bottom). Main difference to Test 2-35 is the shorter focal length for the 1310 VEO giving it a wider view. 44
Figure 3-21: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps 45
Figure 3-22: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps – 2 seconds into the test. The view from the south seems to be dominated by dark smoke and there is fire activity in the north side....46
Figure 3-23: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps – 4 seconds into the test. There is a fire engulfing the enclosure where the arc was initiated, also there is spray of burning metal particulate. The second enclosure seems to be mostly engulfed by the dark smoke with some fire activity on the east side. 46
Figure 3-24: From top left (clockwise): v1310 view at 1.5 seconds into the test while venting in the adjacent enclosure; v7 elevated from the northeast of the test while the east side enclosure vents but the arc starting enclosure suffers the brunt of the test; GoPro outside west during the arc on the west side enclosure; GoPro inside floor notheast view of the damage to the first enclosure while the second enclosure starts venting gases....47
Figure 3-25: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 1 second into the test....48
Figure 3-26: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 4 second into the test and not that different than at the beginning of the test.......48
Figure 3-27: sample frames from synchronized video of 4k and LWIR cameras close to 4 seconds into the test. While there seems to be activity in IR and visible in the back (north side), the IR seems to indicate that the second enclosure is not that hot, even if the first eclosure keeps burning for several minutes after the test. 49
Figure 3-28: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the lower background enclosure. Temperature range from 20 to 150 °C. Notice that the there is minimum change in temperature during the 15 minutes of the three frames, indicating a continuos fire in the enclosure where the arc was started....49
Figure 3-29: Electrical enclosure cross-aisle configuration (Test 2-38) cameras locations (top) with switchgear enclosure configuration (bottom). 51
Figure 3-30: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps. Notice the panel ejected to the east. The arc was initiated in the north enclosure – behind the enclosure in view. 52
Figure 3-31: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – 2 seconds into the test. Burning metal particles are flying out from both ajacent enclosures and the south enclosure is venting fire through its southern panel. Notice the smoke engulfing the test bay....53
Figure 3-32: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – 4 seconds into the test. A fireball is now engulfing the east side of the test bay....53
Figure 3-33: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – almost 5 seconds into the test. 54
Figure 3-34: From top left (clockwise): v1310 view at 1 second into the test before the testbay becomes engulfed by smoke on the west side; v7 elevated from the northeast of the test while showing the east panel being ejected from enclosure where the arc was started; GoPro inside

floor notheast view showing a panel flying from the enclosure where the arc started; GoPro outside southeast view during the test. 55
Figure 3-35: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 1.5 seconds into the test. 56
Figure 3-36: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image at the end of the test. 56
Figure 3-37: Sample frames from synchronized video of 4k and LWIR cameras at the beginning of the test. The LWIR image shows the square profile of the panel ejected from the enclosure where the arc was started, see red arrow. 57
Figure 3-38: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the front center enclosure (red hot on top). Temperature ranges from 20 to 300 °C. The open panel shows hot items inside the enclosure that are still hot and close to 400 °C after more than 11 minutes. 57
Figure 3-39: Electrical enclosure back-to-back configuration (Test 2-39) cameras locations (top) with switchgear enclosure configuration (bottom). 59
Figure 3-40: Test 2-39 imaged through 4k camera first millisecond into the test – camera imaging at 1000 fps – showing a v-shape object being ejected on the top, similar to Test 2-37 where the front access door was also ejected. 60
Figure 3-41: Test 2-39 imaged through 4k camera 46 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing access door being ejected and deforming. 61
Figure 3-42: Test 2-39 imaged through 4k camera 120 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing access door hitting the instrument stand. 61
Figure 3-43: Test 2-39 imaged through 4k camera 230 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing multiple explosion while the rack is falling. 62
Figure 3-44: Test 2-39 imaged through 4k camera 3 seconds into the test – camera imaging at 1000 fps – showing the instrument stand on the ground and the burning in the back of the southeast and northeast enclosures. The southeast enclosure also shows fire coming out from one of its access door. 62
Figure 3-45: From top left (clockwise): v1310 view 0.25 seconds into the test with the access door twirling away from the enclosure; v7 elevated from the northeast of the test bay, at 2.5 seconds, while showing fire at the interface of the southeast and northeast enclosures; GoPro inside floor southeast view showing instrument stand in the ground and he southeast enclosure east side ejecting fire during the test; GoPro southwest view while instrument stand and door enclusure fall to the ground. 63
Figure 3-46: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 3.5 seconds into the test. 64
Figure 3-47: Sample frames from synchronized video of 4k and LWIR cameras close to 1.5 seconds into the test. The LWIR image shows heat (probably fire) at the interface between the north and south enclosures and that part of it is occluded by the smoke. 64
Figure 3-48: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the front center enclosure (red hot on top). Temperature ranges from 20 to 300 °C. The open panel shows hot items inside the enclosure that are still hot and close to 400 °C after more than 11 minutes. 65
Figure 3-49: Different approximations to estimate the velocity of the ejected access door in Test 2-39. Top-left shows a first order approximation where the door is assumed to be ejected straight. Top-Right assumes the door is ejected at an angle, because we can see that it hits the instrument stand. Bottom shows a more complex approximation where the door rotates on one of its hinges before hitting the instrument stand 66

Figure 4-1: Electrical enclosure lineup configuration (Test 2-33A) cameras locations (top) with switchgear enclosure configuration (bottom). 69
Figure 4-2: Test 2-33A imaged through 4k camera 200 ms into the test – camera imaging at 500 fps. 70
Figure 4-3: Test 2-33A imaged through 4k camera 0.5 second into the test – camera imaging at 500 fps. 70
Figure 4-4: Test 2-33A imaged through 4k camera 2.6 seconds after the test finished – camera imaging at 500 fps. 71
Figure 4-5: From top left (clockwise): v1310 view 350 ms into the test; v7 elevated from the northwest of the test bay, at 300 ms; GoPro inside floor northwest view; GoPro southeast view right at the beginning of the test. 72
Figure 4-6: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 400 ms into the test. 72
Figure 4-7: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.7 seconds at the end of the test. 73
Figure 4-8: Sample frames from synchronized video of 4k and LWIR cameras close to 0.6 seconds into the test. The LWIR image shows heat (probably fire) at the bottom of the west enclosure. 73
Figure 4-9: Temperature images from the LWIR camera A655 through 1 minute intervals, starting ~1 minute after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 28.9 to 375 °C. 74
Figure 4-10: Electrical enclosure lineup configuration (Test 2-33B) cameras locations (top) with switchgear enclosure configuration (bottom). 75
Figure 4-11: Test 2-33B imaged through 4k camera. Test that lasted 8 seconds. Pictures are shown at ~1 second intervals during the test (sequenced left to right, top to bottom) – camera imaging at 500 fps. 76
Figure 4-12: From top left (clockwise): v1310 view ~6 seconds into the test; v7 elevated from the northwest of the test bay, at ~7 seconds; GoPro inside floor northwest view; GoPro southwest view in the middle of the test. 77
Figure 4-13: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image. 77
Figure 4-14: Sample frames from synchronized video of 4k and LWIR cameras close to 7.5 seconds into the test. The LWIR image shows heat profile similar to the one collected by the visible camera. 78
Figure 4-15: Temperature images from the LWIR camera A655 through 8.5 minutes intervals, starting right after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 38.9 to 660°C. 78
Figure 4-16: Electrical enclosure lineup configuration (Test 2-34A) cameras locations (top) with switchgear enclosure configuration (bottom). 80
Figure 4-17: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~1.5 seconds into the test – camera imaging at 300 fps. 81
Figure 4-18: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~2 seconds into the test – camera imaging at 300 fps. 82
Figure 4-19: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~3.5 seconds into the test – camera imaging at 300 fps. 82
Figure 4-20: From top left (clockwise): v1310 view ~1 second into the test; v7 elevated from the northwest of the test bay, at ~1.5 seconds; GoPro outside floor southeast view early on the test; GoPro northwest view at the end of the test. 83

Figure 4-21: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 1.7 seconds into the test. 83
Figure 4-22: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 3.8 seconds into the test. 84
Figure 4-23: Sample frames from synchronized video of 4k and LWIR cameras close to 2.8 seconds into the test. The LWIR image shows heat profile similar to the one collected by the visible camera 84
Figure 4-24: Temperature images from the LWIR camera A655 through 2 minutes intervals, starting half a minute after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 23.89 to 660°C. 85
Figure 5-1: Radiance profile for Test 2-40 where the arc is viewed through the breach and is included in the calculations. Notice that the plume is parallel to the bus duct, see white arrow. The white rectangle is the area of summation and averaging. 88
Figure 5-2: Radiance curves for Test 2-40 where the arc fault view is included in the calculations. Notice that the plume is parallel to the bus duct. 89
Figure 5-3: Radiance profile for Test 2-40 where the arc is not included in the calculations. Notice that the plume is parallel to the bus duct or is contained by the access door. The white rectangle is the area of summation and averaging. 90
Figure 5-4: Radiance curves for Test 2-40 where the arc fault view is not included in the calculations. Notice that the plume under the bus duct is parallel to it. 91
Figure 5-5: Radiance profile for Test 2-41 where the arc is viewed through the breach and is included in the calculations. Notice that the plume is parallel to the bus duct, see white arrow. The white rectangle is the area of summation and averaging. 92
Figure 5-6: Radiance curves for Test 2-41 where the arc fault view is included in the calculations. Notice that the plume is parallel to the bus duct. 93
Figure 5-7: Radiance profile for Test 2-41 where the arc is not included in the calculations. Notice that the highest magnitude plume roughly follows the shape of the bus duct. The white rectangle is the area of summation and averaging. 94
Figure 5-8: Radiance curves for Test 2-41 where the arc fault view is not included in the calculations. Notice that the plume under the bus duct is parallel to it. 95

LIST OF TABLES

Table 1-1: Basic specifications of the cameras used in this test campaign. 17
Table 2-1: Camera settings for Test 2-40 25
Table 2-2: Test 2-40 Events 25
Table 2-3: Camera settings for Test 2-41. The 655 LWIR camera is not used in this test. 30
Table 2-4: Test 2-41 Events 30
Table 3-1: Camera settings for Test 2-35 36
Table 3-2: Test 2-35 Events 36
Table 3-3: Camera settings for Test 2-37 43
Table 3-4: Test 2-37 Events 43
Table 3-5: Camera settings for Test 2-36 50
Table 3-6: Test 2-36 Events 50
Table 3-7: Camera settings for Test 2-38 58
Table 3-8: Test 2-38 Events 58
Table 3-9: Camera settings for Test 2-39 68
Table 3-10: Test 2-39 Events 68

Table 4-1: Camera settings for Test 2-33A 74
Table 4-2: Test 2-33A Events 74
Table 4-3: Camera settings for Test 2-33B 79
Table 4-4: Test 2-33B Events 79
Table 4-5: Camera settings for Test 2-34 86
Table 4-6: Test 2-34 Events 86
Table 5-1: Maximum temperature measured at the end of IR camera recording with no smoke and dust in the air – Assumed Emissivity of 0.9 – Assumed Transmission of 0.90 (NaCl Window) 87

EXECUTIVE SUMMARY

This report shows the data collected by high-speed and real-time visible and infrared cameras deployed at the KEMA facility (Chalfont, PA) during the High Energy Arcing Fault (HEAF) test campaign of 2023. The report complements the video data generated. The test campaign was sponsored and directed by the U.S. Nuclear Regulatory Commission (NRC). The report includes the description of the tests, encompassing cameras placement, cameras settings, sample camera views and the table of events determined from the perspective of the cameras.

ACRONYMS AND TERMS

Acronym/Term	Definition
FOV	Field of View
FPS	Frames per Second
HEAF	High Energy Arcing Fault
HS	High- Speed
LWIR	Long Wave Infrared (7.5-12μm)
MWIR	Mid Wave Infrared (3-5μm)
NaN	Not a Number
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
SNL	Sandia National Laboratories
TC7	Test Cell 7
TC9	Test Cell 9

1. TESTING SETTINGS AND CONDITIONS

The medium and low voltage tests were performed at KEMA labs in Chalfont, PA during two weeks in the middle of August of 2023. Figure 1-1 shows the aerial view (from Google maps), showing the full facility where the experiments were performed – white line demarked. The maps also show the two locations where the external high-speed cameras were located depending on the test performed. During the medium voltage tests, the four main high-speed cameras were in front of test cell 9 (TC9) (southeast of the test cell). For the low voltage tests, the external cameras were placed in front of test cell 7 (TC7) (southeast of the test cell).

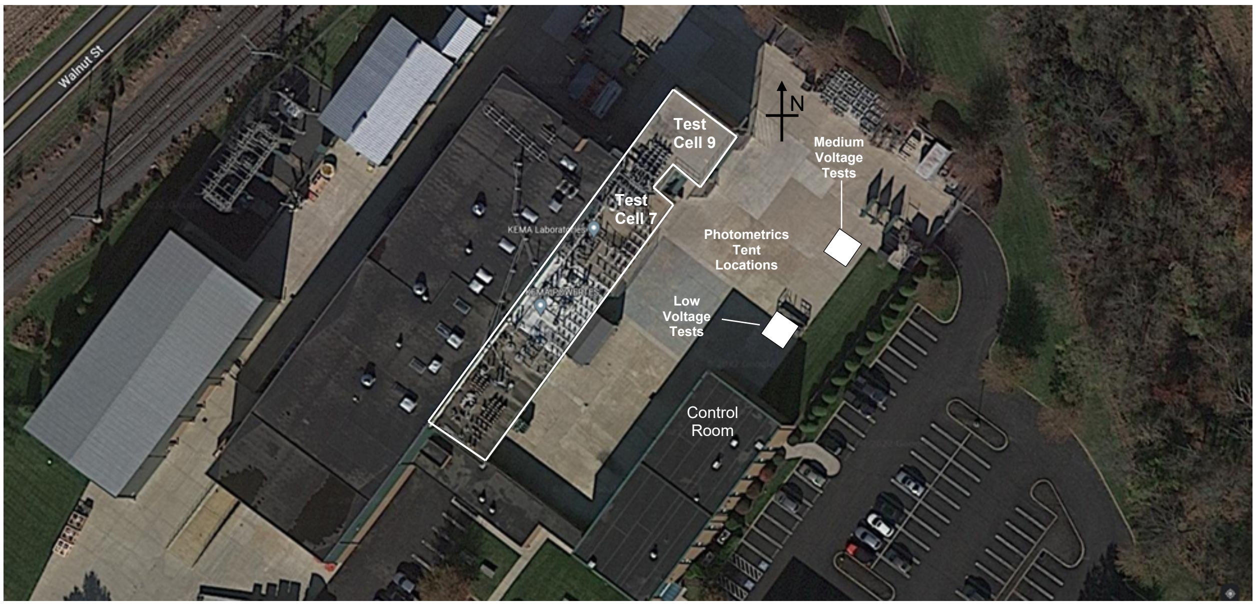


Figure 1-1 Aerial view of the test facility with placement of the tent covering the external cameras for the medium and low-voltage tests – Google Maps

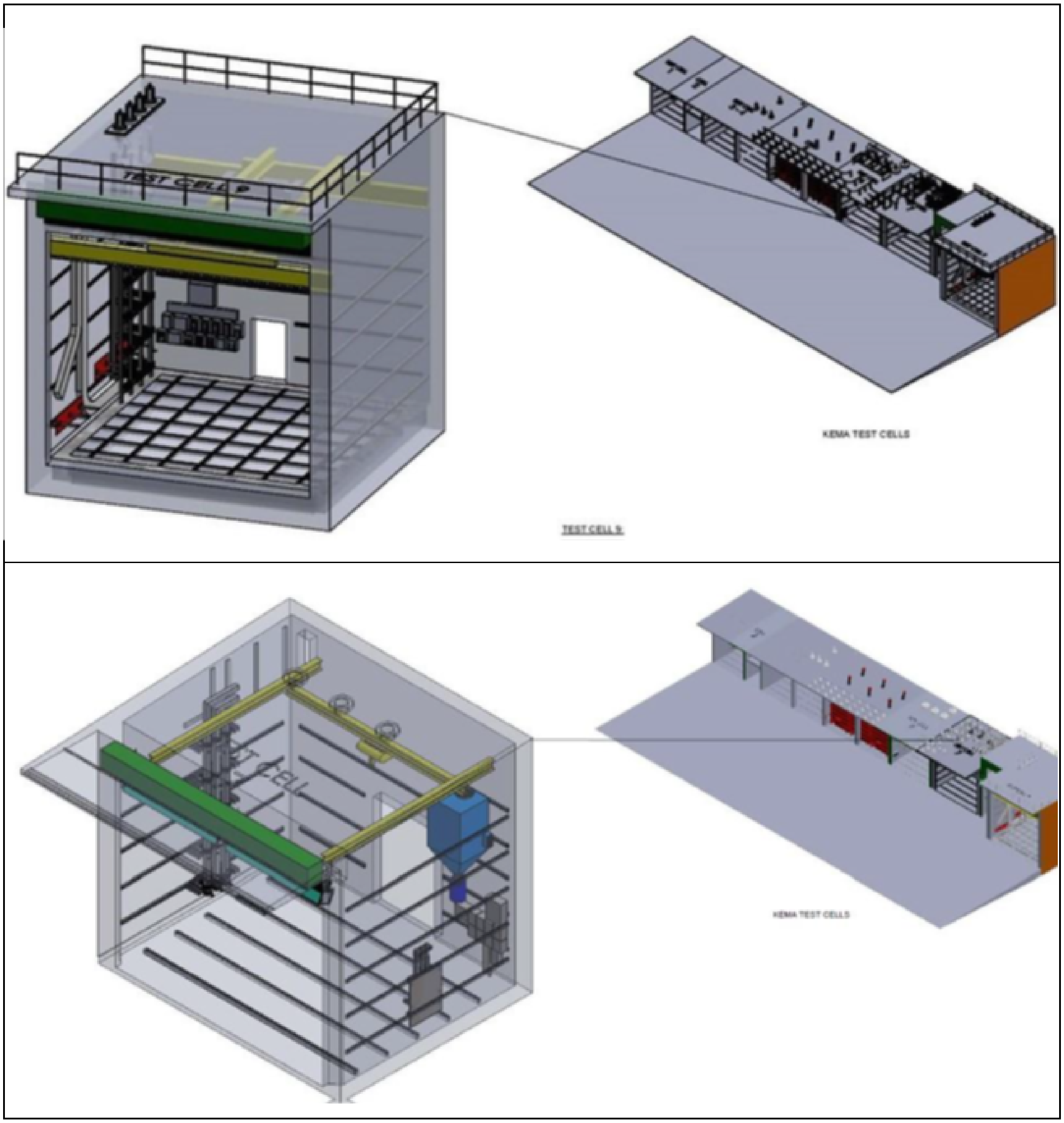


Figure 1-2 Isometric view of Test Cell 9 (top) and Test Cell 7 (bottom) with respect to KEMA facility test bay locations – (KEMA Source).

1.1. Tests Description

There was a total of ten tests performed during this test series with the following current and voltage configurations:

- Two medium-voltage bus ducts tests: 4.16kV – 30kA
- Five medium-voltage switchgear tests: 6.9kV – 32kA
- Three low-voltage switchgear tests: 480/600 V – 8/15kA

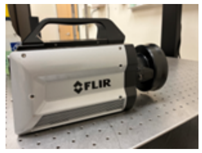
The tests varied in duration (4 seconds for medium-voltage tests and 8 to 17.5 seconds for low-voltage), bus bar material (aluminum and copper), and enclosure material (steel and aluminum) for the bus duct experiments. For the switchgear experiments, multiple switch gear placements were examined but materials were maintained for all tests (copper for the bus, and steel for the enclosure). The data is presented in the following order: first bus ducts, second medium-voltage switchgears, and third low-voltage switchgears.

1.2. Cameras Used

Several cameras were deployed with the intention of providing specific views that would fully capture the HEAF event. The specific location of the cameras was influenced by the risks to the instruments and their capabilities to perform. Table 1-1 shows a list of the different cameras that were deployed during this test series and a brief description of each. Note that one of the parameters included in the table is pixel size. This detail was included in the table to provide a quick record of the cameras' capability and should allow continuity in future experiments. Even if the same exact camera models may not be available, cameras with similar capabilities can be deployed. Also, as documented in the table, some parameters were not maximized so that other functionality could be achieved. For example, the Go Pros were not used at their maximum resolution to allow recording at a frame rate of 120 fps.

Table 1-1: Basic specifications of the cameras used in this test campaign.

Camera Make	Camera Model	Picture	Frame Rate	Spectral Response	Resolution	Pixel Size	Utilization
Vision Research	v1212c		12,000	Visible Bayer Filter	1280x800	28 µm	HS Camera for speed measurements of objects of interest
Vision Research	VEO1310c		10,000	Visible Bayer Filter	1280x960	18 µm	HS camera to provide different view location
Vision Research	VEO 4k 990s		1,000	Visible Bayer Filter	4096x2000	6.75 µm	HS camera for large view of the test
Vision Research	V7		4,000	0.35-1.1 µm	800x600	22 µm	HS camera for view inside the test cell – bus duct testing only
FLIR	X6901 InSb		1,004	3-5 µm	640x512	25 µm	HS MWIR camera for looking through some dust and

Camera Make	Camera Model	Picture	Frame Rate	Spectral Response	Resolution	Pixel Size	Utilization
							radiance measurement
FLIR	X6981 SLS		1,004	7.5-12 µm	640x512	25 µm	HS LWIR camera for looking through some dust and radiance measurement
FLIR	A655		25	7.5-14 µm	640x480	17 µm	Real time LWIR camera to measure temperature for longer times (minutes) after the test
GoPro	HERO7		120	Visible Bayer Filter	1920x1080 (30fps - 3840x2160)	2.2 µm	High risk and sound cameras

Note that the timing is based on the trigger for the high-speed cameras (v1212, the v1310 and the VEO 4k) that used IRIG-B form GPS to time stamp their images. The time was corrected by subtracting 8.333 ms, which corrects the timing clock from selecting a falling edge to trigger the cameras. The end of the test for the cameras is at the end of pulsating flames coming from the systems under test, and the sudden stop of particle ejection pushed by the overpressure from the arc.

Radiance is a radiometric parameter that quantifies the in-band radiant power from an extended surface. In-band means that is restricted to the spectral band of the detector. The MWIR-InSb cameras are set to 3-5 µm and the LWIR-SLS cameras are set to 7.5-12 µm. Radiance is range invariant, ignoring atmospheric losses. The non-microbolometer IR cameras count photon and after calibration for quantum efficiency, spectral response of the imaging system, system losses, linearity range of the sensor, etc., the data from camera is output directly in radiance units. The IR cameras counts photons and express those counts directly as radiance. Since this unit is a direct output of the cameras used for this test series, the data is reported in radiance units. Note that temperature is derived from radiance.

2. MEDIUM-VOLTAGE BUS DUCTS

Figure 2-1 shows the locations of the cameras used in Tests 2-40 and 2-41 and their respective horizontal field of views (the Go Pros field of view are large and fixed; not depicted in figure). The location of the 1310 VEO was intended for easy protection, and to provide an orthogonal view of the bus duct ejecta and the instrument stands. This station had a v1212c, a X6901 (MWIR - InSb), a X6981 (LWIR - SLS) and a 4k VEO. The proximity of the cameras reduced parallax to allow data fusion between the data of the X6901, the X6981 and the 4k VEO. A 1310 VEO Color was deployed near and southwest of the test cell. It was protected with a plexiglass window, something developed during the 2022 campaign. Three Go Pros were used: one in the northeast side of TC9 (inside-floor) and second one inside near the main door at the southwest; and a third one directly south on the floor.

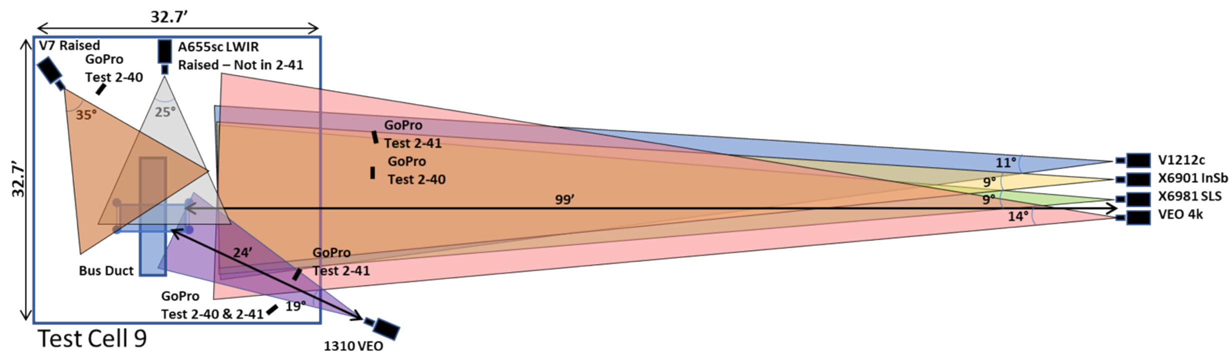


Figure 2-1: Bus duct experiments (Test 2-40 & Test 2-41) cameras locations.

2.1. Test 2-40 (4.16kV – 30kA – Target 4 Seconds – Copper Bus – Aluminum Enclosure) – Bus Duct Configuration – August 7, 2023

The first bus duct test had an intended duration of 4 seconds with an aluminum enclosure and copper bus bars. Figure 2-2 through Figure 2-7 show images of notable features and select events that occurred during Test 2-40.

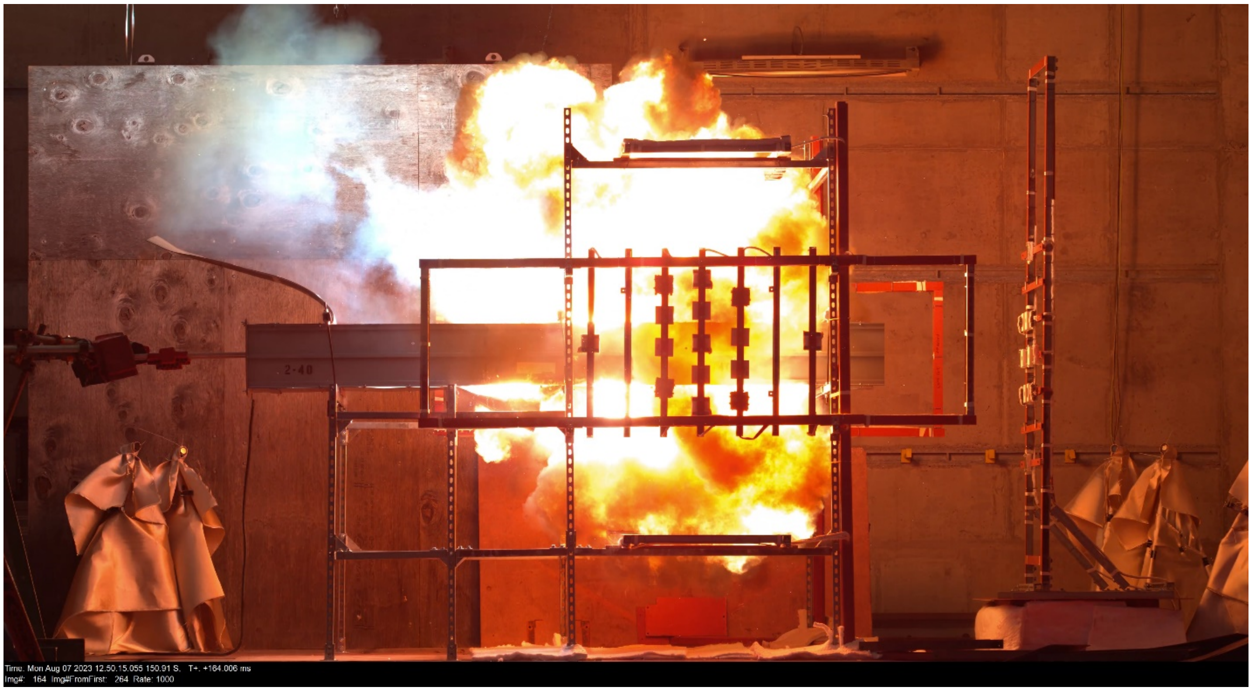


Figure 2-2: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background from the burning of the Cu bus.

Figure 2-3: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice that there is no visibility of the test as the enclosure is being consumed by the arc/fire 3 seconds into the test.

Figure 2-4: Test 2-40 imaged through 4k camera – camera imaging at 1000 fps. Notice that a dark cloud envelope the test bay 4 seconds even if the arc is still going.

Figure 2-5: From top left (clockwise): v1310 at southwest side showing the enclosure being consumed by the arc; v7 elevated from the northeast showing the initial breach; GoPro outside southeast; GoPro inside floor northeast.

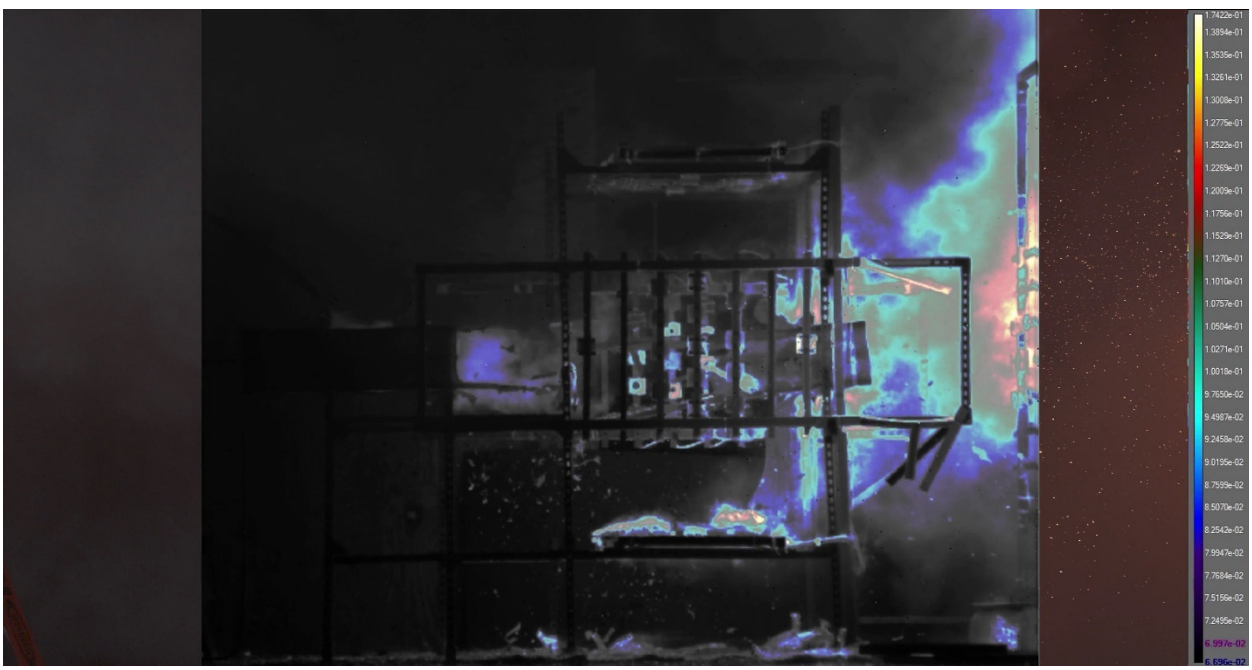


Figure 2-6: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm² sr) synchronized with a visible color camera at the end of the test.

Figure 2-7: Sample frames from synchronized video of 4k and LWIR cameras 4 seconds into the test.

The presence of aluminum results in the combustion of aluminum into a temporary AlO, which emits light in the visible around 485nm, see Figure 2-8, and usually at temperatures in the range of 2800K to 3300K. When these particles cool, the final product is Al_2O_3 or alumina, and it shows as a white powder. In the test it shows in the visible camera as a mostly white light and/or white particles flying away from the test. At the same time, the IR cameras are not able to image the bright region as it is emitting only in the visible. The AlO mechanism can be confused with the plasma from the arc; the white bright particle flying away from the test is an indication of AlO oxidation/burning process, See Figure 2-9 and Figure 2-14. This is important for Tests 2-40 and 2-41 where we were testing aluminum enclosures with aluminum or copper buses.

Because of the ejecta and heat in Test 2-40, the LWIR/real time camera at the top of the test cell was moved for the next test (Test 2-41). The camera was in the path of hot gases and hot particles. The camera had a NaCl window for protection and was located 3 meters above the ground. A lens was damaged during the test and the stickers marking the camera were singed from the heat. It is possible to see during the replay of the video captured by that camera that the view changes focus as the experiment progresses, an indication of the lens being affected by the heat. It took two and half minutes for the camera to recover focus. The GoPro videos shows a test cell that is engulfed by a white glow of particles and gases, with a top of dark smoke and falling hot particles that eventually will become alumina.

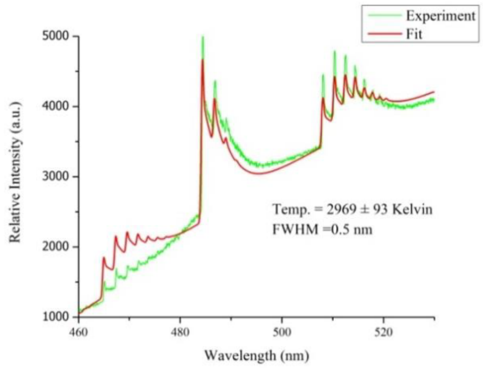


Figure 2-8: Fit to measured AlO spectrum from a solid rocket experiment – Gill et al. [1]**. The curve indicates the spectral location of AlO emission. Expected temperatures for burning Aluminum should be in the range of 2800K to 3300K** [2]**.**

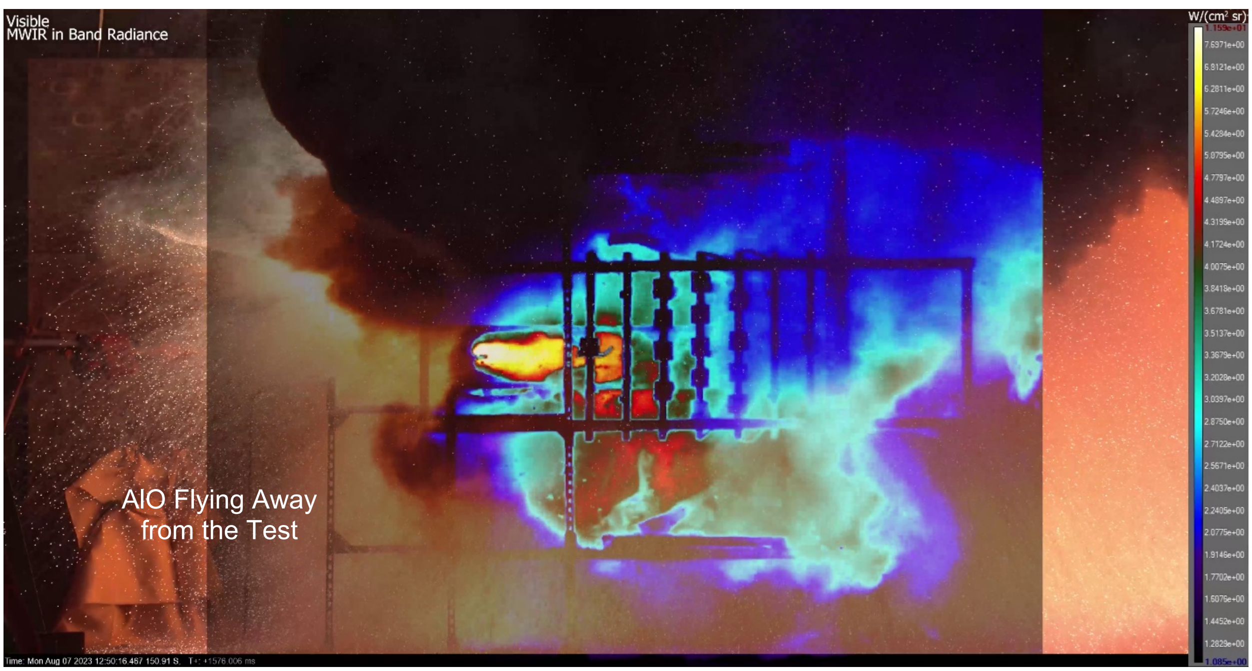


Figure 2-9: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm^2 sr) synchronized with a visible color camera

The camera settings for Test 2-40 are shown in Table 2-1.

Table 2-1: Camera settings for Test 2-40

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (μs) /Calibration	4	150	1	1,000-3,000°C	600-3,000°C	2	100-650°C
f/#	5.6	8	22	2.5	2.5	22	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	115	70	100	100	28	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	13.7	18.7	9.1	9.1	34.9	24.9

Table 2-2 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-40.

Table 2-2: Test 2-40 Events

Event – Delay from Trigger to Current Applied: 26.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-26.3
First Light	37.3	11.0
Breach South Side	442.0	415.7
AlO Particles Ejection – Right Side	476.0	449.7
AlO Particles Ejection – Left Side	606.0	579.7
Smoke and Dust Engulf Test Setup	1628.0	1601.7
End of Arc	NA	4120
Cameras Detect End of Test	4190.0	4163.7

2.2. Test 2-41 (4.16kV – 30kA – Target 4 Seconds – Aluminum Bus – Aluminum Enclosure) – Bus Duct Configuration – August 8, 2023

In the second bus duct test, the X6981 camera was affected by triggering issues and only collected 3,000 frames, with 2,000 set for pre-trigger. While details of the camera setting are being released, data from the camera is not being used. The GoPro videos show a test cell that is engulfed by a white glow of particles and gases. There is a top of dark smoke, in this case brighter than in Test 2-40, and falling hot particles that eventually will become alumina. In this test, the fireball seems to grow until it fills the test cell: in Test 2-40, the fireball is grown to similar size but particles can be easily seen. Figure 2-10 through Figure 2-16 show images of notable features and select events that occurred during Test 2-41. Note, the fireball tends to prevail over other phenomena, see Figure 2-11 and Figure 2-12.

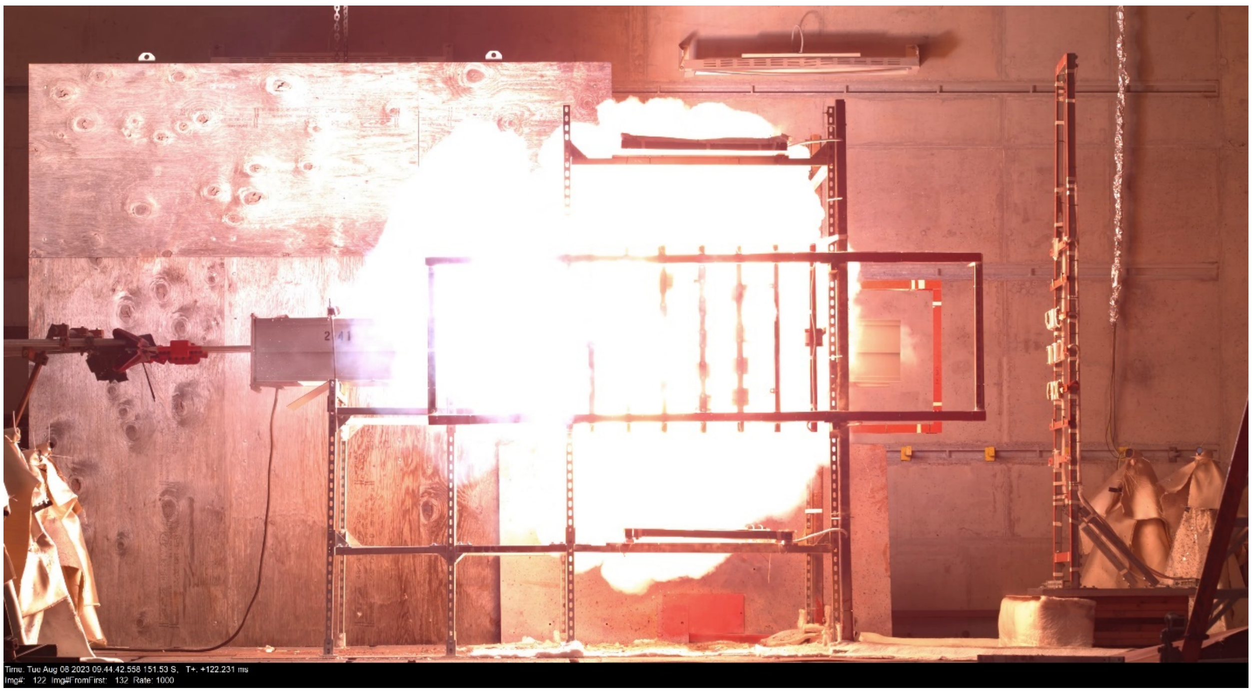


Figure 2-10: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice the white fireball (burning the Al bus). Compared to Test 2-40 where the fireball has more brown and orange colors from burning the Cu bus.

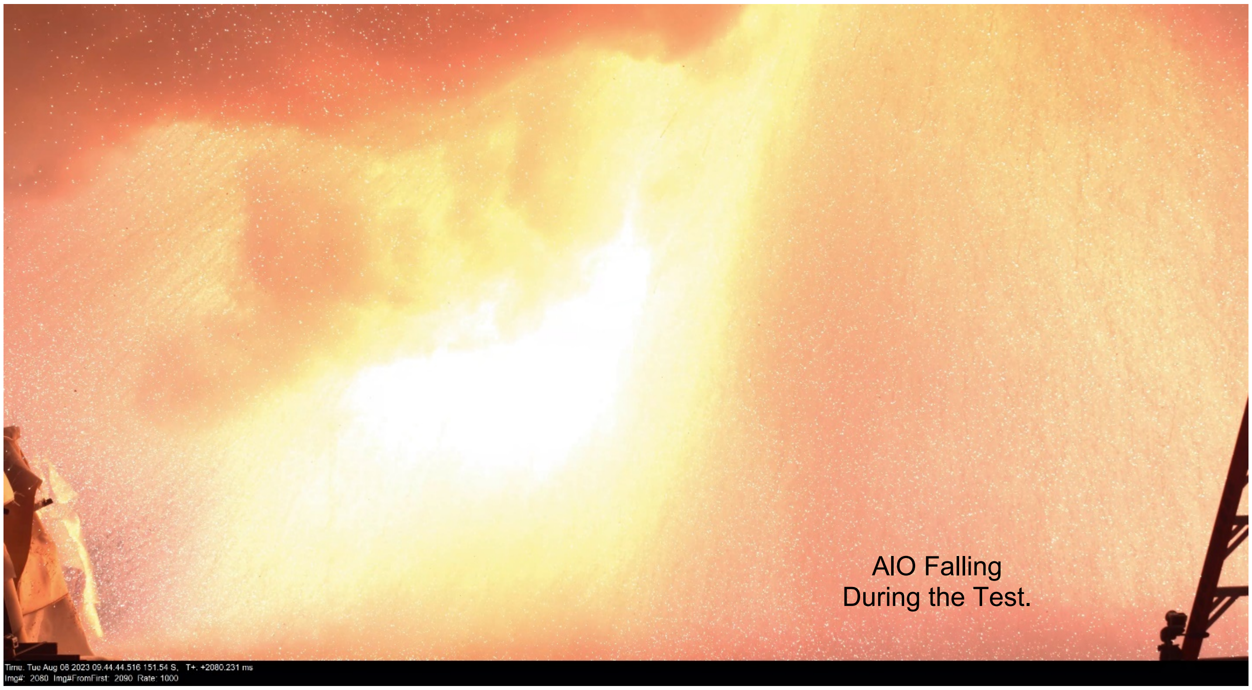


Figure 2-11: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice that there is no visibility of the test as the enclosure is being consumed by the arc/fire 2 seconds into the test.

Figure 2-12: Test 2-41 imaged through 4k camera – camera imaging at 1000 fps. Notice that a dark cloud envelopes the test bay 4 seconds at the end of the test, but the cloud is not as dark as in Test 2-40 due to the high flux from the arc and the aluminum from the bus and the enclosure being burned.

Figure 2-13: From top left (clockwise): v1310 at southwest side; v7 elevated from the northeast of the test; GoPro outside southeast; GoPro inside floor southwest.

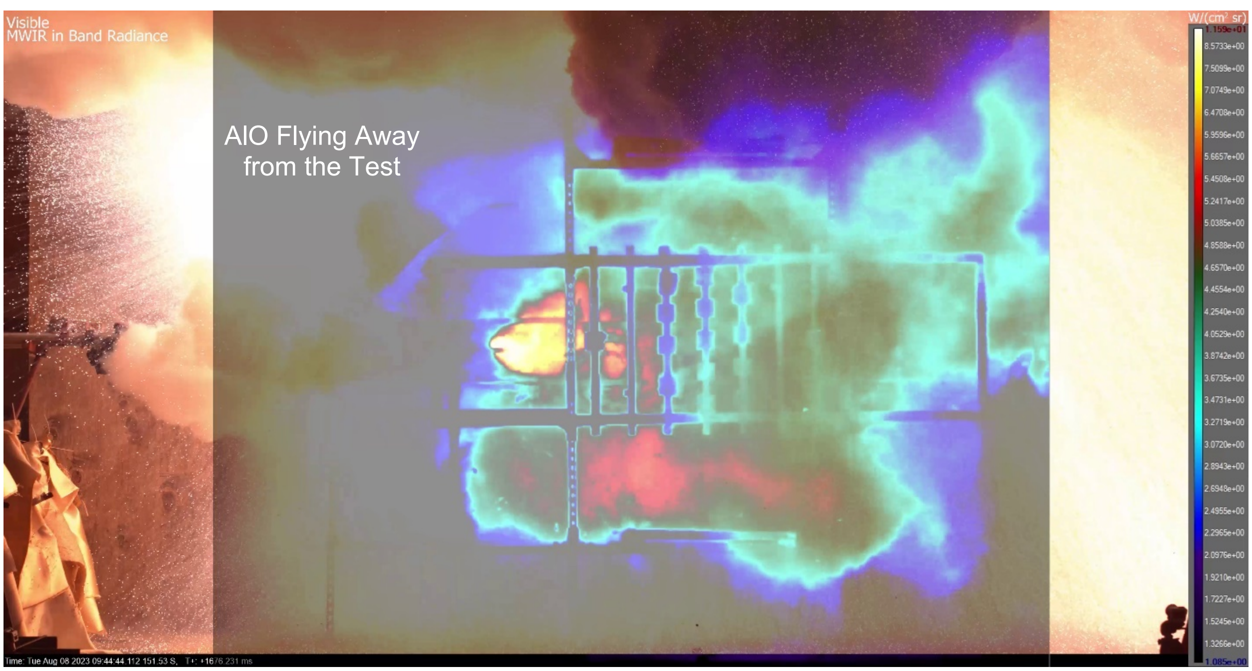


Figure 2-14: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm^2 sr) synchronized with a visible color camera early in the test, similar time as Figure 2-9. Notice that the

visible video background is extremelly bright and that it tends to reduce contrast on the half transparent IR data.

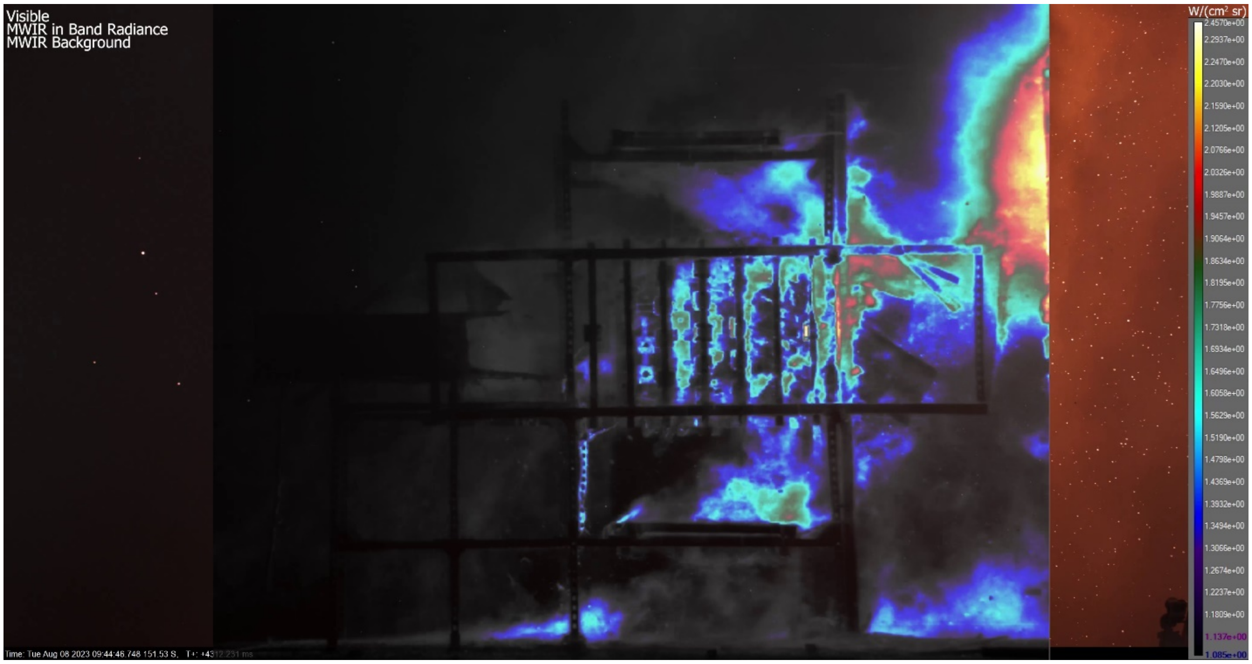


Figure 2-15: Image fusion of IR cameras (MWIR & LWIR – in radiance units of W/cm2 sr) synchronized with a visible color camera at the end of the test.

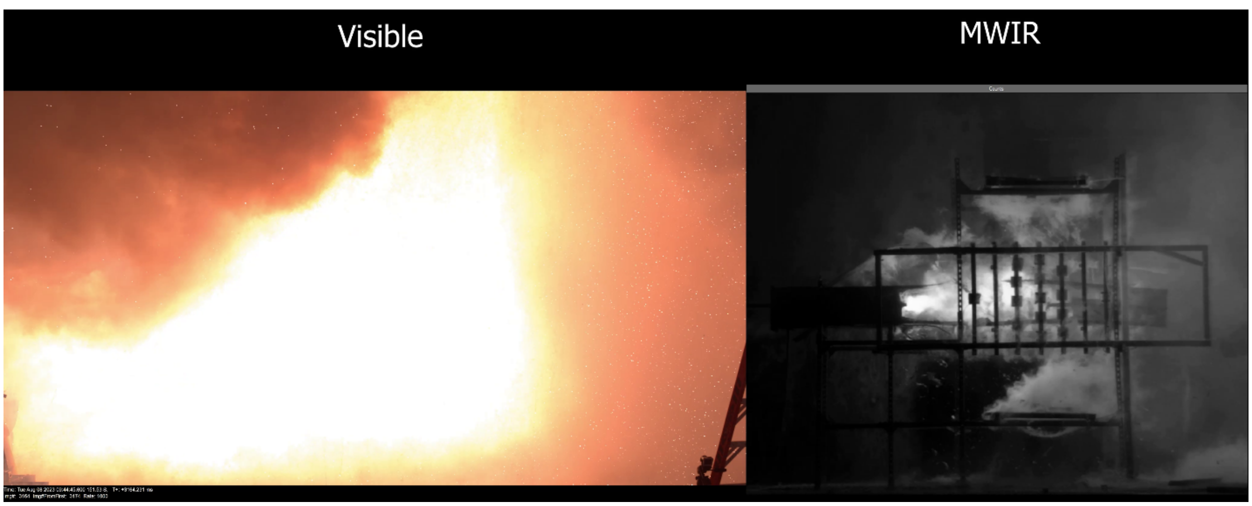


Figure 2-16: Sample frames from synchronized video of 4k and LWIR cameras 3 seconds into the test.

The settings of the cameras in Test 2-41 can be seen in Table 2-3.

Table 2-3: Camera settings for Test 2-41. The 655 LWIR camera is not used in this test.

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000
Exposure (μs) /Calibration	3	150	1	1,000-3,000°C	600-3,000°C	2
f/#	5.6	8	22	2.5	2.5	22
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	195	115	70	100	100	28
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022
H Pixel Count	1,280	4,096	1,280	640	640	800
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6
Field of View (deg)	10.5	13.7	18.7	9.1	9.1	34.9

Table 2-4 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-41.

Table 2-4: Test 2-41 Events

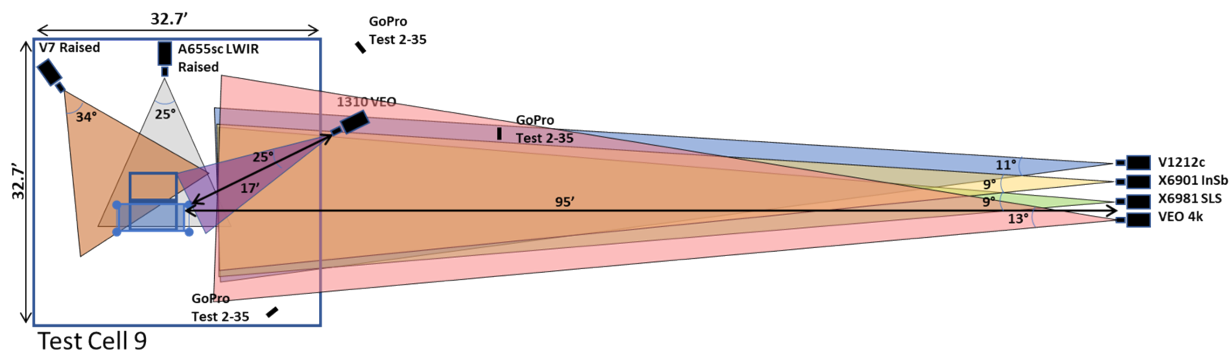
Event – Delay from Trigger to Current Applied: 26.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-26.3
First Light	35.1	8.8
Breach South Side	377.2	350.9
AIO Particles Ejection – Right Side	454.2	427.9
AIO Particles Ejection – Left Side	972.2	945.9
Smoke and Dust Engulf Test Setup	1476.2	1449.9
End of Arc	NA	4137
Cameras Detect End of Test	4202.2	4175.9

3. MEDIUM-VOLTAGE ELECTRICAL ENCLOSURES

The medium-voltage electrical enclosures have the cameras mostly in the same locations, except for the 1310 VEO and the Go Pros. The A655sc was placed back at its elevated location on the top-east side, and the X6981 trigger issue was solved. The location of the 1310 VEO was intended for easy protection, and to provide an orthogonal view of the switchgear's ejecta and the instrument stands. Each test in the medium-voltage electrical enclosures has a different enclosure arrangement and each one will have their own cameras and setup diagram. Test 2-39 is a repeat of Test 2-37 as there is interest in seeing how far south facing access door in Test 2-37 can travel.

3.1. Test 2-35 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration – August 9, 2023

Test 2-35 was the first enclosure test with an intended 4 second duration. This test has steel enclosures with copper bus bars. This test has two enclosures facing south with the west most enclosure having the starting arc inside it. Four external "remote cameras" were used to capture the events of this test; one looking through a plexiglass; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the south; and one at the southeast just outside the main entry. The test lasted a bit more than 4 seconds. Figure 3-1 shows the camera location set-up and enclosure configuration for Test 2-35.



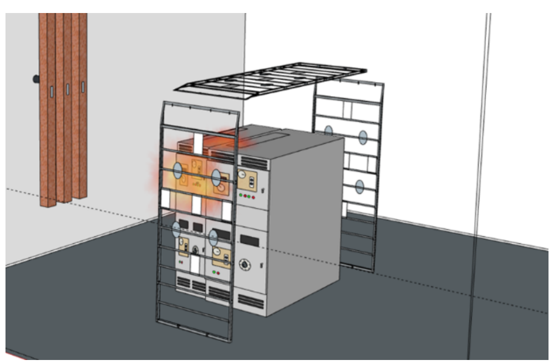


Figure 3-1: Electrical Enclosure (Test 2-35) cameras locations (top) with switchgear enclosure configuration (bottom)

The test has the front door fly open right away at the switchgear with the starting arc. Eventually the damage will transfer to the adjacent switchgear, where plumes of orange particles are ejected. The particles are not detected by the MWIR and LWIR cameras, this would indicate another burning metal. We can detect the timing of the venting and start of fire in the adjacent switchgear and detect venting of the orange particle ejecta on the right side. Figure 3-2 through Figure 3-9 show images of notable features and select events that occurred during Test 2-35.

Figure 3-2: Test 2-35 imaged through 4k camera – camera imaging at 1000 fps.

Figure 3-3: Test 2-35 imaged through 4k camera – notice enlcosure door blown open and venting on top – camera imaging at 1000 fps.

Figure 3-4: Test 2-35 imaged through 4k camera – notice fireball venting from adjacent enclosure and burning particulate ejection – camera imaging at 1000 fps.

Figure 3-5: From top left (clockwise): v1310 while the door is being blown open; v7 elevated from the northeast of the test while the east side enclosure vents; GoPro outside southwest; GoPro outside floor southeast while molten material is dumped out of the east enclosure.

Figure 3-6: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.8 seconds into the test.

Figure 3-7: Image fusion of IR camera (in radiance units of W/cm[2] sr) synchronized with a visible image 3 seconds into the test. Notice that the higher fire activity is occurring on the adjacent enclosure.

Figure 3-8: Sample frames from synchronized video of 4k and LWIR cameras 3 seconds into the test. Notice that the IR doesn't show the metal spray to the right of the second enclosure. The spray of metal particulate that probably emitting light in the visible in a narrow band instead of the continuum from a Planck curve profile.

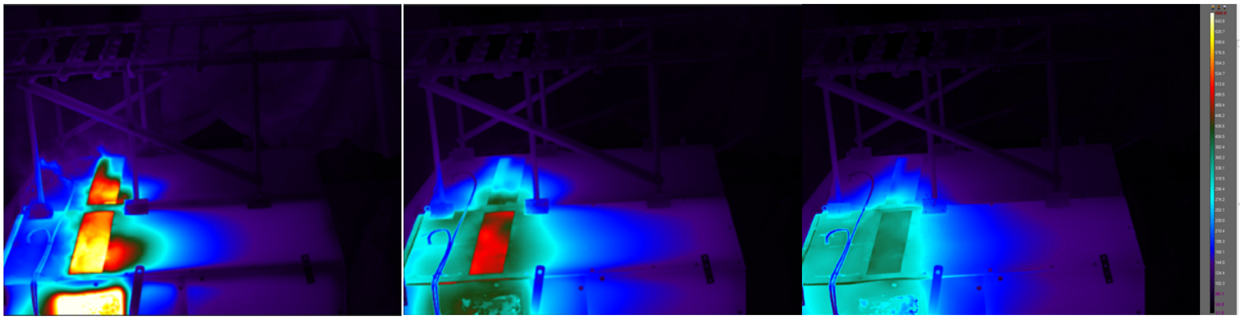


Figure 3-9: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Notice enclosure in the foreground shows highest temperature on the top after the test. Arc is induced in the background enclosure. Temperature range from 31 to 660 °C.

The settings of the cameras in Test 2-35 can be seen in Table 3-1.

Table 3-1: Camera settings for Test 2-35

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (μs) /Calibration	3	150	2	1,000-3,000°C	600-3,000°C	2	100-650°C
f/#	5.6	8	22	2.5	2.5	22	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	125	53	100	100	29	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	12.6	24.5	9.1	9.1	33.9	24.9

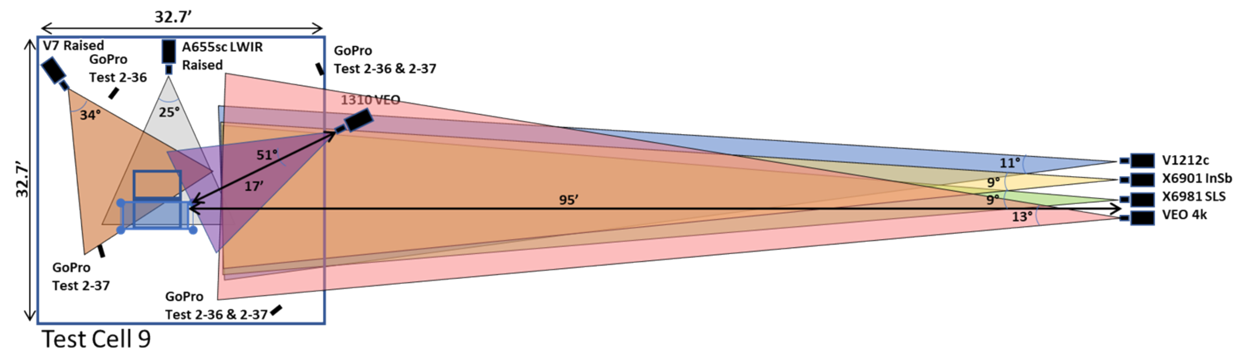
Table 3-2 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-35.

Table 3-2: Test 2-35 Events

Event – Delay from Trigger to Current Applied: 26.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-26.3
First Light	35.0	8.7
Front Door Opens	74.0	47.7
Adjacent Switchgear Starts Venting	168.2	141.9
Adjacent Switchgear Venting Fire	1052.2	1025.9
Ejecta from Breach on Right Side Switchgear	2901.2	2874.9
End of Arc	NA	4120
Cameras Detect End of Test	4176.2	4149.9

3.2. Test 2-37 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration – August 10, 2023

The second enclosure test had an intended 4 second duration. This test has steel enclosures with copper bus bars. This test has two enclosures facing south with the west most enclosure having the starting arc inside it. Four external "remote cameras" were used during this test; one looking through a plexiglass, but with a wider camera view compared to Test 2-35; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the northwest-inside; and one at the southeast just inside by the main entry. The test lasts a bit more than 4 seconds. Figure 3-10 shows the camera location set-up and enclosure configuration for Test 2-37.



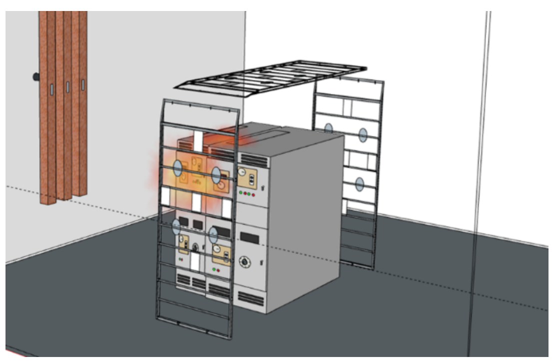


Figure 3-10: Electrical Enclosure (Test 2-36 & Test 2-37) cameras locations (top) with switchgear enclosure configuration (bottom). Main difference to Test 2-35 is the shorter focal length for the 1310 VEO giving it a wider view.

Figure 3-11 through Figure 3-19 show images of notable features and select events that occurred during Test 2-37. In this test,the front access door was ejected and hit the front instrument stand. Three and half seconds later another access panel is ejected by the adjacent switchgear. This is detected by the IR cameras. The velocity of the panel was estimated as follows. Figure 3-15 shows the ejection of an access door in the enclosure where the arc is initiated. It was roughly estimated (using the GoPros that go at 120 fps with a resolution of 8.33 ms) that the door takes 83.4 ms to reach the instrument stand, which is located 3 feet (0.91 m) from the enclosure. This provides an estimate to the velocity of the door of 35 feet/s (10.91 m/s). Using the v1212 that runs at 10,000 fps or a resolution of 100µs, but with a front view (not optimal angle), the door takes about 75.6 ms to reach the rack and this provides a velocity for the door of about 39.7 feet/s (12.1 m/s). Using these two estimates, the velocity can be defined as 37.7±2.4 feet/s (11.49±0.6 m/s).

Figure 3-11: Test 2-37 imaged through 4k camera first millisecond into the test – camera imaging at 1000 fps – showing a v-shape object being ejected on the top.

Figure 3-12: Test 2-37 imaged through 4k camera 1 second into the test – camera imaging at 1000 fps – where the instrument stand is falling after being pushed by the ejected door from the enclosure where the arc is initiated.

Figure 3-13: Test 2-37 imaged through 4k camera 3 second into the test – camera imaging at 1000 fps – where the arc is affecting the second enclosure (mostly in the back). Notice the instrument stand on the ground by this time.

Figure 3-14: Test 2-37 imaged through 4k camera 3.5 seconds into the test – camera imaging at 1000 fps – The second enclosure ejecting a large fireball in side pointing north (this has been going on for half a second), while the first enclosure is consumed by the fire and ejecting sprays of burning metal particulate to the south.

Figure 3-15: From top left (clockwise): v1310 while there isventing in the adjacent enclosure; v7 elevated from the northeast of the test while the west side enclosure vents in the back; GoPro outside southwest while access door is being ejected; GoPro ouside floor southeast view of the same event. Notice instrument stand is being pushed by the ejected door.

Figure 3-16: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 2 seconds into the test.

Figure 3-17: Image fussion of IR camera (in radiance units of W/cm[2] sr) synchronized with a visible image almost 4 seconds into the test showing the ejection of a panel of the adjacent enclosure.

Figure 3-18: Sample frames from synchronized video of 4k and LWIR cameras close to 4 seconds into the test. Notice that the IR shows panel being ejected on the right side.

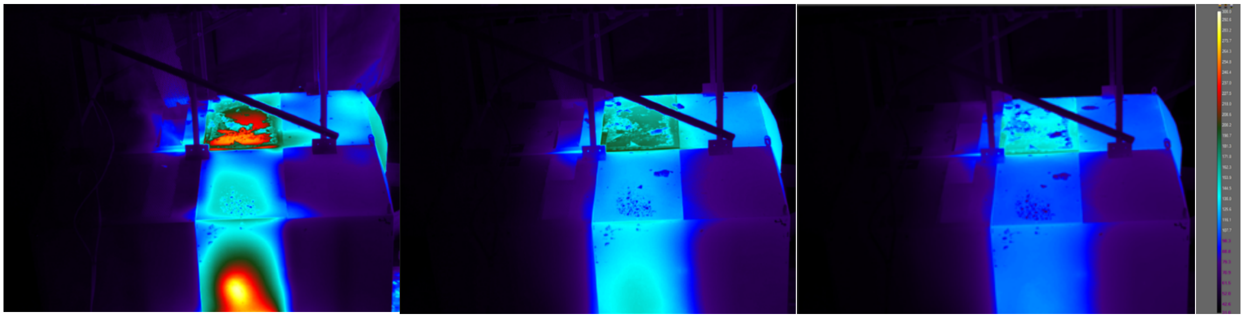


Figure 3-19: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc was induced in the background enclosure. Temperature range from 31 to 300 °C.

The settings of the cameras in Test 2-37 can be seen in Table 3-3.

Table 3-3: Camera settings for Test 2-37

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (µs) /Calibration	5	300	4	1,000-3,000°C	600-3,000°C	6	100-650°C
f/#	5.6	8	22	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	125	24	100	100	29	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	12.6	51.3	9.1	9.1	33.9	24.9

Table 3-4 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-37.

Table 3-4: Test 2-37 Events

Event – Delay from Trigger to Current Applied: 26.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-26.3
First Light	38.0	11.7
Top Panel Starts Ejection	40.4	14.1
Front Door Starts Ejection	45.1	18.8
Front Door Strikes Instrument Stand	79.5±3.9	53.2±3.9
Adjacent Switchgear Starts Venting	3138.3	3112.0
Adjacent Switchgear Venting Fire	3434.3	3408.0
Adjacent Switchgear Ejection Right Panel Detected	3494.3	3468.0
End of Arc	NA	4120

Cameras Detect End of Test	4152.3	4126.0

3.3. Test 2-36 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 11, 2023

The third enclosure test had an intended 4 second duration. This test had steel enclosures with copper bus bars. This test had two enclosures facing south with the west most enclosure having the starting arc inside it. Four external "remote cameras" were used during this test; one looking through a plexiglass, but with a wider camera view compared to Test 2-35; and three Go Pros with similar setup as Test 2-37: one in the southwest near the main entry but inside the test cell; one at the northwest-inside; and one at the southeast just inside by the main entry. The test lasts a bit more than 4 seconds. Figure 3-20 shows the camera location set-up and enclosure configuration for Test 2-36.

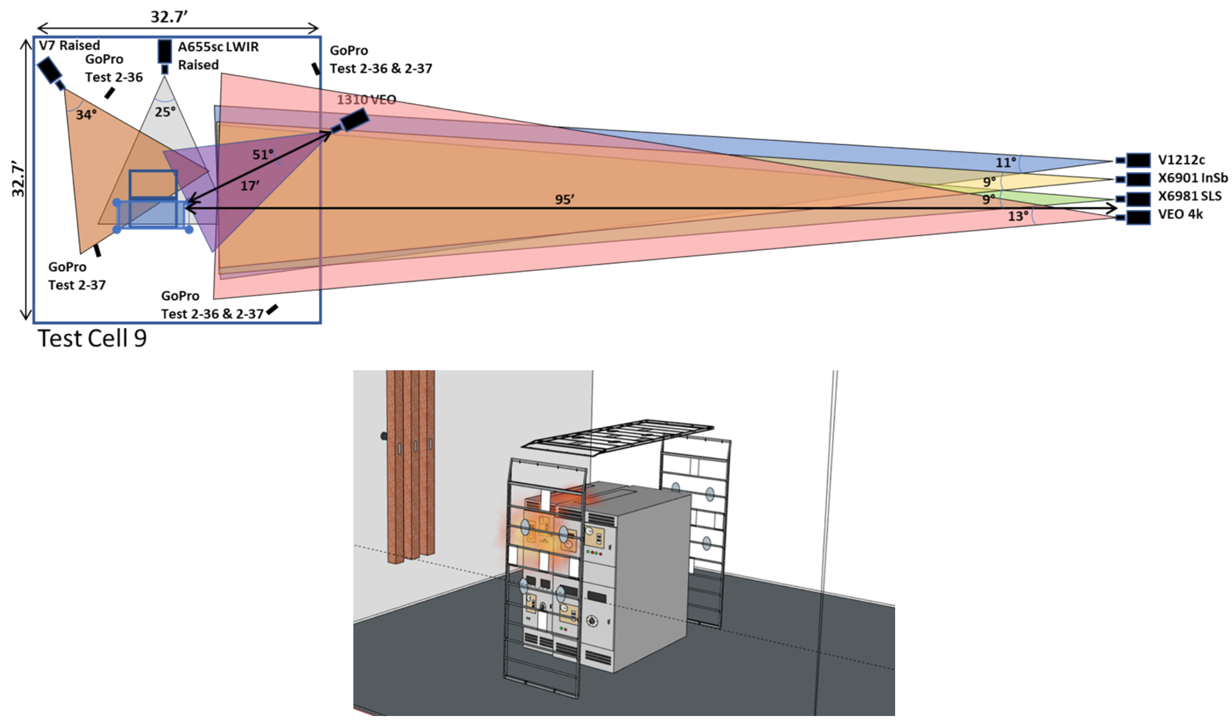


Figure 3-20: Electrical Enclosure (Test 2-36) camera locations (top) with switchgear enclosure configuration (bottom). Main difference to Test 2-35 is the shorter focal length for the 1310 VEO giving it a wider view.

This test seems to have most of the arc activity to the main switchgear, with some fire and venting on the adjacent switchgear, but not as significant as previous tests. Notice that the connection to the 3-phases with the KEMA facility significantly shakes at two distinct times: 37 ms and 3.38 seconds into the test. Figure 3-21 through Figure 3-28 show images of notable features and select events that occurred during Test 2-36.

Figure 3-21: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps

Figure 3-22: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps – 2 seconds into the test. The view from the south seems to be dominated by dark smoke and there is fire activity in the north side.

Figure 3-23: Test 2-36 imaged through 4k camera – camera imaging at 1000 fps – 4 seconds into the test. There is a fire engulfing the enclosure where the arc was initiated, also there is spray of burning metal particulate. The second enclosure seems to be mostly engulfed by the dark smoke with some fire activity on the east side.

Figure 3-24: From top left (clockwise): v1310 view at 1.5 seconds into the test while venting in the adjacent enclosure; v7 elevated from the northeast of the test while the east side enclosure vents but the arc starting enclosure suffers the brunt of the test; GoPro outside west during the arc on the west side enclosure; GoPro inside floor notheast view of the damage to the first enclosure while the second enclosure starts venting gases.

Figure 3-25: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 1 second into the test.

Figure 3-26: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 4 second into the test and not that different than at the beginning of the test.

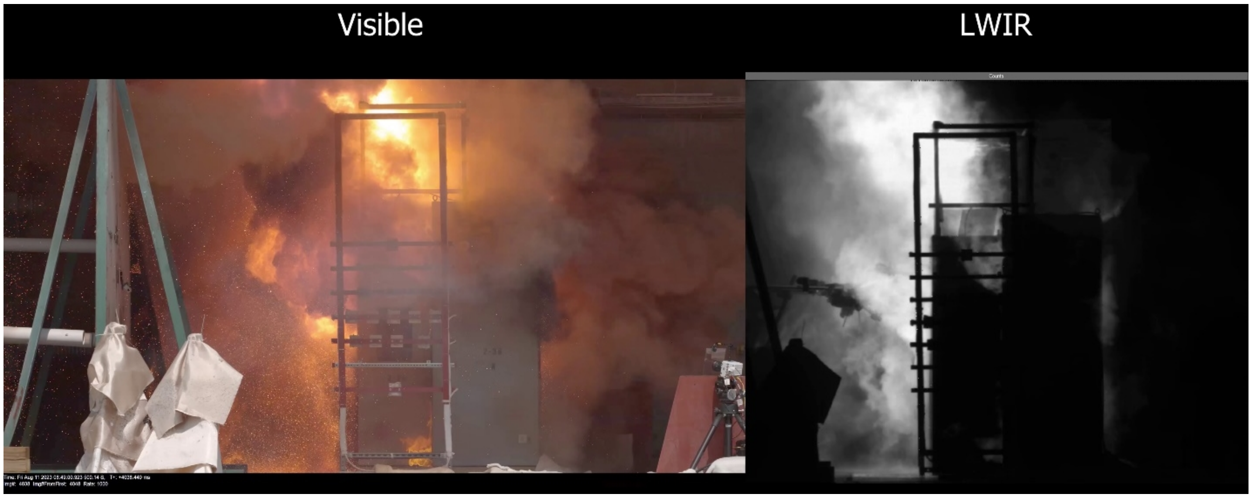


Figure 3-27: sample frames from synchronized video of 4k and LWIR cameras close to 4 seconds into the test. While there seems to be activity in IR and visible in the back (north side), the IR seems to indicate that the second enclosure is not that hot, even if the first eclosure keeps burning for several minutes after the test.

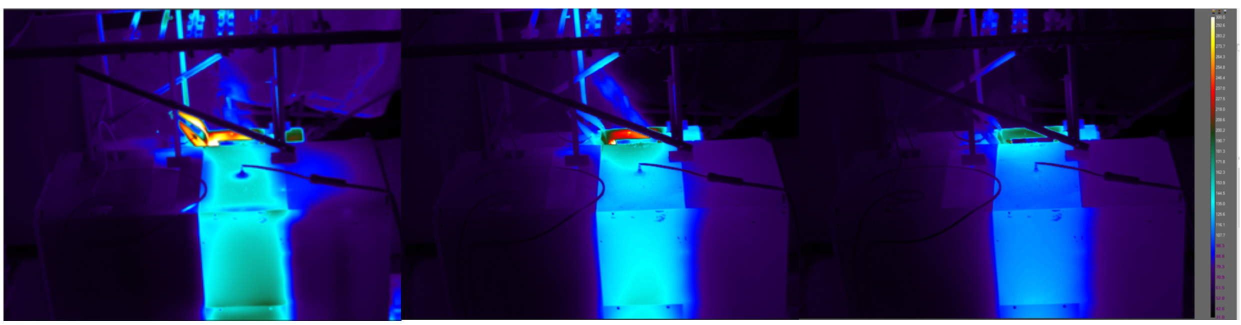


Figure 3-28: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the lower background enclosure. Temperature range from 20 to 150 °C. Notice that the there is minimum change in temperature during the 15 minutes of the three frames, indicating a continuos fire in the enclosure where the arc was started.

The settings of the cameras in Test 2-36 can be seen in Table 3-5.

Table 3-5: Camera settings for Test 2-36

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (μs) /Calibration	15	500	12	1,000-3,000°C	250-1,000°C	20	100-650°C
f/#	5.6	8	22	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	125	24	100	100	29	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	12.6	51.3	9.1	9.1	33.9	24.9

Table 3-6 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-36.

Table 3-6: Test 2-36 Events

Event – Delay from Trigger to Current Applied: 27.6 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-27.6
First Light	36.4	8.8
To Panel Opens	45.3	17.7
3 Phase Connection Shakes	64.4	36.8
Adjacent Switchgear Starts Venting	785.3	757.7
Adjacent Switchgear Venting Fire	1592.9	1535.3
3 Phase Connection Shakes	3408.4	3380.8
End of Arc	NA	4120
Cameras Detect End of Test	4200.4	4172.8

3.4. Test 2-38 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Cross-Aisle Configuration - August 14, 2023

The fourth enclosure test had an intended 4 second duration. This test had steel enclosures with copper bus bars. This test had four enclosures facing east with the north most enclosure having the starting arc inside it, plus two enclosures facing east of the first two. Four external "remote cameras" were used during this test; one looking through a mirror, and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the northeast-inside; and one at the northwest looking at the northside of the test enclosures. The test last a bit more than 4 seconds. Figure 3-29 shows the camera location set-up and enclosure configuration for Test 2-38.

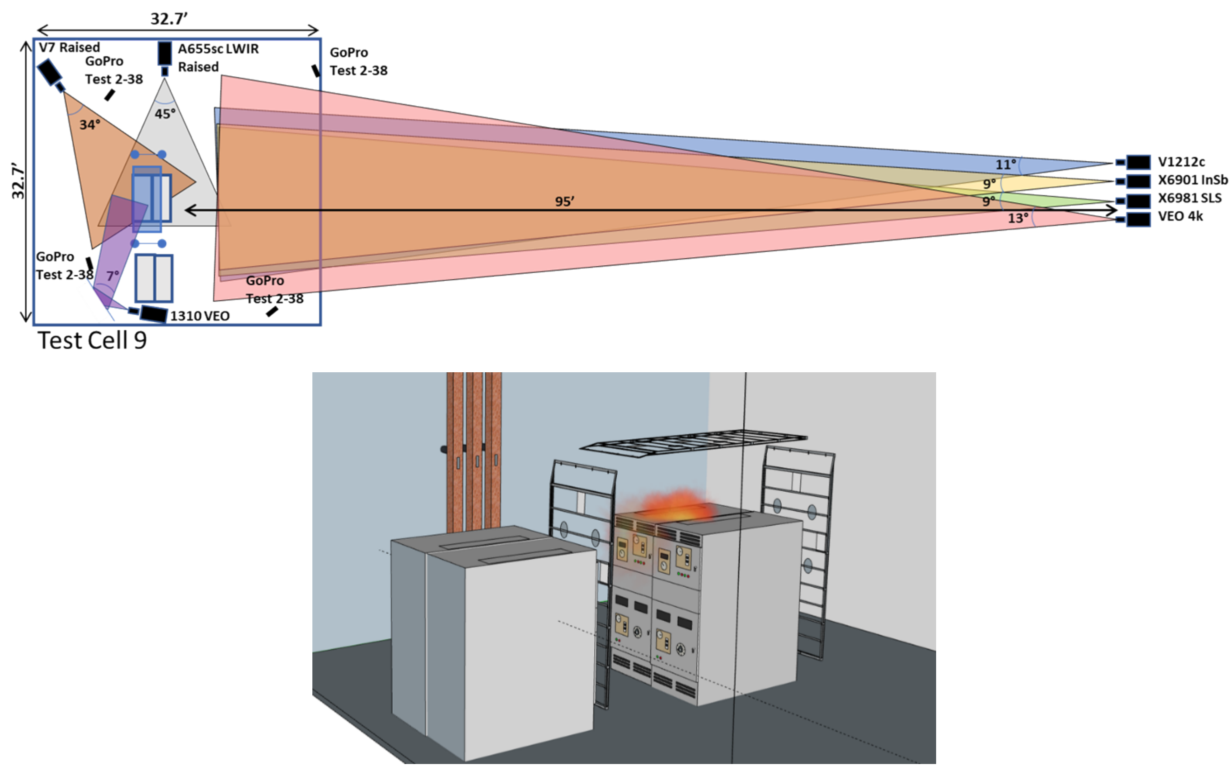


Figure 3-29: Electrical enclosure cross-aisle configuration (Test 2-38) cameras locations (top) with switchgear enclosure configuration (bottom).

Test 2-38 results in open access doors early in the test. The adjacent switchgear starts venting about 1 second into the test and venting fire 400 ms later. Large fireball/fet-fire from the bottom of switch gear starts 2.32 seconds into the test and lasts about 1.8 seconds. Figure 3-30 through Figure 3-38 show images of notable features and select events that occurred during Test 2-38.

Figure 3-30: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps. Notice the panel ejected to the east. The arc was initiated in the north enclosure – behind the enclosure in view.

Figure 3-31: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – 2 seconds into the test. Burning metal particles are flying out from both ajacent enclosures and the south enclosure is venting fire through its southern panel. Notice the smoke engulfing the test bay.

Figure 3-32: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – 4 seconds into the test. A fireball is now engulfing the east side of the test bay.

Figure 3-33: Test 2-38 imaged through 4k camera – camera imaging at 1000 fps – almost 5 seconds into the test.

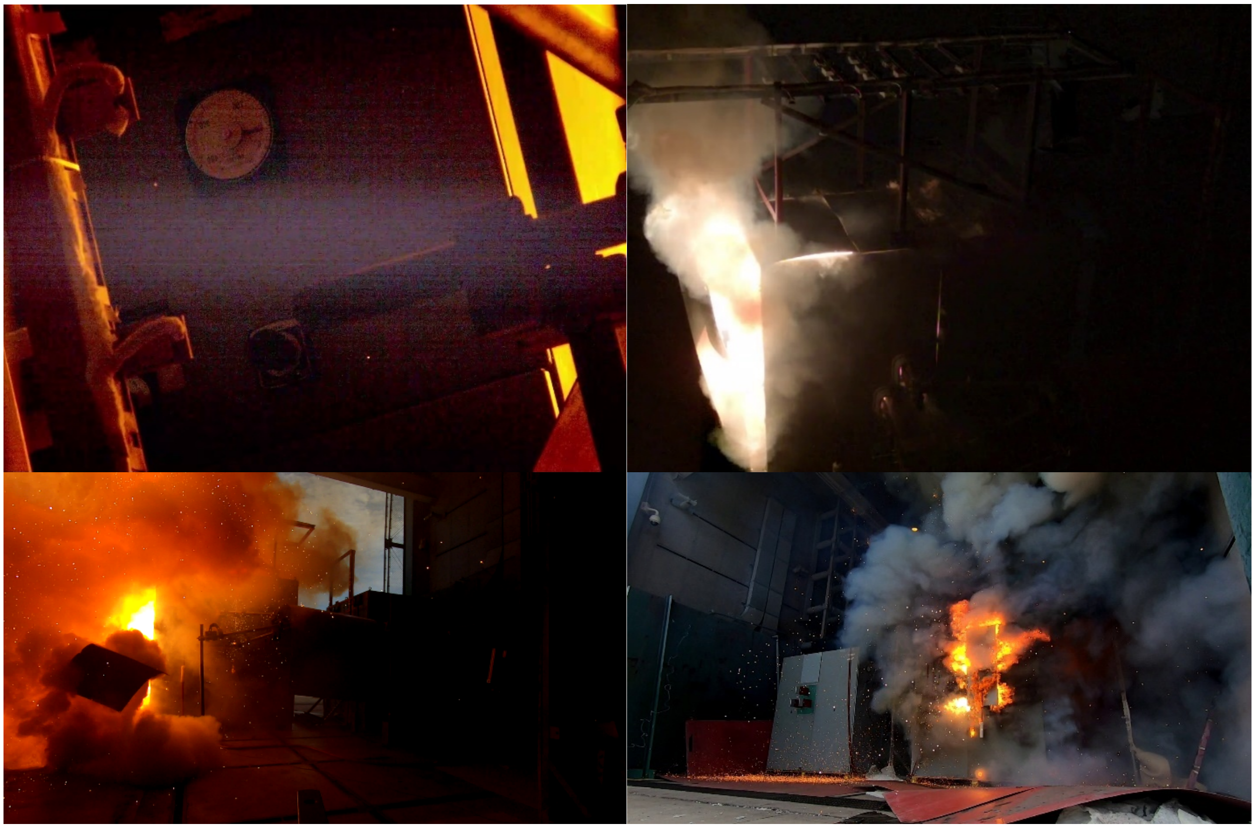


Figure 3-34: From top left (clockwise): v1310 view at 1 second into the test before the testbay becomes engulfed by smoke on the west side; v7 elevated from the northeast of the test while showing the east panel being ejected from enclosure where the arc was started; GoPro inside floor notheast view showing a panel flying from the enclosure where the arc started; GoPro outside southeast view during the test.

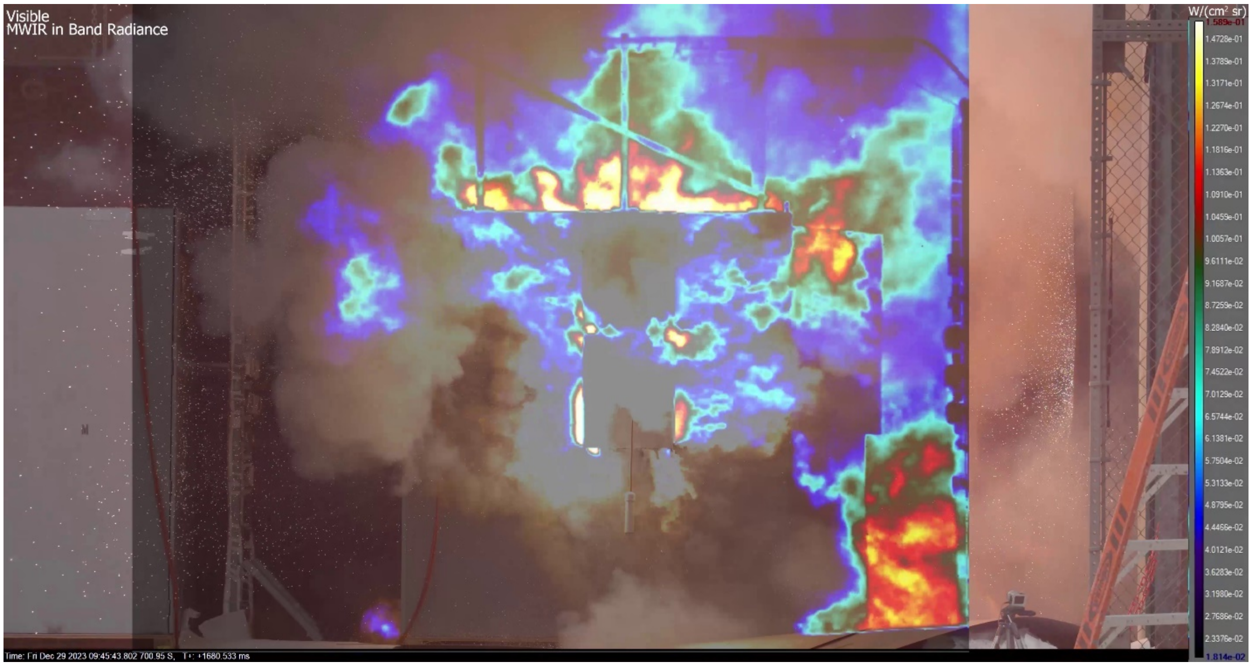


Figure 3-35: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 1.5 seconds into the test.

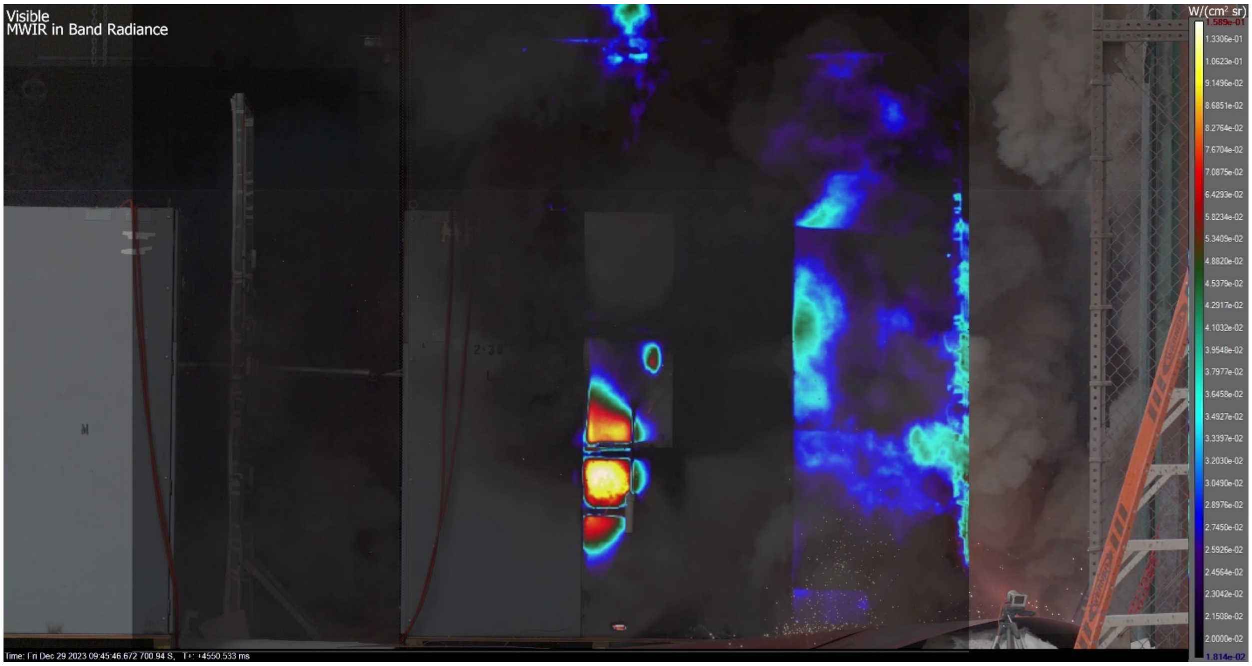


Figure 3-36: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image at the end of the test.

Figure 3-37: Sample frames from synchronized video of 4k and LWIR cameras at the beginning of the test. The LWIR image shows the square profile of the panel ejected from the enclosure where the arc was started, see red arrow.

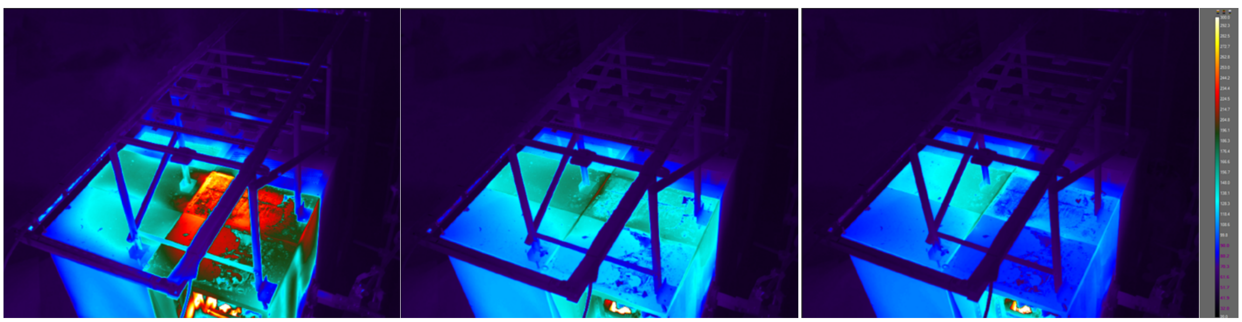


Figure 3-38: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the front center enclosure (red hot on top). Temperature ranges from 20 to 300 °C. The open panel shows hot items inside the enclosure that are still hot and close to 400 °C after more than 11 minutes.

The settings of the cameras in Test 2-38 can be seen in Table 3-7.

Table 3-7: Camera settings for Test 2-38

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (μs) /Calibration	18	700	18	1,000-3,000°C	250-1,000°C	20	100-650°C
f/#	5.6	8	22	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8		100	100	17-35 / f3.5	13.1
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	115	200	100	100	29	13.1
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	13.7	6.6	9.1	9.1	33.9	45.1

Table 3-8 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-38.

Table 3-8: Test 2-38 Events

Event – Delay from Trigger to Current Applied: 27.6 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-27.6
First Light	36.3	8.7
Right Panel Back Door Opens	52.5	24.9
Adjacent Switchgear Starts Venting	1032.6	1005.0
Adjacent Switchgear Venting Fire	1407.4	1379.8
Large Fireball/Jet-Fire from Bottom Starts	2352.5	2324.9
End of Arc	NA	4120
Cameras Detect End of Test	4184.9	4157.3

3.5. Test 2-39 (6.9kV – 25kA – Target 4 Seconds – Copper Bus – Steel Enclosure) – Back-to-Back Configuration - August 15, 2023

The fifth enclosure test had an intended 4 second duration. This test had steel enclosures with copper bus bars. This test had two enclosures facing south with the west most enclosure having the starting arc inside it; and two enclosures opposite to the others and facing north. Four external "remote cameras" were used during this test; one looking through a plexiglass; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the southeast-outside; and one at the southeast inside looking straight to the west. This test is intended to be a repeat of Test 2-37, without an instrument stand in the possible path of an ejecting door. The test lasts a bit more than 4 seconds. Figure 3-39 shows the camera location set-up and enclosure configuration for Test 2-39.

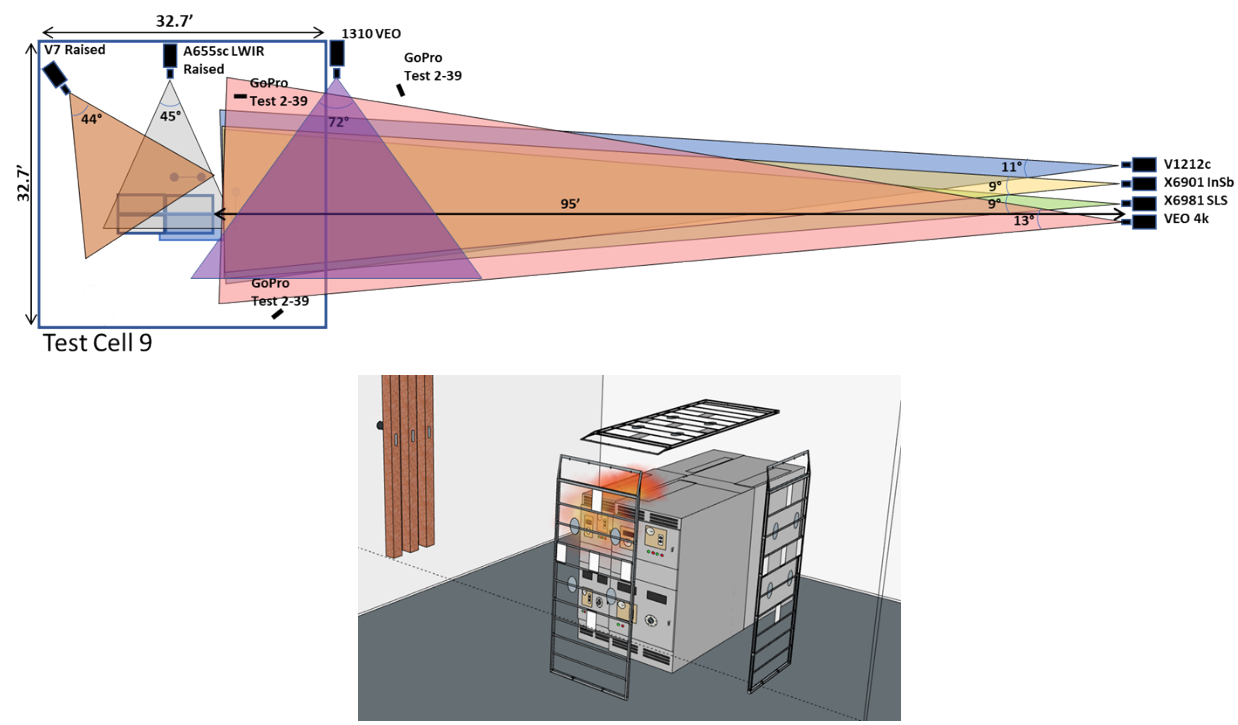


Figure 3-39: Electrical enclosure back-to-back configuration (Test 2-39) cameras locations (top) with switchgear enclosure configuration (bottom).

Figure 3-40 through Figure 3-48 show images of notable features and select events that occurred during Test 2-39. Note that Test 2-39 was deigned to repeat Test 2-37. The expectation was that it would have the access door flight in the same manner but unimpeded by the instrument stand. The 1310 high-speed cameras near the test site were located to measure the ejection speed of the door. Unfortunately the door did not release cleanly and it pivoted to hit the instrument stand. Figure 3-40 to Figure 3-42 show the ejection of the access door in the enclosure where the arc is initiated. The enclosure hit the instrument stand at the southeast side from the enclosure. Using the GoPros and the v1310, it is estimated that it takes 92.9 ms to reach the instrument stand. Because the door is rotating, the velocity estimation is more complicated than in Test 2-37. Figure 3-49 illustrates three methods to estimate the velocity of the ejected access door based on the data collected from the cameras. Three different methods were utilized because there is uncertainty in the exact flight path of the door and the rotational dynamics. Although the three methods used to estimate the velocity are not exact, each provide insight into the possible range of the velocity of the ejected access door.

Figure 3-40: Test 2-39 imaged through 4k camera first millisecond into the test – camera imaging at 1000 fps – showing a v-shape object being ejected on the top, similar to Test 2-37 where the front access door was also ejected.

Figure 3-41: Test 2-39 imaged through 4k camera 46 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing access door being ejected and deforming.

Figure 3-42: Test 2-39 imaged through 4k camera 120 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing access door hitting the instrument stand.

1.

Figure 3-43: Test 2-39 imaged through 4k camera 230 ms after the previous image in Figure 3-40 – camera imaging at 1000 fps – showing multiple explosion while the rack is falling.

Figure 3-44: Test 2-39 imaged through 4k camera 3 seconds into the test – camera imaging at 1000 fps – showing the instrument stand on the ground and the burning in the back of the southeast and northeast enclosures. The southeast enclosure also shows fire coming out from one of its access door.

1.

Figure 3-45: From top left (clockwise): v1310 view 0.25 seconds into the test with the access door twirling away from the enclosure; v7 elevated from the northeast of the test bay, at 2.5 seconds, while showing fire at the interface of the southeast and northeast enclosures; GoPro inside floor southeast view showing instrument stand in the ground and he southeast enclosure east side ejecting fire during the test; GoPro southwest view while instrument stand and door enclusure fall to the ground.

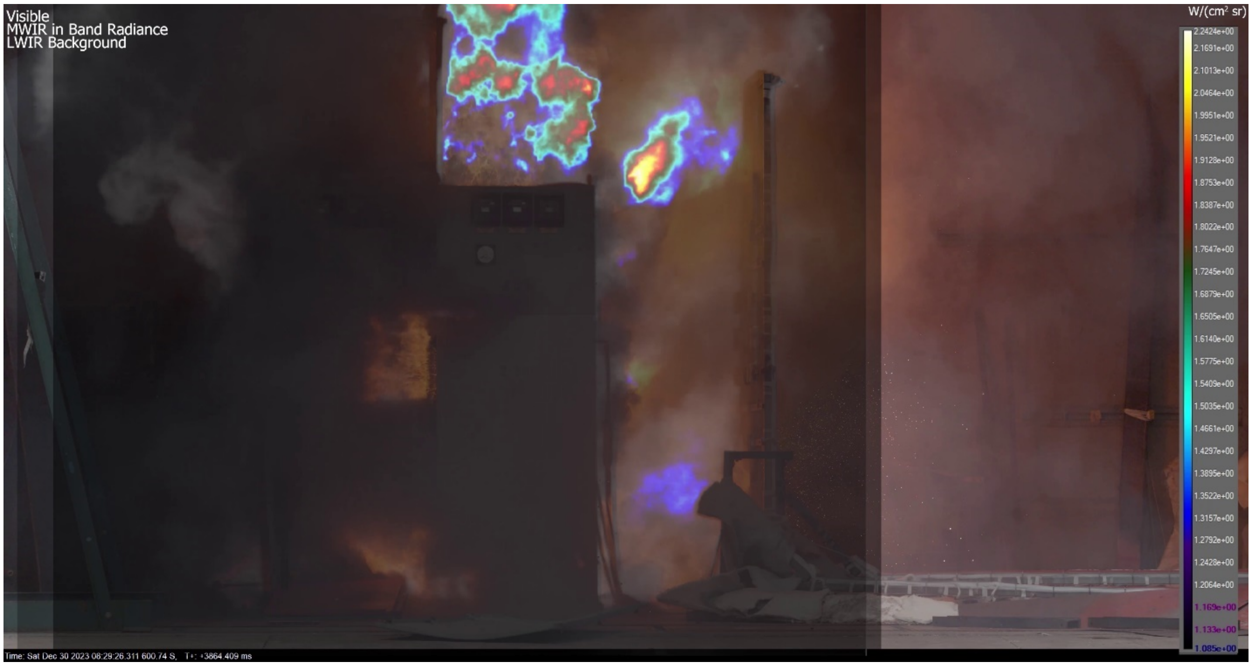


Figure 3-46: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 3.5 seconds into the test.

Figure 3-47: Sample frames from synchronized video of 4k and LWIR cameras close to 1.5 seconds into the test. The LWIR image shows heat (probably fire) at the interface between the north and south enclosures and that part of it is occluded by the smoke.

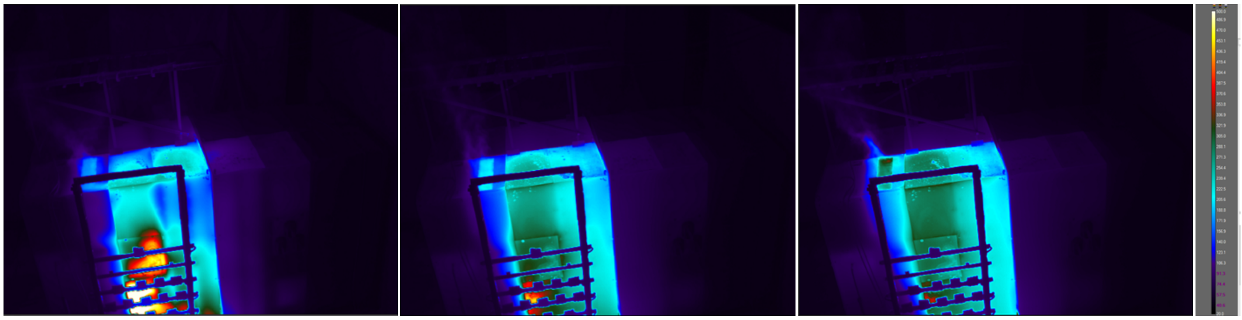


Figure 3-48: Temperature images from the LWIR camera A655 through 5 minutes intervals, starting ~1 minute after the test. Arc is induced in the front center enclosure (red hot on top). Temperature ranges from 20 to 300 °C. The open panel shows hot items inside the enclosure that are still hot and close to 400 °C after more than 11 minutes.

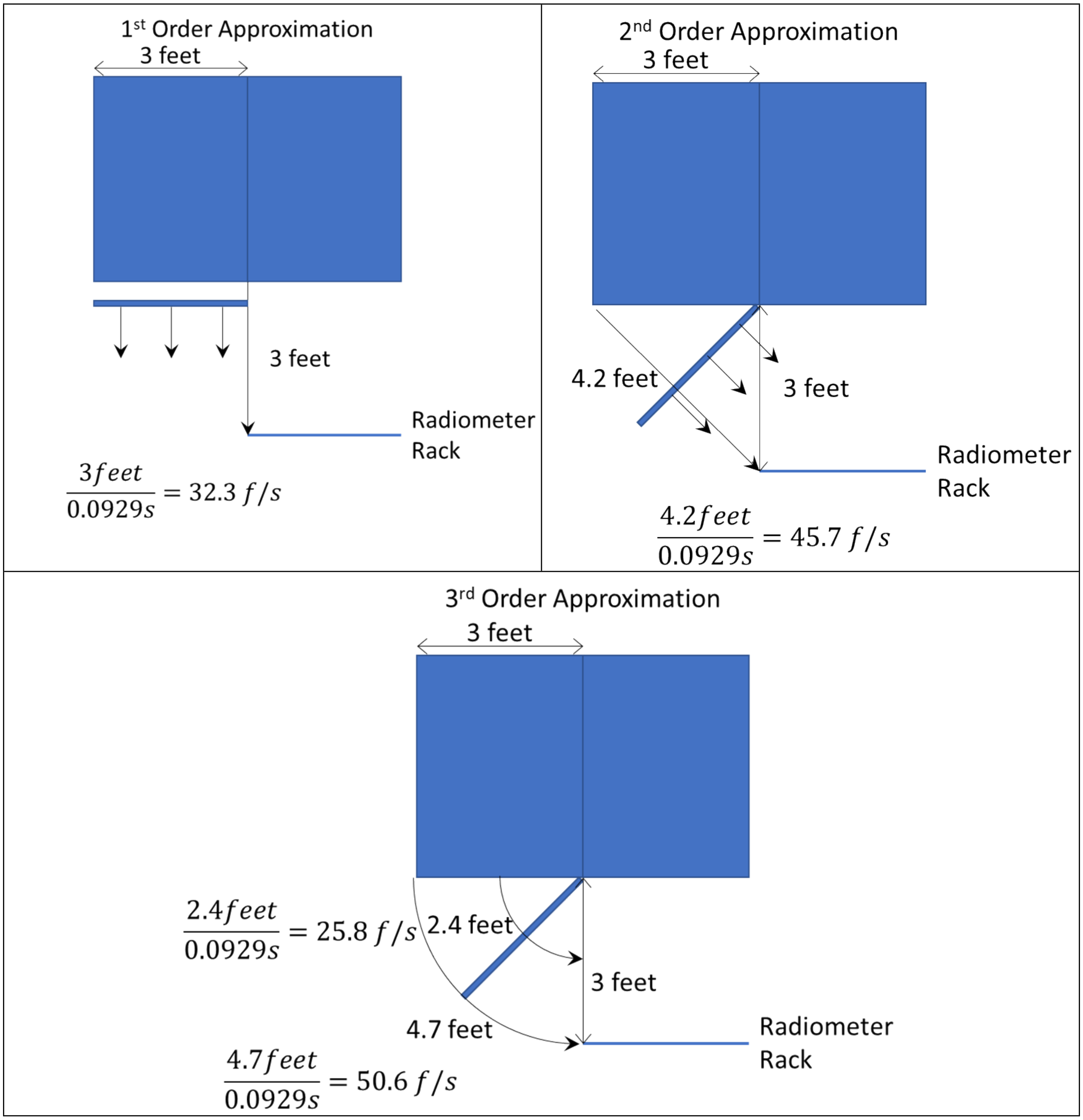


Figure 3-49: Different approximations to estimate the velocity of the ejected access door in Test 2-39. Top-left shows a first order approximation where the door is assumed to be ejected straight. Top-Right assumes the door is ejected at an angle, because we can see that it hits the instrument stand. Bottom shows a more complex approximation where the door rotates on one of its hinges before hitting the instrument stand

1. The 1st order approximation assumes that the door goes straight forward resulting in an estimated speed of 32.3 f/s (9.85 m/s). This estimate is unsatisfactory as the left most side of the door doesn't touch the instrument stand which is obvious in Figure 3-42.
2. The 2nd order approximation assumes that the door moves diagonally in a straight line and this results in an estimated speed of 45.7 f/s (13.9 m/s). This is a non-phyisical behavior, as it assumes that the leftmost side is already in position for the diagonal straight motion.
3. The 3rd order approximation has the door swinging, and it is possible to estimate a tanngential velocity of 50.6 f/s (15.4 ms), which is the velocity of impact of the edge. The tangetial velocity will reduce as you get close to the axis of rotation. As an example at the middle distance the tangential velocity is 25.8 f/s (7.8 m/s). This is a better calculation but not perfect: as the door is rotating around a latch still attached to the enclosure, somewhere along that path it detaches, and the rotational motion gets more complex.

The settings of the cameras in Test 2-39 can be seen in Table 3-9.

Table 3-9: Camera settings for Test 2-39

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	12,000	1,000	10,000	1,004	1,004	4,000	18-20
Exposure (μs) /Calibration	18	600	50	1,000-3,000°C	250-1,000°C	20	100-650°C
f/#	5.6	8	8	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	16-35 / f4	100	100	17-35 / f3.5	13.1
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	115	16	100	100	22	13.1
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	13.7	71.5	9.1	9.1	43.6	45.1

Table 3-10 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-39.

Table 3-10: Test 2-39 Events

Event – Delay from Trigger to Current Applied: 27.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-27.3
First Light	39.6	12.3
Top Panel Ejected	41.2	13.9
Front Door Starts Ejection	47.2	19.9
Front Door Strikes Instrument Stand	140.1	112.8
Adjacent Switchgear Starts Venting	92.4	65.1
Adjacent Switchgear Venting Fire	236.9	209.6
End of Arc	NA	4120
Cameras Detect End of Test	4165.4	4138.1

4. LOW-VOLTAGE ELECTRICAL ENCLOSURES

The low-voltage electrical enclosures test changed locations from TC9 to TC7. Every camera shifted west to that cell. The location of the four remote cameras was replicated for these tests. The X6981sc is running at a lower temperature setting for these tests, 250°C to 1000°C. The 1310 VEO moves to the southwest looking toward the northeast with the same plexiglass protection. The Go Pros move around the test site between tests, and the A655sc is now on the ground at the west wall; the v7 is raised on the north side of the west wall. Each test in the low-voltage electrical enclosures has a different enclosure arrangement and each one has their own unique camera setup diagram. Test 2-33B is a repeat of Test 2-33A as Test 2-33A did not last the intended 8 seconds.

4.1. Test 2-33A (600V – 15kA – Target 8 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 16, 2023

The sixth enclosure test had an intended 8 second duration but lasted only about half a second. This test has three steel enclosures with copper bus bars facing south with the center one having the starting arc inside it. Four external "remote cameras" were used during this test; one looking through a plexiglass; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the southeast-outside; and one at the northwest inside looking to the north side of the enclosures. Figure 4-1 shows the camera location set-up and enclosure configuration for Test 2-33A.

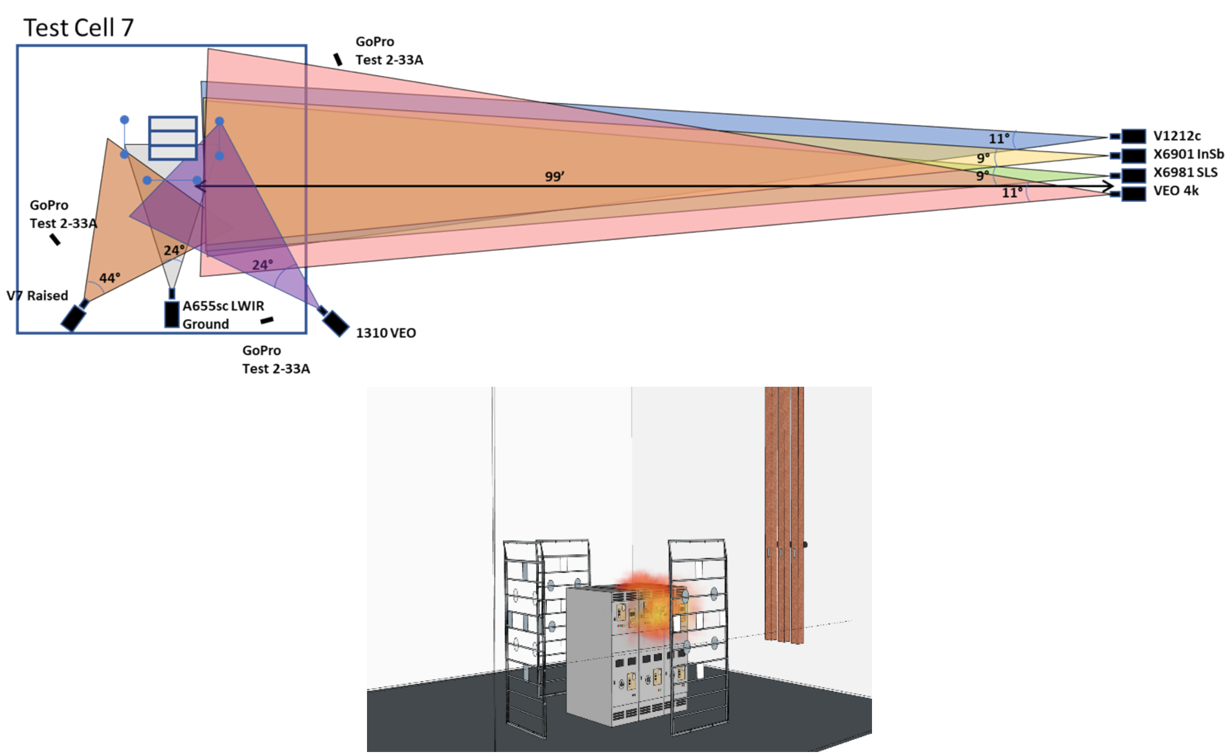


Figure 4-1: Electrical enclosure lineup configuration (Test 2-33A) cameras locations (top) with switchgear enclosure configuration (bottom).

Figure 4-2 through Figure 4-9 show images of notable features and select events that occurred during Test 2-33A. Note that although the test was planned for 8 seconds, it only lasted 0.5 seconds. The test produced a light brown cloud at the end with some flame out in the front and some hot gases coming from orifices in the back. A breach occurs in the left side of the left switchgear around 350 ms.

Figure 4-2: Test 2-33A imaged through 4k camera 200 ms into the test – camera imaging at 500 fps.

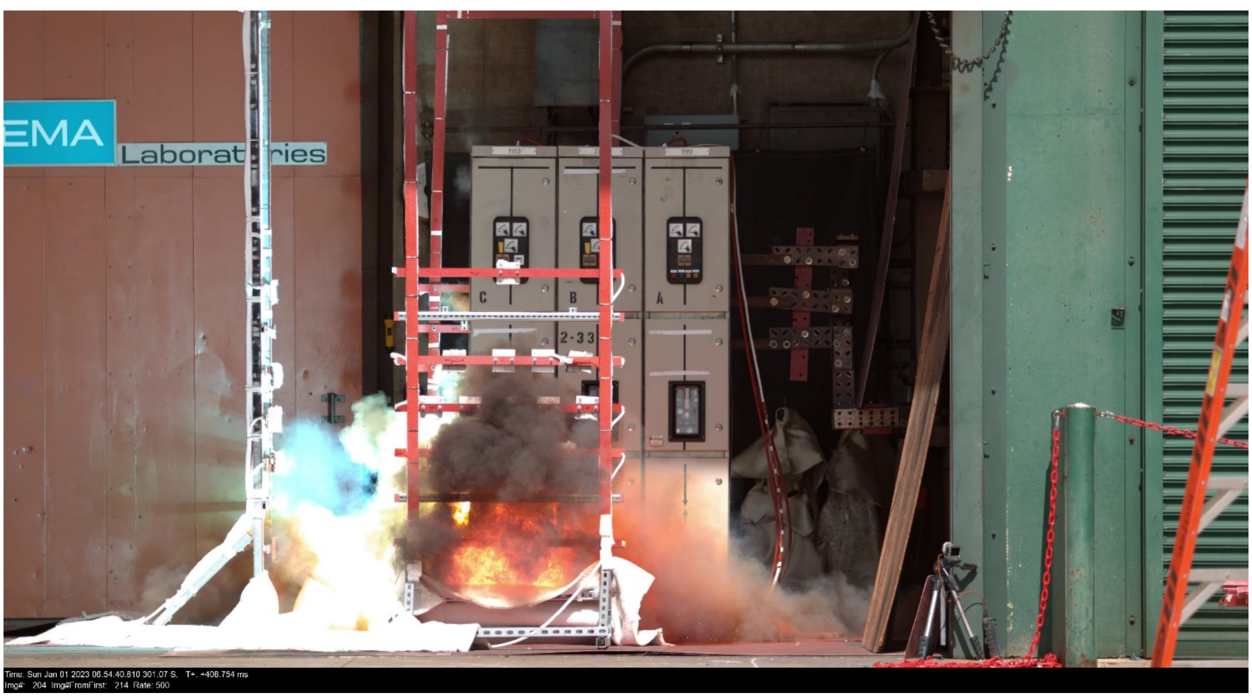


Figure 4-3: Test 2-33A imaged through 4k camera 0.5 second into the test – camera imaging at 500 fps.

Figure 4-4: Test 2-33A imaged through 4k camera 2.6 seconds after the test finished – camera imaging at 500 fps.

Figure 4-5: From top left (clockwise): v1310 view 350 ms into the test; v7 elevated from the northwest of the test bay, at 300 ms; GoPro inside floor northwest view; GoPro southeast view right at the beginning of the test.

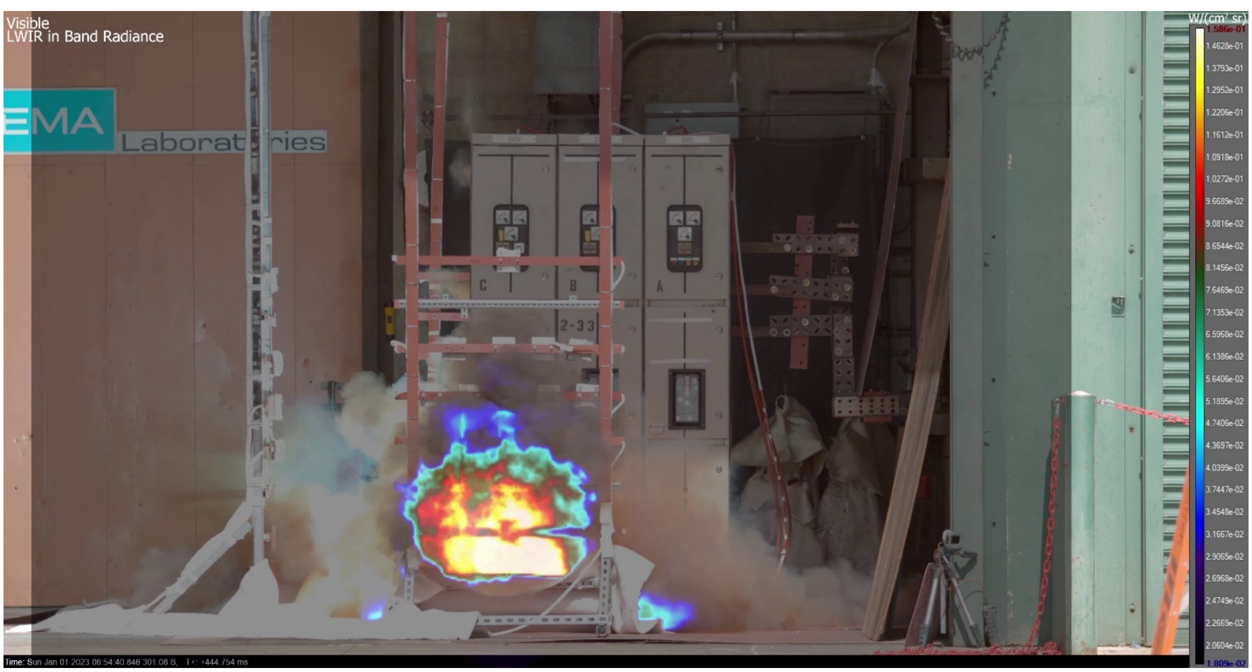


Figure 4-6: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 400 ms into the test.

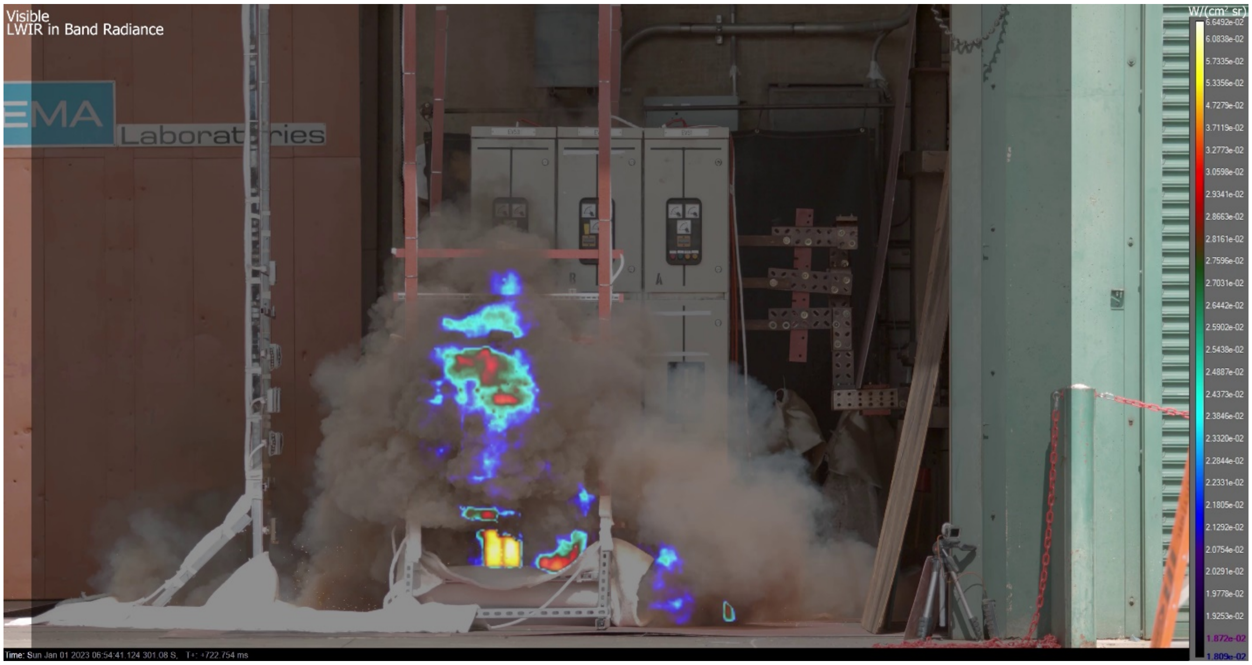


Figure 4-7: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.7 seconds at the end of the test.

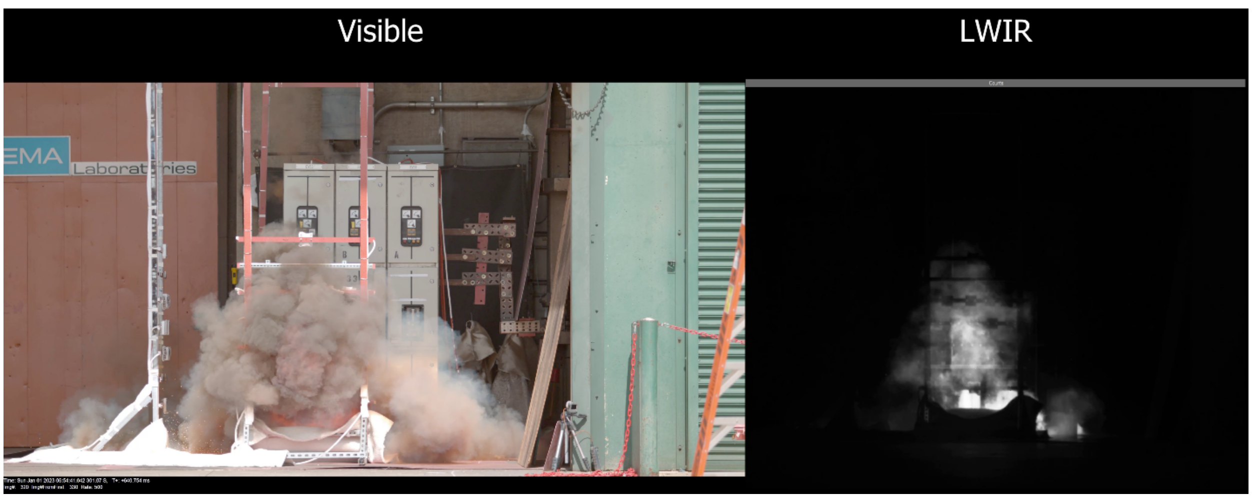


Figure 4-8: Sample frames from synchronized video of 4k and LWIR cameras close to 0.6 seconds into the test. The LWIR image shows heat (probably fire) at the bottom of the west enclosure.

Figure 4-9: Temperature images from the LWIR camera A655 through 1 minute intervals, starting ~1 minute after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 28.9 to 375 °C.

The settings of the cameras in Test 2-33A can be seen in Table 4-1.

Table 4-1: Camera settings for Test 2-33A

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	10,000	500	4,600	1,004	1,004	1,400	18-20
Exposure (µs) /Calibration	30	300	100	1,000-3,000°C	250-1,000°C	710	100-650°C
f/#	5.6	2.8	8	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	145	53	100	100	22	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	10.9	24.5	9.1	9.1	43.6	24.9

Table 4-2 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-33A.

Table 4-2: Test 2-33A Events

Event – Delay from Trigger to Current Applied: 14.3 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-14.3
First Light	27.6	13.3
Middle Window on Left Most Switchgear Opens	35.9	21.6
Switchgear Start Breaching on Left Side	167.5	153.2
Switchgear Vents Through Breach	357.5	343.2
End of Arc	NA	500
Cameras Detect End of Test	567.0	552.7

4.2. Test 2-33B (480V – 15kA – Target 8 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 17, 2023

The seventh enclosure test had an intended 8 second duration and lasting about the full duration. This test is a repeat of Test 2-33A. This test has three steel enclosures with copper bus bars. The enclosures are facing south with the center one having the starting arc inside it. Four external "remote cameras" were used during this test; one looking through a plexiglass; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the southeast-outside; and one at the northwest inside looking to the north side of the enclosures. Figure 4-10 shows the camera location set-up and enclosure configuration for Test 2-33B.

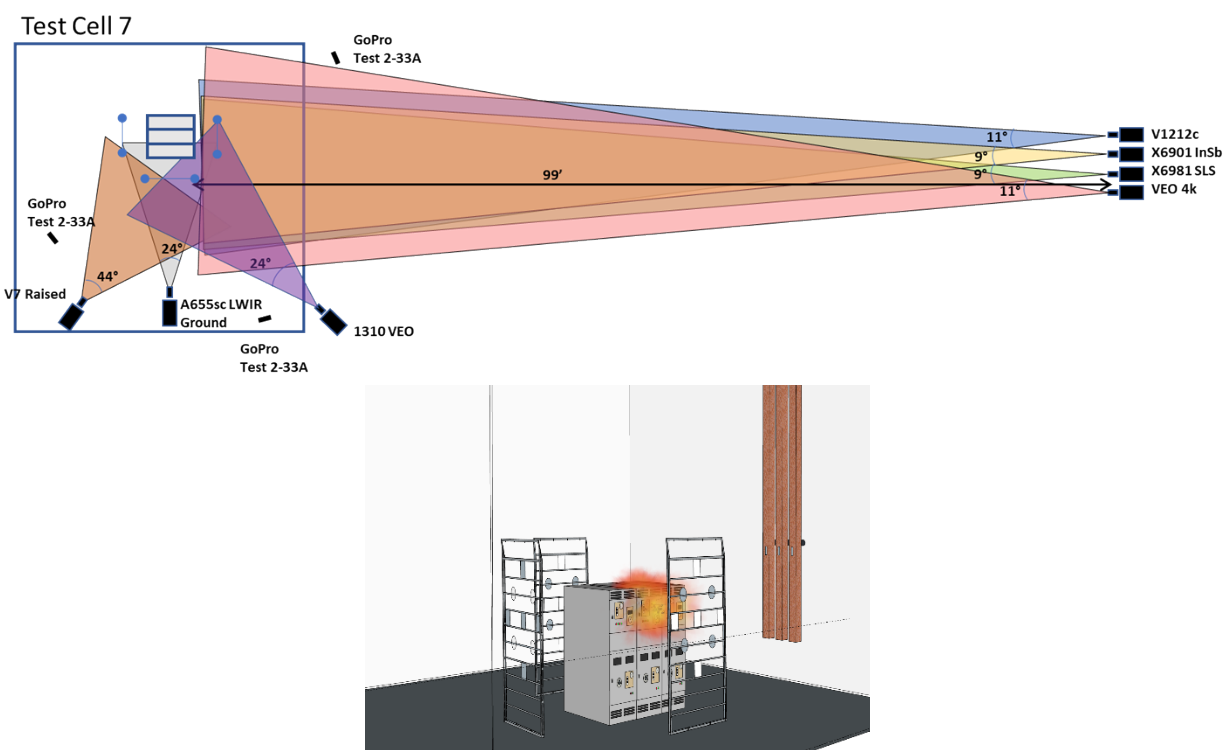


Figure 4-10: Electrical enclosure lineup configuration (Test 2-33B) cameras locations (top) with switchgear enclosure configuration (bottom).

Figure 4-11 through Figure 4-15 show images of notable features and select events that occurred during Test 2-33B. This test lasted the intended 8 seconds and seems to have two phases. Around 5.2 seconds, the activity seems to slow down or even gone, but 400 ms later the arc activity starts again. Seven and a half seconds later the left switchgear breaches. There is particle ejecta 2.28 seconds into the test at the front side and when the breach occurs in the left switchgear at about 7.78 seconds.

Figure 4-11: Test 2-33B imaged through 4k camera. Test that lasted 8 seconds. Pictures are shown at ~1 second intervals during the test (sequenced left to right, top to bottom) – camera imaging at 500 fps.

Figure 4-12: From top left (clockwise): v1310 view ~6 seconds into the test; v7 elevated from the northwest of the test bay, at ~7 seconds; GoPro inside floor northwest view; GoPro southwest view in the middle of the test.

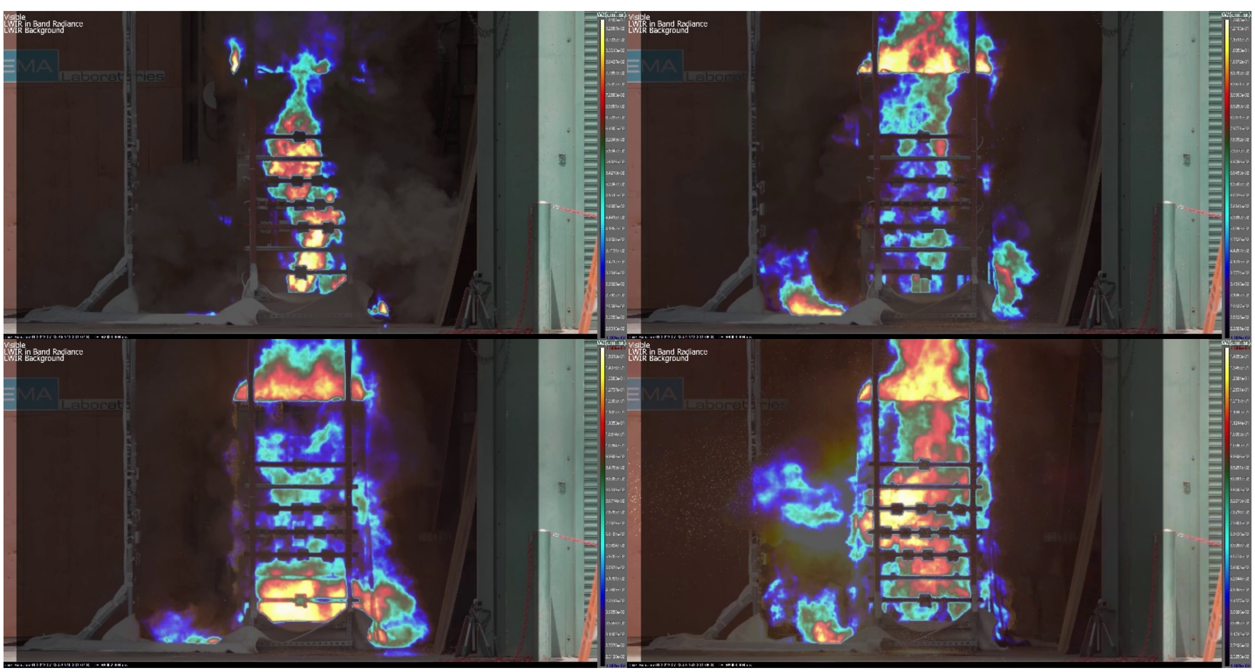


Figure 4-13: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image.

Figure 4-14: Sample frames from synchronized video of 4k and LWIR cameras close to 7.5 seconds into the test. The LWIR image shows heat profile similar to the one collected by the visible camera.

Figure 4-15: Temperature images from the LWIR camera A655 through 8.5 minutes intervals, starting right after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 38.9 to 660°C.

The settings of the cameras in Test 2-33B can be seen in Table 4-3.

Table 4-3: Camera settings for Test 2-33B

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	10,000	500	4,600	1,004	1,004	1,400	18-20
Exposure (μs) /Calibration	30	300	100	1,000-3,000°C	250-1,000°C	710	100-650°C
f/#	5.6	2.8	11	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	145	53	100	100	22	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	10.9	24.5	9.1	9.1	43.6	24.9

Table 4-4 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-33B.

Table 4-4: Test 2-33B Events

Event – Delay from Trigger to Current Applied: 13.2 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-13.2
First Light	26.5	13.3
Particle Ejecta in the Front Side	2294.6	2281.4
Slow Down	5271.0	5257.8
Re-start	5632.6	5619.4
Left Adjacent Switchgear Starts Breaching	7043.7	7030.5
Switchgear Vents Through Breach	7796.1	7782.9
End of Arc	NA	8058
Cameras Detects End of Test	8062.0	8048.8

4.3. Test 2-34A (480V – 8kA – Target 17.5 Seconds – Copper Bus – Steel Enclosure) – Lineup Configuration - August 18, 2023

This is the eighth enclosure test with an intended 17.5 second duration but actually only lasted about 4 seconds. This test had three steel enclosures with copper bus bars facing south with the center one having the starting arc inside it. Three other enclosures are placed adjacent to the first set on their north side. Four external "remote cameras" were used during this test; one looking through a plexiglass; and three Go Pros: one in the southwest near the main entry but inside the test cell; one at the southeast-outside; and one at the northwest inside looking to the north and west side of the enclosures. Figure 4-16 shows the camera location set-up and enclosure configuration for Test 2-34A.

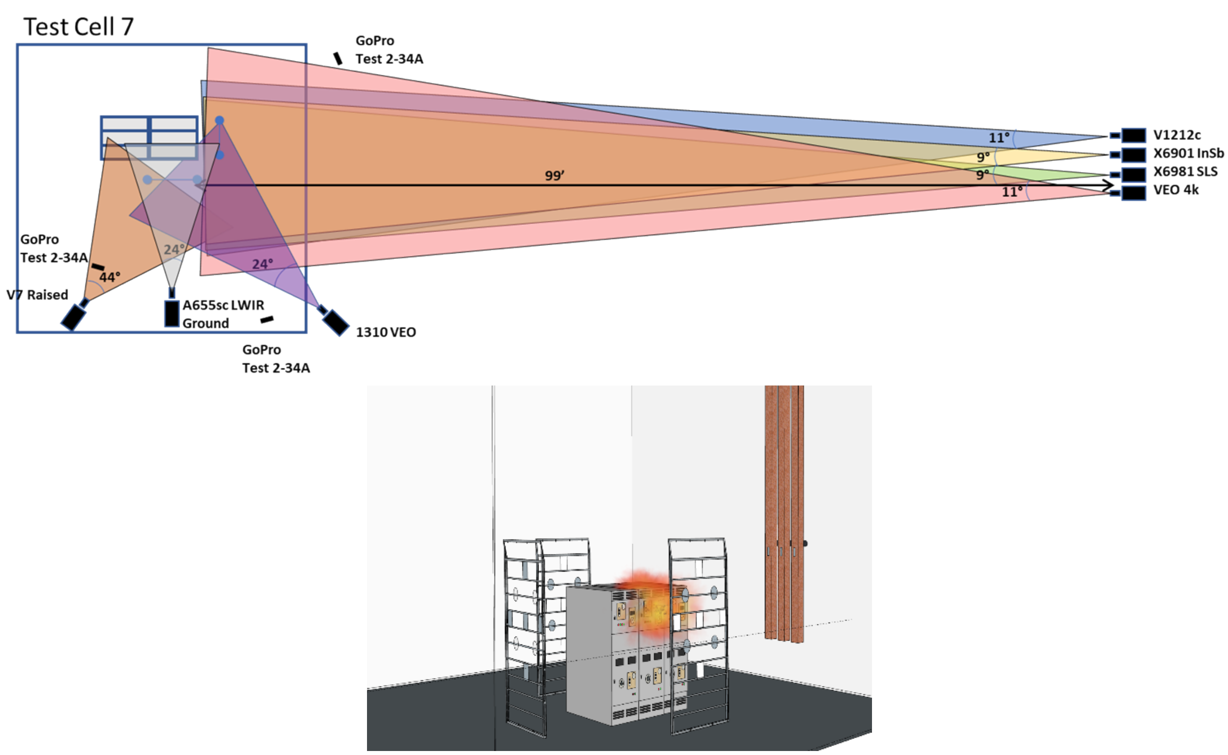


Figure 4-16: Electrical enclosure lineup configuration (Test 2-34A) cameras locations (top) with switchgear enclosure configuration (bottom).

This test starts in the middle switchgear with flameouts early in the test at about 1.6 seconds. The arc passes to the left side switchgear and breaches ~2.45 seconds into the test, filling the test cell with extreme bright light that overwhelms some of the cameras. This seems to indicate that the arc was exposed. The IR cameras show puffs of gases coming out of the two breaches. The first breach points diagonally downward. The second breach starts puffing 300 ms later in a diagonal upward direction from the first one. Figure 4-17 through Figure 4-24 show images of notable features and select events that occurred during Test 2-34A.

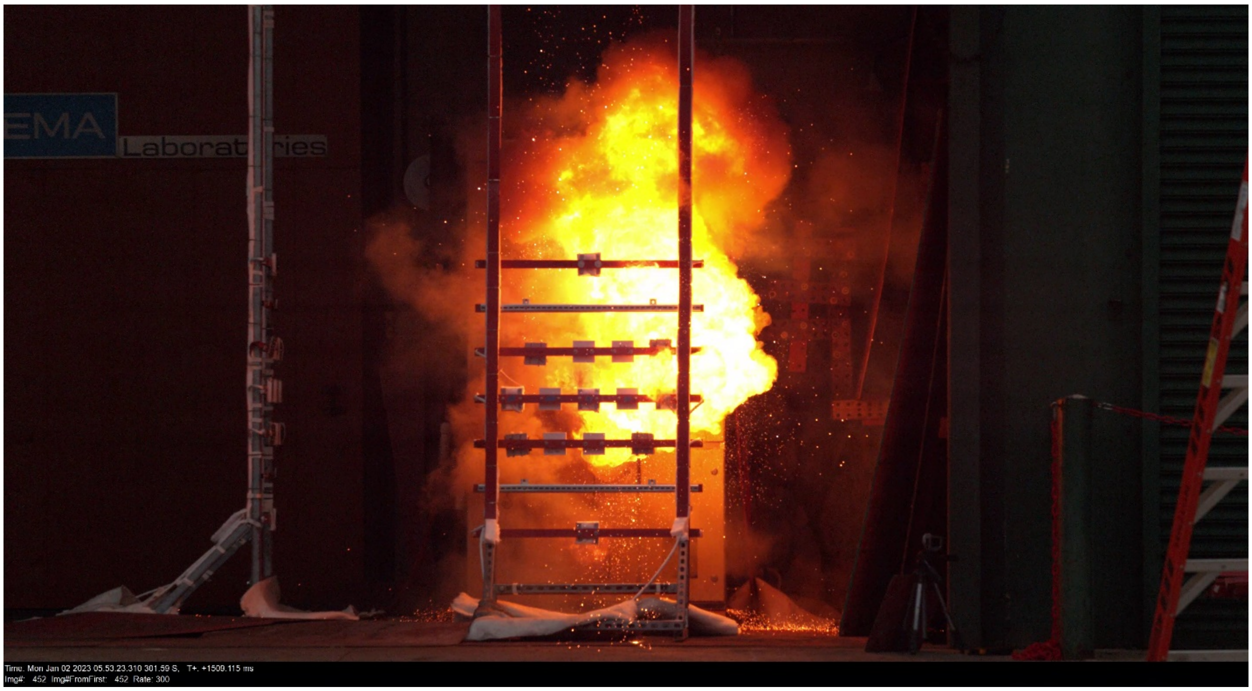


Figure 4-17: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~1.5 seconds into the test – camera imaging at 300 fps.

Figure 4-18: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~2 seconds into the test – camera imaging at 300 fps.

Figure 4-19: Test 2-34 imaged through 4k camera. Test lasted 4 seconds. Picture shows at ~3.5 seconds into the test – camera imaging at 300 fps.

Figure 4-20: From top left (clockwise): v1310 view ~1 second into the test; v7 elevated from the northwest of the test bay, at ~1.5 seconds; GoPro outside floor southeast view early on the test; GoPro northwest view at the end of the test.

Figure 4-21: Image fussion of IR camera (in radiance units of W/cm² sr) synchronized with a visible image 1.7 seconds into the test.

Figure 4-22: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 3.8 seconds into the test.

Figure 4-23: Sample frames from synchronized video of 4k and LWIR cameras close to 2.8 seconds into the test. The LWIR image shows heat profile similar to the one collected by the visible camera.

Figure 4-24: Temperature images from the LWIR camera A655 through 2 minutes intervals, starting half a minute after the test. Arc is induced in the west most enclosure (red hot on top). Temperature ranges from 23.89 to 660°C.

The settings of the cameras in Test 2-34 can be seen in Table 4-5.

Table 4-5: Camera settings for Test 2-34

	v1212-Color	4k VEO-Color	1310 VEO	X6901-MW	X6981-LW	V7	A655-LW
Frame Rate (fps)	7,000	300	2,200	1,004	1,004	800	18-20
Exposure (µs) /Calibration	30	300	100	1,000-3,000°C	250-1,000°C	710	100-650°C
f/#	5.6	8	11	2.5	2.5	11	1
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	100	17-35 / f3.5	24.6
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512	640 x 512	800 x 600	640 x 480
Trigger	Falling	Falling	Falling	Falling	Falling	Falling	NA
Focal Length (mm)	195	145	50	100	100	22	24.6
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.025	0.022	0.017
H Pixel Count	1,280	4,096	1,280	640	640	800	640
Chip Size (mm)	35.84	27.648	23.04	16	16	17.6	10.88
Field of View (deg)	10.5	10.9	24.5	9.1	9.1	43.6	24.9

Table 4-6 shows a list of the notable events detected by the cameras with their corresponding time during Test 2-34.

Table 4-6: Test 2-34 Events

Event – Delay from Trigger to Current Applied: 21.2 ms	Time (ms)	Time Current (ms)
Cameras Triggered	0.00	-21.2
First Light	40.1	18.9
Middle Door in Middle Switchgear Opens	63.9	42.7
Adjacent Left Switchgear Starts Venting	1520.3	1499.1
Center Switchgear Stops Venting – Left One Continues	1715.4	1694.2
Left Side Switch Gear Starts Breaching on Left Side	2434.8	2413.6
Left Side Switch Gear Starts Venting on First Breach Pointing Diagonally Downward	2469.1	2447.9
Left Side Switch Gear Starts Venting on Second Breach Pointing Diagonally Upward	2735.8	2714.6
End of Arc	NA	NA
Cameras Detects End of Test	4470.0	4448.8

5. THERMAL BEHAVIOR

5.1. Temperature Behavior After Testing

Another metric that the cameras were able to capture during this test series was the temperature of the enclosure. This data shows the difference that the enclosure material, bus material, and test duration can have on the maximum temperature. This data was collected mostly by the A655sc real-time LWIR camera. For Test 2-40 and Test 2-41 the camera was not available, and some of the data was estimated from the X6901 MWIR and X6981 LWIR cameras. Table 5-1 shows the maximum temperature for a select group of tests, along with their unique test conditions. As shown, the maximum temperature is higher for the tests with aluminum as the bus or enclosure material.

Table 5-1: Maximum temperature measured at the end of IR camera recording with no smoke and dust in the air – Assumed Emissivity of 0.9 – Assumed Transmission of 0.90 (NaCl Window)

Test	Date	Bus	Enclosure	Comment	Test Duration	Max Temp
2-40	08/07/23	Cu	Al	1000-3000ºC - Decreasing	4s	1062ºC
2-41	08/08/23	Al	Al	1000-3000ºC - Decreasing	4s	1047ºC
2-35	08/09/23	Cu	Steel	100-650ºC - Decreasing	4s	> Range
2-37	08/10/23	Cu	Steel	100-650ºC – Decreasing	4s	362ºC
2-36	08/11/23	Cu	Steel	100-650ºC ~1minute	4s	533ºC
2-38	08/14/23	Cu	Steel	100-650ºC ~15minutes	4s	569ºC
2-39	08/15/23	Cu	Steel	100-650ºC ~14 minutes	4s	> Range
2-33A	08/16/23	Cu	Steel	100-650ºC – Decreases	8s	> Range
2-33B	08/17/23	Cu	Steel	100-650ºC ~15 minutes	8s	> Range
2-34A	08/18/23	Cu	Steel	100-650ºC – Decreasing	17.5s	> Range

5.2. Maximum Radiance and Angles for Bus Duct Testing

The highest radiance (Watts / (cm^2 steradians)) from a plume and its corresponding angle were determined by using a MWIR camera from the two bus duct tests performed in 2023. This analysis was also completed for all bus duct tests performed in 2022. The graphs provide radiance at the index/time for the highest value from the curve of the pixel radiance sum. This data was collected through smoke and dust. Pixels below the camera calibration setting are disqualified by assigning a NaN value and do not contribute to the mean or sum calculations.

5.2.1. Test 2-40 – Aluminum Enclosure – Copper Bus Bar – 4 Seconds Test 4.16kV – 30kA.

For Test 2-40, the peak signal occurs around 1.39 seconds from first light, and the plume is basically parallel to the bus duct. This analysis is looking at the breach where the arc is noticeable, and it is affecting the signal calculation. Figure 5-1 shows the infrared image, with a white arrow indicating the direction of the plume.

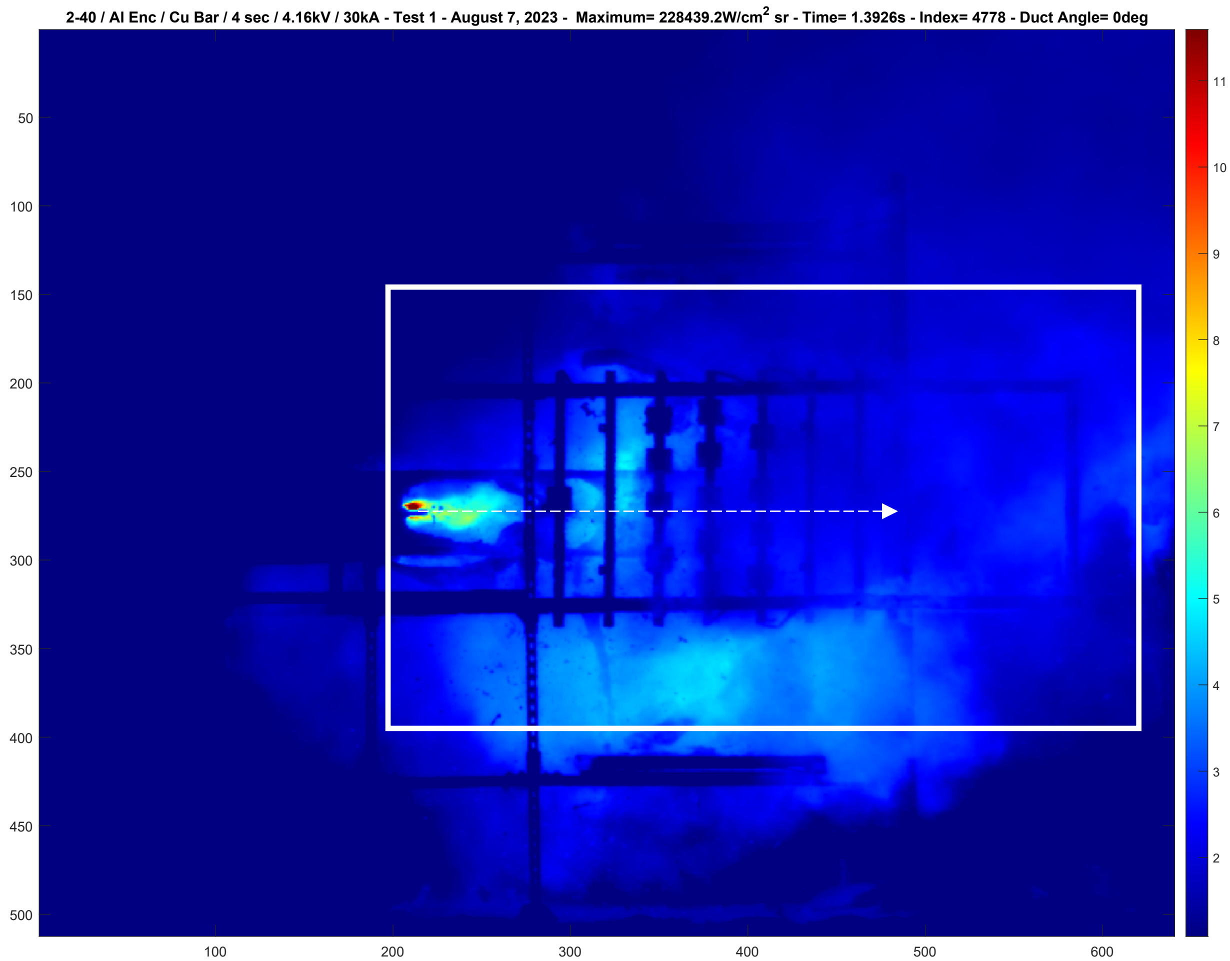


Figure 5-1: Radiance profile for Test 2-40 where the arc is viewed through the breach and is included in the calculations. Notice that the plume is parallel to the bus duct, see white arrow. The white rectangle is the area of summation and averaging.

Figure 5-2 Shows the curves for the average and summed radiance inside the area demarked by a rectangle with white lines. The vertical line shows the time when the maximum occurs.

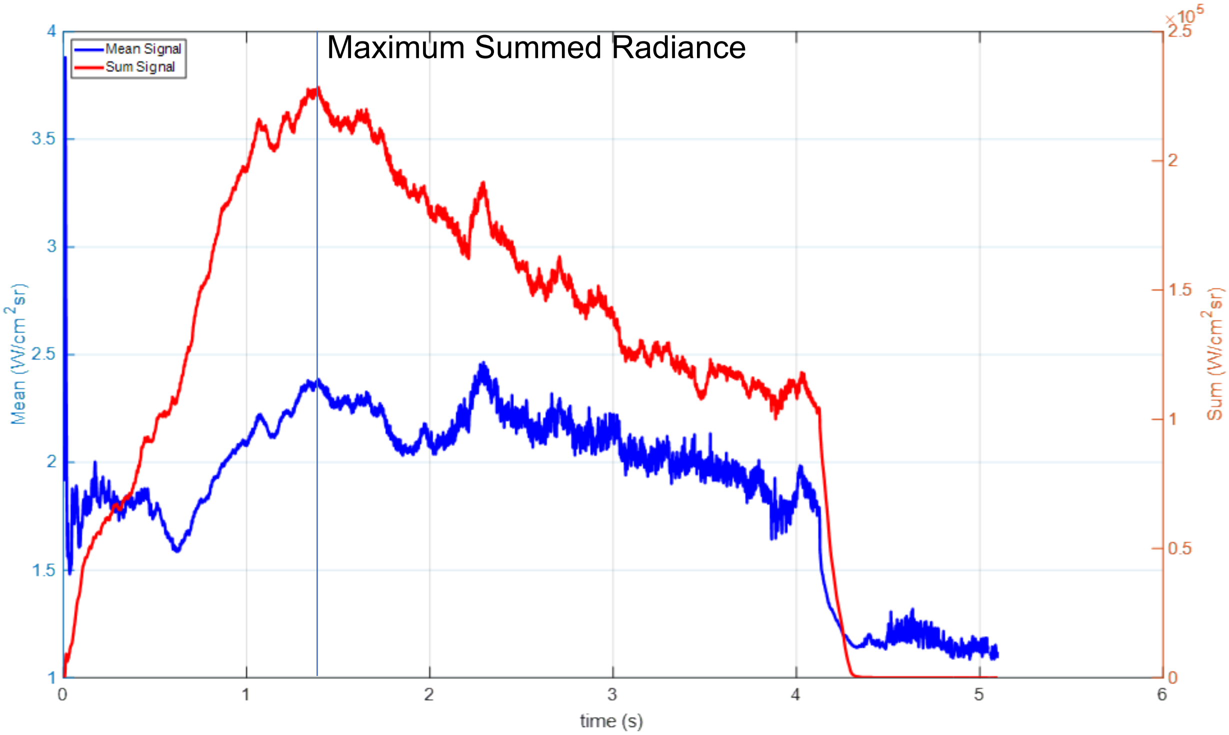


Figure 5-2: Radiance curves for Test 2-40 where the arc fault view is included in the calculations. Notice that the plume is parallel to the bus duct.

If the arc fault is not included in the summation and averaging calculations, see Figure 5-3, we still get a similar timing close to 1.39 seconds. Notice that the main plume is under the bus duct and is parallel to it. There is a second plume above the bus duct that follows the shape of one of the top access doors.

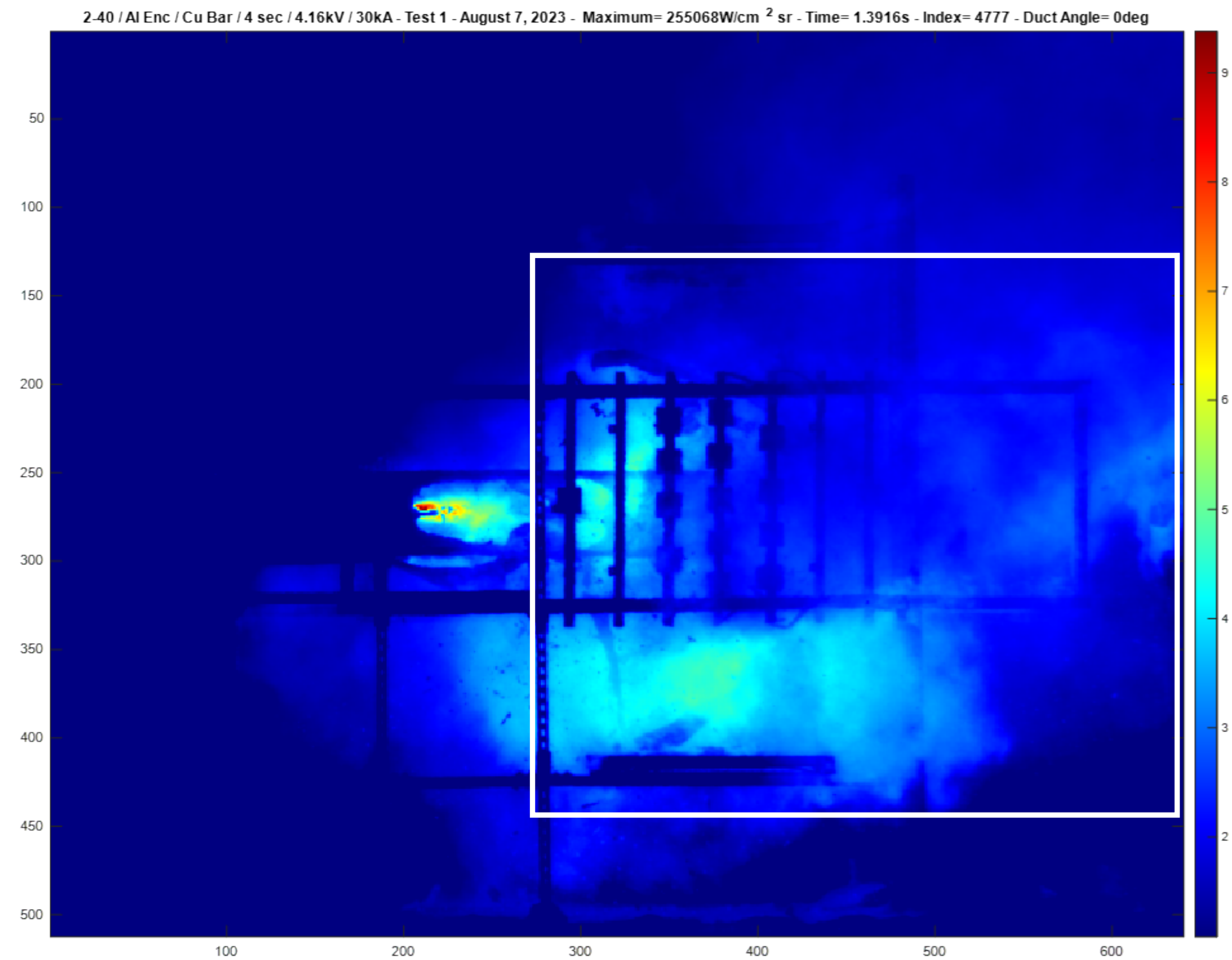


Figure 5-3: Radiance profile for Test 2-40 where the arc is not included in the calculations. Notice that the plume is parallel to the bus duct or is contained by the access door. The white rectangle is the area of summation and averaging.

Figure 5-4 shows the average and summation curves for Test 2-40 when the view of the arc is not included in the calculations. Notice that the average and summation curves have similar shapes, while having different magnitudes

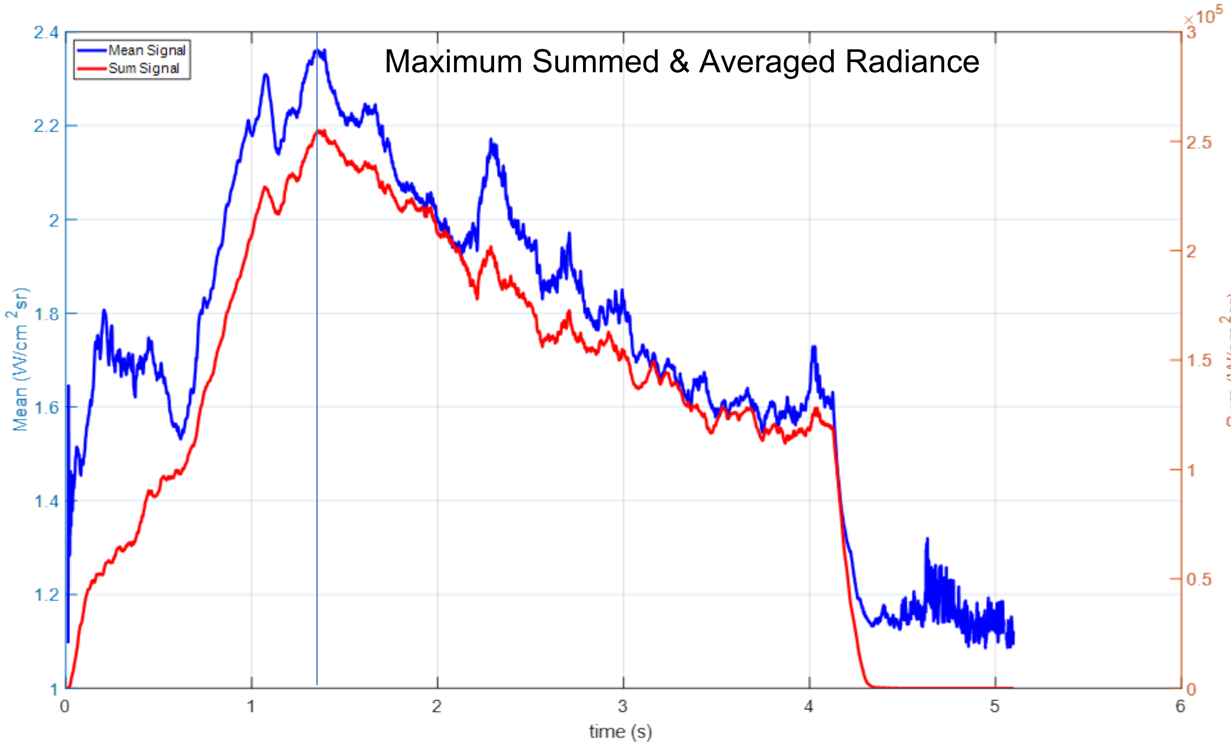


Figure 5-4: Radiance curves for Test 2-40 where the arc fault view is not included in the calculations. Notice that the plume under the bus duct is parallel to it.

5.2.2. *Test 2-41 – Aluminum Enclosure – Aluminum Bus Bar – 4 Seconds Test 4.16kV – 30kA.*

For Test 2-41, the peak signal occurs around 1.67 seconds from first light, and the plume is basically parallel to the bus duct. This analysis is looking at the breach where the arc is noticeable, and it is affecting the signal calculation. See Figure 5-1 for the infrared image, with a white arrow indicating the direction of the plume.

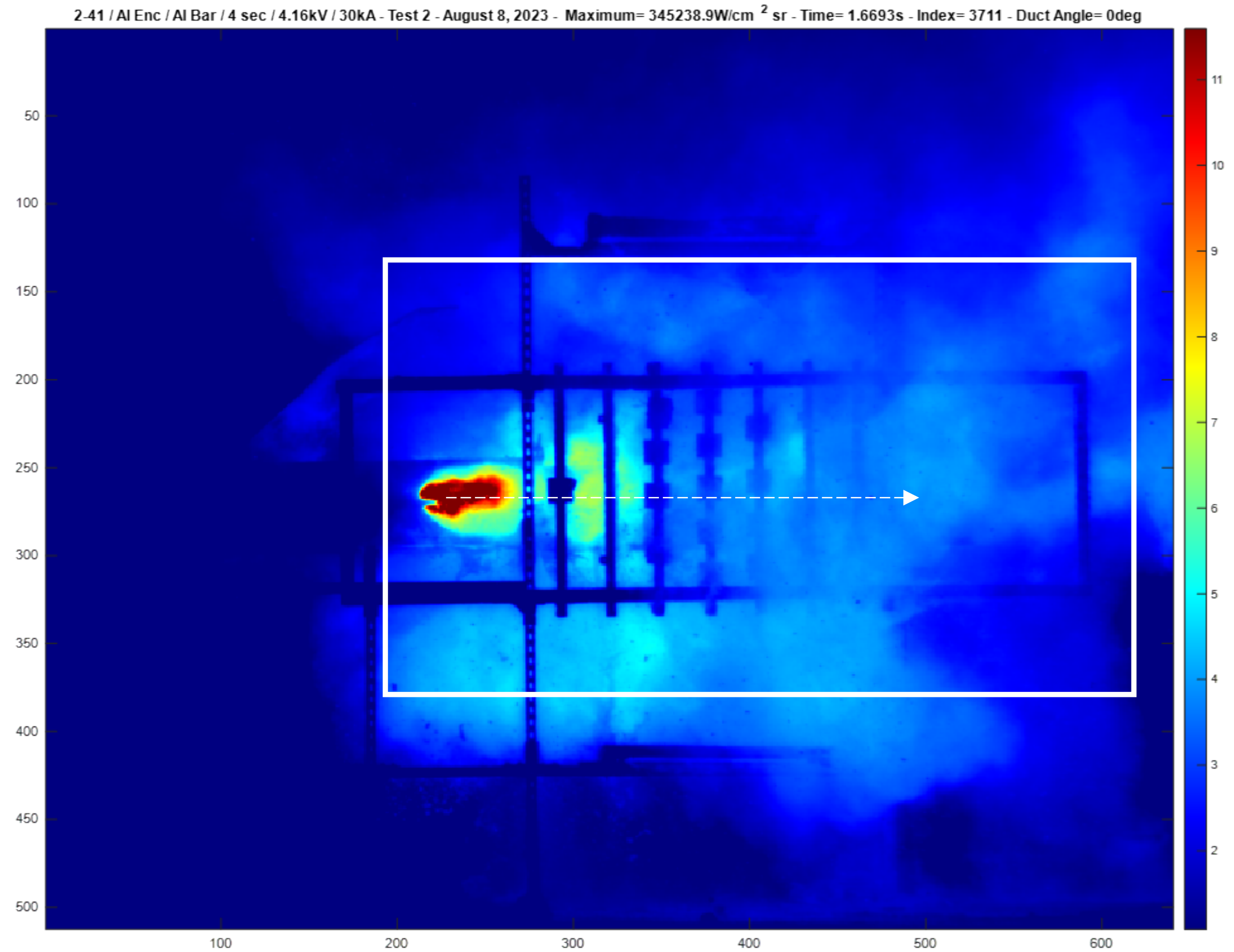


Figure 5-5: Radiance profile for Test 2-41 where the arc is viewed through the breach and is included in the calculations. Notice that the plume is parallel to the bus duct, see white arrow. The white rectangle is the area of summation and averaging.

Figure 5-6 shows the curves for the average and summed radiance inside the area demarked by a rectangle with white lines. The vertical line shows the time when the maximum occurs. Compared to Test 2-40, radiance is higher for Test 2-41 when including the view from the arc.

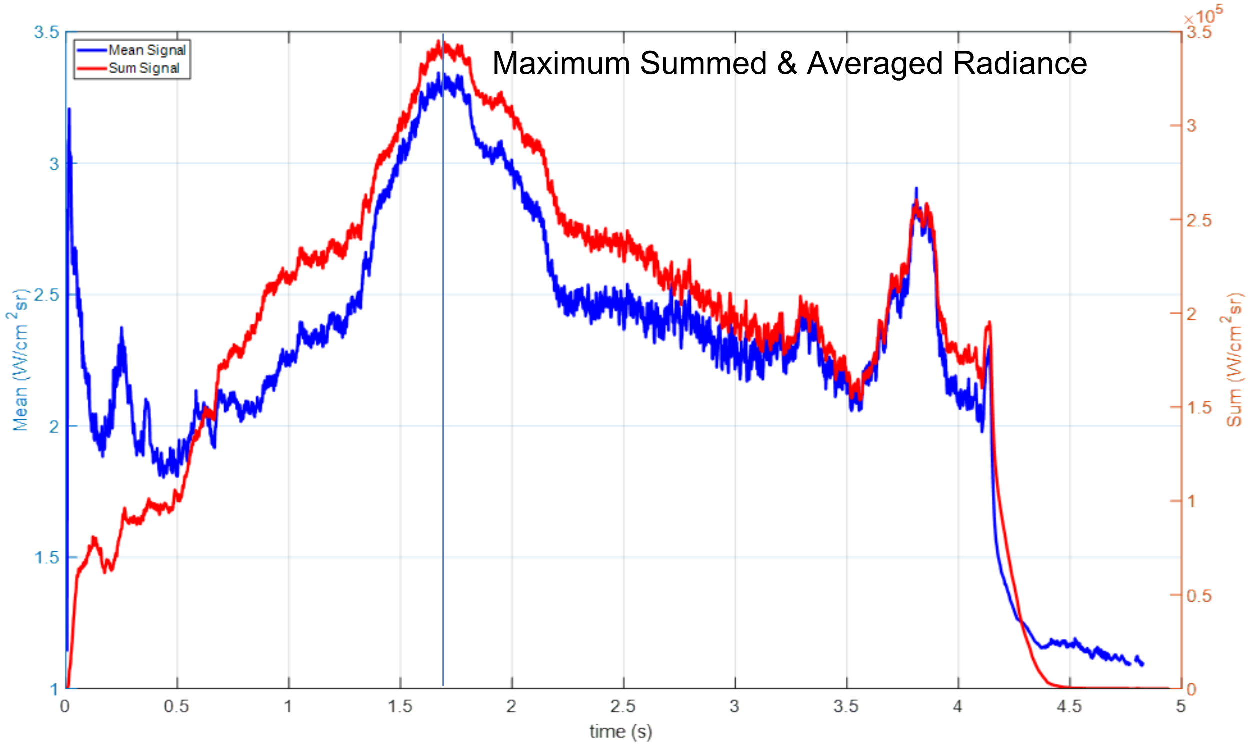


Figure 5-6: Radiance curves for Test 2-41 where the arc fault view is included in the calculations. Notice that the plume is parallel to the bus duct.

If the arc fault is not included in the summation and averaging calculations, see Figure 5-7, there is a slightly different time for the maximum signal at around 1.76 seconds. Notice that the main plume roughly follows the shape of the bus duct on its right side. Also, without including the arc in the calculations, the curves are still showing higher magnitudes compared to Test 2-40, see Figure 5-8.

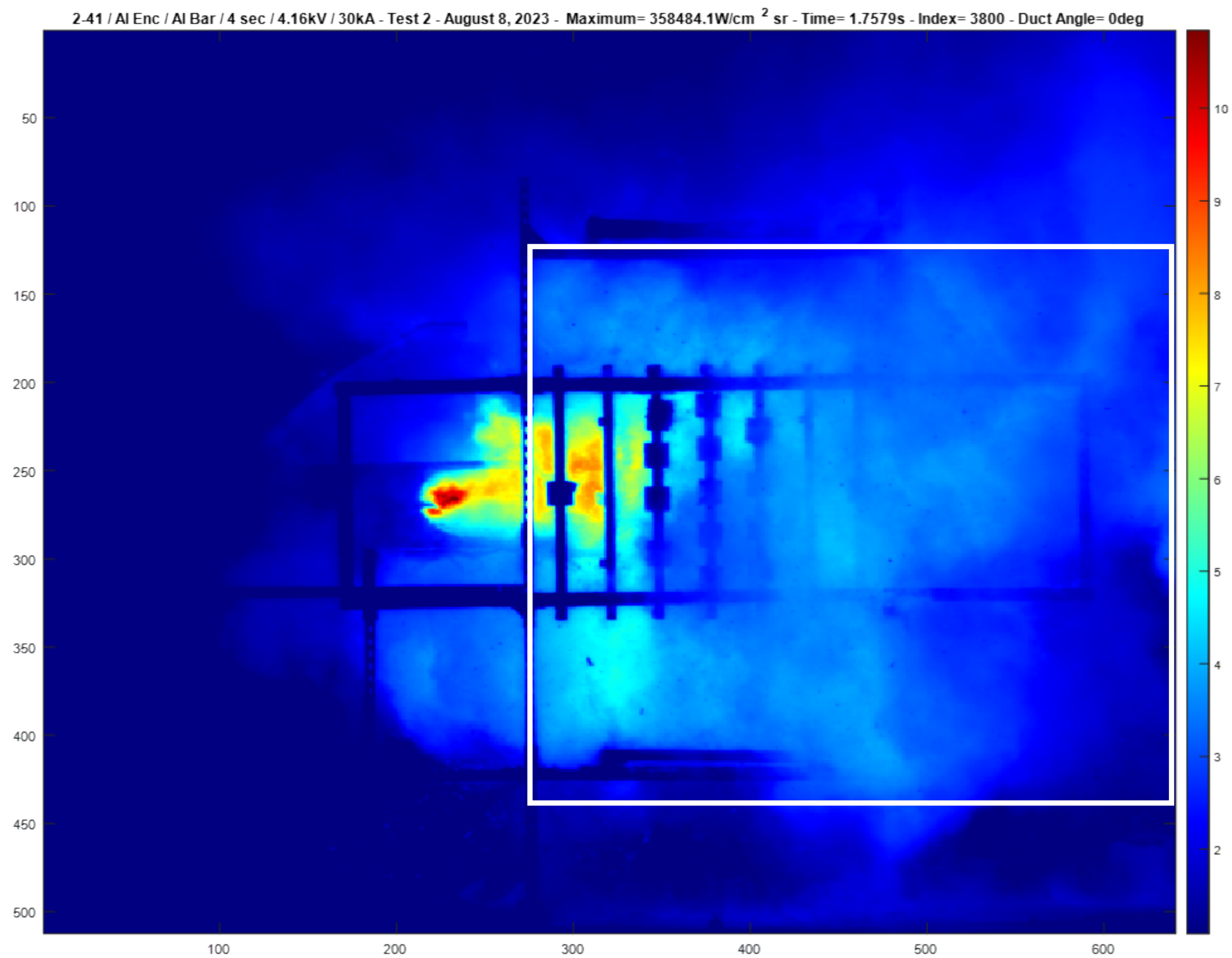


Figure 5-7: Radiance profile for Test 2-41 where the arc is not included in the calculations. Notice that the highest magnitude plume roughly follows the shape of the bus duct. The white rectangle is the area of summation and averaging.

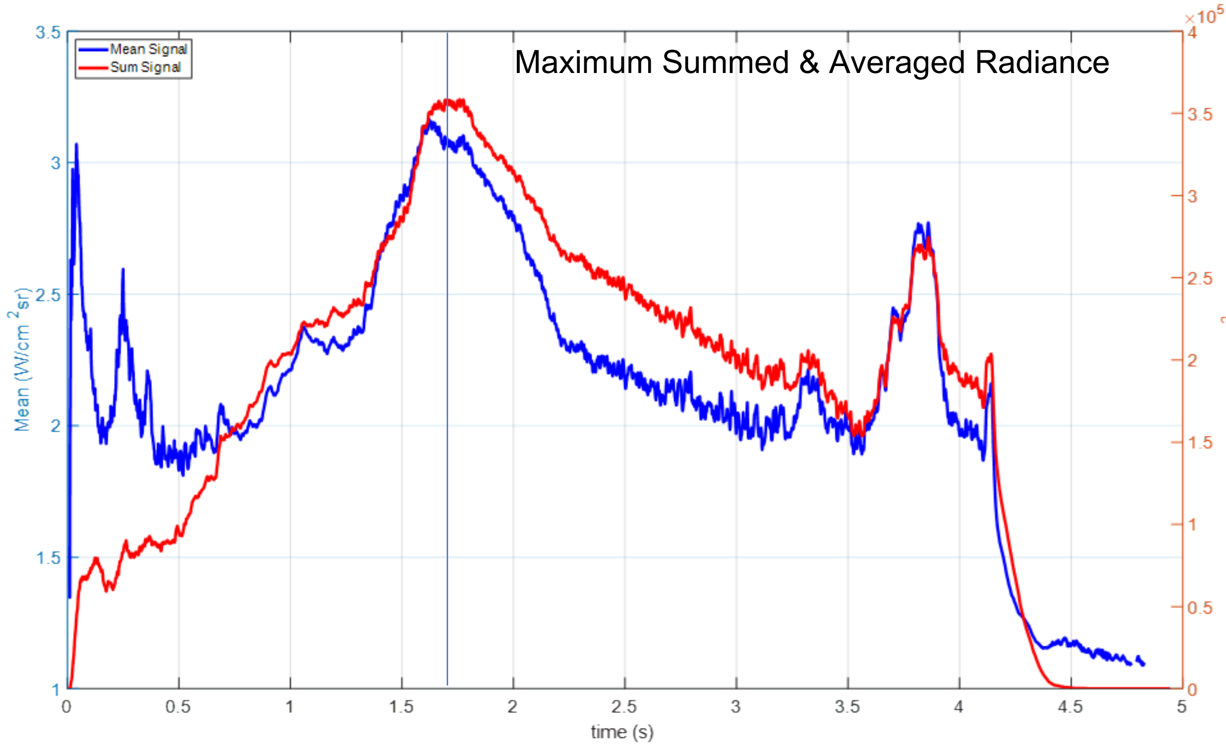


Figure 5-8: Radiance curves for Test 2-41 where the arc fault view is not included in the calculations. Notice that the plume under the bus duct is parallel to it.

For Test 2-40 and Test 2-41 when the arc stops, the leftovers of the bus duct are flowing fire, smoke, and hot gases towards the east of TC-9 due to shockwaves from the arc. They are rising due buoyancy but their radiance magnitude does not match the radiances early in the test.

6. CONCLUSION

This report shows the data collected by high-speed and real-time visible and infrared cameras deployed at the KEMA facility HEAF test campaign of 2023. A significant amount of data was generated through the use of the different high-speed and infrared cameras, and this report complements the video data generated. For each test, the description of the test conditions, the camera placement, camera settings, sample camera views and the table of events determined from the perspective of the cameras was provided. The cameras were able to collect data on the timing of significant events during each test, such as when the breach of the cabinet occurred. Additionally, the data generated from the cameras was used to calculate metrics of interest, such as the velocity of the ejected panel in Test 2-37 and the maximum radiance in the bus duct tests. The data provided in this report and the video data generated is used to inform the environmental conditions after a HEAF occurs, which varies based on the bus/enclosure material as well as the voltage input.

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[2] M. Millogo, S. Bernard and P. Gillard, "Combustion characteristics of pure aluminum and aluminum," *Journal of Loss Prevention in the Process Industries,* no. 68, pp. 1-9, 2020.

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