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REPORT ON HIGH ENERGY ARCING FAULT EXPERIMENTS

Photometrics Report for Medium-Voltage Bus Duct and Switchgear Enclosures

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High Energy Arcing Fault (HEAF) Photometrics 2022 Test 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, 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 2022. SNL provided high speed visible and infrared video/data of ten tests that collected data from HEAFs originated on copper and aluminum buses inside switchgears and bus ducts. Part of the SNL scope was to place cameras with high-speed data collection at different vantage points within the test facility to provide NRC a more complete and granular view of the test events.

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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 (7.5-14µm)
MWIR	Mid Wave Infrared (3-5µm)
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
SNL	Sandia National Laboratories
TC9	Test Cell 9

1. INTRODUCTION

The mid voltage tests were performed at KEMA labs in Chalfont, PA during the last two weeks of August of 2022. Figure 1-1 shows the aerial view (from Google maps) of the test facility. As shown, the full facility consists of nine test cells in which experiments can be performed. Test Cell 9 (TC9) is marked on the figure, and this is where the HEAF tests were conducted during the 2022 test campaign. The map also shows the two locations where the external high-speed cameras were located during the different tests (as marked with white squares). During the switch gear tests, the three main high-speed cameras were lined up directly in front (roll-up door) of TC9 (southeast of the test cell). For the duct bus tests, the external cameras were placed further south of TC9 (southwest of the camera location for the switchgear tests).

Figure 1-1: Aerial view of the test facility – Google Maps

Figure 1-2 shows the top view and front view of TC9. This figure is helpful to identify the camera locations and test article described throughout this report.

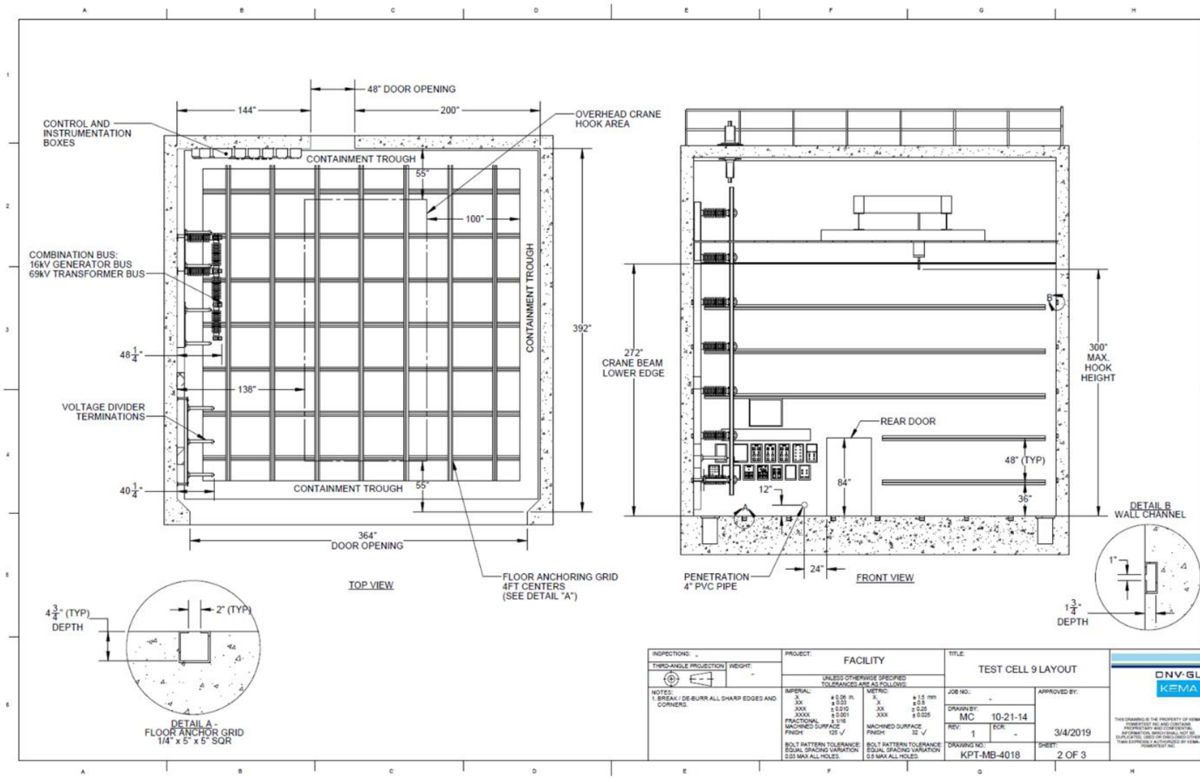

Figure 1-2: KEMA Test Cell 9 Layout (top and front view)

1.1. Test Description

There was a total of ten different tests performed during this test series.

- Two switchgear tests: 6.9kV / 32kA
- Eight bus ducts tests: 4.16kV / 30kA

The tests varied in duration (2 and 4 seconds), bus bar material (aluminum and copper) and enclosure material (steel and aluminum).

1.2. Camera Descriptions and Locations

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. Note that one of the parameters included in the table is pixel pitch. 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 can be achieved. For example, the GoPros 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 Pitch	Utilization
Vision Research	v1212c		12,000	Visible Bayer Filter	1,280x800	28 µm	HS Camera for speed measurements of objects of interest
Vision Research	1310 VEO		10,000	Visible Bayer Filter	1,280x960	18 µm	HS camera to provide different views
Vision Research	4k VEO 990s		1,000	Visible Bayer Filter	4,096x2,000	6.75 µm	HS camera for large FOV of the test
Vision Research	Phantom 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		1,004	3-5 µm	640x512	25 µm	HS IR camera for looking through some dust and radiance measurement
GoPro	HERO 7		120	Visible - Bayer Filter	1,920x1,080 (30fps - 4,000x3,000)	8 µm	High risk and sound recording camera

Note that some cameras were deployed in a group: the v1212s, the 4k VEO and the X6901, as shown in Figure 1-3. This group of cameras was deployed at approximately 97 feet south/southwest from the test article to measure the speed of ejected material, provide fine timing of events, provide imaging through dust and smoke, determine breach timing, and capture an overall view. The cameras were placed close to each other with the intention of reducing parallax.

Figure 1-3: Front (left panel) and back view (right panel) of the HS remote cameras collecting during the bus duct tests.

A Phantom v7, Figure 1-4 (left panel), was deployed inside TC9 at its northeast side corner to look for breach timing at the top and north side of bus ducts. This camera was not deployed for the switchgear tests. Similarly, the 1310 VEO, Figure 1-4 (right panel), was deployed to look from below and the south side of the bus ducts to look for breach timing. The 1310 VEO was also deployed on the switchgear tests behind a wall and looking through a mirror. It was found in these tests that this camera was impacted by smoke and dust in detecting breaches; the IR camera was more effective in detecting breaches for the switchgear tests.

Figure 1-4: Phantom v7 HS camera (left panel) perched at the top of the northeast side of TC9; 1310 VEO (right panel) near the ground and southeast, just outside TC9. Both cameras were looking in these locations at the bus ducts. The insets show close up of the cameras.

2. SWITCHGEAR TESTS

Figure 2-1 shows the locations of the cameras used in Tests 2-10 and 2-12 and their respective horizontal field of views (the GoPros field of view are large and fixed; not depicted in figure). The location of the remote camera station was intended for easy protection, and to provide an orthogonal view of the switchgear ejecta and the radiometer setups. This camera station location was biased to the east to provide access to the NIST equipment which required a direct and perpendicular view of the switchgear itself. This station had a v1212c, a X6901 and a 4k VEO. The proximity of the cameras reduced parallax to allow data fusion between the data of the X6901 and the 4k VEO. A 1310 VEO Color was deployed behind a concrete wall looking at the front side of the switchgear through a mirror. From experience, it has been found that cameras located in this position are usually exposed to ejecta that damages the camera, lens, and cables. Having a concrete block in front of the camera adds a layer of protection. To capture the correct view, a front surface mirror is used to reflect the image to the camera lens. A GoPro was placed in the northeast side of TC9 and second one top looking down to the front of the switchgear.

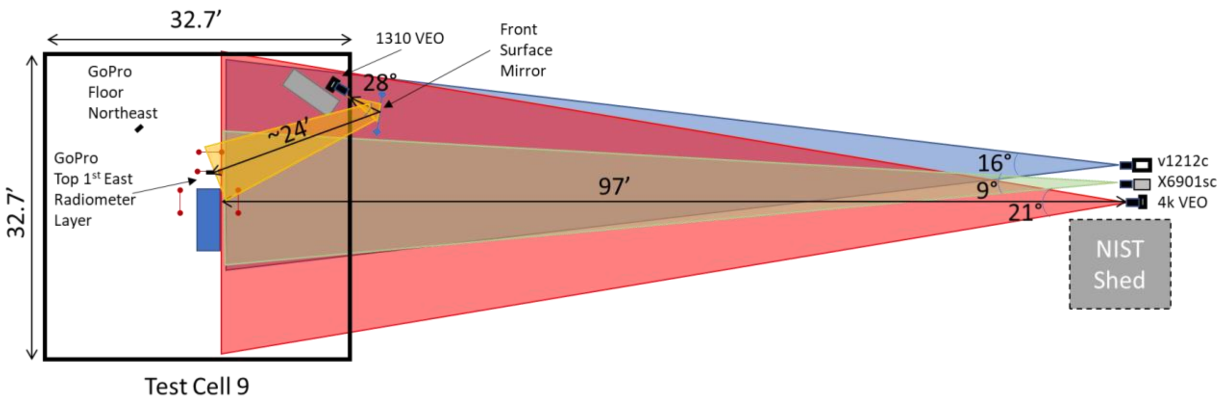

Figure 2-1: Switchgear cameras locations

2.1. Test 2-10 (2 Seconds – Copper Bars – Steel Enclosure)

Figure 2-2: Test 2-10 imaged through 4k VEO camera – camera imaging at 1,000 fps. Notice the yellow orange/red color in the background 0.5 seconds from trigger.

The first switchgear test had an intended duration of 2 seconds with a steel enclosure and copper bars. The test was captured with the three external "remote cameras", the interior camera looking through a mirror, and the two GoPros (one in the northeast side in the floor, and one on the top radiometer rack looking at the front of the switchgear). Note that images from all of the color cameras show orange flames. The high speed v1212 indicates that flame and hot gases are incident into the top radiometer rack for the first time around 55 milliseconds into the test and reaches the first radiometer layer to the east at 71.5 milliseconds elapsed time, engulfing the radiometers in the south at around 74 milliseconds. Smoke occludes the views in the floor at around 173 milliseconds and covers everything at around 1666 milliseconds. Camera settings are shown in Table 2-1.

Table 2-1: Camera settings for Test 2-10

	v1212-Color	4k VEO 990s	1310 VEO	X6901
Frame Rate (fps)	12,000	1,000	10,000	1,004
Exposure (μs) /Calibration	18	500	7.5	500-1,200°C
f/#	8	8	4	2.5
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512
Trigger	Falling	Falling	Falling	Falling
Focal Length (mm)	125	75	47	100
Pixel Size (mm)	0.028	0.00675	0.018	0.025
H Pixel Count (pixels)	1,280	4,096	1,280	640
Chip Size (mm)	35.84	27.648	23.04	16
Field of View (deg)	16.3	20.9	27.5	9.1

Figure 2-3: From top left (clockwise): GoPro at northeast side; 1310 VEO, at 10,000fps, from the south east looking through a mirror (0.5 seconds from trigger); GoPro at top by radiometer rack.

Figure 2-4: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.52 seconds from trigger.

2.2. Test 2-12 (4 Seconds – Copper Bars – Steel Enclosure)

Figure 2-5: Test 2-12 imaged through 4k camera –camera imaging at 1000 fps. Notice the orange/red color in the background 0.17 seconds from trigger.

The second switchgear test had an intended duration of 4 seconds with a steel enclosure and copper bars. This test is captured with the three external "remote cameras", the camera looking through a mirror, and two GoPros. Note, the GoPros were placed in similar locations as the first test. Note that images from all of the color cameras show orange flames, the same as the first test. The high speed v1212 indicates that flame and hot gases are incident into the bottom east radiometers at 70 milliseconds and the top radiometer at 88 milliseconds. Smoke starts occluding the views by the floor at around 85 milliseconds and covers everything at around 2500 milliseconds. The settings of the cameras can be seen in Table 2-2.

Table 2-2: Camera settings for Test 2-12

	v1212-Color	4k VEO 990s	1310 VEO	X6901
Frame Rate (fps)	12,000	1,000	10,000	1,004
Exposure (μs) /Calibration	7	300	3	500-1,200°C
f/#	8	8	22	2.5
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100
Resolution	1,280x800	4,096 x 2000	960 x 1280	640 x 512
Trigger	Falling	Falling	Falling	Falling
Focal Length (mm)	125	75	44	100
Pixel Size (mm)	0.028	0.00675	0.018	0.025
H Pixel Count (pixels)	1,280	4,096	1,280	640
Chip Size (mm)	35.84	27.648	23.04	16
Field of View (deg)	16.3	20.9	29.3	9.1

Figure 2-6: v1310, at 10,000fps, from the south east looking through a mirror 0.08 seconds from trigger.

Figure 2-7: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 2.53 seconds from trigger.

3. BUS-DUCT TESTS

Figure 3-1 shows the locations of the cameras used in the bus duct tests (2-25, 2-26, 2-27, 2-28, 2-30, 2-30B, 2-31 and 2-32) with their respective horizontal field of views (GoPros field of view are large and fixed; not depicted in the figure). The location of the remote camera station was intended for easy protection, and to provide a semi orthogonal view of the bus placement. This camera station location was centered on the bus duct, but as mentioned before it was placed 10 degrees off (counterclockwise looking from the top) to image the west side where the connection to the three phases is located. This station had a v1212c, a X6901 and a 4k VEO. The proximity of the cameras reduced parallax to allow data fusion between the data of the X6901 and the 4k VEO. A 1310 Color was deployed southwest, just outside the rolling doors to visualize the bottom and south of the busduct. A black and white (no Bayer filter) Phantom v7 was placed at the northeast inside corner of TC9, 4.5 meters above the floor to view the top and north side of the bus duct. Two GoPros were placed in different locations near the test duct, and a third GoPro was added to image outside TC9.

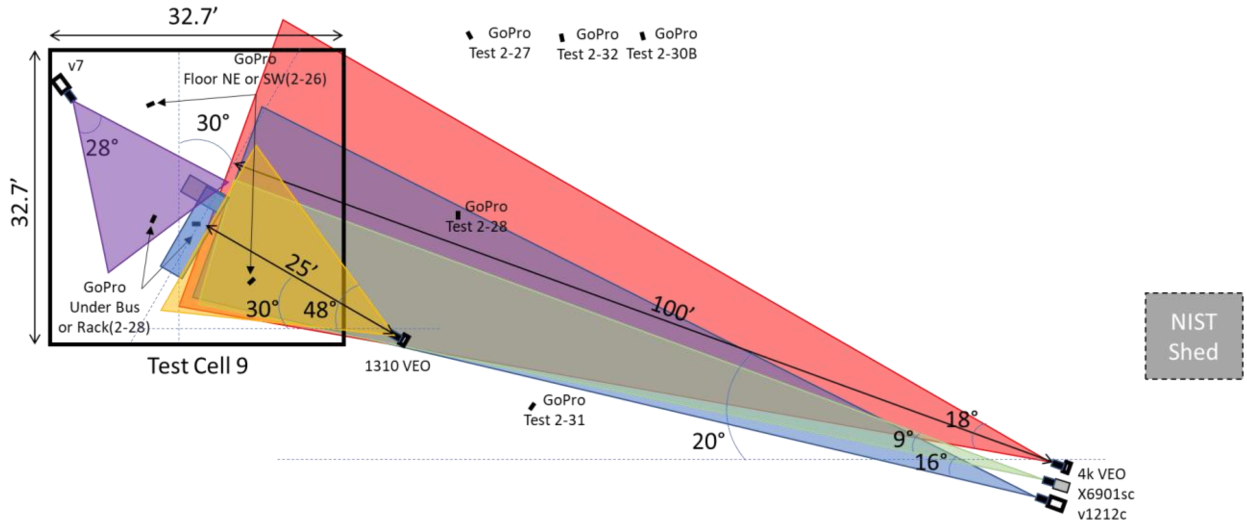

Figure 3-1: Bus duct cameras locations

3.1. Test 2-25 (2 Seconds – Copper Bars – Steel Enclosure)

Figure 3-2: Test 2-25 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background 0.19 seconds from trigger.

Test 2-25 (the first bus duct test) had an intended 2 second duration with a steel enclosure and copper bars. Two GoPros were used in this test: one at the north side (same as the two switchgear tests), and one in the floor under the bus duct. Images from all color cameras show orange flames, the same as the switchgear tests. Smoke becomes dominant around 600 milliseconds with some openings showing the duct connection to the switchgear in fire. At 1.2 seconds, there is an ejection of red/orange particulate. By 2 seconds everything is covered is dark smoke. The settings of the cameras can be seen in Table 3-1.

Table 3-1: Camera settings for Test 2-25

	v1212-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (µs) /Calibration	7	300	2	500-1,200°C	2
f/#	8	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	80	29	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	19.6	43.3	9.1	28.2

Figure 3-3: From left to right: Phantom v7, 4,000 fps, at top northeast side (0.07 seconds from trigger); GoPro at northeast.

Figure 3-4: Image fusion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.37 seconds from trigger.

3.2. Test 2-26 (4 Seconds – Copper Bars – Steel Enclosure)

Figure 3-5: Test 2-26 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background 0.25 seconds from trigger.

Test 2-26 (the second bus duct test) had an intended 4 second duration with steel enclosure and copper bars. Two GoPros were used in this test: one at the southwest side floor, and one in the floor under the bus duct. Images from all of the color cameras show orange flames and dark smoke. Smoke and dust are dominant in the view by 0.45 seconds with red/orange particulate seen at around 2.5 seconds. The settings of the cameras, specially the 1310 VEO, were tweaked due to the proximity to the duct and the changed conditions seen in the test, as shown in Table 3-2.

Table 3-2: Camera settings for Test 2-26

	v1212-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (μs) /Calibration	7	300	1.6	850-2,000°C	2
f/#	8	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	80	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	19.6	47.8	9.1	28.2

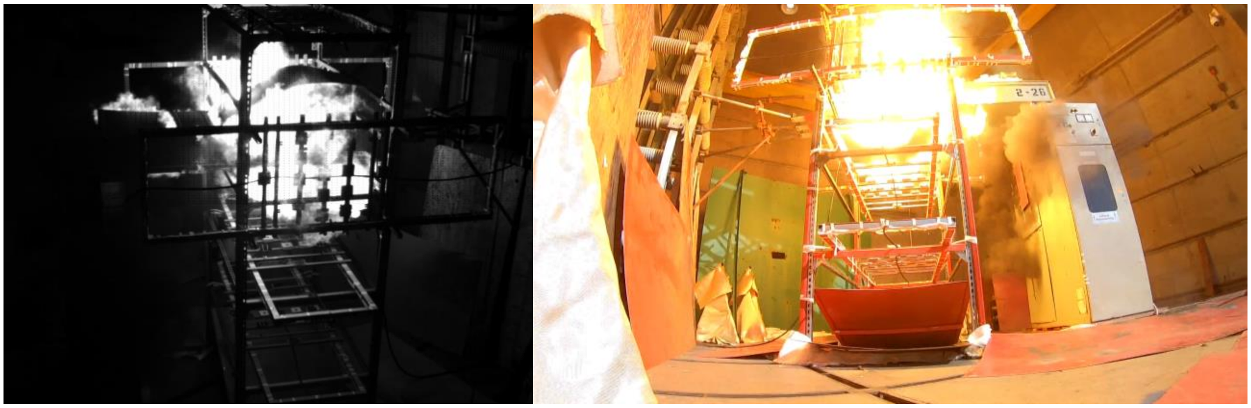

Figure 3-6: From left to right: Phantom v7, 4,000 fps, at top northeast side (0.12 seconds from trigger); GoPro by the rolling doors at souththwest.

Figure 3-7: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 1.68 seconds from trigger.

3.3. Test 2-30 (4 Seconds – Aluminum Bars – Steel Enclosure)

Figure 3-8: Test 2-30 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background 0.24 seconds from trigger. The first 100 milliseconds seems to show a white cloud.

Test 2-30 (the third bus duct test) had an intended 4 seconds duration with steel enclosure and aluminum bars. Two GoPros were used in this test: one at the northeast side floor, and one under the bus duct. Images from all color cameras show orange flames, the same as the switchgear tests. However, the first 100 milliseconds show a white cloud, a possible indication of aluminum burning. An arc at the 3-phase connection was detected by the Phantom v7 at 39.919 µs of the camera triggering (48.252 µs from "data collection start"), and with a 45 µs delay in applying current from "data collection start", the arc started 3.25 µs from applying current. Smoke and dust are dominant in the 4k VEO view by 400 milliseconds, and white bright particulate starts falling after 500 milliseconds, believed to be burning aluminum. After 1 second, there is a large ejection of white particulate towards the east, with the dark smoke still being dominant in the background. The settings of the cameras can be seen in Table 3-3.

Table 3-3: Camera settings for Test 2-30

	v1212-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (µs) /Calibration	4	150	1.0	1,000-3,000°C	2
f/#	8	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	80	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6

Field of View (deg)	16.3	19.6	47.8	9.1	28.2

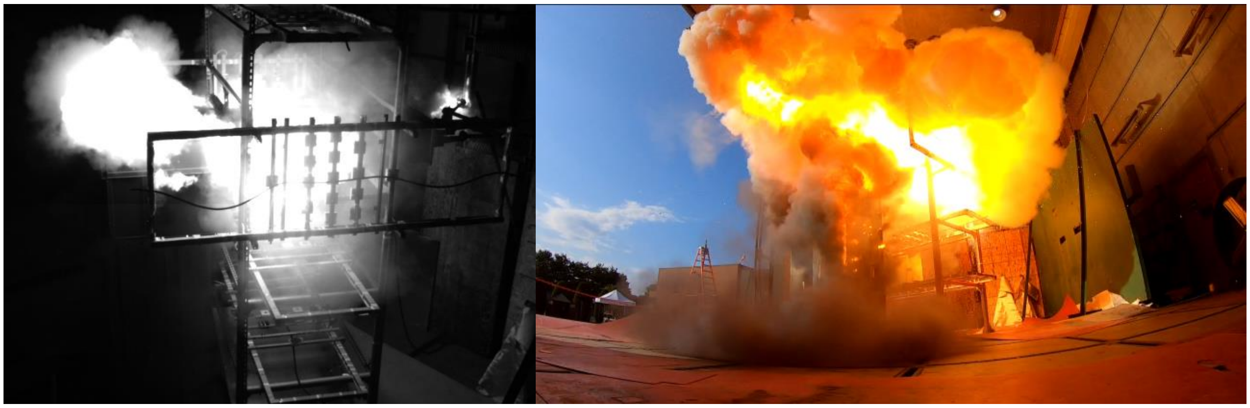

Figure 3-9: From left to right: Phantom v7, 4,000 fps, at top northeast side – notice the arcing at the right side of the image at the juncture between the test and the facility (0.15 seconds from trigger); GoPro inside flor at northeast.

Figure 3-10: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.3 seconds from trigger.

3.4. Test 2-27 (2 Seconds – Copper Bars – Aluminum Enclosure)

Figure 3-11: Test 2-27 imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color flame and dust, and the bright white particulate 0.93 seconds from trigger.

Test 2-27 (the fourth bus duct test) had an intended 2 second duration with an aluminum enclosure and copper bars. Three GoPros were used in this test: one at the northeast side floor, one under the bus duct, and the last one outside southeast of TC9 about 30 feet from the rolling doors. Images from all color cameras show orange flames and dark smoke on the east side of the setup. At about 300 milliseconds, a breach is detected which starts showing what seems to be burning aluminum particulate flying towards the east from the test setup. Eventually bright particulate starts falling under the arc too. The settings of the cameras can be seen in Table 3-4.

Table 3-4: Camera settings for Test 2-27

	v1212-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (µs) /Calibration	4	150	1.6	1,000-3,000°C	2
f/#	8	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	85	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	18.5	47.8	9.1	28.2

Figure 3-12: From left to right: Phantom v7, 4,000 fps, at top northeast side 0.08 seconds from trigger; GoPro at the bottom of the radiometer racks.

Figure 3-13: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.2 seconds from trigger.

3.5. Test 2-28 (4 Seconds – Copper Bars – Aluminum Enclosure)

Figure 3-14: Test 2-28 imaged through 4k camera – camera imaging at 1000 fps Notice the orange/red color flame and dust, and the bright white particulate ejected towards the east 0.65 seconds from trigger.

Test 2-28 (the fifth bus duct test) had an intended 4 second duration with aluminum enclosure and copper bars. Three GoPros were used in this test: one at the northeast side floor, one by the first lower radiometer rack north of the bus duct, and the last one outside south of TC9 about 30 feet from the rolling doors. Images from all color cameras show orange flames and dark smoke that envelopes the duct 100 milliseconds into the test. At about 350 milliseconds, it is possible to see two plumes of bright white particulate flying towards the east, which is believed to be burning aluminum. About a second into the test, it is possible to see falling burning particles with white smoke (burning aluminum) right under the arc. The settings of the cameras can be seen in Table 3-5.

Table 3-5: Camera settings for Test 2-28

	v1212-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (µs) /Calibration	4	150	2.0	1,000-3,000°C	2
f/#	11	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	85	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	18.5	47.8	9.1	28.2

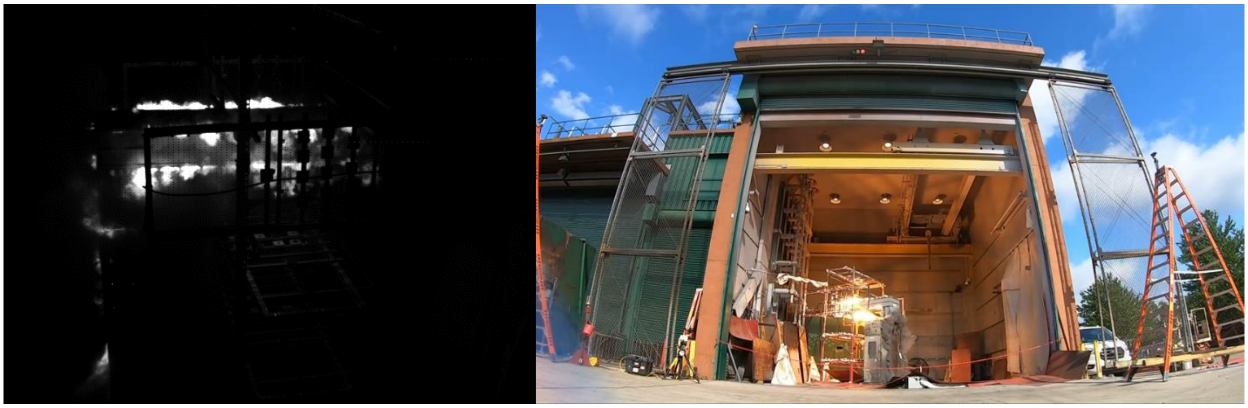

Figure 3-15: From left to right: Phantom v7, 4,000 fps, at top northeast side 0.13 seconds from trigger; GoPro outside at southeast.

Figure 3-16: From left to right: GoPro located northeast looking at the bottom of the bus duct before and after.

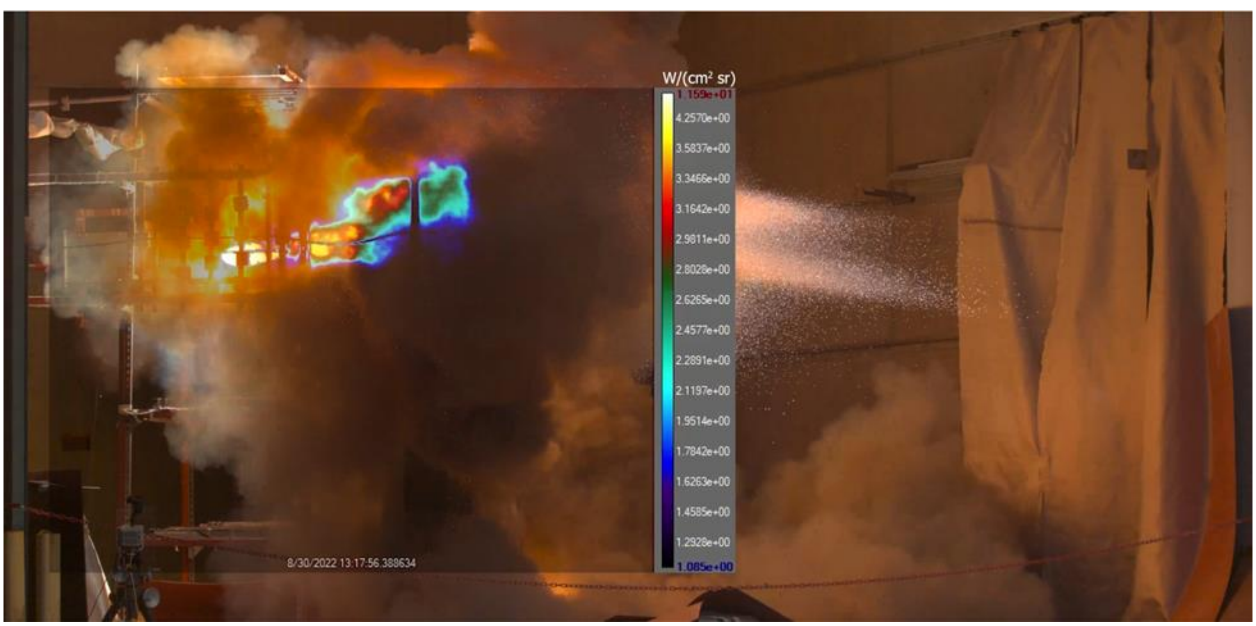

Figure 3-17: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.65 seconds from trigger.

3.6. Test 2-30B (4 Seconds – Aluminum Bars – Steel Enclosure)

Figure 3-18: Test 2-30B imaged through 4k camera – camera imaging at 1000 fps. Notice the orange/red color in the background 0.180 seconds from trigger. The first 130 milliseconds seems to show a white burning cloud.

Test 2-30B (the sixth bus duct test) had an intended 4 second duration with a steel enclosure and aluminum bars. Three GoPros were used in this test: one at the northeast side floor, one under the bus duct, and the last one outside southeast of TC9 about 50 feet from the rolling doors. Images from all color cameras show a white burning cloud that engulfs the duct during the first 130 milliseconds. Afterwards, there is an orange flame illuminating the white smoke which gets thick and dark towards the end. At around 900 milliseconds into the test, bright white particulate are ejected towards the east. The settings of the cameras can be seen in Table 3-6.

Table 3-6: Camera settings for Test 2-30B

	1212-2-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (μs) /Calibration	4	150	3.0	1,000-3,000°C	2
f/#	11	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	85	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	18.5	47.8	9.1	28.2

Figure 3-19: From left to right: Phantom v7, 4,000 fps, at top northeast side 0.150 seconds from trigger; GoPro at the bottom of the radiometer racks after the end of the arcing and some of the smoke is cleared.

Figure 3-20: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.12 seconds from trigger.

3.7. Test 2-31 (2 Seconds – Aluminum Bars – Aluminum Enclosure)

Figure 3-21: Test 2-31 imaged through 4k camera – camera imaging at 1000 fps. Notice the luminosity of the white cloud of Alumina illuminated by the arc and the burning aluminum 0.09 seconds from trigger.

Test 2-31 (the seventh bus duct test) had an intended 2 second duration with an aluminum enclosure and aluminum bars. Three GoPros were used in this test: one at the northeast side floor, one under the bus duct, and the last one outside southwest of TC9 about 50 feet from the rolling doors. Images from all color cameras show a test dominated by white smoke (compared to the previous tests) and bright particulate that is ejected to the east at 400 milliseconds, and eventually under the arc. The falling particulate dominates the view of the cameras with the luminous smoke in the background at the middle and end of the test. The settings of the cameras can be seen in Table 3-7.

Table 3-7: Camera settings for Test 2-31

	1212-2-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (μs) /Calibration	4	150	2.5	1,000-3,000°C	2
f/#	11	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	85	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	18.5	47.8	9.1	28.2

Figure 3-22: From left to right: Phantom v7, 4,000 fps, at top northeast side 0.07 seconds from trigger; GoPro at floor at north side.

Figure 3-23: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 0.64 seconds from trigger.

3.8. Test 2-32 (4 Seconds – Aluminum Bars – Aluminum Enclosure)

Figure 3-24: Test 2-32 imaged through 4k camera – camera imaging at 1000 fps. Notice the luminosity of the white cloud of Alumina (similar to 2-31) illuminated by the arc and the burning aluminum 0.08 seconds from trigger.

Test 2-32 (the eighth bus duct test) had an intended 4 second duration with an aluminum enclosure and aluminum bars. Three GoPros were used in this test: one at the northeast side floor, one under the bus duct, and the last one outside southeast of TC9 about 50 feet from the rolling doors. Images from all color cameras show a test that is not as dominated by white smoke (compared to Test 2-31). There is bright particulate that is ejected at 350 milliseconds towards the east, and eventually under the arc. It is worth noting that the connecting enclosure duct to the switchgear is made of steel. The falling particulate dominates the view of the cameras with a still luminous smoke (despite the orange/dark smoke) in the background at the middle and latest stages of the test. The settings of the cameras can be seen in Table 3-8.

Table 3-8: Camera settings for Test 2-32

	1212-2-Color	4k VEO 990s	1310 VEO	X6901	Phantom v7
Frame Rate (fps)	12,000	1,000	10,000	1,004	4,000
Exposure (μs) /Calibration	4	150	2.5	1,000-3,000°C	2
f/#	11	8	22	2.5	8
Lens	80-200 / f2.8	70-200 / f2.8	24-70 / f4	100	28-70 / f2.8
Resolution	1,280x800	4,096 x 2000	960 x 1,280	640 x 512	800 x 600
Trigger	Falling	Falling	Falling	Falling	Falling
Focal Length (mm)	125	85	26	100	35
Pixel Size (mm)	0.028	0.00675	0.018	0.025	0.022
H Pixel Count (pixels)	1,280	4,096	1,280	640	800
Chip Size (mm)	35.84	27.648	23.04	16	17.6
Field of View (deg)	16.3	18.5	47.8	9.1	28.2

Figure 3-25: From left to right: Phantom v7, 4,000 fps, at top northeast side; GoPro at floor at north side with view of the first frame of the arcing 2.4 seconds from trigger.

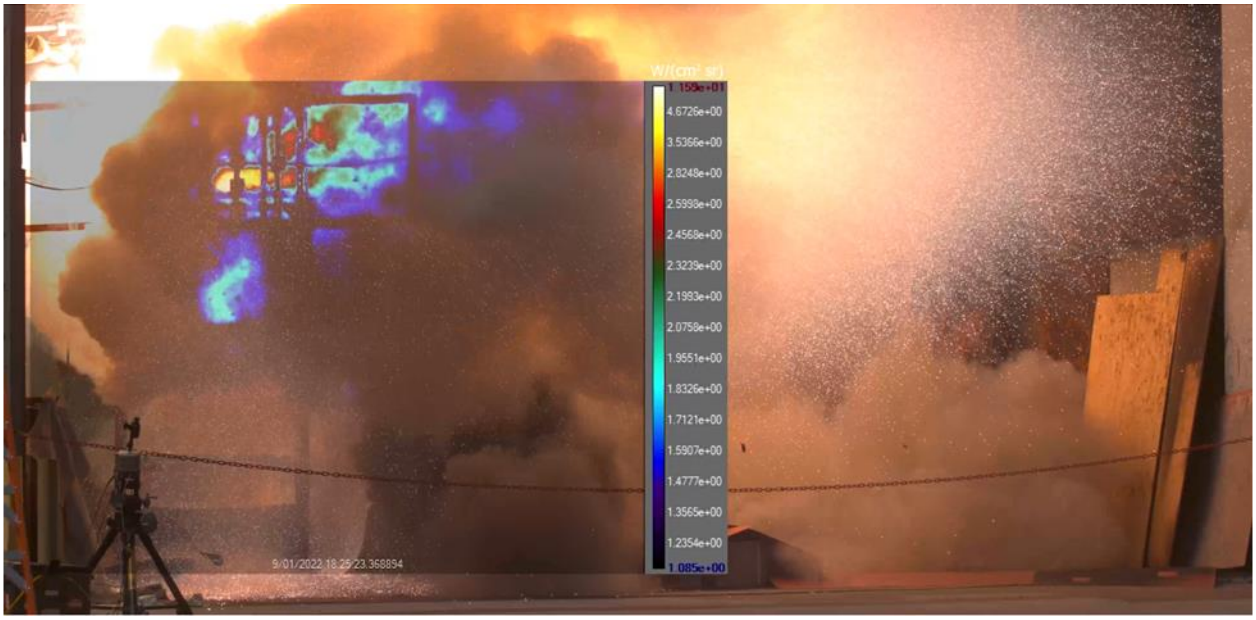

Figure 3-26: Image fussion of IR camera (in radiance units of W/cm^2 sr) synchronized with a visible image 1.17 seconds from trigger.

4. RESULTS

4.1. Breach Times

The breach times were calculated using IRIG-B to create timestamps for each frame (images) in the video. IRIG-B protocol uses GPS signals to get discrete times, which is then transmitted to the Phantom v7 and FLIR cameras. The timing from the IRIG-B protocol has a minimum resolution of 1 μs. The fastest camera deployed for this test campaign is the v1212c, with a frame rate of 12,000 Hz, and a resolution of 83.33$\underline{3}$ μs. This camera was used to determine the time of the trigger. The Phantom v7 provides a "location" or computer time stamp and the FLIR camera provides a UTC time stamp.

Because the requirement for falling slope trigger on the FLIR camera, all the high-speed cameras were set for falling slope trigger, and that generated a delay of 1/120 of a second, or 0.00833$\underline{3}$ seconds with respect to the start of data collection at KEMA. Therefore, 1/120 of a second needed to be subtracted from the cameras' trigger time to match the KEMA start of data collection. KEMA applied current into the test setup at about 44-45 milliseconds. The delay from start of data collection varies between tests, so KEMA provided that delay for each case (see Table 4-1). The delay from the start of data collection varied as 44.8±0.15 milliseconds. That time is added to the corrected time stamps of the cameras and indicates the time when of the breach compared to the time of application of current.

The breach is detected by visual inspection. The time stamp at detection is subtracted by the time stamp of when current is applied and that determines the breach time. The error on these measurements is on the order of ±5 frames for the FLIR X6901, and +/-10 frames for the Phantom v7, given that this is determined through visual inspection. This gives us an error for the FLIR X6901 of ±5 ms and an error of ±2.5 ms for the Phantom v7.

Notice that for the two breaches that occur at the bottom side of the bus duct (for Tests 2-25 and 2-30), the IR camera doesn't have a direct view because it is located ~100 feet from the test article. In these cases, the breach time is determined when particulate is continuously falling, indicating the arc eating away at the metal. For the tests with higher concentrations of smoke and dust, and when IR cameras have a direct line of sight, they perform better than the visible cameras at detecting breaches. For future test campaigns, having more IR cameras would be beneficial.

Table 4-1: Breach time for Tests

Test	Test Date	Device	Duration	Bus Bars	Enclosure	Start of Data Collection	Delay Applying Current (ms)	Time Current Applied	First Breach from Applying Current (s)	Breach Location
2-10	8/22/2022	Switchgear	2s	Cu	Steel	14:52:37.891	44.8	14:52:37.891269	No Breach	NA
2-12	8/23/2022	Switchgear	4s	Cu	Steel	10:32:28.817	44.8	10:32:28.861808	1.762	Top Side
2-25	8/24/2022	Bus Duct	2s	Cu	Steel	11:49:27.619	44.8	11:49:27.664176	<1.084	Bottom Side
2-26	8/25/2022	Bus Duct	4s	Cu	Steel	09:18:33.680	44.7	09:18:33.725124	No Breach	NA
2-30	8/26/2022	Bus Duct	4s	Al	Steel	08:48:27.078	45.0	08:48:27.123838	<0.679	Bottom Side
2-27	8/29/2022	Bus Duct	2s	Cu	Al	11:02:10.957	44.9	11:02:11.001988	0.225	North Side
2-28 *	8/30/2022	Bus Duct	4s	Cu	Al	09:17:55.730	44.7	09:17:55.775538	0.261 *	South Side *
2-30B	8/31/2022	Bus Duct	4s	Al	Steel	10:12:00.586	44.7	10:12:00.631371	0.815	South Side
2-31 **	9/1/2022	Bus Duct	2s	Al	Al	09:18:55.615	44.9	09:18:55.660821	0.318 **	South Side **
2-32	9/1/2022	Bus Duct	4s	Al	Al	14:25:22.198	44.7	14:25:22.243121	0.280	South Side

* There are clear indications of breach from the FLIR X6901sc (0.262 ms) and the Phantom v7 (0.268 ms). The FLIR X6901sc is officially reported,

** There is uncertainty in the breach of the bus duct for Test 2-31. The camera looking at the top and north side (the Phantom v7) is occluded by the brightness of the arc and later by dust and smoke at 0.026. At the end of the test, those sections were mostly consumed; it is plausible that a breach could have occurred between occlusion of the Phantom v7 at 0.026 seconds and the breach detected by the IR camera at 0.318 seconds on the south side of the duct bus.

4.2. Thermal Behavior of Enclosure Metal

The data obtained from the IR camera when looking at the end of its recording (after the arc) seems to show that thermal radiation has a more nuanced behavior, see Table 4-2. The tests seemed to indicate a rapid and violent burn of aluminum enclosures whereby the end of the arcing most of the enclosure has turned into alumina (Al2O3) dust. A middle stage of aluminum oxidation is the early reaction with oxygen, forming a temporary AlO molecule that reaches and exceeds temperatures on the order of 3000°C **[1]**. This is a known process that is used to boost the energy of solid rockets **[2]**. Test 2-28 shows an enclosure made from aluminum and is completely consumed after the test. Twenty seconds after finishing the test there is a minimal IR signature. Figure 4-1 in the left panel shows that enclosure doesn't register temperature. We can see the remains of the enclosure by looking at the uncalibrated counts on the right panel.

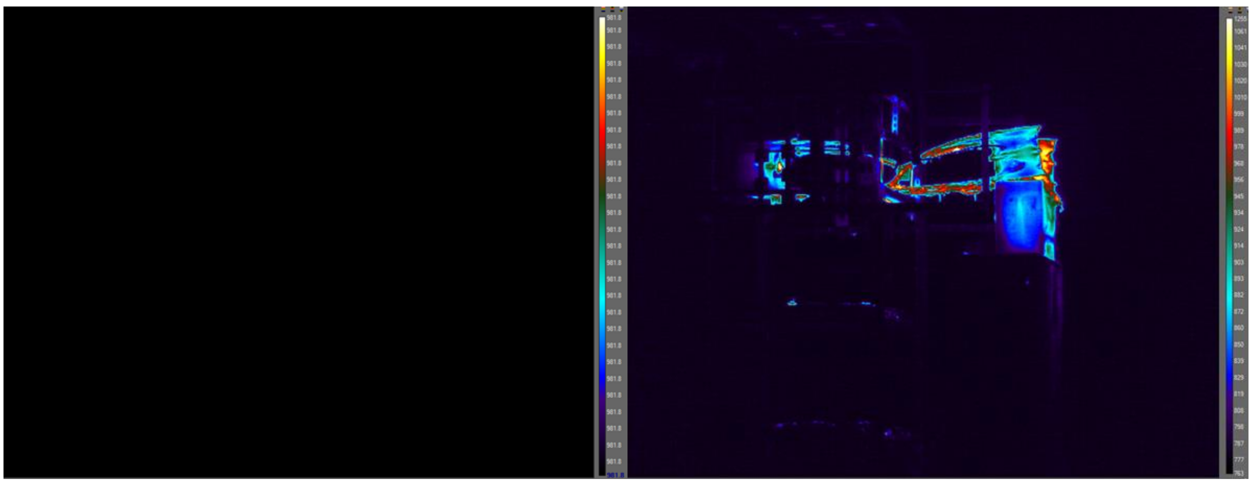

Figure 4-1: Test 2-28 – Cu bars – Al enclosure – 4 seconds. Left panel is the calibrated temperature (°C) with no signal. The right panel is the uncalibrated counts (counts below 12% of 16384 counts are considered uncalibrated). The panels are the data after 20 seconds of finishing the test.

The steel enclosures do not go through the same process as aluminum. Steel is not as rapidly consumed by the arc. At the end of the IR camera recording (~20 seconds), the steel temperature is still close to 1,000°C in some regions. This is significant, given that the measurements from the camera at this time are reliable because there is minimum smoke and dust in the air. See Figure 4-2 for Test 2-30B

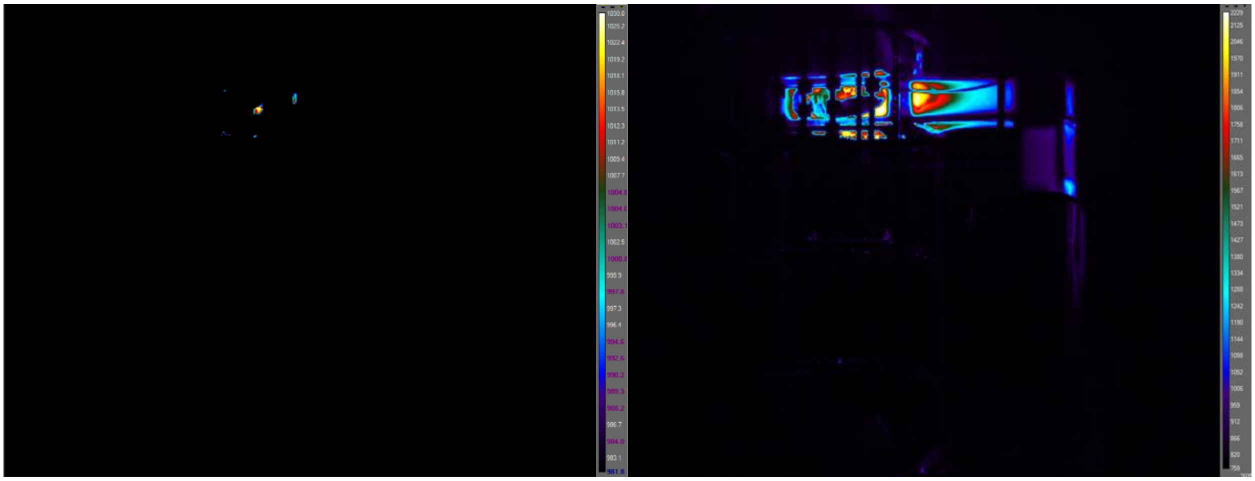

Figure 4-2: Test 2-30B – Al bars – Steel enclosure – 4 seconds. Left panel is the calibrated temperature (°C) with some signal. The right panel is the uncalibrated counts (counts below 12% of 16384 counts are considered uncalibrated). The panels are the data after 20 seconds of finishing the test.

These results seem to indicate that the aluminum enclosures will be hotter but will be consumed in a matter of few seconds. Conversely, the steel enclosures would continue to radiate heat for several tens of seconds after the arc is finished. A better measurement should be considered if this is a real problem. For this suggested measurement, slow frame rate LWIR cameras should be used. These cameras can record for several minutes after the arc finishes and the smoke and dust settle, and they also provide a larger temperature range.

Table 4-2: Maximum temperature measured at the end of IR camera recording with no smoke and dust in the air

Test	Bars	Enclosure	IR Camera Range	Test Duration	Time After Arcing Drops Below Temp Range	Temp
2-25	Cu	Steel	500-1200 ºC	2s	23s	843 ºC
2-26	Cu	Steel	850-2000 ºC	4s	21s	877 ºC
2-30	Al	Steel	1000-3000 ºC	4s	21s	1,028 ºC
2-27	Cu	Al	1000-3000 ºC	2s	0.4s	< Min Range
2-28	Cu	Al	1000-3000 ºC	4s	0.6s	< Min Range
2-30B	Al	Steel	1000-3000 ºC	4s	21s	1,031 ºC
2-31	Al	Al	1000-3000 ºC	2s	0.4s	< Min Range
2-32 *	Al	Al	1000-3000 ºC	4s	19s	< Min Range

* The bus duct was attached to the end of the dummy switchgear using a steel duct (instead of the aluminum one as for the other tests), which was kept hotter than 1000°C for at least 19 seconds even though it wasn't located in front of where the arc occurred.

4.3. Conclusions

Through review of the video, it is possible to see differences in the arc reaction for different enclosure and bar materials. For steel enclosures and copper bus bars, orange flames with dark thick smoke were seen with some ejection of orange/red particulate. For aluminum enclosures with aluminum bus bars, white smoke and significant bright white particulate were seen. For aluminum enclosures with copper bars and steel enclosures with aluminum bars, a combination of red/orange dark smoke and bright particulate were seen. It is worth mentioning that aluminum enclosures are almost if not fully consumed by the end of the tests.

For tests with high potential of smoke and dust, the IR camera seems to perform better than visible cameras in detecting breaches. It would be beneficial to have more IR cameras in a future test campaign that is similar to the one performed in August 2022. SNL now has multiple high speed IR cameras (two MWIR, and one LWIR), and they could be deployed in the courtyard as well as inside the test bay.

A question that arose through analysis of the video is the ability to improve breach detection. A LWIR camera would lead to significant improvement when compared to a MWIR camera. A LWIR camera collects light that can penetrate deeper into clouds of dust and smoke compared to an equivalent MWIR camera. Conversely, flames tend to be more invisible to LWIR cameras.

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[2] L. Meda, G. Marra, L. Galfetti, F. Severini and L. De Luca, "Nano-aluminum as energetic material for rocket propellants," *Materials Science and Engineering,* vol. C 27, pp. 1393-1396, 2007.

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