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International Agreement Report

Nuclear Regulatory Authority Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena

Basic Arc Test Experimental Data

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ABSTRACT

A High Energy Arcing Fault (HEAF) occurred in a high-voltage (6.9 kV) switchgear (SWGR) in Unit 1 of the Onagawa Nuclear Power Plant of the Tohoku Electric Power Company on March 11, 2011 during the Great East Earthquake in Japan. While HEAF events are not common, they have occurred in nuclear power plants (NPP) worldwide. The operating experience seen from the Onagawa event illustrate that HEAFs can present a potential threat to the safe operation of NPPs. As a result, the nuclear power industry has placed a new emphasis on understanding and developing evaluation methods for these events.

To investigate the HEAF event sequence and to understand the phenomena, the Regulatory Standard and Research Department, Secretariat of the Nuclear Regulation Authority (S/NRA/R) (Japan) conducted HEAF tests by simulating the design and operating conditions of the SWGR HEAF at Onagawa NPP in addition to simulating the HEAF energy effects using a “Rocket Fuel Arc Simulator” (RFAS). Tests of 480 V Motor Control Center (MCC) and Distribution Panel (DP) cabinets were also conducted to understand HEAF characteristics. Previous tests performed in 2013 through 2015 described in Volume 1 of this publication used realistic SWGR, MCC, and DP cabinet configurations. The SWGR tests showed damage similar to the damage in the earthquake but less severe. Data for temperatures, heat flux, heat release rate, arc energy, and pressure were collected and analyzed. The results were generally as expected but provided a new appreciation for and recognition of the high thermal energy from the oxidation of aluminum bus bars used in the SWGR tests.

The objective of the tests performed in 2016 and described in this report was to study basic arc electrical properties and thermal effects using one arc event with arc energies from 0.6 MJ to 137.3 MJ. The energy was set by changing the arc voltage, current, and arc duration. The supply open circuit voltages (OCV) were 7.1 kV for the SWGR and 484 V and 600 V for the DP. No MCCs were tested. The test items had similar geometry to the previous tests but internal walls and obstructions were removed and the front and rear exterior panels were removed to allow direct observations of the arc. Metal targets with temperature detection labels and samples of cables and plastics were also placed at various distances from the arc to assess ignition and damage at various distances from the arc. Bundles of cables were placed near the arc to investigate cable ignition and damage. The key observations were:

- The DP would not sustain an arc at the same conditions as the January 2013 tests, so some tests had very short duration and low energy. The OCV was increased from 484 to 600 volts in the final two tests and the arc sustained for the planned duration (up to 4 seconds).
- It was very difficult to get heat flux measurements because the external flames and plasma quickly escaped through the open panels and contacted the slug calorimeters and the data was not valid.
- Except for cases where cable samples were very close to the arc (<50 cm) the cable samples did not ignite. For targets that had minor to heavy damage, post-test cable resistance measurements showed only one failure (short circuit between the cable conductors) in more than 300 samples.
- The cable bundles in the tests did not have sustained fires probably because the cabinets were open and the heat escaped.

The results and data in this report in combination with operating experience and other HEAF test data, will be used by international teams to develop consensus conclusions on HEAF behavior, understand the potential for HEAF damage including ensuing fires, establish HEAF evaluation criteria to support Fire Hazard Analyses (FHA), and recommend protection measures.

FOREWORD

This work was sponsored by the Japan Nuclear Regulatory Authority (NRA).

The Regulatory Standard and Research Department, Secretariat of the Nuclear Regulation Authority (S/NRA/R) (Japan) was the lead organization for the tests and prepared the analysis and results. NRC attended all tests and provided support for specialized instrumentation, technical advice, and general testing support. The NRC also completed the final preparation of this report for publication.

The contents of this report should not be viewed as an official NRC endorsement of the results or observations in this report. Nor should this report be viewed as binding the NRC in its rulemaking, licensing, or adjudicatory process.

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EXECUTIVE SUMMARY

A High Energy Arcing Fault (HEAF) occurred in a high-voltage (6.9 kV) switchgear (SWGR) at Unit 1 of the Onagawa Nuclear Power Plant of the Tohoku Electric Power Company on March 11, 2011 during the Great East Earthquake in Japan. The Onagawa nuclear power plant (NPP) was the closest plant to the epicenter of the 2011 Great Eastern Earthquake. (To learn more about the effects of the earthquake and tsunami on the Onagawa NPP please see reference [1].) This type of HEAF event has occurred in electric equipment in NPPs worldwide and HEAF events have gained high interest in the safe operation of NPPs with an emphasis on developing evaluation methods.

To investigate the HEAF event sequence and to understand the phenomena, the Regulatory Standard and Research Department, Secretariat of the Nuclear Regulation Authority (S/NRA/R) (Japan) conducted HEAF tests in 2013 through 2015 by simulating the design and operating conditions of the SWGR HEAF at Onagawa in addition to simulating the HEAF energy effects using a Rocket Fuel Arc Simulator (RFAS). Tests of 480 V Motor Control Center (MCC) and Distribution Panel (DP) cabinets were also conducted to understand HEAF characteristics.

The objectives of the 2013-2015 tests were not only to understand the Onagawa event but also to obtain measurements of HEAF phenomenon such as pressures, temperatures, heat fluxes, electrical characteristics, and ability to cause ensuing (secondary) fires within the equipment and of external cables. The objectives also included making observations to assess current HEAF evaluation guidance, including the Zone of Influence (ZOI), in NUREG/CR-6850, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities: Detailed Methodology, Appendix M for Chapter 11, High Energy Arcing Faults” (NUREG/CR 6850) [2]. This report contains only analyzed data and observations. Regulatory impacts will be evaluated by international teams to develop consensus conclusions on HEAF behavior, understand the potential for HEAF damage including ensuing fires, establish HEAF evaluation criteria to support Fire Hazards Analyses (FHA), and recommend protection measures.

As described in Volume 1 of this publication [3], the results of the HEAF 2013-2015 tests simulating the SWGR at Onagawa NPP showed similar damage to the actual HEAF with respect to the duration time, energy level, and ensuing cable fires. However, the overall structural damage and extent of the internal fire damage was much less severe than Onagawa. The tests for the MCC and the DP provide insight on HEAF behavior and ensuing fires in low voltage systems. Data such as temperature, heat flux, heat release rate during the arc and ensuing fires due to HEAF conditions were successfully simulated by the RFAS test.

The results in previous tests were generally consistent with the previously observed behavior from the earthquake. However, the tests also provided a new appreciation for and recognition of the high thermal energy from the oxidation of aluminum bus bars, such as those used in the SWGR tests. Since aluminum is sometimes used in bus bars, the energetic effects of an arc involving this material should be considered when analyzing HEAF effects.

The objective of the tests performed in February 2016 (referred to as “FY15 tests” based on the Japan Fiscal Year) documented in this report was to study basic arc electrical properties and thermal effects for various arc energies that were set by changing the arc voltage, current, and arc duration. The High Voltage (HV) SWGR and Low Voltage (LV) DP test items had similar geometry to the previous tests, but internal walls and obstructions were removed, and the front and rear exterior panels were removed to allow direct observations of the arc. Metal targets with temperature detection labels and samples of cables and plastics were also placed at

various distances from the arc to assess arc effects. Bundles of cables were placed near the arc to investigate ensuing cable fire ignition.

As in the 2013-2015 tests documented in Volume 1 [3], the electrical arc tests were generally conducted per IEEE C37.20.7 "IEEE Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal Arcing Faults" that tests if SWGR cabinets remain intact and the HEAF cannot injure workers [4]. The key part of IEEE C37.20.7 for these tests is the initial arc was created by putting a wire between the bus bars to cause a direct short circuit at the desired position for the HEAF. Tests with electrical arcs were conducted at KEMA Laboratories Chalfont (KEMA), located in Chalfont, Pennsylvania in February 2016, using specialized large capacity electrical systems to create the arc and provide the high energy for the HEAF (up to 137 MJ for a 4.1 second arc duration). The KEMA facilities are qualified to meet IEEE C37.30.7 requirements.

The FY15 SWGR tests were similar to tests in June 2013 but had simple cabinets and there was only one arc event. The Distribution Panel (DP) tests were also similar to those in January 2013 but with simple cabinets.

The key observations were:

- The DP would not sustain an arc at the same conditions as the previous January 2013 tests. So, the Open Circuit Voltage (OCV) was increased from 484 to 600 volts.
- The SWGR voltage was different than anticipated because the basis for the voltage prediction in the test plan from the previous tests was based on the wrong arc length.
- It was very difficult to obtain arc heat flux measurements because the external flames and plasma quickly escaped through the open panels and contacted the slug calorimeters, and the data was not valid.
- Except for cases where cable samples were very close to the arc (<50 cm) the cable samples did not ignite. For targets that had minor to heavy damage, post-test cable resistance measurements showed only one failure (short circuit between the cable conductors) in more than 300 samples.
- The cable bundles in the tests did not have sustained fires probably because the cabinets were open and the heat escaped.
- The arcs were successfully observed with IR video on two SWGR tests and one DP test and looked as anticipated based on other videos from tests by others.
- The maximum lengths of external flames from the arc ejected through the open panels was roughly 1.9 meters for the DP (66 MJ arc) and 3.5 meters for the SWGR (137 MJ arc).

See Chapter 4 for more detailed observations for the tests.

CITATIONS

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The NRC team observing and supporting the tests was led by Mark Henry Salley with support from Nicholas Melly and David Stroup. Shivani Mehta and Stephen Turner were responsible for the final NUREG/IA preparation.

The tests were managed by Stephen Turner and supported by various contractors. Karen Carpenter of Southwest Research Institute provided test management support and thermal imaging at KEMA. Matthew Muthard, Kresimir Starcevic, Victor Savulak, Richard McLaughlin, Dennis Samuel, and George Khoury coordinated and managed the tests at KEMA Laboratories Chalfont. Robert Taylor of Brendan Stanton Incorporated (BSI) managed the assembly and installation of the test items with engineering support from Benny Lee and fabrication and technician support by other technical staff. David Muir of Advanced Motor Controls in cooperation with Paul Grein and Kyle Fincher at Circuit Breaker Sales provided the test cabinets.

ACRONYMS AND ABBREVIATIONS

A	Ampere
ASTM	ASTM International
Cab	Cabinet
CHF	Critical Heat Flux
chng	change
cm	Centimeter
CV	A type of cable
DP	Distribution Panel
EMI	Electromagnetic Interference
EPRI	Electric Power Research Institute
F	Front
FHA	Fire Hazards Analysis
FLIR	Forward Looking Infrared, also a camera manufacturer
FY	Fiscal Year
g	gram
GE	General Electric
HD	High Definition
HEAF	High Energy Arcing Fault
HRR	Heat Release Rate
HS	High Speed
HV	High Voltage
HS&T	Sumiden- Hitachi LTD
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
in	Inch
IR	Infrared
JIS	Japan Industrial Standard
k	1,000
kA	Kiloampere
KEMA	KEMA Power Test, LLC
kg	Kilogram

kPa	Kilopascal
kV	Kilovolt
kVA	Kilovolt Ampere
kW	Kilowatt
LLC	Limited Liability Corporation
LV	Low Voltage
LS	Left Side
m	meter
MCC	Motor Control Center
MCCB	Molded Case Circuit Breaker
MJ	Megajoule
MV	Medium Voltage
MVA	Megavolt Ampere
N/A	Not Applicable
NEA	Nuclear Energy Agency (of the OECD)
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRA	Nuclear Regulation Authority (Japan, also see S/NRA/R)
NRC	Nuclear Regulatory Commission (United State of America)
OCV	Open Circuit Voltage
OECD	Organization for Economic Cooperation and Development
Pa	Pascal
PRA	Probabilistic Risk Assessment
psi	Pounds per Square Inch
PT	Plate Thermometer
PRT	Pressure Transducer
PVC	Polyvinyl Chloride
R	Rear
RES	Nuclear Regulatory Commission, Office of Nuclear Regulatory Research
RFI	Radio Frequency Interference
RS	Right Side
RFAS	Rocket Fuel Arc Simulators

s	Second
S	Slug calorimeter
S/NRA/R	Regulatory Standard and Research Department, Secretariat of Nuclear Reulatory Authority (Japan, also see NRA)
SNL	Sandia National Laboratories
SWGR	Switchgear
SwRI	Southwest Research Institute
Sym.	Symmetrical (current)
T	Top
TC	Thermocouples
TP	Thermoplastic
TS	Thermoset
U.S.	United States (of America)
V	Volt
XLPE	Cross-Linked Polyethylene
ZOI	Zone of Influence

1 INTRODUCTION

1.1 Background

The High Energy Arcing Fault (HEAF) tests in this report were basic arc tests conducted to support research on a HEAF event that occurred during the 2011 Great East Earthquake at the Onagawa Nuclear Power Plant (NPP) that damaged a row of Switchgear (SWGR) panels [1]. Section 1.2 of Volume 1 [3] discusses the Onagawa conditions of interest for the S/NRA/R HEAF research test series.

HEAFs are a fast energy release that occurs in the form of heat, light, molten metal, and pressure rise from electrical shorts inside of electrical equipment cabinets. HEAFs are a hazard that can cause ensuing (or secondary) fires that destroy targets such as the power and control cables inside and outside the cabinet. Understanding HEAFs and their consequences is important, as demonstrated by a large HEAF in a high-voltage (HV)[1] 6.9 kV SWGR and ensuing fire that occurred at the Onagawa NPP during the March 11, 2011 Great East Japan Earthquake.

In general, the electrical power industry refers to HEAF as an “arc-blast” or “arc-flash” and the basic behavior is documented in IEEE 1584 [5], which has a case history of arc-flash events. Industry has mainly been concerned about the effects of arc flash on workers and the protective equipment that is needed for workers to safely operate, maintain, and install electrical systems. The nuclear industry has focused more on evaluating the impact of ensuing fires as part of Fire Hazards Analysis (FHA). NRC Probabilistic Risk Assessment (PRA) guidance in NUREG/CR 6850 [2] specifically addresses analysis of HEAFs. The Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA) began an international activity to investigate HEAFs in 2009 and compiled information on 48 HEAF events [6].

The guidance in NUREG/CR 6850, Appendix M prescribes that the ensuing fire(s) typically includes ignition of combustible material within the HEAF Zone of Influence (ZOI). The resulting fire may be due to the ejection of hot particles or piloted ignition of combustibles. HEAF events are of concern due to their potential to impact adjacent items important to safety and current limitations in characterizing the ZOI. The ZOI was determined based on a review and characterization of the damage and detection/suppression behavior for the energetic phase of high-energy-arcing faults of 11 incidents that occurred in U.S. nuclear power industry between 1979 and 2001. Specifically, the ZOI boundaries are at 1.5 m (5 ft) above the cabinet and 0.91 m (3 ft) from the sides of the cabinet, in all directions.

The objective of the tests performed in FY15 was to study basic arc electrical properties and thermal effects for various arc energies that were set by changing the arc voltage, current, and arc duration. The HV SWGR and Low Voltage (LV) DP test cabinets had similar geometry to the actual operational cabinets previous tests in Volume 1 but the internal walls and obstructions were removed and the front and rear exterior panels were removed to allow direct observations of the arc. Metal targets with temperature detection labels and samples of cables and plastics were also placed at various distances from the arc to assess arc effects including ignition and damage to the cable samples on targets. Bundles of cables were placed near the arc to investigate ensuing cable fire ignition and damage.

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[1] Japan considers 6.9k kV as “High Voltage”, most other countries, including the U.S., consider 6.9 kV as “Medium Voltage”.

1.2 Test Approach and Electrical Test Conditions

Tests were generally conducted per IEEE C37.20.7 [4] that evaluates SWGR to determine if it meets the “arc proof” requirements in IEEE 1584 [5]. “Arc proof” testing ensures that SWGR cabinets remain intact and the HEAF cannot injure workers. The key part of IEEE C37.20.7 used in these tests is the creation of the initial arc by putting a wire between the bus bars to cause a short at the desired position for the HEAF. The tests are intentionally creating an arc path at a specific location which will mimic event scenarios within cabinets. The cabinets are not connected to full electrical systems of breakers - this allows the arc to persist without safety mitigation strategies such as breaker trips.

Tests with electrical arcs were performed at the KEMA Laboratories Chalfont (KEMA) using specialized large capacity electrical systems to create the arc and provide the high energy for the HEAF (usually 10-75 MJ over 2 or 3 seconds). Details of the KEMA facilities are discussed in Appendix B. HEAFs have the ability to cause severe, short duration, thermal insults that were characterized by heat flux measurements using slug calorimeters at KEMA. HEAF heat release rate (HRR) is another important parameter to assess thermal properties but HRR cannot be measured at KEMA.

Table 1-1 summarizes the tests conducted in this series. The test conditions listed in the table are the target test conditions (not the voltage and current achieved) but the arc duration and energy from the tests are reported. The arc current and arc duration for the tests were much higher than properly designed circuits allow. Circuits are designed to limit the arc energy and duration during a fault so HEAFs do not occur.

1.2.1 Arc Current

The bolted fault current that is the maximum feasible fault current for an electric circuit was used in the tests in Volume 1 and for these tests. The calculations used as a basis for the target test currents are provided in Appendix D. KEMA used the bolted fault current as a target specified by S/NRA/R as a peak current target in no-load calibration runs with shorted busses before the current is applied to the test item. The actual symmetrical current in the tests was slightly lower because of the impedance of the arc (it acts similar to a load). The peak current was slightly higher than the symmetrical current but it only lasted for a few electrical cycles at the start of the arc.

1.2.2 Arc Duration

The planned target arc durations were nominally 2 seconds for most tests as in the Volume 1 tests but were increased to 4 seconds in some cases to increase the energy in attempts to ignite ensuing fires. The 2 seconds was based on an assumption that older systems in Japan require long times for clearing a fault. This was a conservative duration to create very high energy. There are cases of reported HEAF events as long as 5 to 10 seconds [6].

Table 1-1 Summary of S/NRA/R FY15 HEAF Tests

Test	Tests/ Type of Test	Test Conditions (1)	Results	Report Chapter
DP	2 electrical arc tests	Tests 7, 7A: 1 arc 480 V, 53 kA, 0.238- 0.42 s Energy 4.3 – 0.6 MJ Open Cabinet	Difficult for arc to sustain, minor damage, same DP cabinet used for both tests	2.8
DP	2 electrical arc tests	Tests 8, 9: 1 arc 600 V, 53 kA 1.9- - 3.1 s Energy 39.7 – 66.8 MJ Open cabinet	Increased voltage to get sustained arc, heavy damage, cable burned	2.9, 2.10
1-cabinet SWGR	2 electrical arc tests	Tests 7, 9, 1 arc 7.1 kV, 23 kA 2.8 – 4.1 s Energy 88.2 – 137.3 MJ Open Cabinet	Major damage, interior cables charred but did not short, flames extend more than 2 meters from cabinet	3.8, 3.11
1-cabinet SWGR	1 electrical arc test	Test 8, 1 arc, 7.1 kV, 23 kA 3.5 s Energy 89.1 MJ Open Cabinet	Ground bar moved to decrease arc voltage, similar damage to SWGR Tests 7, 9	3.10
1-cabinet SWGR	1 electrical arc test	Test 10, 1 arc 7.1 kV 0.8 s Energy 24.0 MJ Closed Cabinet	Major damage, interior cables charred but did not short	3.12

(1) The energy is the electrical energy input only; no energy from copper bus bar oxidation is included.

1.3 Measurements and Instrumentation

The measurement items for the tests are shown in Table 1-2. More information on the instrumentation is in Appendix A. Instrument positions are in the test configuration discussions in Section 2.2 for DP tests and Section 3.2 for SWGR tests. Some measurements used in the Volume 1 tests are also described for reference.

Table 1-2 Measurements and Instrumentation

Measurement Item	Measurement Method
1. Current waveform measuring device	Voltage dividers, coaxial shunts, and other coils provided current and voltage waveforms to calculate energy.
2. Pressure a. Internal b. External	a. Internal: Strain-gauge type pneumatic transducers were used by KEMA. Gauge pressure is reported. b. External: Not used. Pencil-type gauges were used at the January 2013 tests at KEMA by Sandia National Laboratory (SNL) and at Southwest Research Institute (SwRI). The measurements were not useful in the swirling air around the HEAF and fire.
3. Temperatures	Thermocouples (TC), passive temperature indicator labels. The TCs could not be placed directly on the cabinets in the electrical tests for safety. TC were added to some of the cable sample targets in Item 9.
4. Heat Flux	Slug calorimeters built to ASTM F1959 [7] were used at the ZOI positions in tests at KEMA (see Appendix A). Other methods used by SNL in previous tests were not effective, see Reference [8].
5. Oxygen calorimeter	Not used. The National Institute of Standards and Technology (NIST) calorimetry hood was used in the March 2015 tests but was not useful during the arcs [9].
6. Infrared and visible light high-speed photography	FLIR T300 and SC6700 thermal Imaging cameras to see the HEAF ensuing fire effects and general thermal conditions, High Speed (HS) camera at 500 – 1000 frames per second to study ignition and cabinet deformation; Infrared (IR) filters were used to observe the arc. Various High Definition (HD) videos from many positions were used to see the HEAF effects.
7. IEEE C37.20.7 indicators	Not used. Used to study debris that escapes the cabinet at KEMA for Volume 1 tests. The DP and MCC cabinets are not arc proof so debris escaped. The SWGR cabinets showed little debris.
8. Oxygen monitor	Not used. Used at SwRI to measure oxygen depletion in Cabinet 8 caused by RFAS ignition in the SWGR tests. All oxygen calorimeter results include oxygen measurement.
9. Cable/Plastic Samples, Cable bundles	Short samples of cable and plastic on steel plates were placed at several internal and external positions. See Section 1.4. Cable bundles were placed in the DP and SWGR cabinets.

1.4 Cable/Plastic Targets

Cable/plastic targets with short lengths of cable and rectangular plastic samples were mounted on steel plates and attached to the interior cabinet walls, an internal measurement platform, and the exterior instrument mounts. The purpose of the targets was to indicate damage of cable samples and plastic samples at various positions. The targets are described in Section E.1 and had these samples:

- Three, 10 cm lengths of CCV cable samples with properties shown in Appendix C. CCV cables with only 2 conductors were used to provide a smaller target that may burn more easily.
- The plastic samples were 5 cm by 5 cm polyvinylchloride (PVC). The PVC target samples were either 3.18 mm or 1.60 mm thick. Since the plastic mainly melted or partially pyrolized, the selection of the plastic was not critical.

The damage of cables and plastic targets are presented in Appendix F with the type and location of the target, type of damage, corresponding temperature data and notes. In order to be able to compare the damage to the targets, the terminology and pictorial examples are shown in Table 1-3 and Figure 1.4-1. The labels in the pictures show the target number and the test number at the time of the test (tests DP-1 through DP-4 revised to DP-7, 7A, 8, and 9 and tests SWGR-1 through SWGR-4 changed to SWGR-7-10 for this report to continue the test numbers from previous reports. Section E.2 and the introduction to Appendix F also describe how the damage results are presented in this report.

Table 1-3 Target Damage Descriptions

Identifier	Damage Description	Types of Damage
1	None	No damage; cable and plastic the same as installed and can be reused. Usually low temperatures. May look slightly brown from minor copper minor deposition. No smoke soot. May be reused.
2	Sooted	No damage to cable or plastic. Soot from smoke from other combustibles or copper covers the cable. The cable jacket color is dull and the letters on the cable are hard to see.
3	Minor damage	Light charring or discoloration of the target and cables, minor charring.
4	Medium damage	Charring of cables; plastic bent slightly.
5	Heavy damage	Deep charring of cable. Cables may be missing; plastic samples may be missing. This usually occurs for targets within 50 to 100 cm of arc. Plastic is bent over metal target mount. Orange steel after cool down indicates high heat.
6	Destroyed	Cable or plastic samples are no longer attached. This usually occurs for targets within 40 cm of the arcs, on long duration arcs. Bright orange steel indicates very high heat.

(a) 1 – None

(b) 2 – Soot

(c) 3 – Minor Damage

(d) 4 – Medium Damage

(e) 5 – Heavy Damage

(f) 6 - Destroyed

Figure 1.4-1 Damage Examples with Test Number (During the Testing) and Target Number

2 LOW VOLTAGE DISTRIBUTION PANEL HEAF TEST

2.1 DP Test Overview

There were two (2) 484 V Open Circuit Voltage (OCV) tests with GE Spectra Series APN-B Distribution Panel (DP). These are similar to the January 2013 tests described in Volume 1 [3]. An arc could not be sustained in the first two tests at 484 V. Therefore, two additional tests were done at a higher 600 V, resulting in sustained arcs. The DP is nominally 1.11 m wide by 2.13 m high and 0.89 m deep. Japanese CV-2 cable that is typical of power cable was added as the combustible load. Cable/plastic targets with short lengths of cable and rectangular plastic samples were mounted on steel plates and attached to the interior cabinet walls, an internal measurement platform, and the exterior instrument mounts to assess damage to the sample materials at various distances.

2.2 DP Tests Summary of Results

The target test OCV was nominally 480 V and the target test current was 53 kA (sym.). However, the OCV was changed to 600 V for Tests DP-8 and DP-9 to achieve a sustained arc. The values for similar tests, Tests DP 1 through 3 from Volume 1 [3], are shown for comparison. The key test parameters and results are in the Table 2-1.

The observations for the DP tests are in Section 2.13 and Chapter 4. The test results were mostly as expected but surprisingly no cable samples failed (based on post test conductor-conductor resistance measurements). Also, in the initial tests the DP would not sustain an arc at the same conditions as the previous January 2013 tests. So, the OCV was increased from 484 to 600 volts.

Table 2-1 DP Test Summary of Results

Test	Volt (V) (1) Current (kA) (2)	Test Peak Current (kA) (3)	Arc Duration (sec) (4)	Arc Energy (MJ)/ Arc Power (MW)	Internal Max Press kPa	Ext Max Flux (kW/m^2)	Ensuing fire? Key Observations
1	484 / 404 43.3 / 30	71.2	2.0 1.574	28.6 15-20	14.5 ± 2.8	53.8 (5)	Yes. After 7 minutes.
2	484/ 394 38.4 / 31.6	66.9	2.0 1.446	26.3 15-20	18.6 ± 2.1	63.2 (5)	No. Arc energy too low.
3	484/ 416 41.4/ 32.0	63.0	2.0 2.011	37.1 15-22	13.8 ± 6.9	22.2 (6)	Yes. After 50 seconds.
7	484/362 45.9/34.2	84.4	1.65 0.238	4.32 15-22	19.3 ± 5.5	23.1 (7)	Cable bundle sooted.
7A	484/394 (8)	101.5	1.65 0.22/0.20 (9)	0.587 (9) 15-20	20.1 ± 1.4	66.2 (10)	Cable bundle sooted.
8	600/463 46.0/25.3	102.6	1.90 1.893	39.7 20-25	15.2 ± 1.0	(11)	Cable bundle charred.
9	600/450 46.2/22.7	100.0	3.00 3.144	66.8 20-25	13.1 ± 0.5	80.1 (12)	Cable bundle burned.

(1) The voltage is shown as the OCV / arc Line-to- Line (L-L) voltage.
(2) The symmetric arc current slowly drops during the test as the arc impedance increases. This shows the *test start current/ test end current*. These are average currents of all three phases.
(3) This is the peak current of any part of the test, usually the asymmetric current at the start.
(4) The duration is shown as the target duration and the actual test duration.
(5) The maximum flux was seen at 0.91 m at the rear of the cabinet at the height of the arc, 56 cm from the floor (S8).
(6) The maximum flux was seen at the bottom, 0.91 m to the left side of the cabinet (S7). A higher flux of 186.9 kW/m^2 was measured but was not reported because it was only at 30.48 cm from the cabinet (S8), not at the 0.91 m, as in other tests and was a one-off test that should not be compared to other tests.
(7) The maximum flux was seen 0.91 m to the side on the right side and 1.19 m high (S1). The maximum heat flux at the 1.52 m above the cabinet was 10.3 kW/m^2 (S11)
(8) Duration was too short to get current data.
(9) Two short duration arcs, energy is the total of both short arcs
(10) This value is an average of S3 and S4, located 0.91 in front of the cabinet. Several slugs hit by flames
(11) Data lost during the test.
(12) The maximum heat flux was seen 0.91 m in front of the cabinet, 0.9 m from the floor (S2). The maximum heat flux at the 1.52 m above the cabinet was 28.3 kW/m^2 (S11). Flames impinged several slugs.

2.3 DP Test Configuration

The GE APN-B DP has copper horizontal and vertical bus bars, as shown in Figure 2.3-1. This DP cabinet is less deep than the ones used in previous tests in June 2013 in Volume 1 by 15 cm. The breakers and components in the DP cabinet are the combustible load. The DP cabinets were configured as follows:

- A single DP was used for each test. The DP was 15 cm less deep than previous tests to provide a shorter distance to the rear slug calorimeters.
- The bus bars were the GE “bolt in” configuration, identical to the January 2013 tests that had long arc durations.
- No Molded Case Circuit Breakers (MCCBs) or switches were installed.
- The interior was open to the extent possible to provide a line-of-sight from the arc to the cable/plastic targets.
- The front and rear panels had large openings with metal screens to observe the arc. The openings to provide ventilation were 0.91 m high by 1.07 m wide (36 in high x 42 in wide).
- The top vents were open to exhaust smoke so the arc could more easily be observed.
- The existing vents all around the bottom were closed off with metal plates.
- Cable/plastic targets were used to indicate damage and measure target mount temperatures.

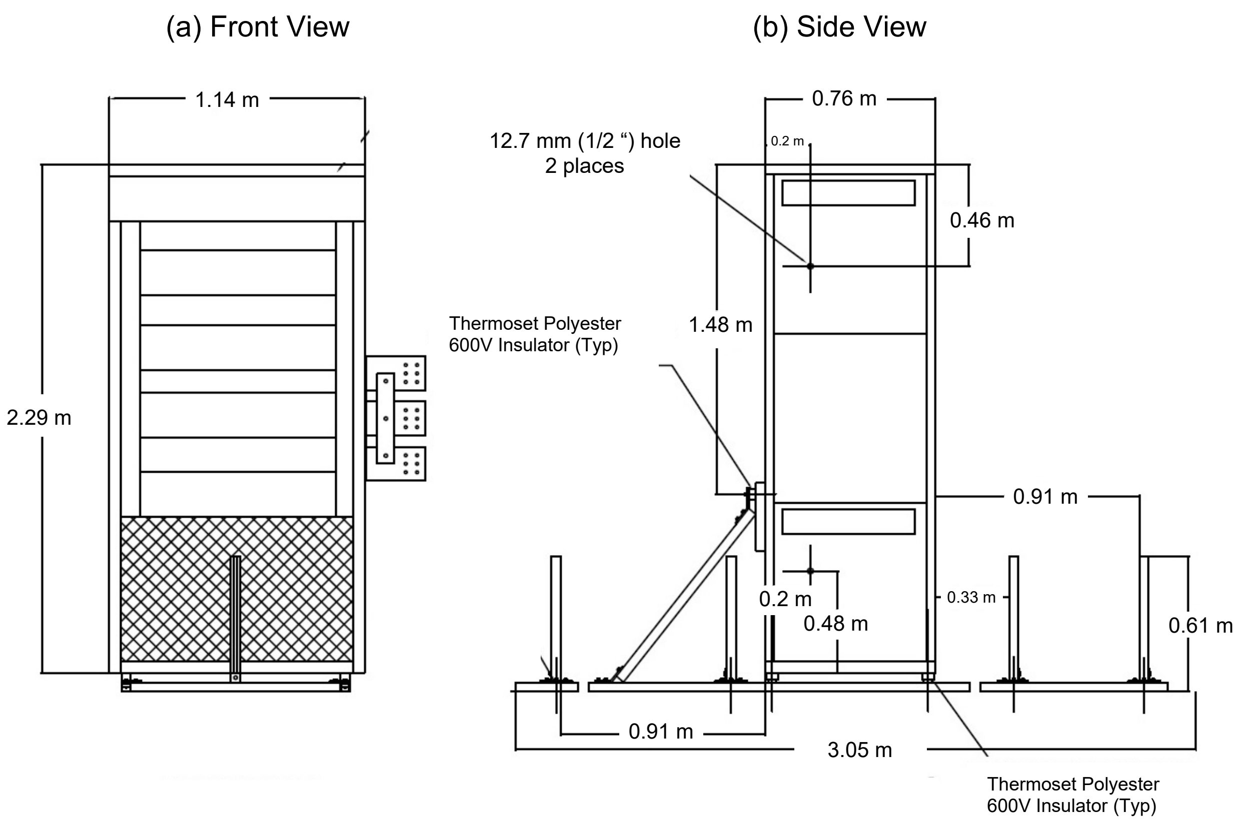


Figure 2.3-1 DP Test Configuration

c. Screens used on front and rear – 86% open area

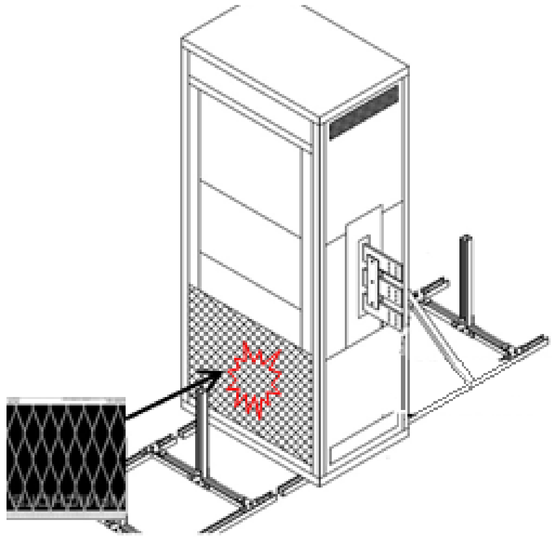


Figure 2.3-1 DP Test Configuration (continued)

2.4 DP Test Cable Combustible Loading

Japanese Type CV-2 control cables with heat resistant PVC sheath and XLPE (Cross-Linked Polyethylene) insulation were used for the combustible cable load in each test (see Appendix C for the properties). In NPPs, these cables are typically used as power cables from the MCCB controllers to motors, and from the DP breakers to the loads. In these tests, the cable bundle combustible loads were smaller than in previous tests since these tests study cable ignition and not a full ensuing fire. The combustible cables are shown as green lines in Figure 2.4-1. There are two bundles of five cables per bundle of CV-2 cable (10 cables total) from Sumiden-Hitachi LTD (HS&T) that are 0.91 m long and mounted in the right, front of the DP.

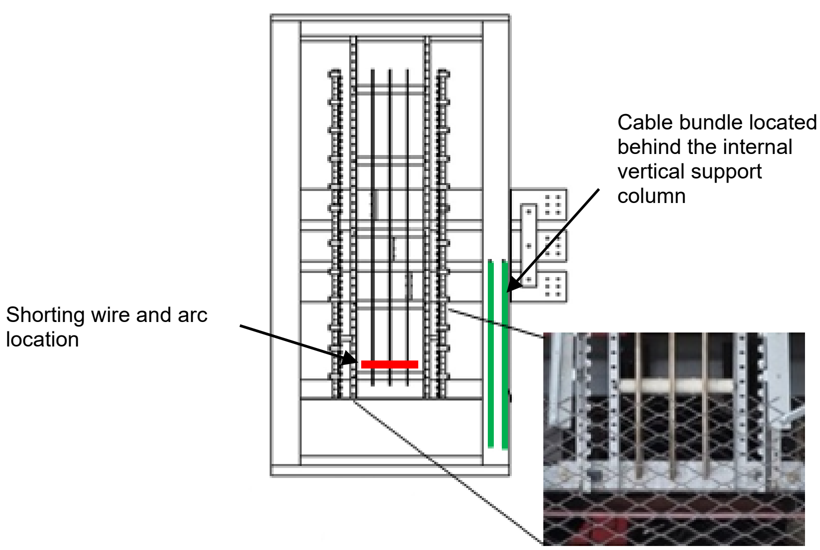


Figure 2.4-1 DP Test Cable Bundle Combustible Load

2.5 DP Test Temperature and Heat Flux Instrumentation

Slug calorimeter (slug, S) and thermocouple (TC) locations are shown in Figure 2.5-1, and described in Table 2-2 and Table 2-3. Slugs 1 and 2 have the same positions as in previous Tests (DP Tests 2 and 3, see Volume 1 [3] so that the results can be compared. The other positions have two slug calorimeters at nominally the same location to average the measurements. The slugs that view the arc (S3 through S10) are positioned at the height of the arc. Slug S11 is located 152 cm from the top of the cabinet to compare to results in previous tests. Photos of the slug positions are in the next section.

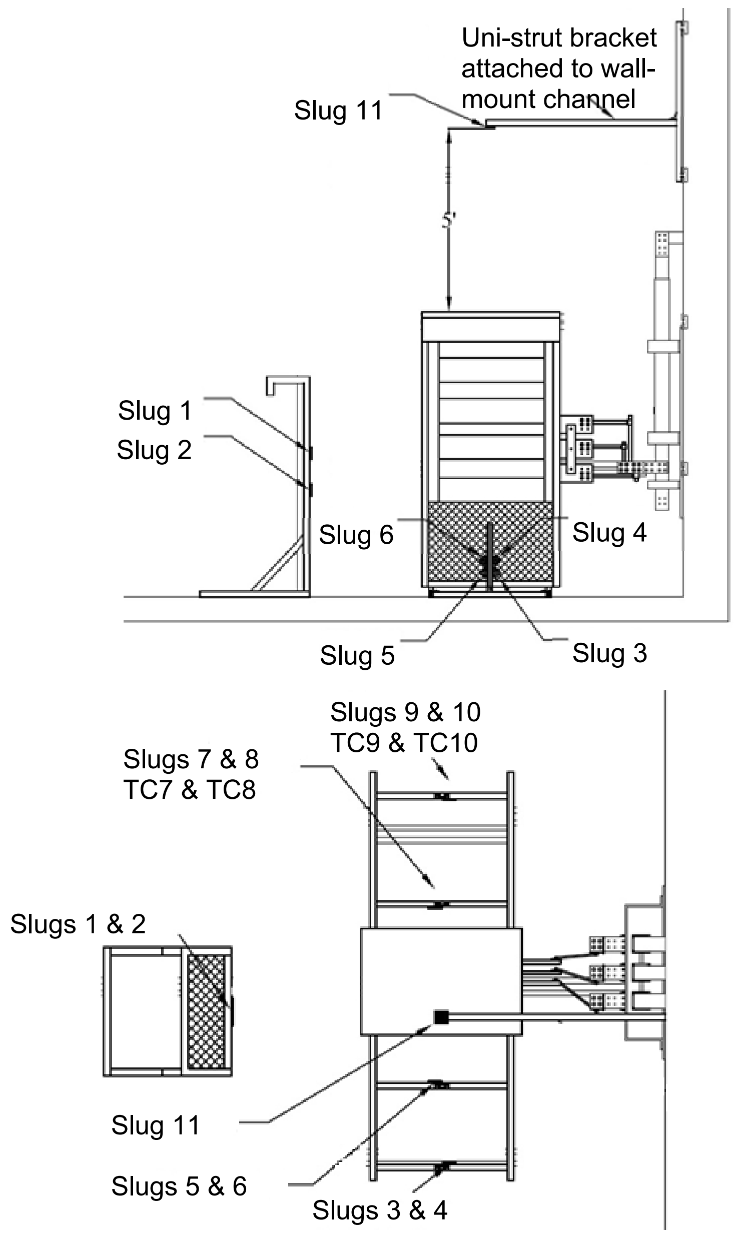


Figure 2.5-1 DP Test Instrumentation Layout

Table 2-2 DP Tests 7, 7A and 8 Calorimeter Locations

Slug	From Floor cm (in)(1)	Position	From Cabinet cm (in)	Slug Name Name- Height- inches from cabinet	From Arc cm
S1	119 (47) (2)	Left Side (LS)	91 (36)	S1-LS-47-36	157 (3)
S2	89 (35) (2)	Left Side (LS)	91 (36)	S2-LS-35-36	152 (3)
S3	66 (26)	Front (F)	91 (36)	S3-F-26-36	109
S4	41 (16)	Front (F)	91 (36)	S4-F-16-36	109
S5	46 (18)	Front (F)	33 (13)	S5-F-18-13	51
S6	56 (22)	Front (F)	33 (13)	S6-F-22-13	51
S7	46 (18)	Rear (R)	15 (6)	S7-R-18-6	62
S8	56 (22)	Rear (R)	15 (6)	S8-R-22-6	62
S9	66 (26)	Rear (R)	91 (36)	S9-R-26-36	138
S10	41 (16)	Rear (R)	91 (36)	S10-R-18-36	138
S11	381 (150)	Top (T)	152 (60)	S11-T-150-60	340 (3)

(1) The “from floor height” includes the Unistrut support which is 4 cm (1.625 in).
(2) Position matches previous DP tests for comparison.
(3) The flux is through the cabinet wall

Table 2-3 DP Test 9 Calorimeter Locations

Slug	From Floor cm (in) (1)	Position	From Cabinet cm (in)	Slug Name Name- Height- inches from cabinet	From Arc cm
S1	198 (78) (2)	Left Side (LS)	91 (36)	S1-LS-78-36	157 (3)
S2	89 (35) (2)	Left Side	91 (36)	S2-LS-35-36	152 (3)
S3	61 (24)	Front (F)	91	S3-F-24-59	167
S4	48 (19)	Front (F)	91 (36)	S4-F-19-59	167
S5	43 (17)	Front (F)	91 (36)	S5-F-17-36	109
S6	30.5 (12)	Front (F)	91 (36)	S6-F-12-36	109
S7	43 (17)	Rear (R)	91 (36)	S7-R-17-36	144
S8	30 (12)	Rear (R)	91 (36)	S8-R-12-36	144
S9	61 (24)	Rear (R)	155 (61)	S9-R-24-61	202
S10	48 (19)	Rear (R)	155 (61)	S10-R-18-61	202
S11	381 (150)	Top	152 (60)	S11-T-150-60	340 (3)

(1) The “from floor height” includes the Unistrut support which is 4 cm (1.625 in).
(2) Position matches previous DP tests for comparison.
(3) The flux is through the cabinet wall

2.6 DP Cable/Plastic Targets

The targets with the cable and plastic samples ("cable/plastic targets" or just "targets"), described in Appendix E, are placed at internal and external locations to observe cable and plastic damage at various distances from the arc.

2.6.1 DP External Targets

The external targets are co-located with the slug calorimeters. External targets are placed with calorimeters S3 through S10, and are numbered to match the slug number, e.g., the PVC target located with S3 is named "E3". Targets are mounted at different angles, but all face directly toward the center of the arcs. Temperature measurements on the target surfaces are taken with temperature labels (see Appendix A.3 for details). For confirmation of readings on the labels, TC are also placed on targets E7 through E10. Figure 2.6-1, Table 2-2 and Table 2-3 show the external slug calorimeter locations at nominal positions. Note the slightly different slug locations for DP Test 9 and therefore different external target locations.

2.6.2 DP Internal Targets

Targets were placed inside the cabinets in view of the arc to capture the maximum radiative heat flux. The targets closer to the arc do not block the view of the targets further from the arc. Targets are at different angles to face directly toward the center of the arcs. However, there are internal bus bars and other obstructions that partially block the view directly to the arc. In these cases, the targets view the plasma around the arc, which also results in high radiative heat transfer. The locations for the internal targets are shown in Table 2-4 and Figure 2.6-2.

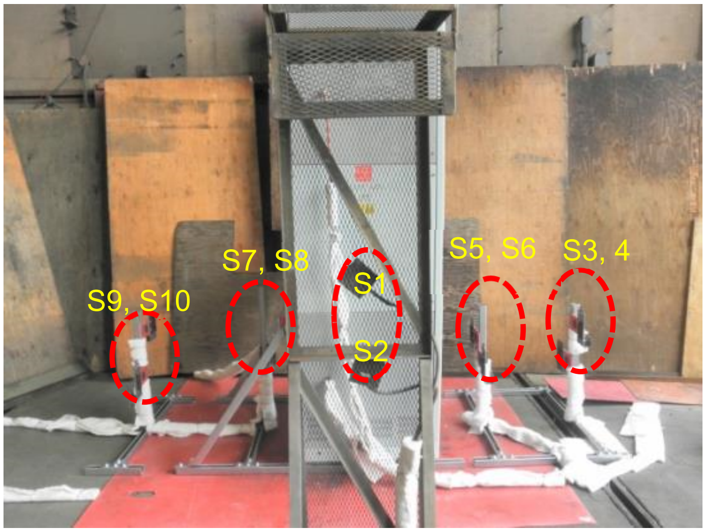
Table 2-4 DP Internal Target Locations

Target	To Arc center (cm)	Comment
T 1R, 1L	30	On instrument mount
T 2R, 2L	48.3	On instrument mount
T 3R, 3L	44.5	On rear panel
T 4R, 4L	57	On side panel
T 5R, 5L	74	On side panel
T 6R, 6L	96	On side panel
T 7R, 7L	126	On side panel
T 8R, 8L	164.5	On side panel

The locations of all the targets are shown in the Figure 2.6-3. The targets in interior positions are duplicated on the left and right. For reference, two circles are drawn on the figure, at a radius of 50 cm and 100 cm.

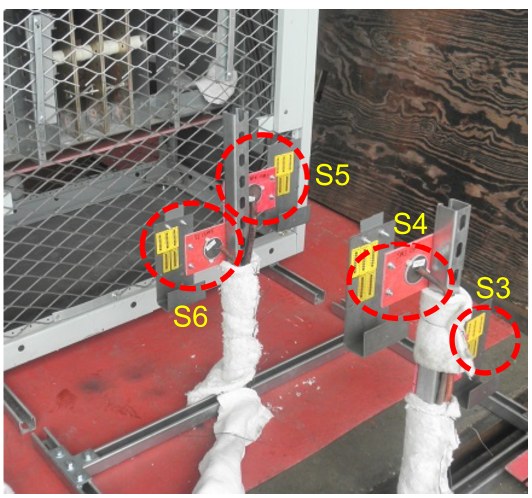
Target numbers in Figure 2.6-3 are used for the post-test photos. Target positions in Figure 2.6-4 using "T" and "E' designations are used for the results tables in the "Target Damage" results sections for each test. Note the "T" and "E" labels do not designate individual targets; they indicate horizontal and vertical positions as an imaginary line that have two targets in the same line. The results add an additional designation of Left (L) and Right (R) to indicate an individual target position in the damage tables.

(a) Side view, external slugs (S3 to S10)



(b) Top slug (S11)

(c) Slugs in front of cabinet (S3 to S6)



(d) Slugs at the rear of the cabinet (S7 to S10)

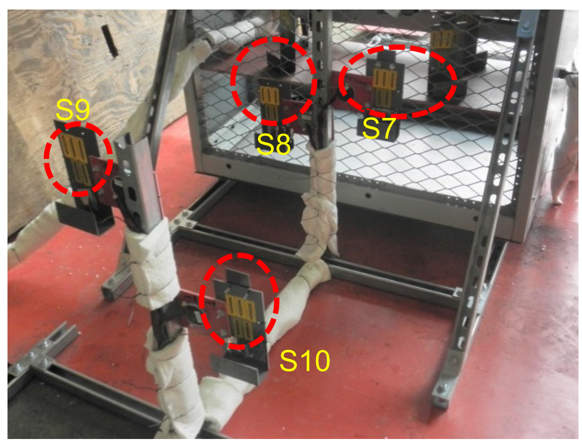
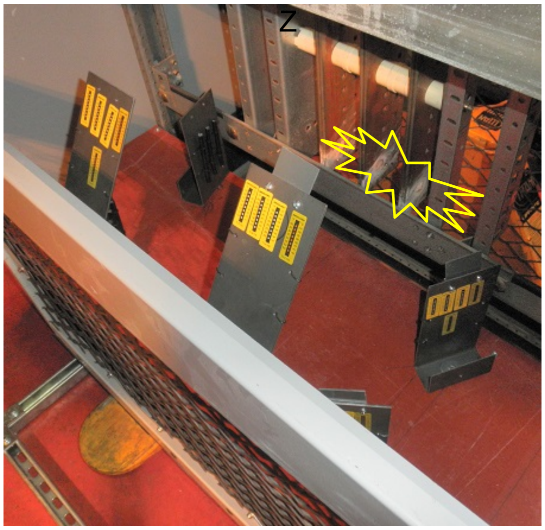


Figure 2.6-1 DP Calorimeter and External Target Locations

(a) Targets T1, T2, T3 (seen from rear)



(b) Target T1L

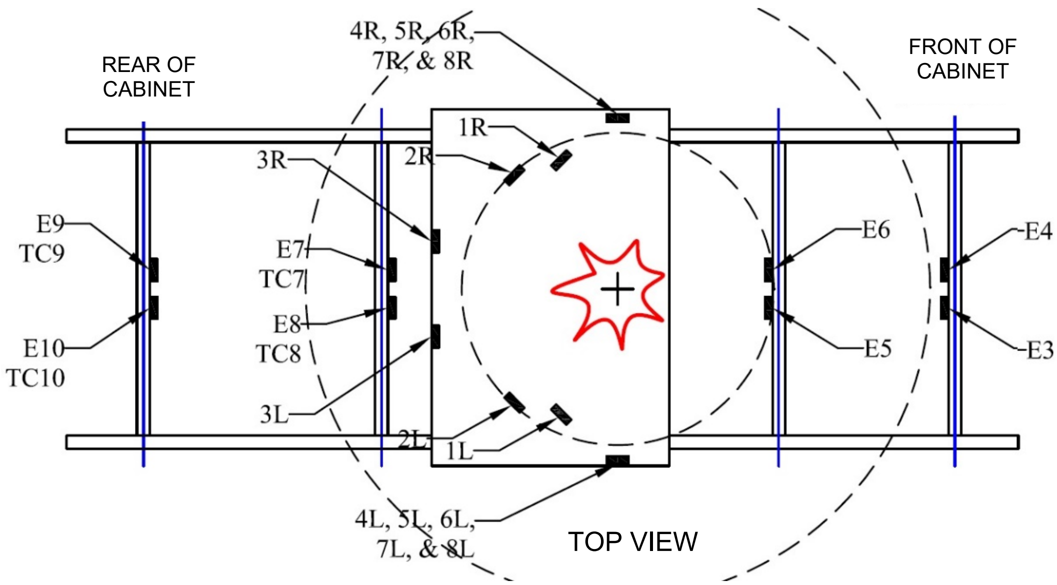
(c) Targets T4L, T5L and T6L (from rear)

(d) All targets

Targets T7 and T8 at the top, from rear

Figure 2.6-2 DP Target Interior Locations

(a) Top view of all Target Locations



(b) Side view of all Target Locations

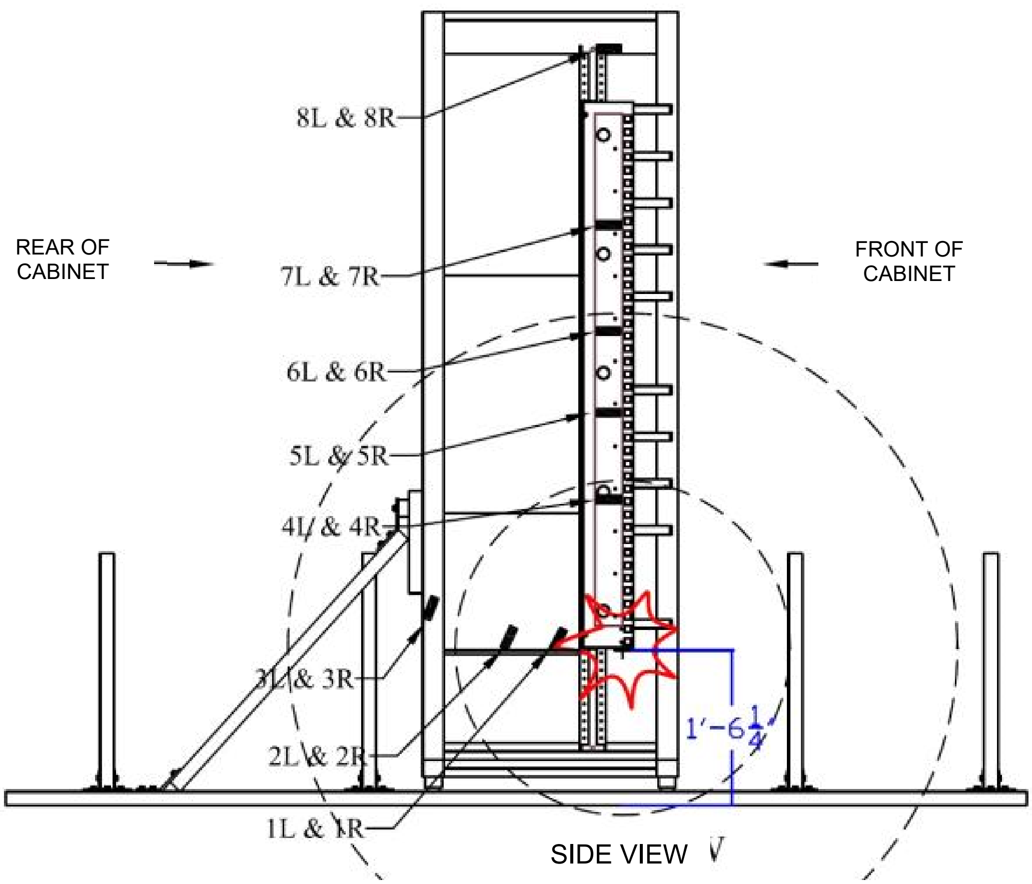


Figure 2.6-3 DP Target Locations Showing Arc Location and 50 cm and 100 cm Radial Distances

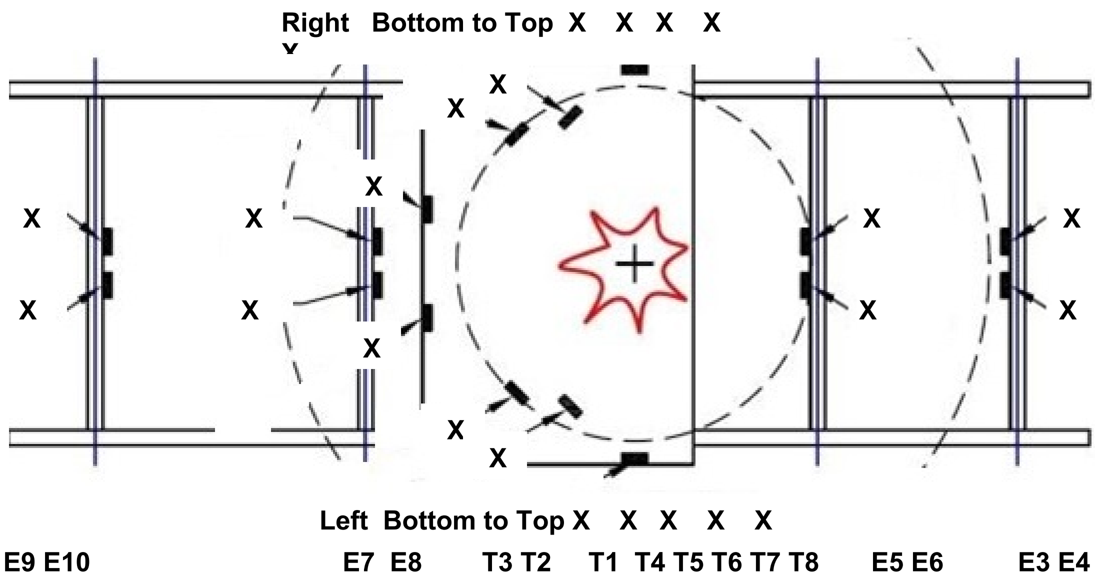


Figure 2.6-4 DP Target Locations for Damage Results Tables Showing Arc Location and 50 cm and 100 cm Radial Distances with Example Results (X= 1 - 6)

2.7 DP Test Pressure Instrumentation

Two Dynisco Pressure Transducer PT150-50 strain gauge type pressure transducers (PRT) were used on the right side of the DP, at the top and bottom, as shown below in Figure 2.7-1. The locations are at the 12.7 mm holes in Figure 2.3-1. The gauges are in PVC pipe to protect them from fire. The measurement analysis method is discussed in Appendix A. Gauge pressure is reported.

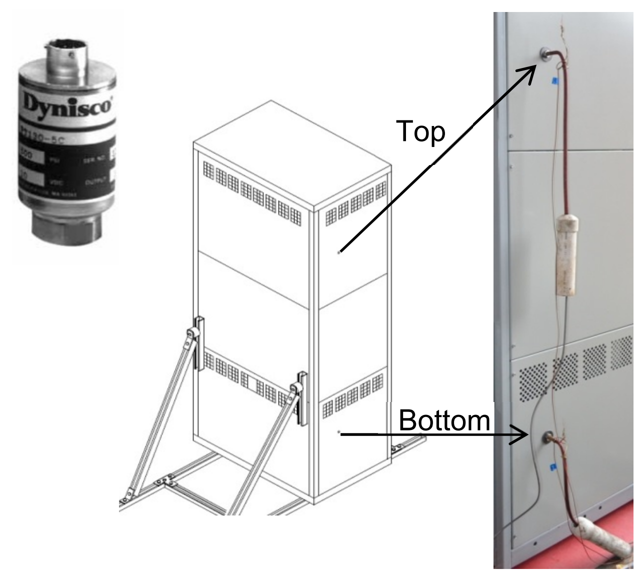


Figure 2.7-1 DP Tests 7 through 9 Pressure Transducer and Locations (Rear View)

2.8 DP Tests 7 and 7A Key Observations

This cabinet test was initiated at 484 V and 54 kA, with a target duration of 1.65 seconds but the arc quenched at 0.238 seconds. The total energy was 4.32 MJ, with a power of about 15 to 25 MW. Figure 2.8-1 shows the arc sequence observed at the front of the DP.

(a) Before arc (b) 0.1 seconds

Figure 2.8-1 DP Test 7 Arc

There was only minor damage to the cabinet after DP Test 7. Taking advantage of the cabinet still in place, a new arc wire was added to attempt a sustained arc as DP Test 7A. The arc failed to sustain again and there were two very short duration arcs that self-extinguished. The first arc lasted 0.022 seconds followed by a second arc lasting for 0.020 seconds, about 0.022 seconds after the first arc. The total energy of both Test 7A arcs was 0.587 MJ, with a power of 15 to 20 MW. Figure 2.8-2 shows the Test 7A arc event after the power was applied.

(a) 0.07 seconds after arc start (b) 0.1 seconds after arc start

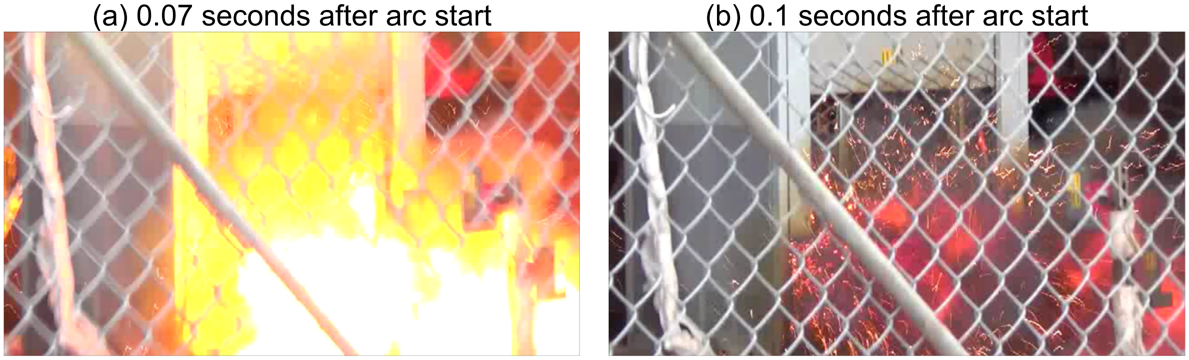


Figure 2.8-2 DP Test 7A Arc

Photos from the HD cameras, Figure 2.8-3 and Figure 2.8-4, inside the test cell can be used to determine the distance the flames traveled, and if the flames made contact with the slugs during the tests. Note the flames extended out of the front and rear cabinet openings past the postulated NUREG 6850 ZOI of 0.91m. See Section 4.1.

(a) DP Test 7 Side View- Front
(b) DP Test 7 Test Side View- Rear
(c) Front, 0.07 sec
(d) Rear, 0.20 sec
(e) Front, 0.13 sec
(f) Rear, 0.29 sec

Figure 2.8-3 DP Test 7 Flames during Arc

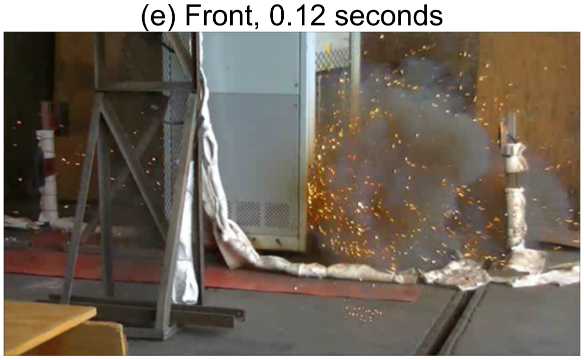
(a) DP Test 7A Side View- Front

(b) DP Test 7A Test Side View- Rear

(c) Front, 0.06 seconds

(d) Rear, 0.03 seconds

(e) Front, 0.12 seconds



(f) Rear, 0.06 seconds

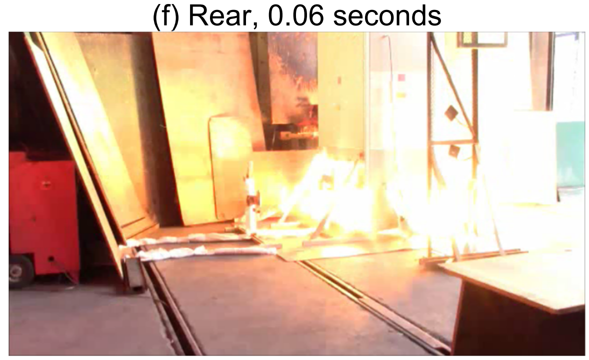


Figure 2.8-4 DP Test 7A Flames during Arc

Figure 2.8-5 and Figure 2.8-6 show IR camera images. The IR camera was on auto-scale and indicated low maximum temperatures. Past tests showed that arcs typically result in temperatures greater than 650 ˚C (1202 ˚F), however, in these tests, the temperatures did not exceed 345 ˚C (653 ˚F).

(a) 0.40 - seconds hot gas escaping

(b) 0.63 seconds - max temperature observed 345 ˚C (653 ˚F)

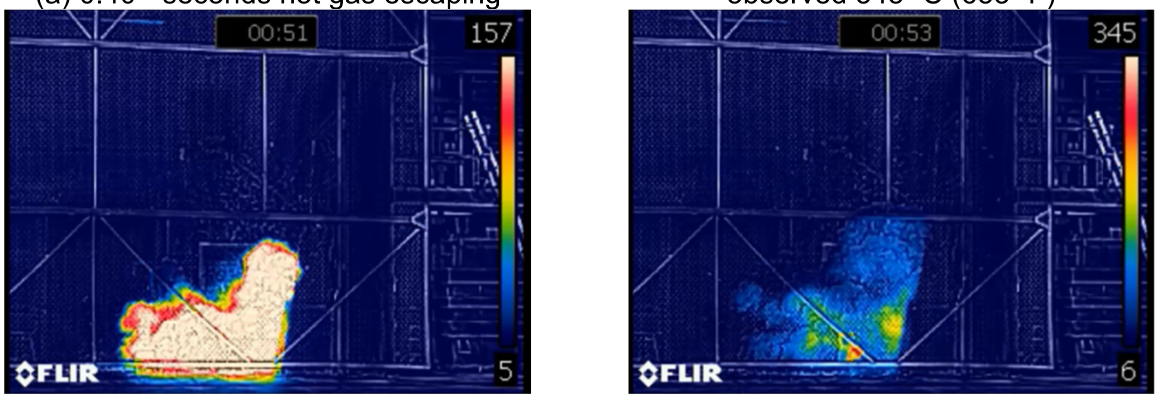


Figure 2.8-5 DP Test 7 Thermal Images

(a) 0.17 - seconds hot gas escaping

(b) 0.26 seconds - max temperature observed 107 ˚C (225 ˚F)

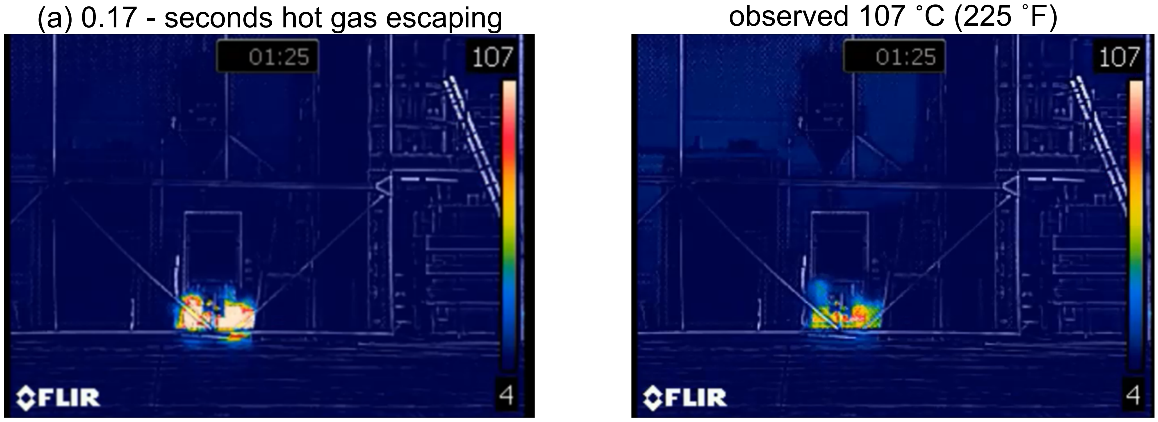


Figure 2.8-6 DP Test 7A Thermal Images

2.8.1 DP Tests 7 and 7A Exterior Damage

There was little damage to the cabinet exteriors, shown in Figure 2.8-7, because of the very low arc energies. The only damage was minor discoloration of the front panel and screen. As the damage was minor; the DP cabinet was reused for DP Test 9 with only minor repairs at the arc location.

(a) After DP test 7 (b) After DP Test 7A

Figure 2.8-7 DP Tests 7 and 7A, Exterior Damage

2.8.2 DP Tests 7 and 7A Interior Damage

Interior cable damage is shown in Figure 2.8-8. The damage was "minor" within about 15 cm of the ends near the arc. Soot deposits from the copper vaporization were seen higher up the cables. Resistance measurements after the tests showed that none of the CV-2 cables failed by conductor-to-conductor shorting. Additional discussion is in Section 4.2.

Figure 2.8-8 DP Test 7 Interior Cable Bundle Damage

The damage to the vertical bus bars is shown in Figure 2.8-9. There was little damage because of the very low arc energies. The bus bars lost 0.5 cm each, in length, which translates to a total loss of 0.177 kg of copper. The calculation details of the mass loss are in Appendix G.

(a) Front View (b) Rear View

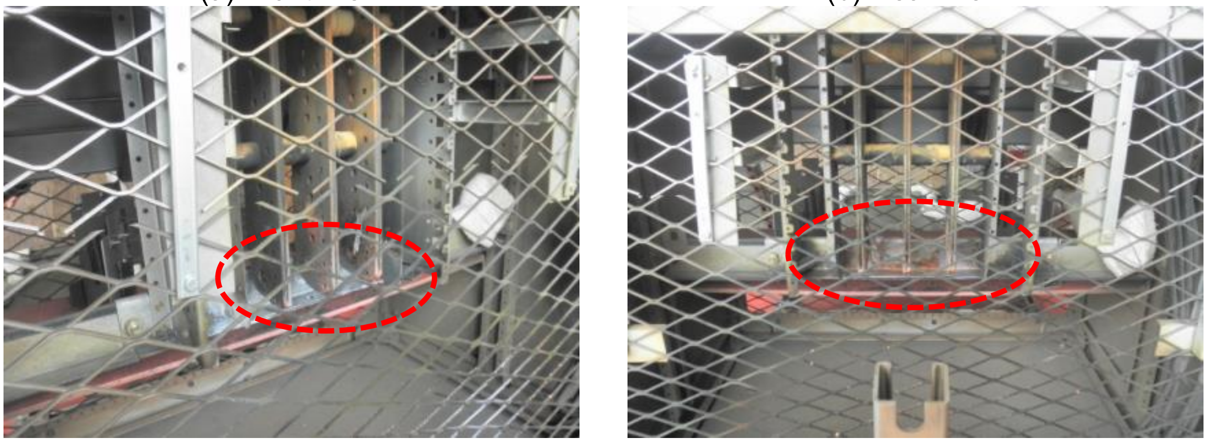


Figure 2.8-9 DP Tests 7 and 7A, Bus Bar Damage

2.8.3 DP Tests 7 and 7A Target Damage

Results are in Figure 2.8-10 and Table 2.-5. See Figure 2.6-4 for target locations. Detailed photographs of the target damage are in Appendix F.

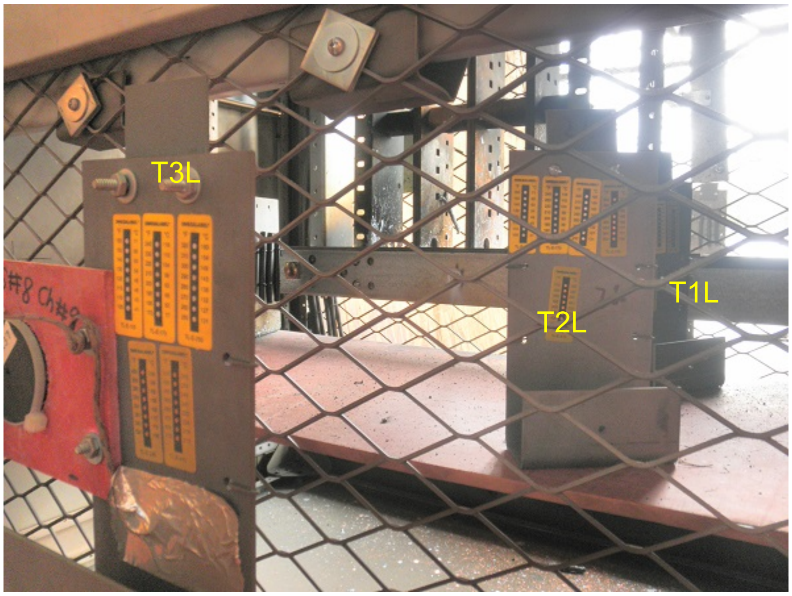


Figure 2.8-10 DP Test 7, 7A Target Damage

Cable Damage:

- Little damage because of the very low arc energies.
- Sooting occurred on internal targets only and only targets above the arc (T1, T2, and T3 are at arc level).
- Minor damage at closest targets: T1 (30 cm from arc) E5 and E6 (58 cm from arc). The damage was charring.

- Targets more than 44 cm from the arc had no damage.

Plastic damage:

- Little damage because of the very low arc energies. Sooting similar to cables but only damage at T5 and T6 50 cm in the front inside of the cabinet near the arc.
- E3-E8 all had flame contact based on video but only E5 and E6 had a temperature increase.

Other:

- Low energy, low target damage

Table 2-5 DP Test 7 and 7A Target Damage

Target (cm)		Damage Description		Label Temp.(˚C)	Note
		Cable	Plastic		
T1 30	L	3. minor damage	1. none	<41	minor cable damage on bottom
	R	3. minor damage	no sample	<41	minor cable damage on bottom
T2 48	L	1. none	1. none	<41	
	R	1. none	no sample	<41	
T3 45	L	1. none	1. none	<41	
	R	1. none	no sample	<41	
T4 57	L	2. sooted	2. sooted	<41	
	R	2. sooted	no sample	<41	
T5 74	L	2. sooted	2. sooted	<41	
	R	2. sooted	no sample	<41	
T6 96	L	2. sooted	2. sooted	<41	
	R	2. sooted	no sample	<41	
T7 126	L	2. sooted	2. sooted	<41	
	R	2. sooted	no sample	<41	
T8 165	L	2. sooted	2. sooted	<41	
	R	2. sooted	no sample	<41	
E3 109		1. none	1. none	<41	this target is reused
E4 109		1. none	1. none	<41	this target is reused
E5 51		3. minor damage	3. minor damage	160-166	
E6 51		3. minor damage	no sample	160-166	
E7 62		1. none	1. none	<41	this target is reused
E8 62		1. none	1. none	<41	this target is reused
E9 138		1. none	1. none	<41	this target is reused
E10 138		1. none	1. none	<41	this target is reused

2.8.4 DP Tests 7 and 7A Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 2.8-11 and Figure 2.8-12. In DP Test 7, slugs located 0.91 m from the sides and 1.5 m from the top (NUREG 6850 ZOI locations) were low due to low arc energy. Also, flames contacted many of the slugs. In DP Test 7A all of the temperatures were low. Since flames impinged onto S5 and S6, the data are not valid.

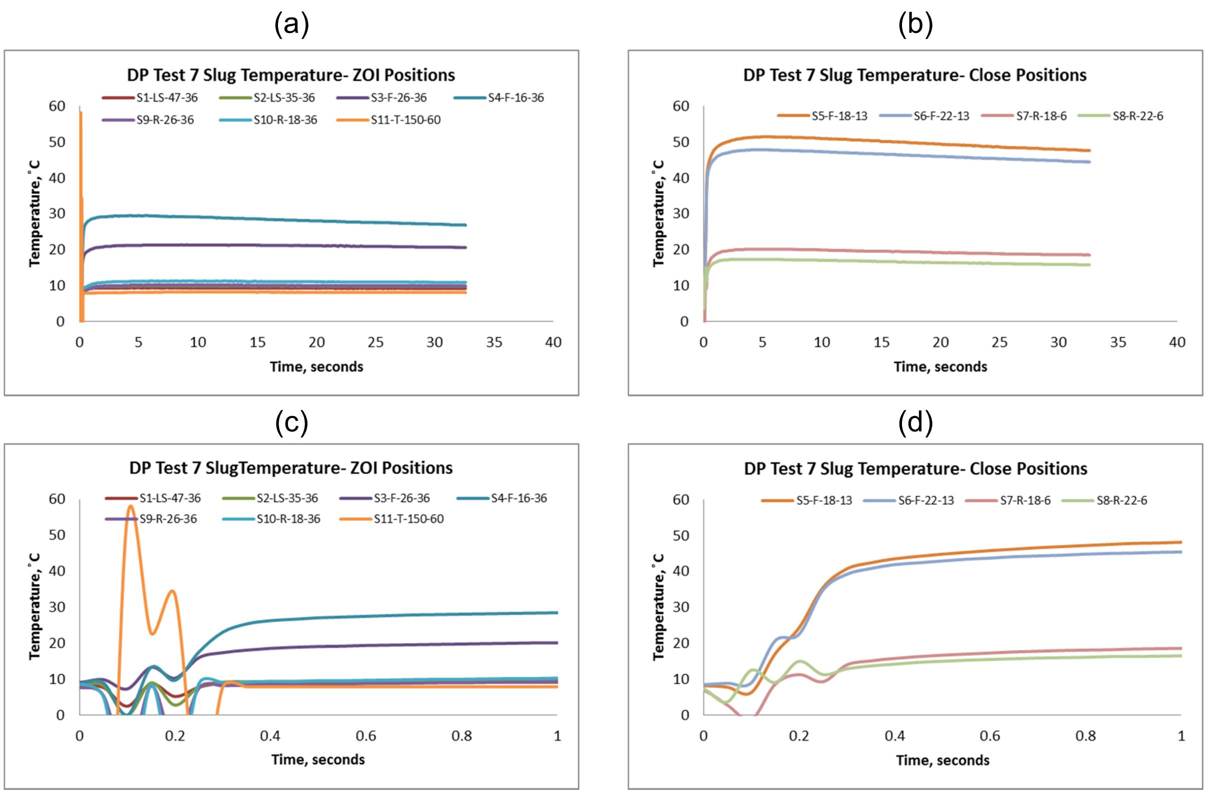


Figure 2.8-11 DP Test 7 Slug Calorimetry Temperature Data

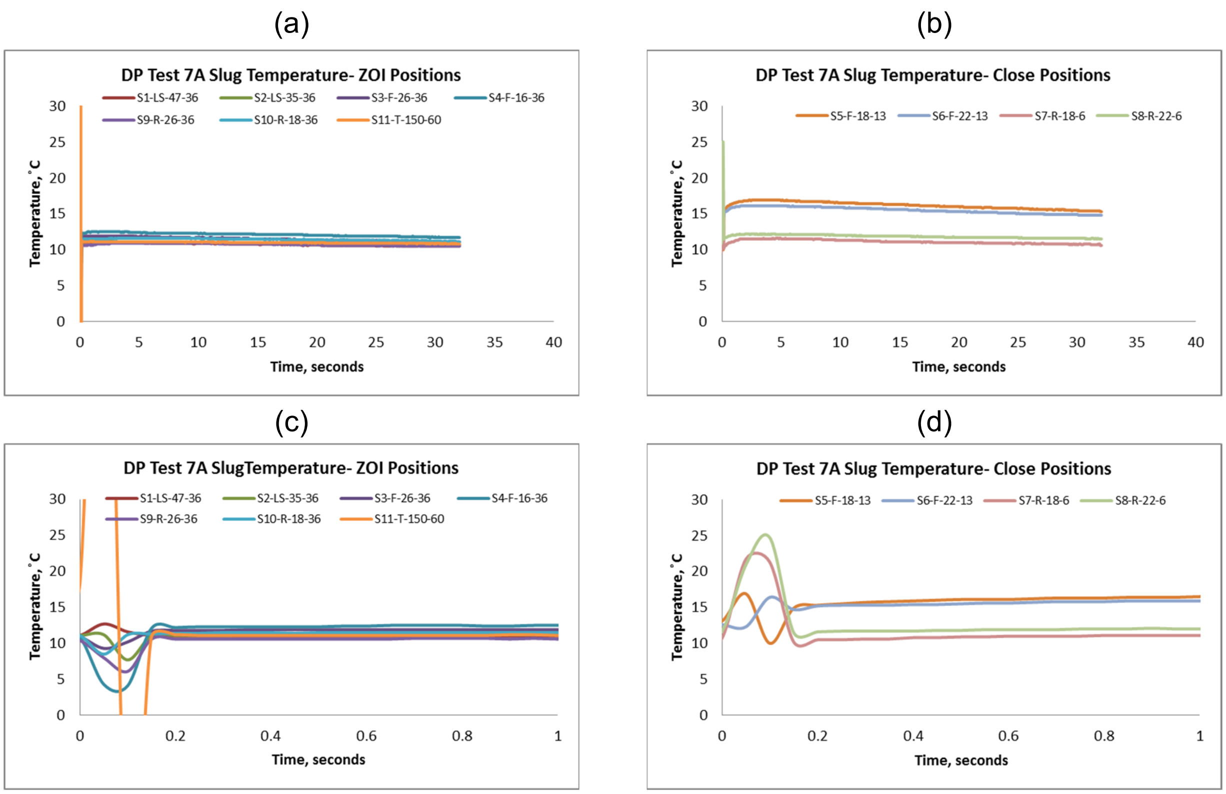


Figure 2.8-12 DP Test 7A Slug Calorimetry Temperature Data

Table 2-6 and Table 2-7 show the flux calculated per the ASTM F1959 flux method using the temperature of the calorimeter slug before and after the arc. The flux is an average of the flux during the arc. However, if flames made contact with the slug, the flux reading was not valid. Results for DP Test 7A are a low heat case for a short arc.

Table 2-6 DP Test 1 Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comments
S1-LS-47-36	0.9	23.1	9	23.1 kW/m^2
S2-LS-35-36	0.8	20.5	10	20.5 kW/m^2
S3-F-26-36	6.9	177.2	21	Flame contact
S4-F-16-36	8.8	226.0	30	Flame contact
S5-F-18-13	27.3	703.1	51	Flame contact
S6-F-22-13	26.3	677.3	48	Flame contact
S7-R-18-6	2.0	51.3	20	Flame contact (1)
S8-R-22-6	4.0	102.6	17	Flame contact
S9-R-26-36	0.6	15.4	10	Average is 14.1 kW/m^2
S10-R-18-36	0.5	12.8	11	
S11-T-150-60	0.4	10.3	8	10.3 kW/m^2

(1) S7 is low typical of measurements with no flame contact but flame contact is obvious in the video.

Table 2-7 DP Test 7A Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comments
S1-LS-47-36	0.1	10.2	11	Low flux and temperatures. 10.2 is minimum detectable for this short arc
S2-LS-35-36	0.0	0	11	
S3-F-26-36	0.6	61.1	12	Average is 66.2 kW/m^2
S4-F-16-36	0.7	71.3	13	
S5-F-18-13	2.2	224.2	17	Flame contact
S6-F-22-13	2.0	203.8	16	Flame contact
S7-R-18-6	0.5	50.9	12	Average is 56.0 kW/m^2
S8-R-22-6	0.6	61.1	12	
S9-R-26-36	0.0	0	11	No heat reached this position
S10-R-18-36	0.0	0	12	
S11-T-150-60	0.0	0	11	No heat reached this position

2.8.5 DP Tests 7 and 7A Temperature Data

The temperatures measured by the TCs on the external targets E7 through E10, which are co-located with slugs of the same numbers, at the rear of the cabinet are seen in Figure 2.8-13 and Figure 2.8-14. Temperatures recorded at the end of the arc, and the maximum during the arc are reported in Table 2-8 and Table 2-9.

(a) (b)

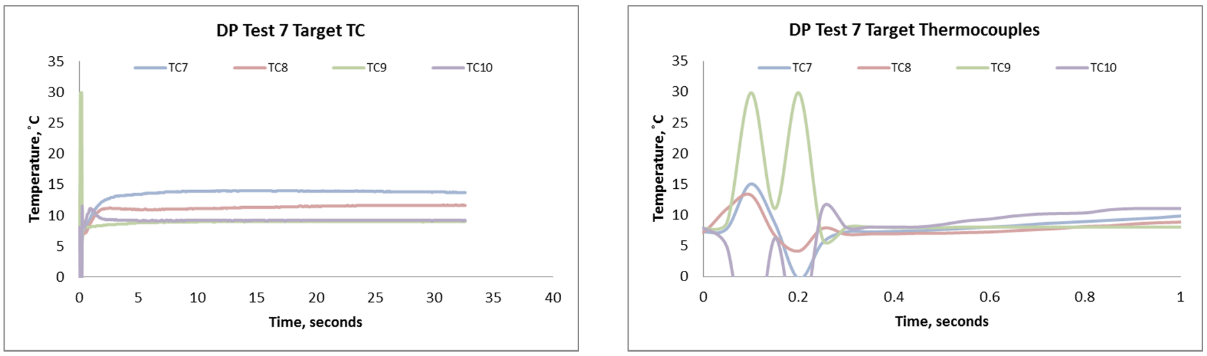


Figure 2.8-13 DP Test 7 Thermocouple Data

(a) (b)

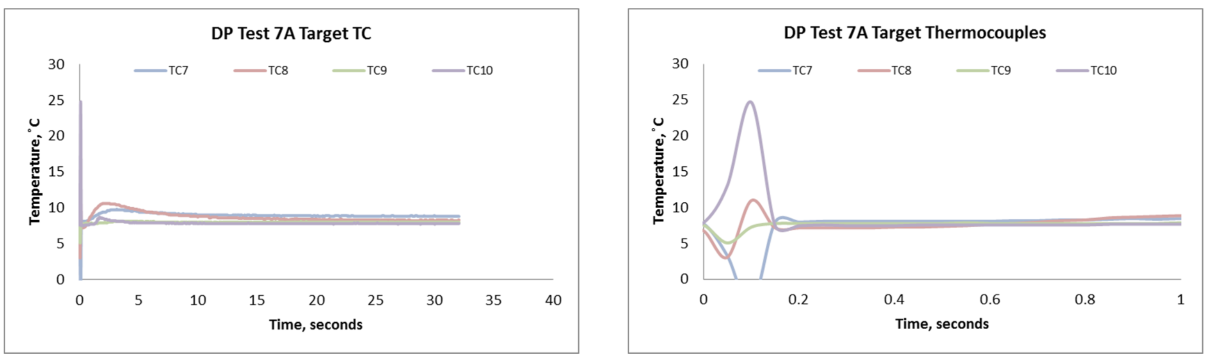


Figure 2.8-14 DP Test 7A Thermocouple Data

Table 2-8 DP Test 7 TC Results

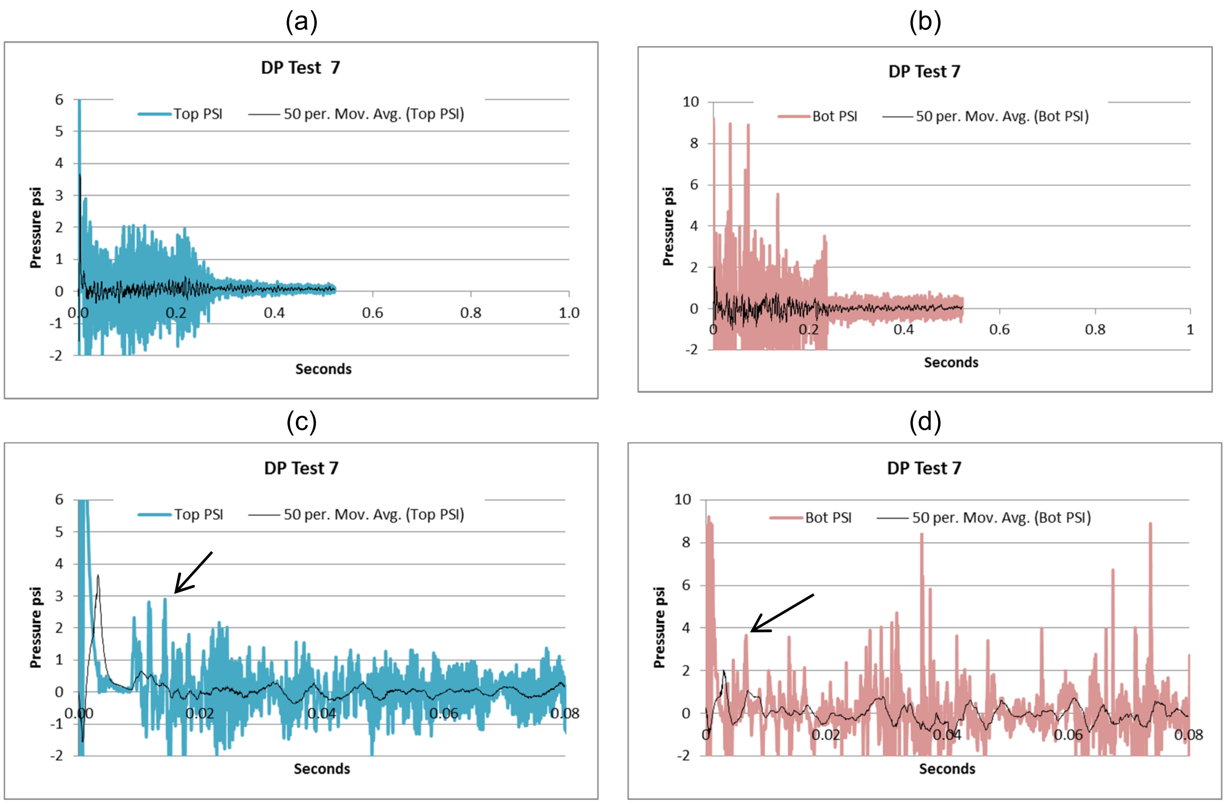
TC	Arc End (˚C)	Max T (˚C)
TC7	6	14
TC8	8	12
TC9	6	9
TC10	11	11

Table 2-9 DP Test 7A TC Results

TC	Arc End (˚C)	Max T (˚C)	Label T (˚C)
TC7	8	10	<41
TC8	7	11	<41
TC9	8	8	<41
TC10	8	9	<41

2.8.6 DP Tests 7 and 7A Pressure Data

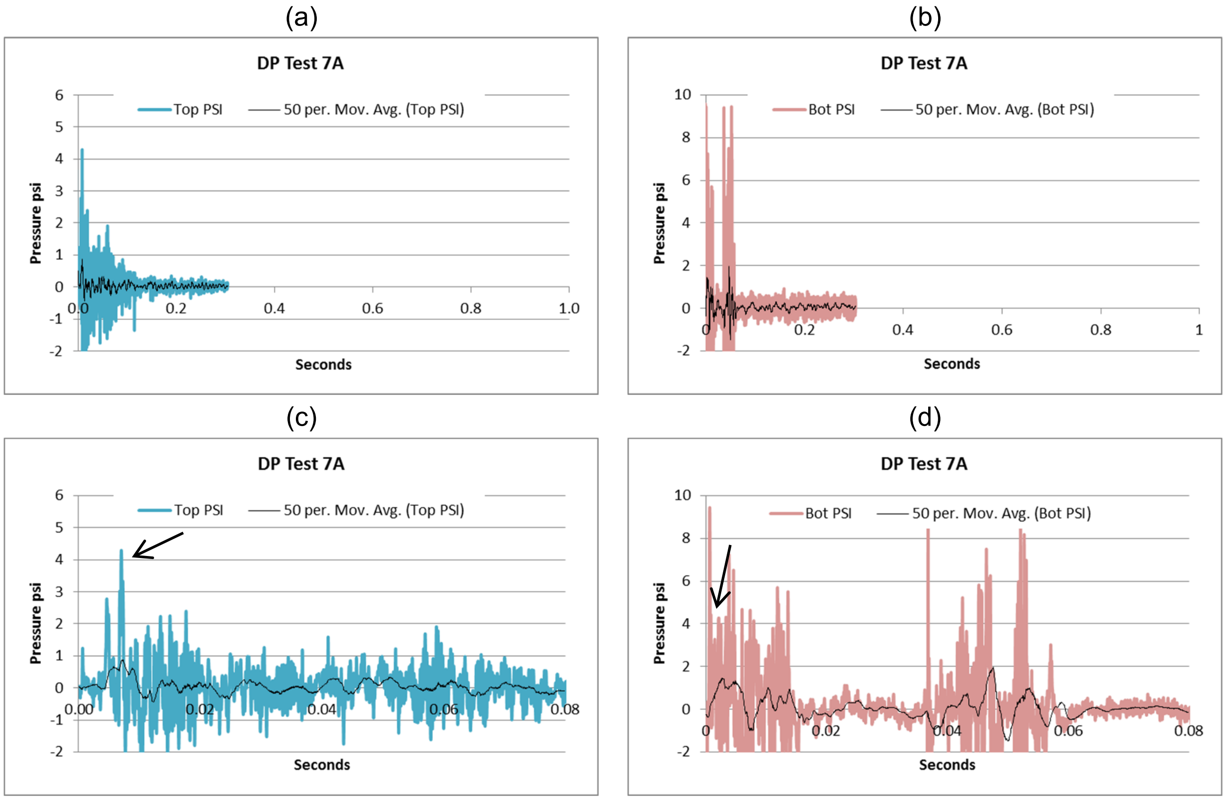
The gauge pressures during the arcs are seen in Figure 2.8-15 and Figure 2.8-16. The maximum pressures are indicated by the arrows in the charts. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc. The arcs were unsteady so the data is very noisy, especially for PRT-2 (bottom) near the arc.



Test 7 PRT1 (top)
13.8 ± 1.0 (2.0 ± 0.15 psi)
@ 0.0117 second

Test 7 PRT2 (bottom)
19.3 ± 5.5 kPa (2.8 ± 0.8 psi)
@ 0.0068 second

Figure 2.8-15 DP Test 7 Pressure



Test 7A PRT1 (top)	Test 7 PRT2 (bottom)
20.1 ± 1.4 (.0 ± 0.2 psi)	20.1 ± 6.9 kPa (3.0 ± 1.0 psi)
@ 0.0128 second	@ 0.0066 second

Figure 2.8-16 DP Test 7A Pressure

2.8.7 DP Tests 7 and 7A Arc Energy

For DP Test 7 total electrical energy was 4.32 MJ and the power was 15 to 25 MW, as shown in Figure 2.8-17. The "Energy" is calculated as volts multiplied current multiplied by the time step and each time step is shown. "Energy Total" is the cumulative sum of the energy in each time step.

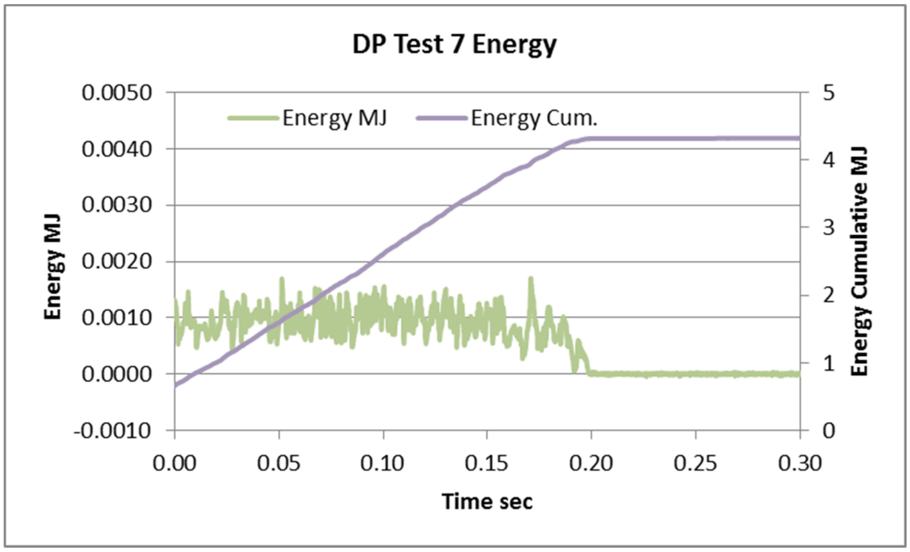


Figure 2.8-17 DP Test 7 Arc Energy

For Test DP 7A the arc would not start and there were two short arcs. The total electrical energy of both arcs was 0.59 MJ and the power was 15 MW to 20 MW, as shown in Figure 2.8-18.

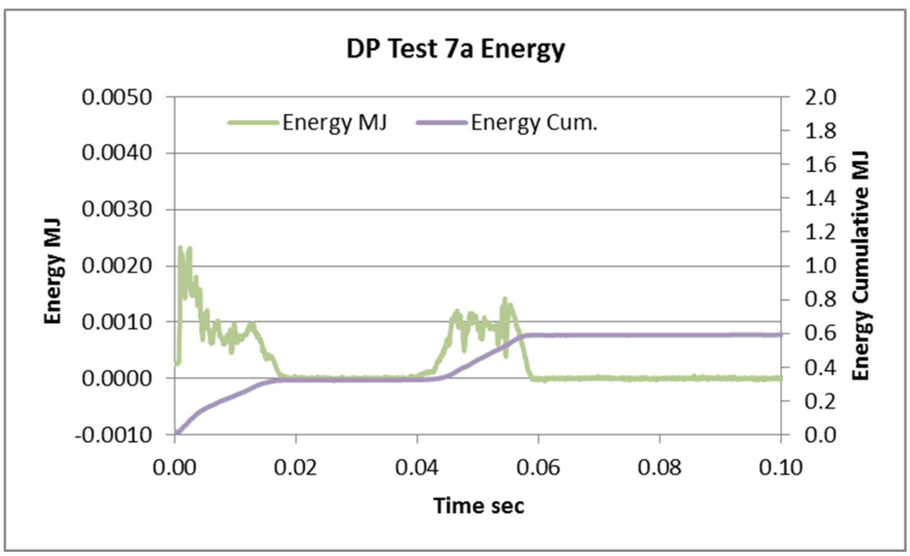
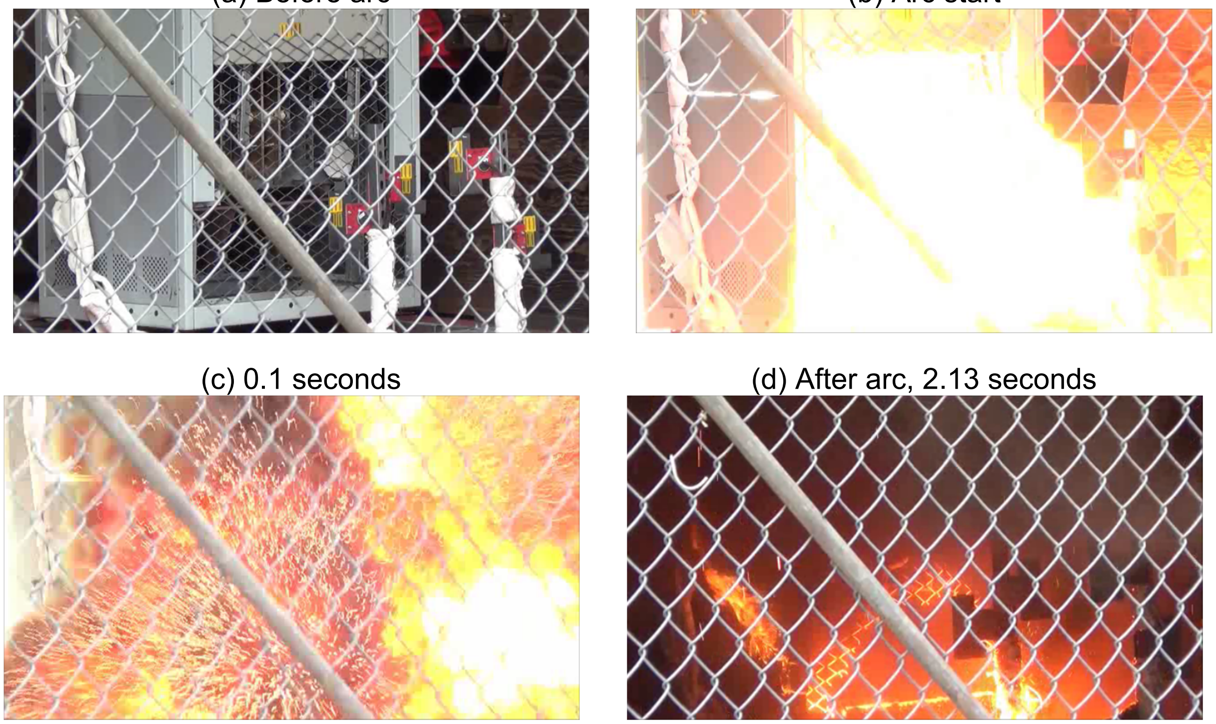


Figure 2.8-18 DP Test 7A Arc Energy

2.9 DP Test 8 Key Observations

This cabinet test was initiated at 600 V and 54 kA, with a target duration of 1.9 seconds. The arc quenched at 1.893 seconds, as planned by the KEMA power system. The total energy was 39.7 MJ and power of 20 to 25 MW. Figure 2.9-1 shows the arc sequence observed at the front of the DP.



(a) Before arc

(b) Arc start

(c) 0.1 seconds

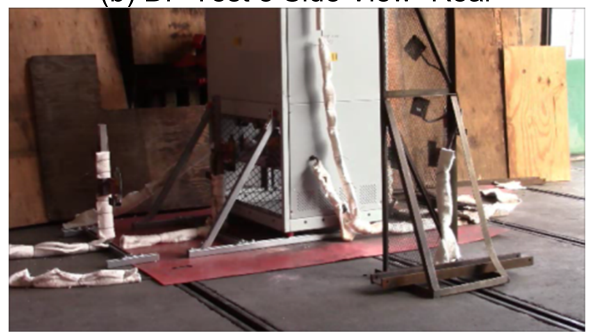
(d) After arc, 2.13 seconds

Figure 2.9-1 DP Test 8 Arc

Photos from HD cameras inside the test cell, seen in Figure 2.9-2, indicate the distance the flames traveled, and if the flames made contact with the slugs during the tests. Note the flames during the arc reached past the instrumentation stands, which are 0.91 m in front of and rear of cabinet openings. Flame contact with front S3 through S6 are shown in Figure 2.9-2(c). Flames contacting with S7 through S10 are shown in Figure 2.9-2(d), (e), and (f).

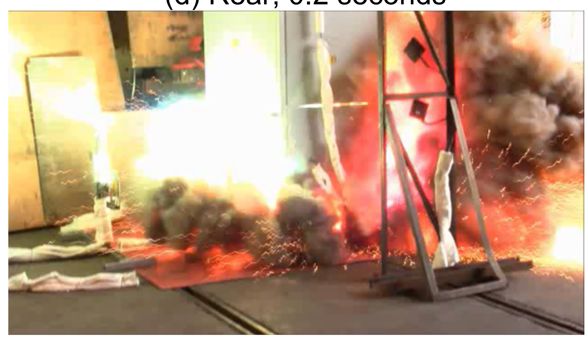
(a) DP Test 8 Side View- Front

(b) DP Test 8 Side View- Rear

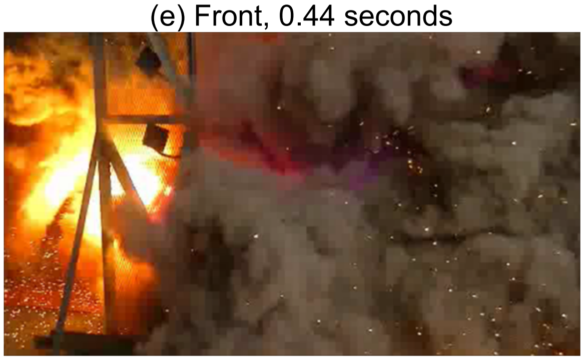


(c) Front, 0.06 seconds

(d) Rear, 0.2 seconds



(e) Front, 0.44 seconds



(f) Rear, 0.74 seconds

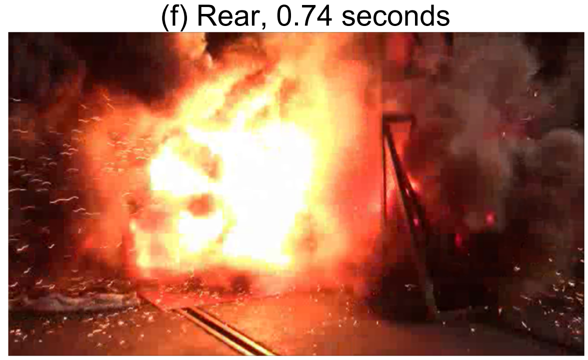
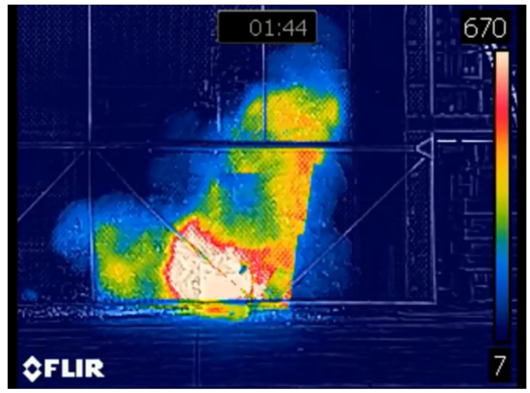


Figure 2.9-2 DP Test 8 Flames during the Arc

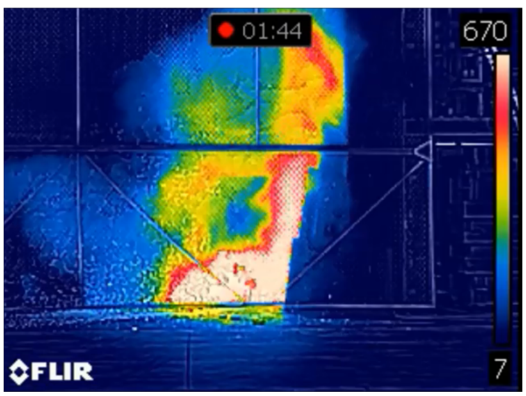
The IR camera images are shown in Figure 2.9-3. The IR camera was on auto-scale and the maximum temperature detected (670 ˚C) was about 1 second that is typical for previous arc tests.

(a) Arc Start

(b) 1.03 seconds, Max Temperature achieved (670 ˚C)



(c) 1.5 seconds



(d) 2.5 seconds (0.6 sec after arc)

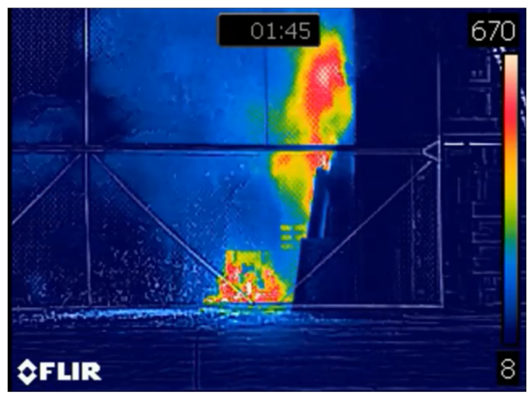


Figure 2.9-3 DP Test 8 Thermal Images

2.9.1 DP Test 8 Exterior Damage

The exterior damage to the cabinet is shown in Figure 2.9-4. The flames burned through the front screens (closest to the arc). There was charring on the cabinet around the openings and soot deposited above the openings. There were no holes burned in the cabinet.

(a) Front

(b) Rear

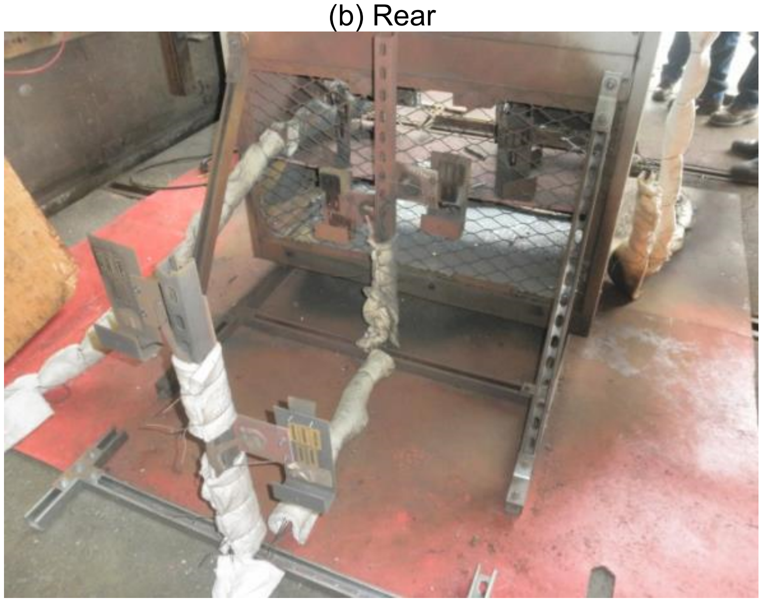


Figure 2.9-4 DP Test 8 Exterior Damage

2.9.2 DP Test 8 Interior Damage

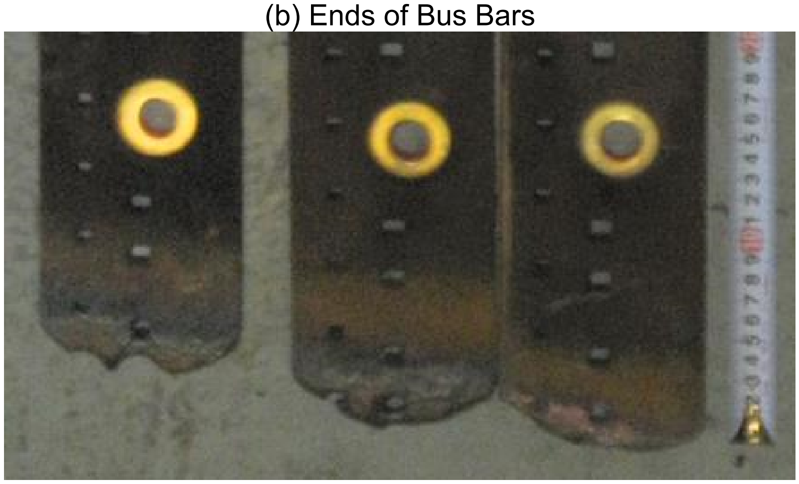
The damage to the cables is shown in Figure 2.9-5. The 15 cm of the cables near the arc is characterized as “destroyed.” The remaining cable section is characterized as, “medium.” Post-test resistance measurements were not made because the cable was assumed to be failed by conductor-to-conductor shorting at the ends. Additional discussion is in Section 4.2.

Figure 2.9-5 DP Test 8 Interior Cable Damage

The damage to the vertical bus bars is shown in Figure 2.9-6. About 7 to 10 cm of copper bus bar were burned and the steel angle bracket was burned. The mass loss of the copper bus bars was 2.668 kg. The mass loss calculations are detailed in Appendix G.

(a) Front View

(b) Ends of Bus Bars



(c) Bus Bars

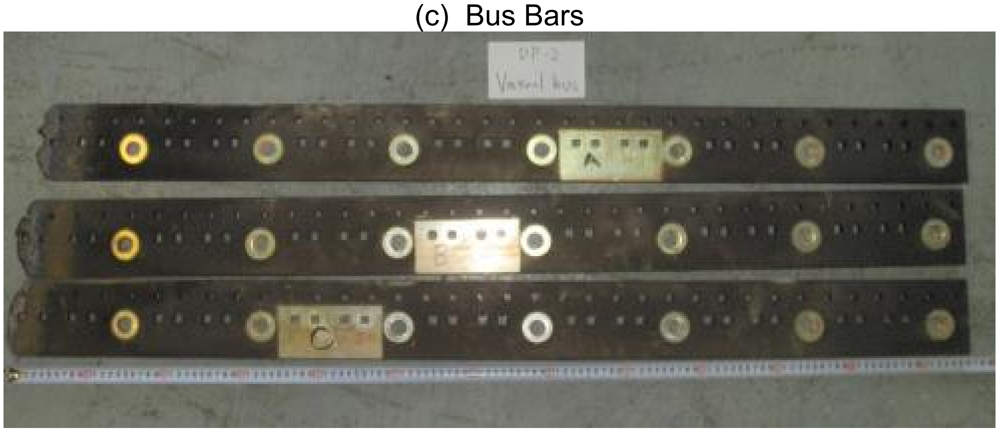


Figure 2.9-6 DP Test 8 Interior Bus Bar Damage

2.9.3 DP Test 8 Target Damage

The results are shown in Figure 2.9-7 and Table 2-10. See Figure 2.6-4 for target locations. Detailed photographs of the target damage are in Appendix F.

Cable Damage:

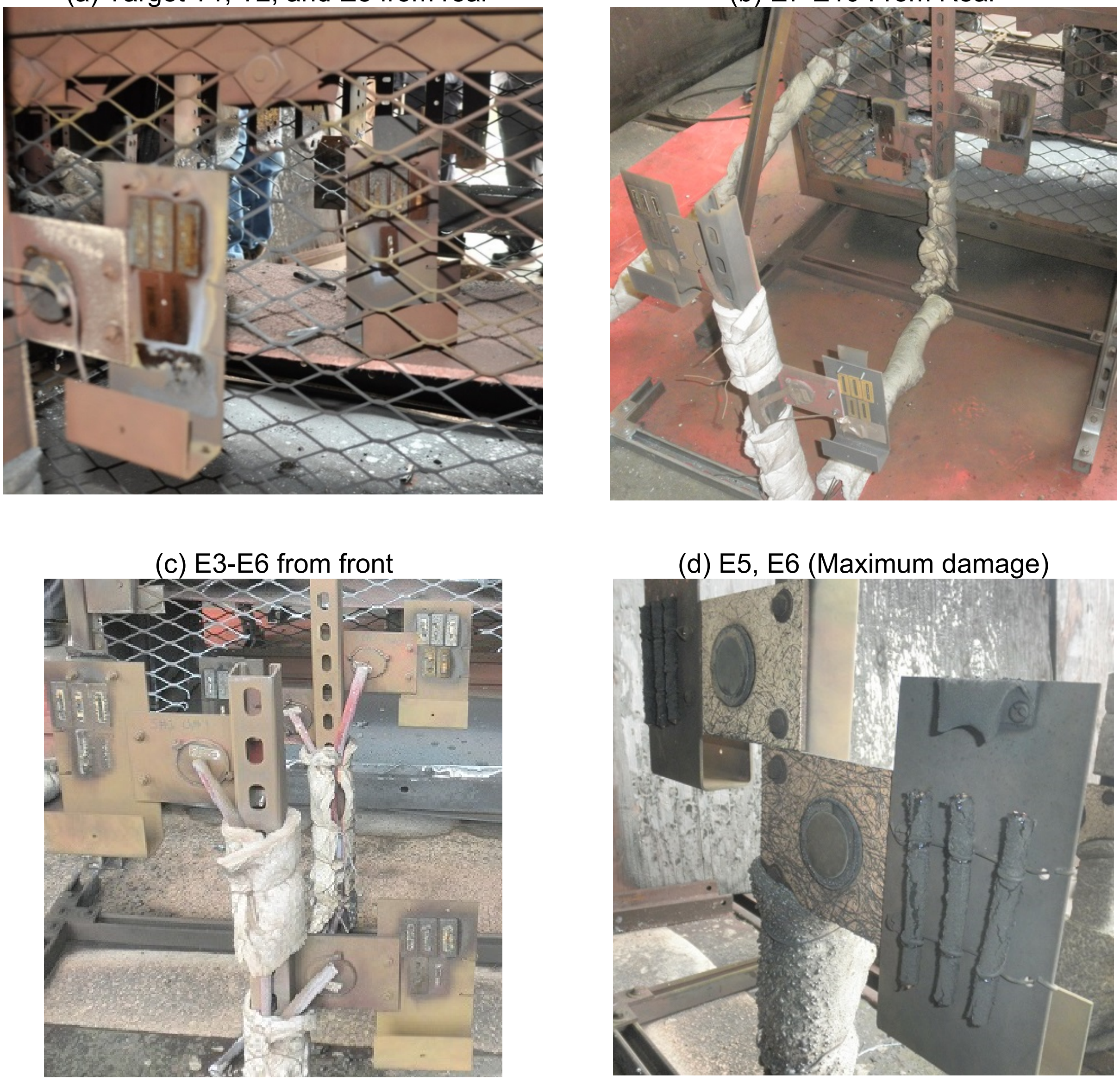
- Internal cable damage up to T6 (97 cm). Sooting on other internal targets > 97 cm.
- T3 had more damage than T1 or T2 perhaps because T1 and T2 were shielded behind the steel bar that did not burn through.
- External cable damage at all targets out to E10 (138 cm).

Plastic damage:

- Internal minor plastic damage at T4 (51 cm) and T5 (75 cm).
- External heavy damage atE5 and E6 nominally 60 cm from the arc where the flames exited the front of the cabinet.

Other:

- Gray heavy metal coating on T1 and T2 that is the steel bar where the arc attached.
- External metal coating out to E8 (62 cm), heavy metal coating internally out to 48 cm at arc level.



(a) Target T1, T2, and E8 from rear

(b) E7-E10 From Rear

(c) E3-E6 from front

(d) E5, E6 (Maximum damage)

Figure 2.9-7 DP Test 8 Target Damage and Target Numbers

Table 2-10 DP Test 8 Target Damage

Target (Cm)		Damage Description: Cable	Damage Description: Plastic	Label Temp. (˚C)	Note
T1 30	L	2. sooted	2. sooted	burnt	heavily sooted, bottom of target plate is coated with metal
	R	2. sooted	No sample	burnt	heavily sooted, bottom of target plate is coated with metal
T2 48	L	2. sooted	2. sooted	burnt	heavily sooted, bottom of target plate is coated with metal
	R	2. sooted	2. sooted	burnt	heavily sooted, bottom of target plate is coated with metal
T3 45	L	4. medium damage	2. sooted	burnt	
	R	4. medium damage	2. sooted	burnt	
T4 57	L	4. medium damage	2. sooted	burnt	
	R	4. medium damage	3. minor damage	burnt	
T5 74	L	4. medium damage	3. minor damage	160-166	
	R	4. medium damage	3. minor damage	160-166	
T6 96	L	3. minor damage	2. sooted	149-154	
	R	3. minor damage	2. sooted	116-121	
T7 126	L	2. sooted	2. sooted	71-77	
	R	2. sooted	2. sooted	71-77	
T8 165	L	2. sooted	2. sooted	82-88	
	R	2. sooted	2. sooted	71-77	
E3 109		4. medium damage	4. medium damage	burnt	plastic is bent backward
E4 109		4. medium damage	no sample	burnt	
E5 51		5. heavy damage	5. heavy damage	burnt	plastic is bent fully forward
E6 51		4. medium damage	no sample	burnt	
E7 62		4. medium damage	5. heavy damage	burnt	plastic is bent fully forward

Table 2-10 DP Test 8 Target Damage (continued)

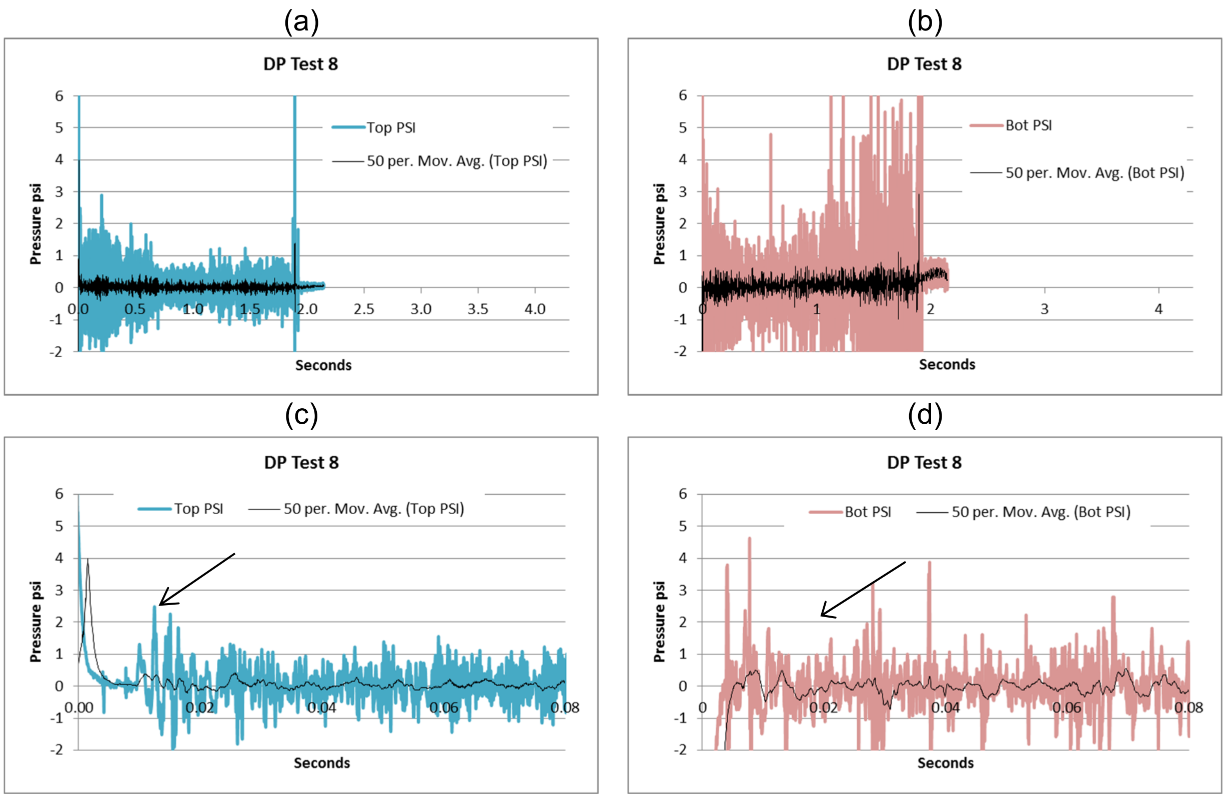
Target (Cm)	Damage Description		Label Temp. (˚C)	Note
E8 62	4. medium damage	no sample	burnt	top of target plate is coated with metal
E9 138	4. medium damage	no sample	burnt	
E10 138	4. medium damage	3. minor damage	99-104	

2.9.4 DP Test 8 Calorimetry and Temperature Data

The data acquisition failed to trigger and collect data. The parameters of DP Test 8 were repeated as DP Test 9 to obtain calorimetry and temperature data. However, temperature labels showed the internal labels were burned out to T4 (51 cm). Temperatures were generally decreasing with distance as expected. The external labels were all burnt out to E10 (138 cm) and all external targets had flame contact.

2.9.5 DP Test 8 Pressure Data

The gauge pressures during the arc are seen in Figure 2.9-8. The maximum pressures are indicated by the arrows in the charts. Although the noise levels are especially high for PRT2 (bottom), there was a zero shift near the end of the arc. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc.



Test 8 PRT1 (top)	Test 8 PRT2 (bottom)
15.2 ± 1.0 kPa (2.2 ± 0.15 psi)	14.5 ± 5.5 kPa (2.1 ± 0.8 psi)
@ 0.0135 second	@ 0.0081 second

Figure 2.9-8 DP Test 8 Pressure

2.9.6 DP Test 8 Arc Energy

The total energy was 39.7 MJ, seen in Figure 2.9-9. The "Energy" is calculated as volts multiplied current multiplied by the time step and each time step is shown. "Energy Total" is the cumulative sum of the energy in each time step.

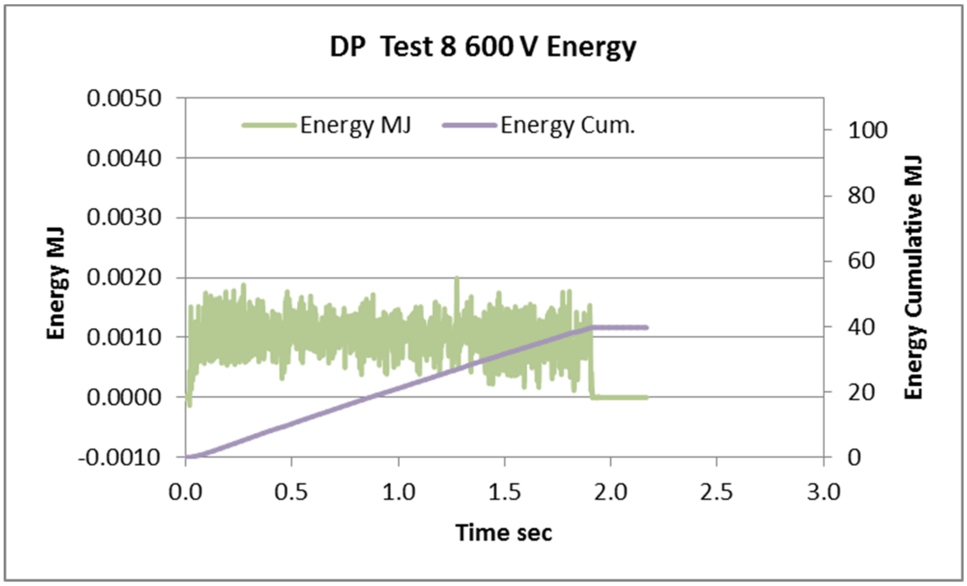


Figure 2.9-9 DP Test 8 Arc Energy

2.10 <u>Changes from DP Test 8 to Test 9</u>

In the previous test, the bus bars and metal bracket where the arc attached was almost completely burned. The arc self-extinguishes when the point of attachment is no longer available. In order to ensure a longer sustained arc duration, an additional steel plate was added above the bracket, as shown in Figure 2.10-1, for DP Test 9. The plate was also modified to have two brackets to provide additional metal at the arc starting point. This method was effective and the plate was almost consumed by the arc.

(a) After DP Test 8 (b) Addition of Steel Plate for DP Test 9

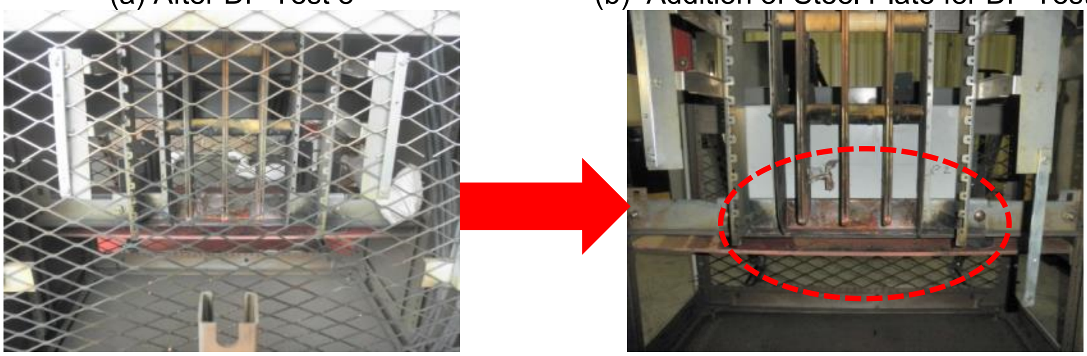


Figure 2.10-1 DP Test 9 Change to Bus Bar Configuration

2.11 DP Test 9 Key Observations

This cabinet test was initiated at 600 V and 54 kA, with a target duration of 3 seconds that was achieved, and exceeded to 3.144 seconds, with a total energy of 66.8 MJ. Figure 2.11-1 shows the arc sequence.

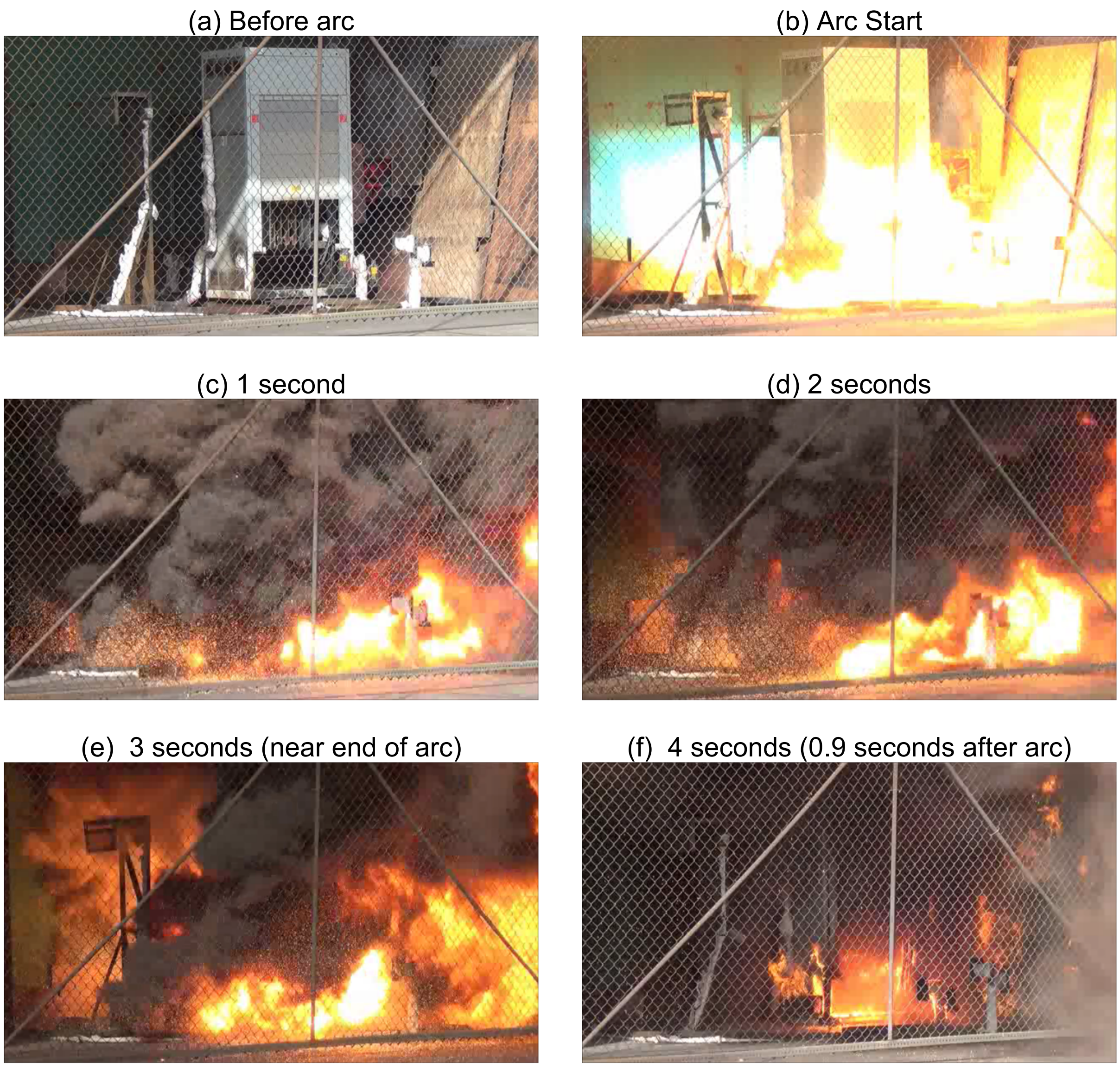


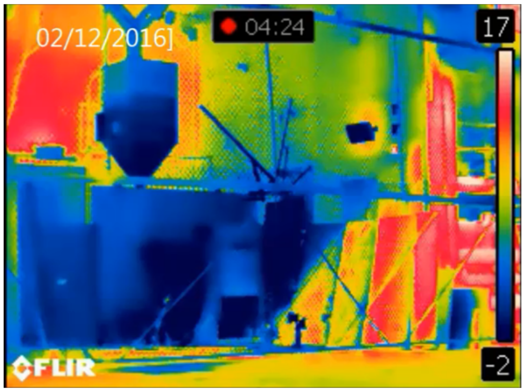
Figure 2.11-1 DP Test 9 Arc

Photos from HD cameras inside the test cell, seen in Figure 2.11-2, indicate the distance the flames traveled and if the flames made contact with the slugs during the tests. Note the flames during the arc reached past the instrumentation stands, which are located 0.91 m in front of and rear of cabinet openings. See Section 4.1 for more discussion. Flames made contacted with S3 through S10.

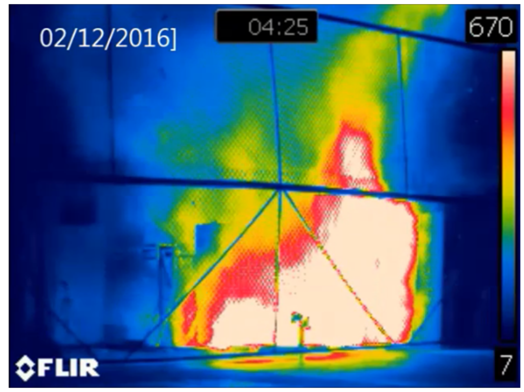
Figure 2.11-2 DP Test 9 Flames During Arc

Images from the IR camera are shown in Figure 2.11-3. The FLIR camera was on auto-scale and the maximum temperature that could be detected (670 ˚C) was within about 1 second that is typical for previous arc tests.

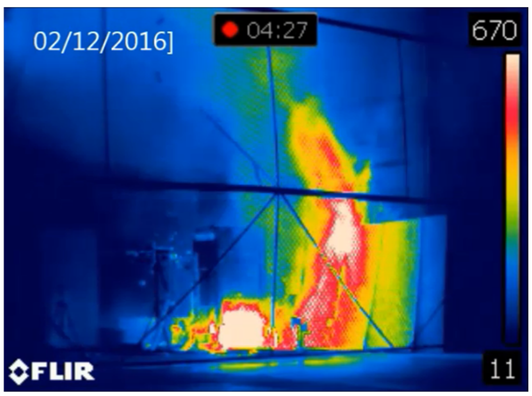
(a). Arc Start



(b) 1.10 seconds - max temperature achieved, 670 ˚C



(c) 2.5 seconds



(d) 3.7 seconds (0.6 seconds after arc)

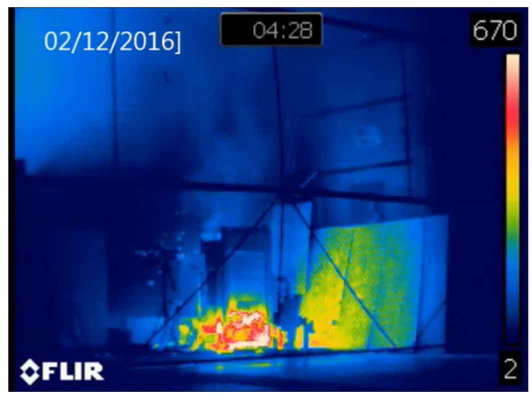


Figure 2.11-3 DP Test 9 Thermal Images

2.11.1 DP Test 9 Exterior Damage

Figure 2.11-4 shows the exterior cabinet damage; unlike previous tests, the test was run without a front screen. There was charring on the cabinet around the openings and soot deposits above the openings. The soot and discoloration were heavy on the rear panel at the location of Target T3R. The lower sides, near the arc, showed discoloration from high temperatures and almost burned through. The panels were deformed, allowing for flames to escape, as shown in Figure 2.11-2(f). The panels were discolored and showed soot deposits on the exterior, as well as metal spatter on the front panel.

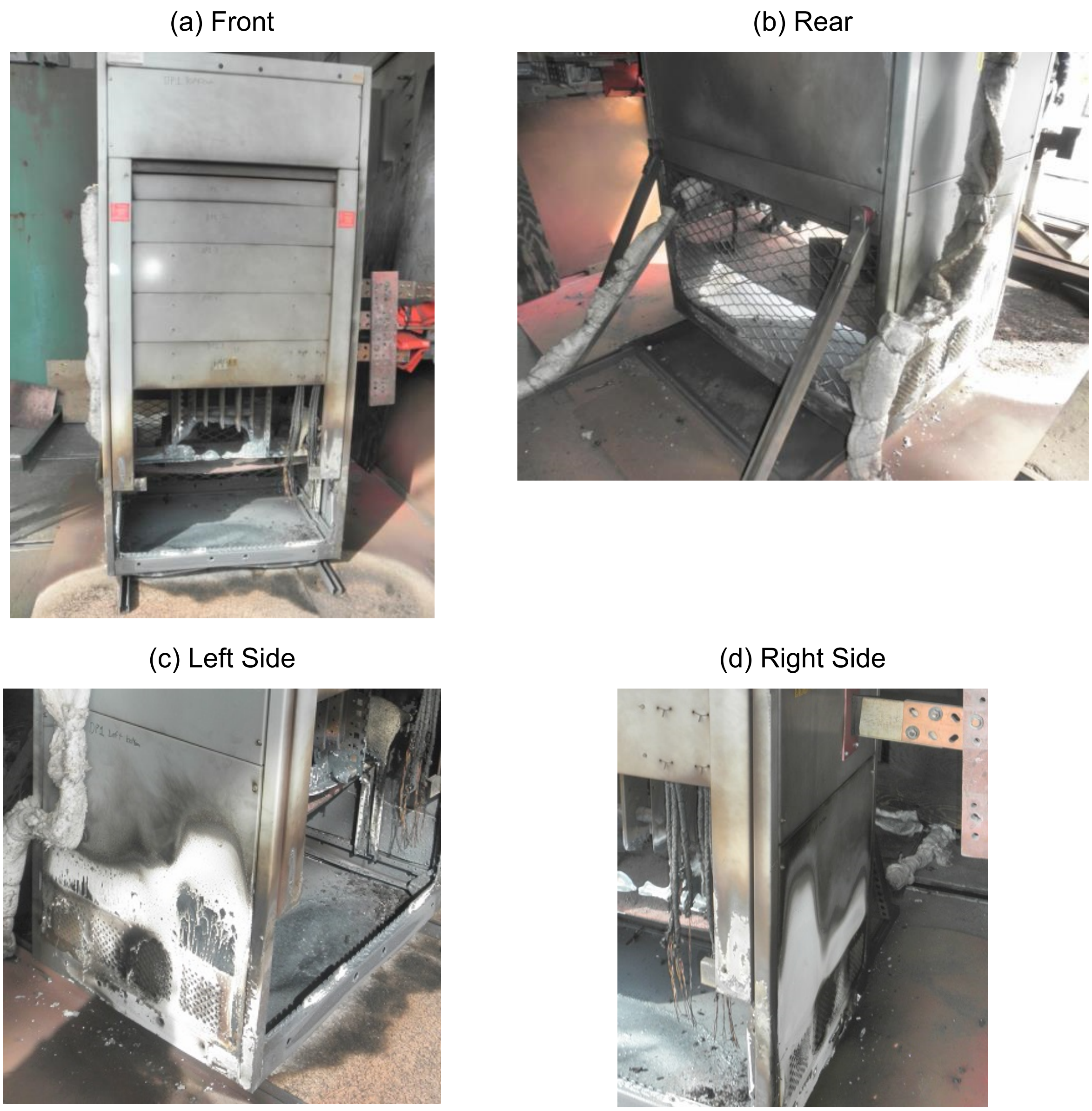


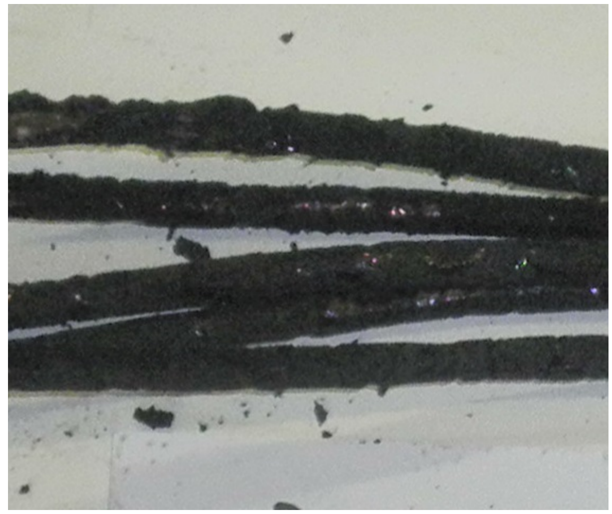
Figure 2.11-4 DP Test 9 Exterior Cabinet Damage

2.11.2 DP Test 9 Interior Damage

The damage to the cables is shown in Figure 2.11-5. The bottom 40 to 50 cm of cable near the arc showed a damage state of “destroyed” and “heavy” higher up based on the damage criteria in Table 1-3 Target Damage Descriptions The insulation was completely consumed in the destroyed part of the cables. Since no ensuing fire was observed, this damage likely occurred during the arc as the arc flames forcefully impacted the cables and stripped the cables. The upper parts of the cables did not burn, suggesting the open panel allowed the arc heat to escape instead of sustaining a cable fire. Resistance measurements were not made after the test because the cable was assumed to have failed by conductor-to-conductor shorting. Additional discussion is in Section 4.2.

(a) In-situ damage

(b) Detail above ends: “heavy” damage



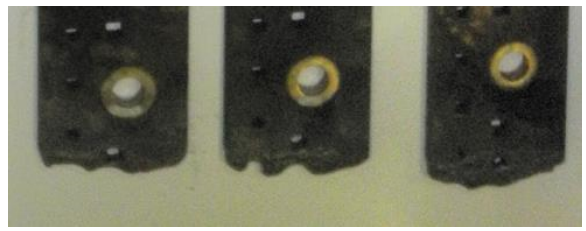
(c) 40-50 cm of cable, at the ends: “destroyed”

Figure 2.11-5 DP Test 9 Interior Cable Damage

DP Test 9 had more vertical bus bar loss than other DP tests in this series and almost burned to the first large hole for the insulator as shown in Figure 2.11-6(b). The damage to the bus bars and plate are shown in Figure 2.11-6. The ends of the copper bus bar were consumed and the steel plate where the arc connected was nearly consumed. The steel from the plates coated several targets and the Unistrut supporting S5 and S6, in front of the cabinet. The mass loss of the copper bus bars was of 4.74 kg and the lengths changed 13-17 cm. The calculation details of the mass loss are in Appendix G.

(a) Rear View Shows Plate Damage

(b) Bus Bar Ends with Insulator Holes



(c) Bus Bars

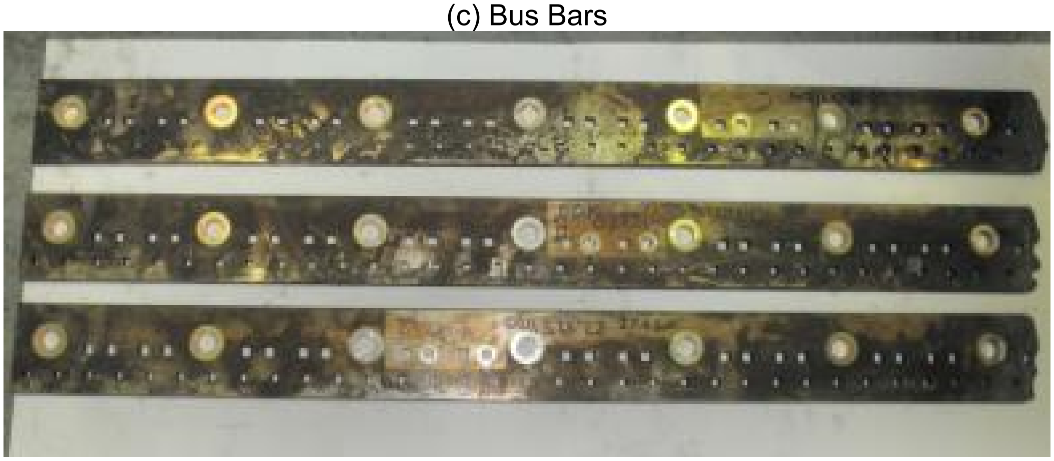


Figure 2.11-6 DP Test 9 Bus Bar Damage

2.11.3 DP Test 9 Target Damage

The results are shown in Figure 2.11-7 and Table 2-11. See Figure 2.6-4 for target locations. Detailed photographs of the target damage are in Appendix F.

The locations of the targets are slightly different in this test than for Tests 7, 7A and 8. However, the locations are generally similar.

Cable Damage:

- Internal cable damage up to T6 (96 cm) similar to Test DP-8. Sooting on other internal targets > 96 cm.
- External cable damage at all targets out to E10 (202 cm) but cables except E3 passed resistance tests.
- A cable on Target E3 failed the resistance check and indicated conductor-to-conductor shorting- a failure. This was the only target cable tested that failed. However, E3 is 167 cm from the arc and also showed low temperature on the label.

Plastic damage:

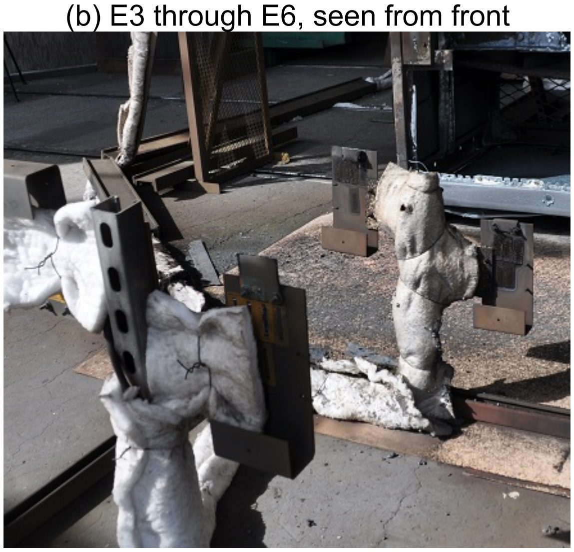
- Internal medium plastic damage out to T5 (75 cm). More damage than Test DP-8 perhaps from longer arc time and more energy.
- External heavy damage out to E7 (144 cm) so more damage than Test DP-8.

Other:

- Metal coating out to E6 (122 cm), Extern E8 (62 cm) also had some coating. Heavy metal coating internally out to 48 cm at arc level.

(a) Targets T1 and T2 from rear

(b) E3 through E6, seen from front



(c) E7 through E10, seen from rear

Figure 2.11-7 DP Test 9 Target Damage and Target Numbers

Table 2-11 DP Test 9 Target Damage

Target (cm)		Damage Description		Label Temp (° C)	Note
		Cable	Plastic		
T1 30	L	6. destroyed	6. destroyed	burnt	all the targets are gone, plate is coated with metal
	R	5. heavy damage	5. heavy damage	burnt	one cable is gone, plastic is bent forward, plate is coated with metal
T2 48	L	6. destroyed	5. heavy damage	burnt	all cables are gone, plastic is bent forward, plate is coated with metal
	R	4. medium damage	4. medium damage	burnt	plate is coated with metal
T3 45	L	4. medium damage	5. heavy damage	burnt	plastic is bent forward
	R	4. medium damage	4. medium damage	burnt	
T4 57	L	5. heavy damage	5. heavy damage	177-182	plastic is bent forward
	R	4. medium damage	4. medium damage	160-166	
T5 74	L	2. sooted	4. medium damage	82-88	plastic is bent forward
	R	3. minor damage	2. sooted	121-127	
T6 96	L	2. sooted	2. sooted	71-77	
	R	3. minor damage	2. sooted	110-116	
T7 126	L	2. sooted	2. sooted	71-77	
	R	2. sooted	2. sooted	77-82	
T8 165	L	2. sooted	2. sooted	43-46	
	R	2. sooted	2. sooted	82-88	
E3 167		4. medium damage	4. medium damage	71-77	left cable is failed by conductor-to-conductor shorting
E4 167		4. medium damage	4. medium damage	burnt	
E5 109		5. heavy damage	5. heavy damage	burnt	plastic is burnt backward target plate is coated with metal
E6 109		5. heavy damage	5. heavy damage	burnt	plastic is burnt forward target plate is coated with metal
E7 144		5. heavy damage	5. heavy damage	burnt	plastic is bent backward
E8 144		4. medium damage	4. medium damage	burnt	
E9 202		4. medium damage	4. medium damage	burnt	
E10 202		4. medium damage	4. medium damage	burnt	

2.11.4 DP Test 9 Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 2.11-8. Slug 8 showed the highest reading of all DP tests. Flames made contact with S3 through S10. Additionally, S6 and S7 may also have had TC connection problems after the arc. It is clear that S10 malfunctioned around 8 to 9 seconds. Table 2-12 shows the flux results based on the method in Section A.1. The flux is an average of the flux during the arc. The table shows the slug calorimeters that were impinged by flames, in which case the flux is not valid.

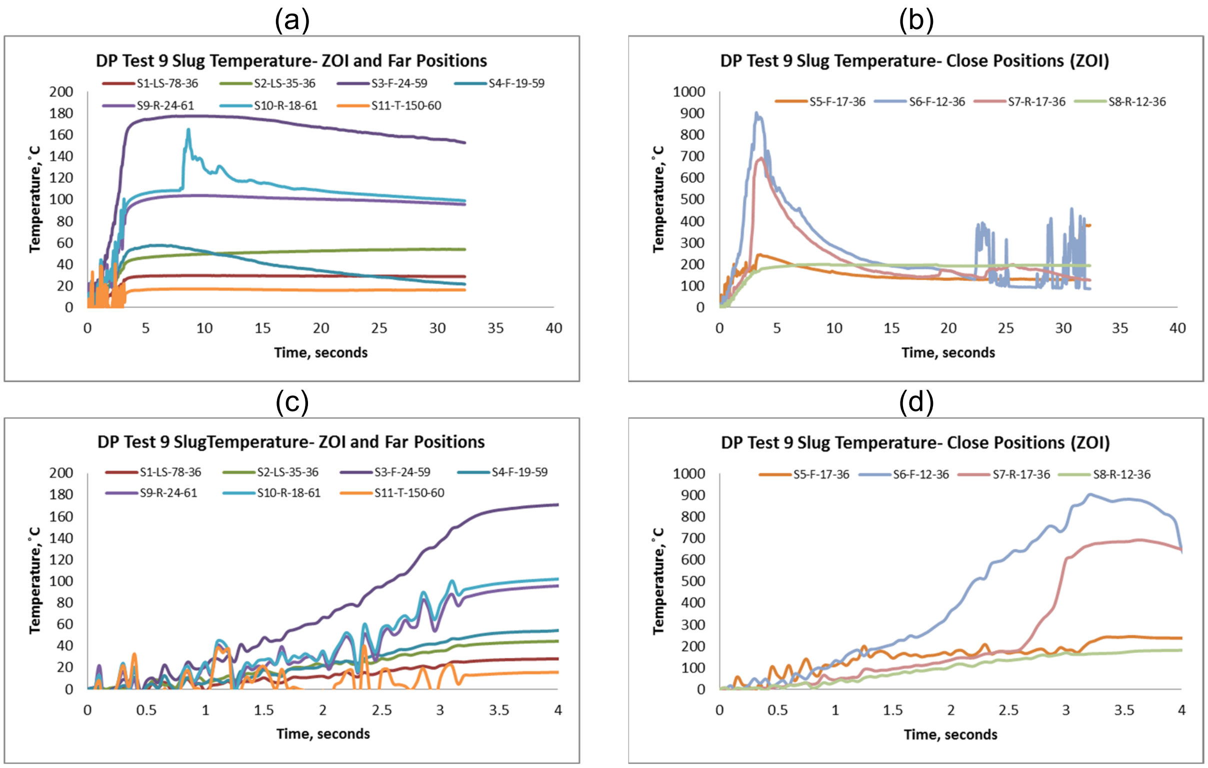


Figure 2.11-8 DP Test 9 Calorimetry Temperature Data

Table 2-12 DP Test 9 Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comment
S1-LS-78-36	26	50.8	30	50.7 kW/m^2
S2-LS-35-36	41	80.7	54	80.7 kW/m^2
S3-F-24-59	160	318.1	177	Flame Contact
S4-F-19-59	49	96.0	58	Flame Contact (1)
S5-F-17-36	235	471.6	381	Flame Contact
S6-F-12-36	886	1,923.4	902	Flame Contact
S7-R-17-36	678	1,420.4	692	Flame Contact
S8-R-12-36	165	328.5	200	Flame Contact
S9-R-24-61	91	177.9	104	Flame Contact
S10-R-18-61	97	190,866	165	Flame Contact
S11-T-150-60	15	28,320	22	28.3 kW/m^2

(1) Although the flux at S4 is less than 100 kW/m^2, it is assumed that there was flame impingement since videos show S3, which is next to S4, clearly being in the flames.

2.11.5 DP Test 9 Temperature Data

The temperatures measured by the TCs on the external targets E7 through E10, which are co-located with slugs of the same numbers, at the rear of the cabinet are seen in the Figure 2.11-9. The temperature increases in TC8 and TC7 after the arc indicates some local burning. TC7 has an error at 12 seconds.

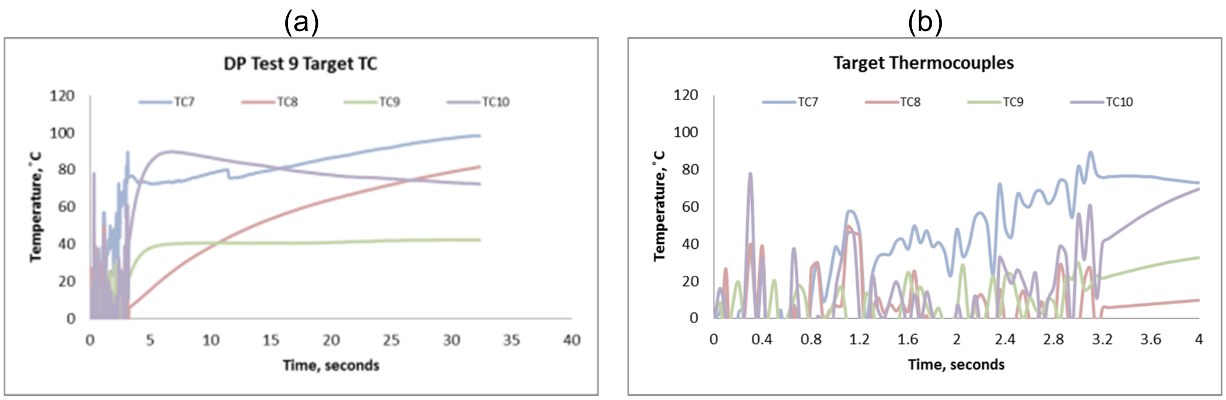


Figure 2.11-9 DP Test 9 Thermocouple Data

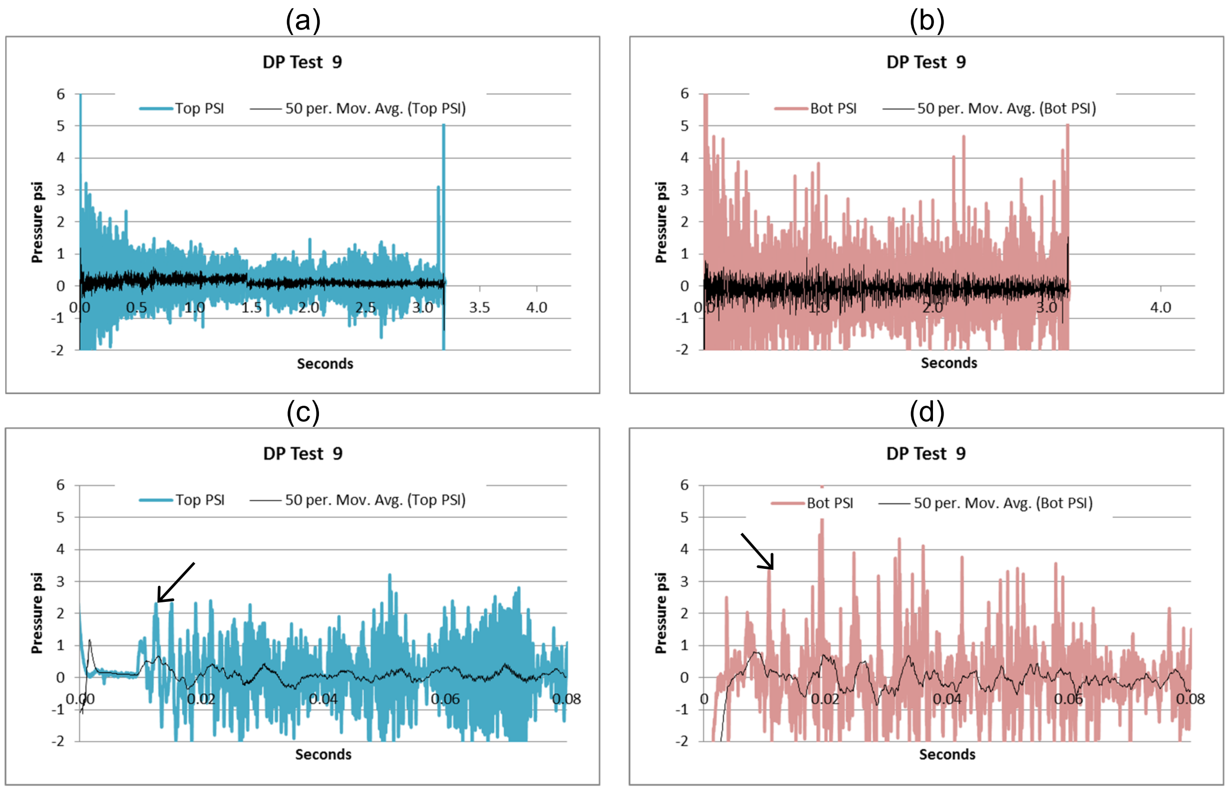
Table 2-13 shows the temperatures for the target TCs at the end of the arc and the maximum during the test. “Label” is the temperature indicated by the Omega temperature label on the back of the target near the TC. The labels were probably burned from the flame contact. The interior labels, T1 through T4 were burned. Temperatures generally decreasing with distance. All of the external labels, up to E10 (202 cm) also burned, except E3 (167 cm) that showed a low temperature (the reason is not known). All external targets had flame contact.

Table 2-13 DP Test 9 TC Results

TC	Arc End (˚C)	Max T (˚C)	Label
TC7	76	98	Burnt
TC8	6	82	Burnt
TC9	24	42	Burnt
TC10	45	90	Burnt

2.11.6 DP Test 9 Pressure Data

The gauge pressures during the arc are seen in Figure 2.11-10. The maximum pressures are indicated by the arrows in the charts. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc. The noise is lower than other DP tests possibly because the metal walls added to the test cell provided shielding to the instrument rack that reduced electrical noise usually present in the test cell. Until 1.4 seconds PRT1 showed a zero drift, and a zero shift afterwards.



Test 9 PRT1 (top)	Test 9 PRT2 (bottom)
13.1 ± 0.5 kPa (1.9 ± 0.07 psi)	11.7 ± 1.4 kPa (1.7 ± 0.2 psi)
@ 0.0146 second	@ 0.0092 second

Figure 2.11-10 DP Test 9 Pressure

2.11.7 DP Test 9 Arc Energy

The total electrical energy was 66.8 MJ and the power was 20 to 25 MW, as shown in Figure 2.11-11. The “Energy” is calculated as volts multiplied current multiplied by the time step and each time step is shown. “Energy Total” is the cumulative sum of the energy in each time step.

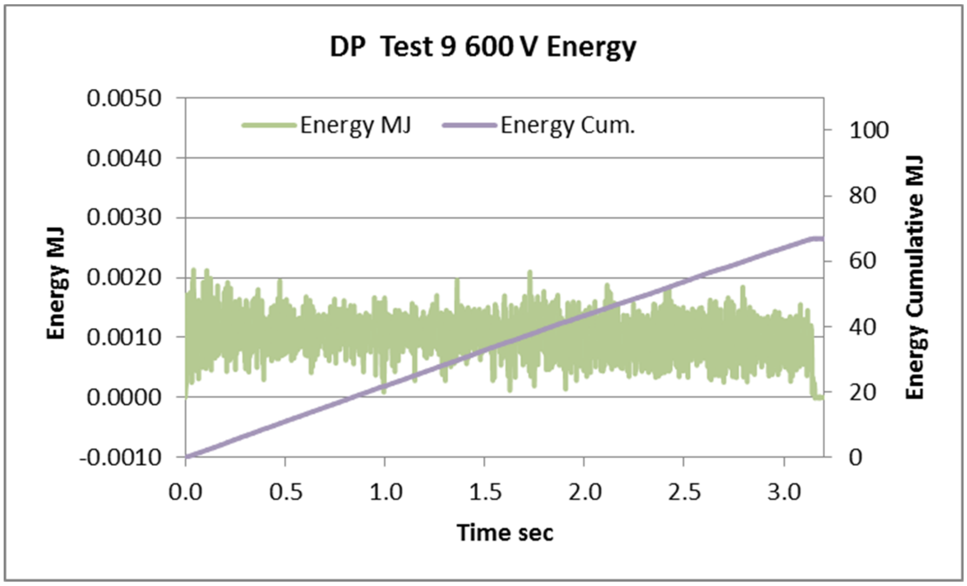


Figure 2.11-11 DP Test 9 Arc Energy

2.12 DP Tests 7 through 9: Summary of Electrical Conditions

The table shows the electrical conditions measured by KEMA.

Table 2-14 DP Tests 7 through 9 Electrical Results

Test	OCV (V)	Phase	Sym (kA)	Peak (kA)	Sym @End (kA)	Curr. Dur. (sec)	Arc Energy (MJ)	Freq @End (Hz)	Phase Arc Volts
7	484	A	45.7	83.4	37.6	0.24	1.48	47.7	A-N 199
		B	45.7	69.7	32.3		1.40		B-N 211
		C	46.2	84.4	32.7		1.44		C-N 217
		AVG	45.9	79.2	34.2		Σ 4.32		AVG L-L 362
7A	484	A	(1)	101.5	(1)	0.22 0.20 (2)	0.25	47.7	A-N 224
		B		52.8			0.15		B-N207
		C		95.5			0.19		C-N 251
		AVG		83.3			Σ 0.59		AVG L-L 394
8	600	A	44.9	97.5	25.3	1.9	15.4	46.6	A-N 255
		B	50.5	98.7	27.8		13.0		B-N 275
		C	42.6	102.6	22.7		11.3		C-N 272
		AVG	46.0	99.6	25.3		Σ 39.7		AVG L-L 463
9	600	A	51.1	100	27.1	3.1	24.8	49.3	A-N 253
		B	40.3	68.0	21.7		22.8		B-N 262
		C	47.1	92.6	19.2		19.2		C-N 264
		AVG	46.2	86.9	22.7		Σ 66.8		AVG L-L 450

Notes:

(1) Symmetric currents could not be calculated due to short arc durations and non-sinusoidal wave form.

(2) Two arcs were initiated 0.022 seconds apart.

Table 2-15 Acronyms and Abbreviations for Electrical Test Results

@End	At the end of the test
AVG	Average
Bot	Bottom
Curr	Current
Dur	Duration
Freq	Frequency
L-L	Line to Line
Max	Maximum
N	Neutral
OCV	Open Circuit Voltage
Press	Pressure
psi	pounds per square inch
Sym	Symmetrical

2.13 DP Tests 7 through 9 Qualitative Summary

The most surprising observation was that DP Test 7 and 7A could not start and sustain an arc in the same conditions as the DP tests in January 2013. Consequently, the OCV was increased to 600 V (from 484 V) for DP Tests 8 and 9. This increased the arc voltage from 394 V to 450 V, and this was adequate to sustain a long duration arc (3 seconds).

1. Ensuing Fires: There were no cable fire ignitions that propagated. Perhaps the heat loss through the open panels prevented a fire from propagating. DP Tests 8 and 9 had conductor to conductor shorts based on post-test resistance measurements and heavy damage probably because the cables were very close to the arc plasma for a long arc duration.

2. Damage: The cabinet damage was consistent with previous tests in Volume 1 [3]. The damage to the steel plate used for the arc attachment that was added in DP Test 9 indicates that an attachment point for the arc is necessary for long durations at low voltage. Heavy metal coating from the steel bar where the arc was attached was within 50 cm of the arc internally.

   a. Bus Bar Damage
      - The bus bars burned as expected with mass losses consistent with the arc energy. The leading edge of the burn had a V-shape and losses were similar to those in previous tests, see Appendix G. The bus bars burned as expected with mass losses consistent with the arc energy.

   b. Cable/Plastic Target Damage:
      - Although internal cable targets were protected by the internal components, internal heavy target cable damage was observed up to 1 m from the arc. samples
      - Medium damage of the external cable targets was observed on all targets up to 2.02 m from the arc.
      - Despite the damage, all of the cables passed the post-test resistance check.

   c. Plastic target damage:
      - Internally, medium (see damage criteria in Section 1.4) plastic damage was seen out to 75 cm from the arc.
      - Externally, heavy damage was seen out to 144 cm from the arc.
      - Plastic melted and partly pyrolized but did not appear to burn freely in any case.

   d. Temperature Labels:
      - Almost all of the temperature labels from the cabinet out to 2.02 m burned during the tests
      - Internally, the labels located greater than 50 cm from the arc survived since the flames escaped through openings in other directions.

3. Calorimetry: It was difficult to make direct flux measurements of the arc because of flame contact. DP Test 9 results are compared to DP Test 3 results in Table 2-16. The energy ratio of DP Test 9 to DP Test 3 was 1.8, and a similar flux ratio would be expected. The fluxes seen at the left side of the cabinet, 1.98 m from the floor and 0.91 m from the side, have similar energy and flux ratios. However, the fluxes seen lower on the left side, namely 1.2 m from the floor in DP Test 3 and 0.89 m from the floor in DP Test 9, are quite different.

The much higher flux for DP Test 9 may be explained by the clear view of the large fire balls released from the front and rear openings of the cabinets (see Figure 2.11-2(c) and (f)). The fire was smaller than in Cabinet DP Test 3; the cabinet was closed and the flames escaped from the vent holes in the bottom of the cabinet. SWGR Test 3 was selected for comparison because it had the most similar conditions to the FY15 tests.

Table 2-16 DP Flux Compared to Previous Tests

Slug Position cm		DP Test 3 (37.1 MJ)		DP Test 9 (66.8 MJ)		Comparison
DP Test 3	DP Test 9	FLUX (kW/m^2)	ΔT (˚C)	FLUX (kW/m^2)	ΔT (˚C)	DP Test 9/ DP Test 3
1.98 m (78 in) high, 0.91 m (36 in) from left side		26.8	9	50.7	26	1.9
1.19 m high 0.91 m from left side	0.89 m high 0.91 m from left side	23.6	8	80.7	41	3.4
1.5 m above cabinet		13.1	5	28.3	15	2.2

4. Temperature: The TC on the external cable/plastic targets in the rear of the cabinets appeared to work but had inconsistent agreement with the temperature labels. Temperatures measured by the more reliable TC's behaved as expected with a maximum temperature of 98 ˚C about 5 seconds after the arc quenched for DP Test 9 for measurements closest to the arc (see Figure 2.11-9). In all tests the maximum temperatures occurred within 5 seconds after the arc quenched. Test 7 had a maximum temperature of only 10 ˚C because the arc duration was short and the energy was low. Note: The temperature data was not available for DP Test 8.

5. Pressure Data: The measured pressures were in the same range as previous DP tests. This was somewhat surprising because the cabinets did not have open front and rear panels in the previous tests. This suggests the initial pressure measured in these tests is from the initial shock wave emanating from the arc start up because the shock strength would not be greatly impacted by openings in the cabinets.

6. Arc Energy and Power: Arc energies from DP Test 7 and 7A were very small. The energy from DP Test 8 was consistent with DP Test 3, which had similar duration and electrical characteristics. Arc energy and power were higher in DP Tests 8 and 9 that had higher arc voltage as expected.

7. Arc Voltage: Arc voltage slowly increased in all tests that supports the theory that the arc gap increases as the bus material is consumed and the arc voltage increases.

8. Arc Observations: The arc was successfully viewed in DP Test 9 using the HS camera and IR filters as discussed in Section A.5. The arcs in Figure 2.13-1 sweep out around the arc point and the attachment point at 60 hz (see Section 3.11 for 60 hz calculation). This video clarifies that the arc is between the bus bars and the cabinet steel cross bar and not bus-to-bus as commonly believed. The steel bar where the arc from each phase attaches completes the 3-phase circuit. The figure shows the frame numbers for the videos and the frames are 1,600 μs.

9. External Conditions: DP Test 9 had the highest energy and the maximum slug calorimeter temperature for S6 at 0.91 m in front of the cabinet (close to the NUREG/CR-6850 postulated ZOI) that was 902℃ that decreased to less than 200℃ in about 15 seconds (see Figure 2.11-8). As discussed in Section 4.1, the maximum distance for metal sputtering was 3.3 m from the arc. Based on video reviews the flame extended to 1.9 m from the front of the cabinet.

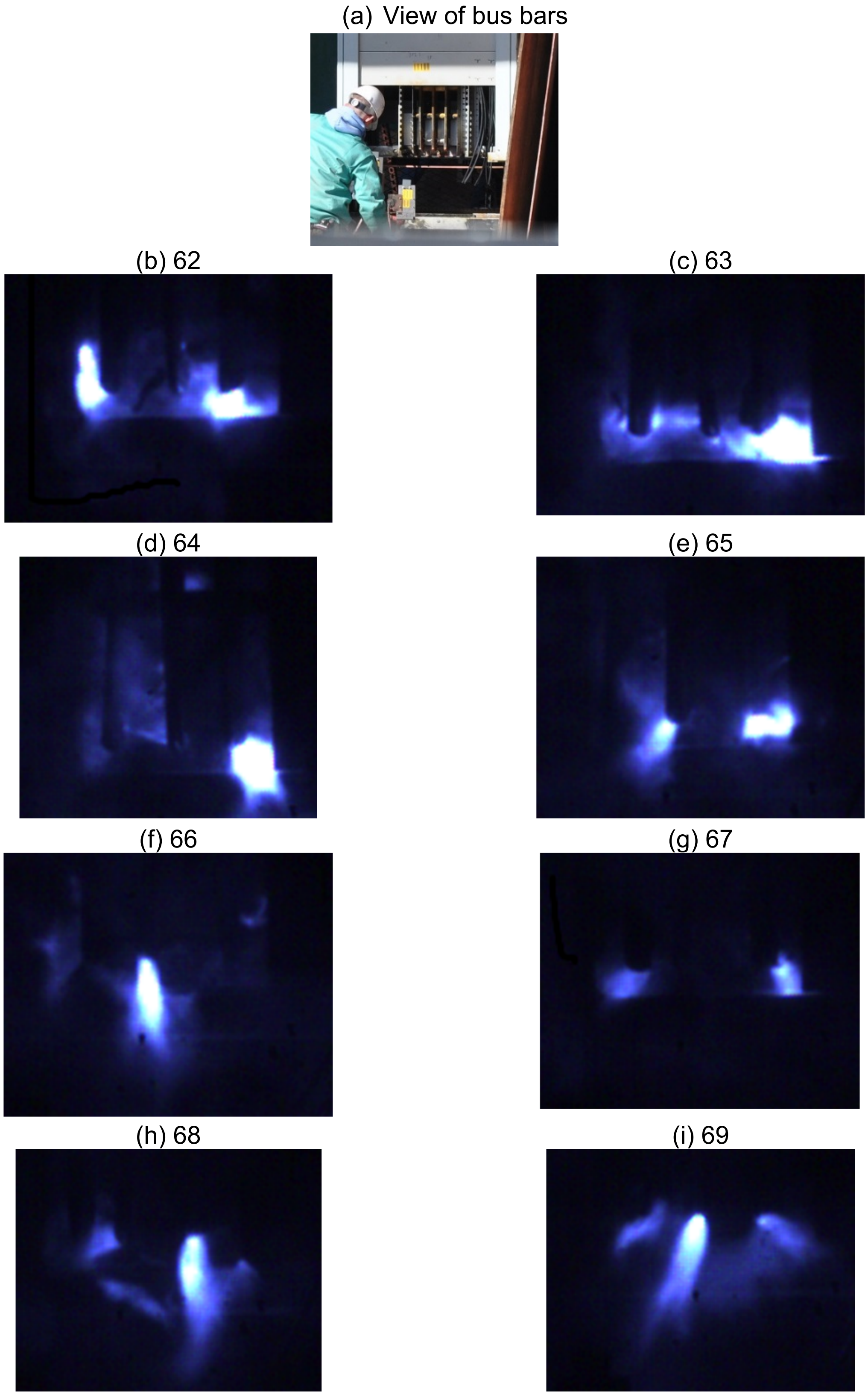


Figure 2.13-1 DP Test 9 Arc Observation by HS Camera Frame

3 HIGH VOLTAGE SWGR HEAF TESTING

3.1 SWGR Tests 7 through 10 Overview

Four (4) tests were conducted for individual GE M-36 Magneblast SWGR cabinet similar to the tests in Volume 1 [3]. The tests in this report are named SWGR-7, SWGR-8, SWGR-9, and SWGR-10 to follow the previous six SWGR tests. The key test parameters are in Table 3-1. The parameters were revised during the test by S/NRA/R based on results as this series of tests progressed as discussed in Section 3.3.

3.2 SWGR Tests 7 through 10 Summary of Results

The key test parameters and results are in the table below. The tests were single arc events; the target test voltage was nominally 6.9 kV and the target test current was 23 kA (symmetrical, sym.).

Table 3-1 SWGR Tests 7 through 10 Summary of Results

Test	Volt (kV) (1) Curr (kA) (2)	Test Peak Current (kA) (3)	Arc Duration (sec) (4)	Arc Energy (MJ)	Internal Max Press (5) (kPa)	Ext Max Flux (kW/m^2)	Key Damage Observations
7	7.1/0.897 25.8/23.1	68.4	2.80 (2.8)	88.2 30	4.1 ± 0.07	61.3 (6)	Heavy scorching but no cable fire.
8	7.1/0.816 (7) 25.7/22.8	67.4	3.47 (3.5)	89.1 22-32	4.0 ± 0.2	81.7 (8)	Heavy scorching but no cable fire.
9	7.1/0.966 25.5/23.6	71.7	4.06 (4.0)	137.3 30-35	3.1 ± 0.07	42.3 (9)	Heavy scorching but no cable fire.
10	7.1/0.949 25.6/25.6	68.2	0.804 (0.8)	24.0 30 (10)	4.8 ± 0.07 (11)	80.4 (12)	Heavy scorching but no cable fire.

Notes:

(1) The voltage is shown as the target voltage / arc Line-to- Line (L-L) voltage (L-L is the “arc voltage”).

(2) The symmetric arc current slowly drops during the test as the arc impedance increases. This shows the test start current/ test end current, which is the average over all 3 phases.

(3) This is the peak current for any phase or time, usually the asymmetric current at the start.

(4) The actual test duration is shown, with the target duration in parentheses.

(5) This is the maximum pressure at the PRT1 position; in Tests 9 and 10, PRT1 and PRT2 pressures were the same.

(6) Maximum flux was at 0.91 m from right side, and 1.8 m high (S1). Flux 1.5 m above cabinet (S11) was 17.0 kW/m^2, much lower than previous SWGR tests in Volume 1 where the S11 position was the maximum. Several slugs had flame contact.

Table 3-1 SWGR Tests 7 through 10 Summary of Results (continued)

(7) SWGR ground bar positioned was changed to 15 cm (was 0.3 m) from end of bus bar to reduce arc voltage

(8) Maximum flux was at 0.91 m from the right side, and 0.91 m high (S2). Flux 1.5 m above cabinet (S11) was 29.9 kW/m^2, much lower than previous SWGR tests. Several slugs had flame contact.

(9) Maximum flux was at 0.91 m from the right side, and 0.91 m high (S2). Flux 1.5 m above cabinet (S11) was 41.2 kW/m^2, much lower than previous SWGR tests. Several slugs had flame contact.

(10) Power varied from 20 to 40 MW; 30 MW was nominal average.

(11) Door opened so pressure is for an open cabinet.

(12) The maximum was 1.5 m above the cabinet (S11). On the right side at 0.91 m (the postulated ZOI in NUREG/CR-6850), S1 was 20.5 kW/m2 and S2 was 23.5 kW/m^2. No flux measured on the rear; cabinet was closed.

The observations for the SWGR tests are in Section 3.14 and Chapter 4. The test results were mostly as expected but surprisingly only 1 cable sample failed (based on post test conductor-conductor resistance measurements). Also, the SWGR voltage was different than anticipated because the basis for the voltage prediction in the test plan from the previous tests was based on the wrong arc length, see Section 3.3.

3.3 SWGR Tests 7 through 10 Current and Voltage

The original S/NRA/R specification for these tests was 7 kV and 23.5 kA, similar to the June 2013 SWGR tests, for a minimum of 4 seconds. However, the target arc parameters were changed to reduce the total energy targets as shown in Table 3-2.

Table 3-2 FY15 (February 2016) SWGR Tests

Test Cabinet ventilation	Target V_{arc}, I, Duration, energy	Purpose	Comment/Results
SWGR7 High Vent (1)	600 V 29.5 kA 55 MJ 2.8 s	• Capture IR images of the arc to check arc position. • Confirm arc voltage is 600 V • Measure maximum external fluxes. • Test cable/plastic ignition using targets and cable bundles. • Does voltage increase with duration because bus bar is vaporized that increases the arc length.	• IR images were unsuccessful. • Arc voltage higher than expected for the ground bar position. (4) • Screens on the front and back to observe the arc position and provide maximum external flux. • Target data obtained. • Arc voltage higher than expected (897 vs. 600 V) so energy was 88.2 vs. 55 MJ.
SWGR8 High Vent (1)	600 V 29.5 kA 90 MJ 3.5 s	• Make IR arc images of the arc to check arc position. • Test cable/plastic ignition using targets and cable bundles. • Test if voltage increases with duration as materials are vaporized and arc length increases.	• IR images successful. • Target data obtained. • Arc voltage decreased in SWGR 8, as expected with shorter arc gap but the decrease was much smaller than expected. (4)
SWGR9 High Vent (1)	600 V 29.5 kA >110 MJ 4 s		
SWGR10 Low Vent (2)	966 V 23.5 kA 25 MJ 0.8 s (3)	• To see if 25 MJ is enough for ensuing fire in SWGR cabinet by igniting the cables in the front at the top. • Test cable/plastic ignition using targets and cable bundles.	• The cables were heavily charred but did not ignite probably because the door opened and the arc heat escaped. • The target arc duration was reduced based on 966 V for SWGR Test 9: 24.02 MJ arc energy was achieved.

Notes:

(1) "High vent" had screens on the front and back panels as shown in Section 3.4.

(2) "Low vent" was similar to the previous SWGR tests; only the top vent is open. No video of the arc was possible. The exterior flux measurements are outside the SWGR panels and door and not directly from the arc but from exterior wall radiation

(3) S/NRA/R reduced the arc duration to achieve the target 25 MJ and was successful.

(4) The initial ground bar position was a rough estimate to get 600 V based on previous SWGR results. However, the voltage was higher than expected because the arc length in the previous SWGR tests in Volume 1 used as the basis to set the voltage was probably shorter than assumed. The gap was reduced by 15 cm for Tests 8 as a one-off trial. See separate discussion.

Previous SWGR Test 2 (see Volume 1 [3]) had a long duration and high energy that was good for planning these tests, as shown in Figure 3.3-1. SWGR Test 2 was conducted at 7.1 kV and 23.5 kA for 3 seconds, resulting in a total energy of 58.2 MJ and 608 V arc voltage. So, for example, a 2.8 second arc should provide the 55 MJ target in SWGR Test 7 based on the energy vs duration line in Figure 3.3-1 assuming the arc voltage was around 600 volts (this assumption was proven wrong as discussed below).

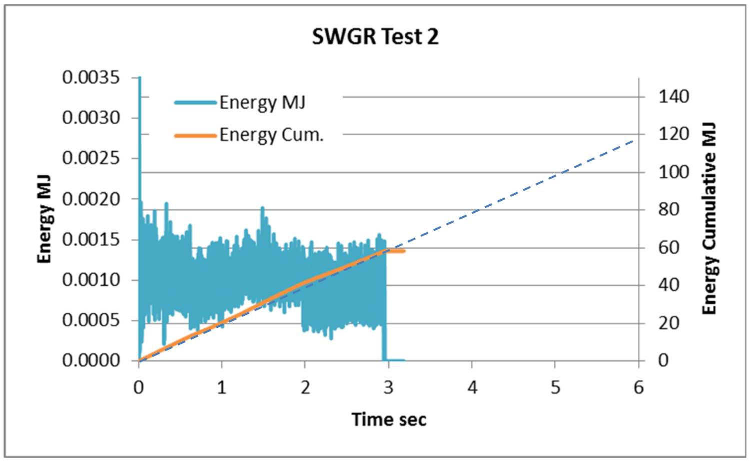


Figure 3.3-1 2016 Test Design Basis: Arc Energy for Previous SWGR Test 2

However, there was an issue using Figure 3.3-1 for planning because the expected arc voltages in the FY15 tests were higher than the 608 V seen in SWGR Test 2. The arc voltage for the FY15 tests was set by the steel ground bar position that formed the arc gap between the ends of the copper bus bars and the cabinet. The 30 cm arc gap for these FY15 tests was based on the assumption that the arc gap in SWGR Test 2 was 32 cm between the ends of the bus bars and the bottom of the bus compartment as shown in Figure 3.3-2. However, the FY15 results indicate the gap in Test 2 was probably shorter because the arc voltages were much higher than expected.

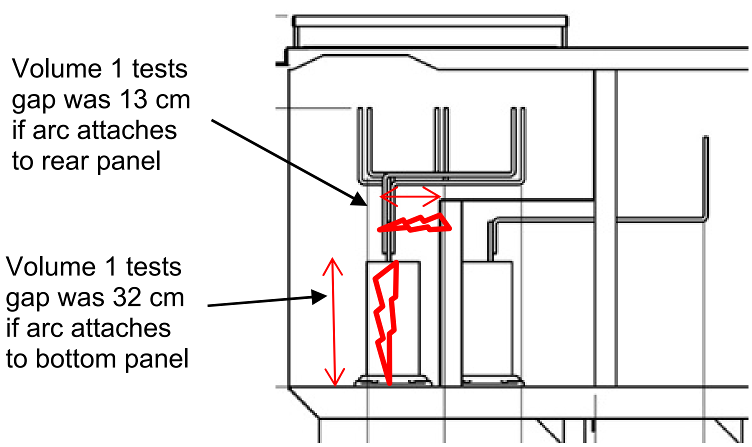


Figure 3.3-2 Arc Gaps for SWGR Tests 1 through 3 and Tests 4 through 6, Arc 1

In previous tests 1 through 3, the arc was assumed to attach to the bottom or to the back panel of the compartment. The starting arc gaps were:

Arc attached to bottom: 32 cm, or
Arc attached to back panel: 13 cm

The initial arc gap of 30 cm for the FY15 tests in Figure 3.3-3 was based on the arc attached from the end of the bus bars to the ground bar that would cause an arc voltage of about 600 V. The 30 cm accounts for about 4 cm of bus bar melting so the gap after the arc is 28 cm. The specified start gap is the average of the starting gap 32 cm and the final gap 28 cm or 30 cm.

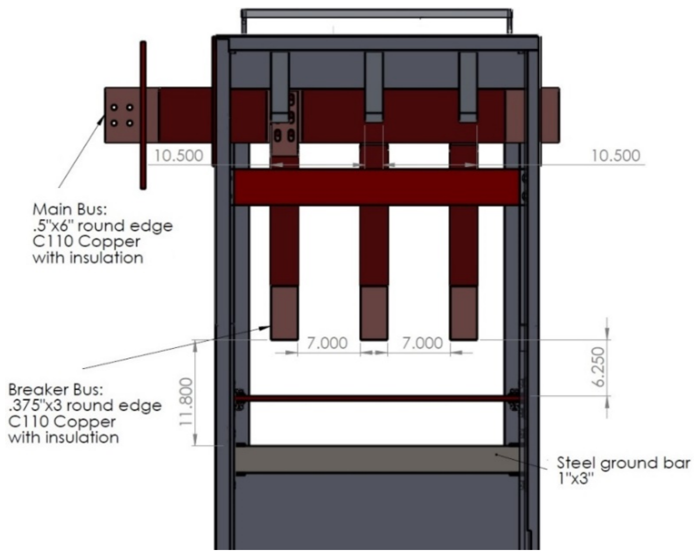


Figure 3.3-3 Initial 30 cm Arc Gap for FY15 SWGR Test

In SWGR Tests 7 through 10, the voltage was higher than the expected 600 V. (Note: in SWGR Test 7 the arc attached to the cabinet walls and not the ground bar, thus the arc gap was uncertain; the arc voltage was lower than SWGR Tests 8 through 10). This implies that the assumption of a 32 cm gap to the bottom in previous tests was wrong. In the previous tests, the arc probably attached to the back panel and sidewalls where the gap was perhaps 13 cm. But it is not certain where the arc attached in previous tests. In the end, it appears the observed arc voltages for the previous SWGR tests were not a good basis to set the arc voltages for the FY15 tests and the arc voltages and energies were much higher than the targets.

Another observation is that reducing the arc gap by shortening the distance from the ground bar to the ends of the bus bars by 15 cm for Test 8 (see Note (4) in Table 3-1) did not cause a large reduction in the arc voltage as expected. The reason is not clear. Perhaps the presumed arc path from the ends of the bus bars to the ground bar is not the actual path to complete the arc circuit. Perhaps the circuit is mainly completed in the air around the bus bars that does not change the arc length and voltage as the bus bar to ground bar gap is changed.

Notice that using the energy and arc voltage results of Test 9 to set the arc duration in Test 10 was successful in achieving the target 25 MJ. This shows that if the arc voltage of a particular configuration is known, one can predict the arc total energy based on the duration only, if the current is the same as in this case.

3.4 SWGR Tests 7 through 10 Cabinet Configuration

A modified GE SWGR M36 cabinet, as in previous tests, was used for the "box" for the HV tests, as seen in Figure 3.4-1. The key characteristics for the cabinets in this test series were:

- A single SWGR cabinet, 91 cm x 218 cm, was used.
- Most internal panels were removed to:
  - provide a line-of-sight from the arc to the cable/plastic targets and cable bundle, and
  - encourage the arc to stay near the bus bars and not attach to the cabinet (this should be more repeatable than the previous tests).
- A breaker was not needed
- There was a top vent in the cabinet (similar to the Onagawa cabinets).
- The front door and back panel had openings with a screen so the arc could be observed for the "high ventilation" case for SWGR Tests 7, 9, and 8. These were closed with sheet metal for the "low ventilation" case for Test 10.
- There is a red board Instrument Mount Plate in the rear for the cable/plastic targets.
- The arc is assumed to be from the ends of the bus bars to the ground bar.

The SWGR bus bar configuration is shown in Figure 3.4-2. Each phase has two copper bus bars that are called "front" and "rear" and have a 0.375-inch space between them. The phases are A, B and C from left to right. The bus bars are 6.35 mm thick and 76.2 mm wide. Bus bars did not need to be supported by bus bar insulators/bushings. The bus bars have polymer insulation on them but this was removed before weighing after the test. The bus bar weight from the manufacturer was measured before the polymer insulation was installed.

The internal vertical bus bars were located so that the slugs were 28 cm closer to the arc than previous tests in Volume 1 [03]. The arc attached to the sidewall in SWGR Test 7. To prevent this, red board insulation was added to the inside of the cabinet walls near the bus bars for SWGR Tests 8- through 10.

The arcs were at a similar position to previous tests as shown in Figure 3.2-2. However, the vertical bus bars were longer in the FY15 tests so the arc was near the vertical center of the cabinet. The arc positions were confirmed by video cameras with an IR filter.

The cable bundle combustible loads were smaller than in previous tests because the 2016 tests investigated cable ignition and not larger, realistic ensuing fires. The combustible load cables are shown in Figure 3.4-1. There were three bundles of five cables per bundle CV-2 cable (15 cables total) from Sumiden- Hitachi LTD (HS&T) that were 0.91 m long and mounted in the top, front of the SWGR on hooks.

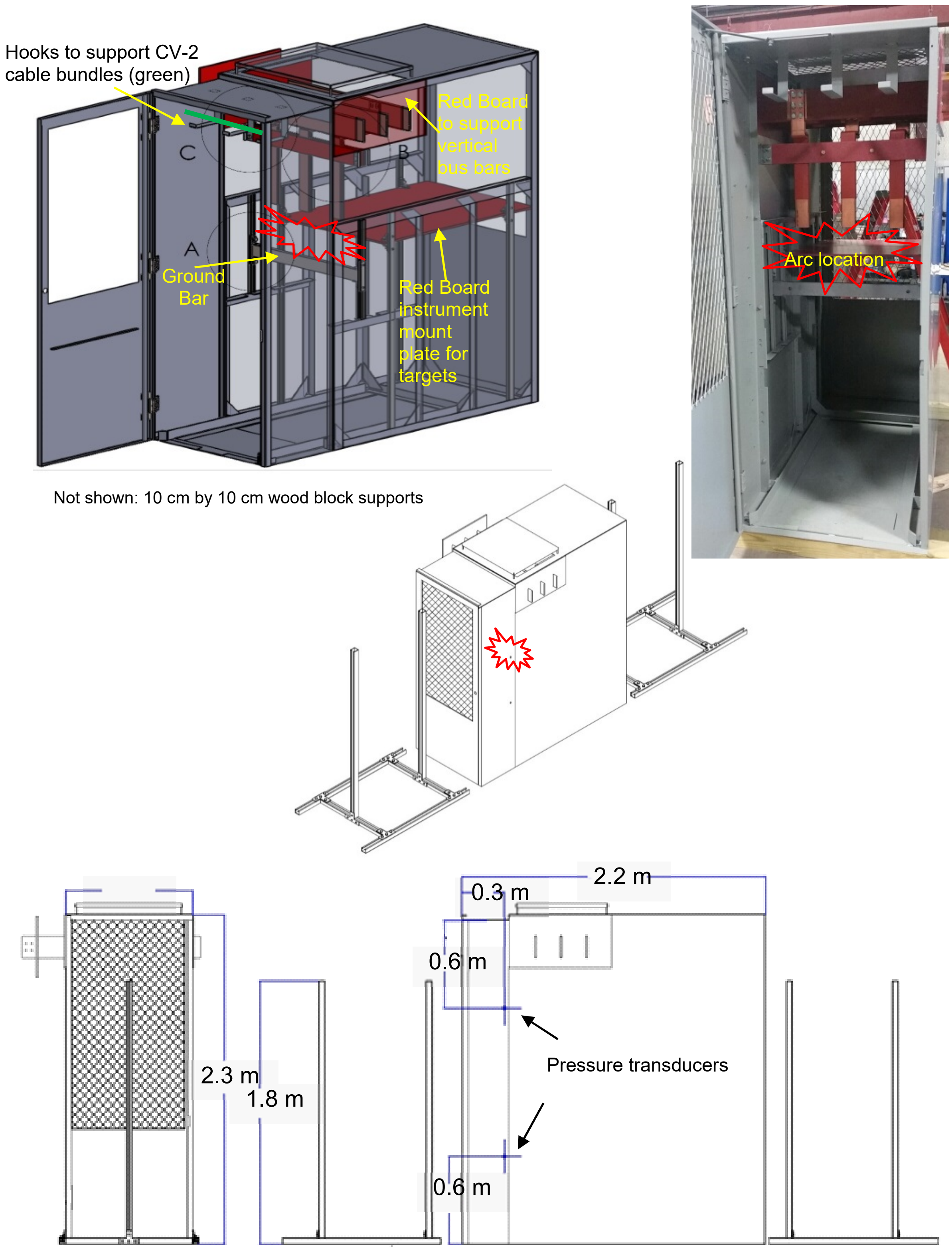
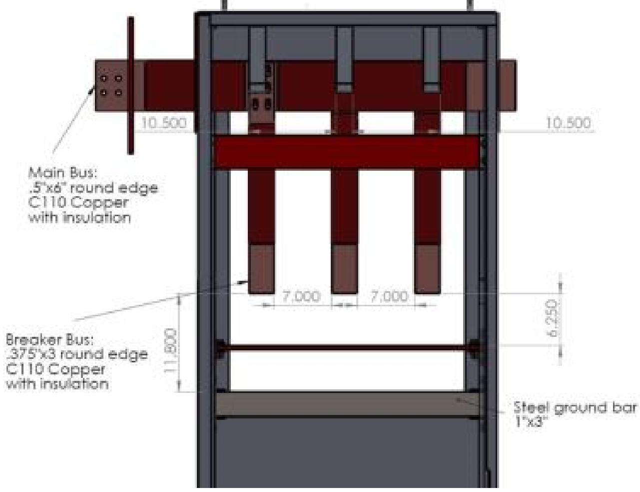
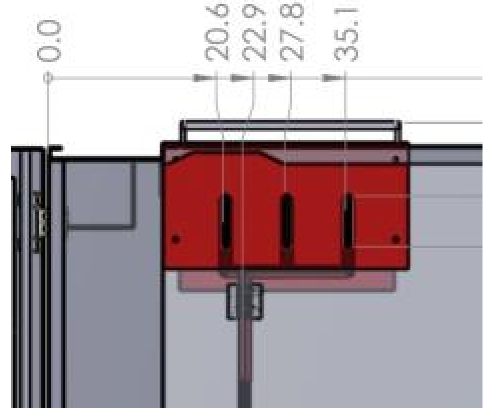


Figure 3.4-1 SWGR Cabinet Test Configuration

(a) Bus bar and Ground Bar positions



(b) Bus Bars and Top Vent with Plate



® Looking from front

Figure 3.4-2 SWGR Bus Bar and Top Vent Configuration

3.5 <u>SWGR Tests 7 through 10 Heat Flux Instrumentation</u>

Slug calorimeter (slug, S) and TC locations are seen in Figure 3.5-1, and described in Table 3-3.
Figure 3.5-2 shows the slug calorimeter locations at the nominal positions. Slug calorimeters 3 through 6 were moved to the right to provide a view for the HS camera to view the arc. Some adjustments were also made for SWGR Tests 9 and 10.

Slugs 1 and 2 have the same positions as in previous SWGR Tests 2 and 3 in Volume [03] so that the results can be compared. The other positions have two slug calorimeters at nominally the same location to average the measurements. The slugs that view the arc (S3 through S10) are positioned at the height of the arc. Slug S11 is located 152 cm from the top of the cabinet to compare to results in previous tests. Note: the naming scheme was changed from previous tests to include the distance from the cabinet since some have moved.

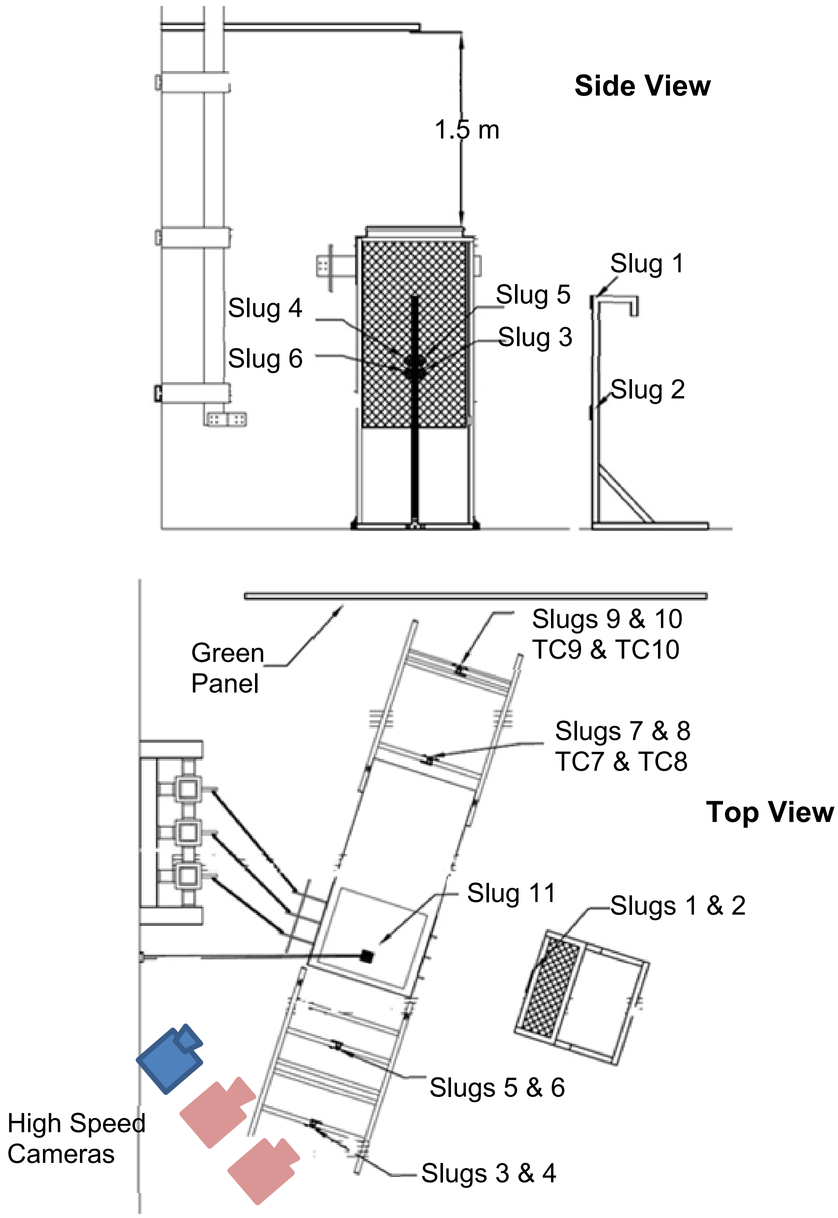


Figure 3.5-1 SWGR Test Instrumentation

(a) Right Side Slugs

(b) Top Slug, S11

Figure 3.5-2 SWGR Tests 7 through 10 Slug Calorimeter (and External Target) Locations

Table 3-3 Calorimeter Locations SWGR Tests 7 through 10

Test	Slug	Height cm (in)	Position	From cabinet (1) cm (in)	Slug Name	From Arc cm
SWGR 7	S1	178 (70)	Right Side (RS)	91 (36)	S1-RS-70-36	139
	S2	91 (36)	Right Side (RS)	91 (36)	S2-RS-36-36	134
	S3	133 (53)	Front (F)	91 (36)	S3-F-53-36	155
	S4	152 (60)	Front (F)	91 (36)	S4-F-60-36	155
	S5	104 (41)	Front (F)	22 (8.5)	S5-F-41-8.5	91
	S6	170 (67)	Front (F)	22 (8.5)	S6-F-67-8.5	91
	S7	149 (59)	Rear (R)	15 (6)	S7-R-59-6	155
	S8	163(64)	Rear (R)	15 (6)	S8-R-64-6	155
	S9	141 (56)	Rear (R)	91 (36)	S9-R-56-36	231
	S10	166 (66)	Rear (R)	91 (36)	S10-R-66-36	231
	S11	381 (150)	Top (T)	152 (60)	S11-T-150-60	254
SWGR 8	S1	178 (70)	Right Side (RS)	91 (36)	S1-RS-70-36	139
	S2	91 (36)	Right Side (RS)	91 (36)	S2-RS-35-36	134
	S3	133 (53)	Front (F)	91 (36)	S3-F-53-36	155
	S4	152 (60)	Front (F)	91 (36)	S4-F-60-36	155
	S5	104 (41)	Front (F)	22 (8.5)	S5-F-41-8.5	91
	S6	170 (67)	Front (F)	22 (8.5)	S6-F-67-8.5	91
	S7	149 (59)	Rear (R)	15 (6)	S7-R-59-6	155
	S8	163 (64)	Rear (R)	15 (6)	S8-R-64-6	155
	S9	141 (56)	Rear (R)	91 (36)	S9-R-56-36	231
	S10	166 (66)	Rear (R)	91 (36)	S10-R-66-36	231
	S11	381 (150)	Top (T)	152 (60)	S11-T-150-60	254
SWGR 9	S1	178 (70)	Right Side (RS)	91 (36)	S1-RS-70-36	139
	S2	91 (36)	Right Side (RS)	91 (36)	S2-RS-35-36	134
	S3	133 (53)	Front (F)	178 (70)	S3-F-53-70	239
	S4	152 (60)	Front (F)	71 (180)	S4-F-60-71	239
	S5	104 (41)	Front (F)	107 (42)	S5-F-41-42	160
	S6	170 (67)	Front (F)	107 (42)	S6-F-67-42	158
	S7	149 (59)	Rear (R)	71 (28)	S7-R-59-28	211
	S8	163 (64)	Rear (R)	71 (28)	S8-R-64-28	211
	S9	141 (56)	Rear (R)	147 (58)	S9-R-56-58	287
	S10	166 (66)	Rear (R)	147 (58)	S10-R-66-58	287
	S11	381 (150)	Top (T)	152 (60)	S11-T-150-60	254

Table 3-3 Calorimeter Locations SWGR Tests 7 through 10 (continued)

Test	Slug	Height cm (in)	Position	From cabinet (1) cm (in)	Slug Name	From Arc cm
SWGR 10	S1	178 (70)	Right Side (RS)	91 (36)	S1-RS-70-36	139
	S2	91 (36)	Right Side (RS)	91 (36)	S2-RS-35-36	134
	S3	133 (53)	Front (F)	91 (36)	S3-F-53-36	150
	S4	152 (60)	Front (F)	91 (36)	S4-F-60-36	150
	S5	104 (41)	Front (F)	22 (8.5)	S5-F-41-8.5	184
	S6	170 (67)	Front (F)	22 (8.5)	S6-F-67-8.5	184
	S7	149 (59)	Rear (R)	71 (28)	S7-R-59-28	211
	S8	163 (64)	Rear (R)	71 (28)	S8-R-64-28	211
	S9	141 (56)	Rear (R)	147 (58)	S9-R-56-58	287
	S10	166 (66)	Rear (R)	147 (58)	S10-R-66-58	287
	S11	381 (150)	Top (T)	152 (60)	S11-T-150-60	254

(1) Slug positions were adjusted during the tests so the height and distance from arc are different than in the original test plan. These are the final measured positions.

3.6 SWGR Tests 7 through 10 Targets

Metal targets with cable samples and plastic samples (targets), described in Appendix E, are placed at internal and external locations to observe cable and plastic damage at various distances from the arc.

3.6.1 External Targets

The external targets are co-located with the slug calorimeters. External targets, denoted by "E#," are co-located with calorimeters S3 through S10, and are numbered to match the slug number, e.g., the target located with S3 is named "E3." Targets are mounted at different angles, but all face directly toward the center of the arcs. Temperature measurements on the target surfaces are taken with temperature labels (see 1.1.1.1.1 Appendix Afor details). For confirmation of readings on the labels, thermocouples (TC) are also placed on targets E7 through E10. Figure 3.5-2, Figure 3.6-1, and Table 3-3 show the external slug calorimeter locations at nominal positions. The calorimeter positions in the front and rear of the cabinet also have cable/plastic targets.

(a) E3 through E6 Front – offset to right in SWGR Tests 7-9 (Looking front to rear)

(b) E7 through E8 Rear (Looking rear to front)

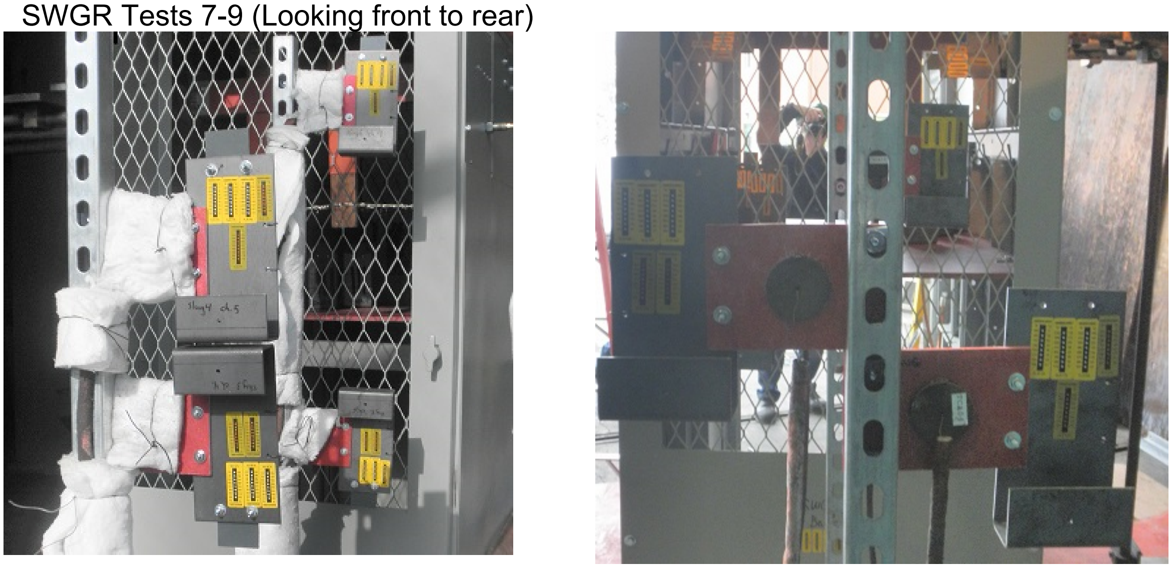


Figure 3.6-1 SWGR Tests Exterior Target Details

3.6.2 Internal Targets

Targets were placed inside the cabinets in view of the arc to capture the maximum radiative heat flux. The targets closer to the arc do not block the view of the targets further from the arc. Targets are at different angles to face directly toward the center of the arcs. Figure 3.6-2 shows the internal cable/plastic targets on the target platform, the bus bars with a shorting wire, and the ground bar.at the nominal 30 cm from the end of the bus bars. The ground bar is connected to the cabinet by large braided copper cables.

The locations for the internal cable/plastic targets are shown in Figure 3.6-3, Figure 3.6-4, and Table 3-4. The targets are placed closer together near the arc where the flux is changing rapidly with distance. The targets are placed so the targets closer to the arc do not block the view of the targets further from the arc. The targets are described in 1.1.1.1.1 Appendix E.

Figure 3.6-2 SWGR Tests 7 through 10 Bus Bars and Internal Cable/Plastic Targets

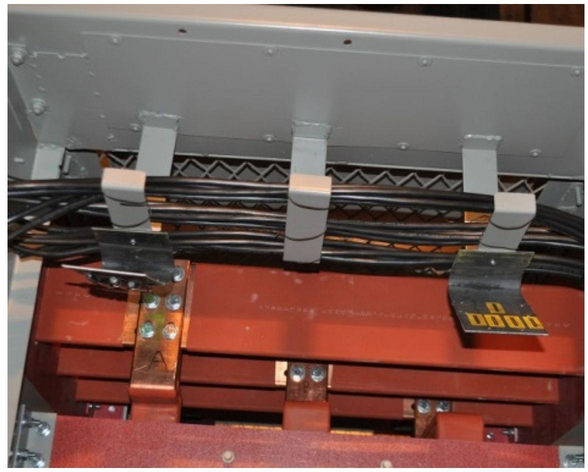
Table 3-4 SWGR Internal Cable/Plastic Target Locations

Target Install (Photo)(1)	To Cabinet Centerline cm	To Arc Center cm	Height, from floor cm	Comment
1L, 1R (3L, 3R)	±40	47.5	127	On instrument mount
2L, 2R (4L, 4R)	±35.5	54.8	127	On instrument mount
3L, 3R (5L, 5R)	±28	63.7	127	On instrument mount
4L, 4R (6L, 6R)	±20.5	80	127	On instrument mount
5L, 5R (7L, 7R)	±13	100	127	On instrument mount
6L, 6R (8L, 8R)	±5.5	120	127	On instrument mount
7L, 7R (2L, 2R)	±26.7	48.3	206	Front, attached to cable support hooks
8L, 8R (1L, 1R)	±27.9	86	30	Front, bottom
9L, 9R (9L, 9R)	±40.6	200	218	Rear, top, corners (2)

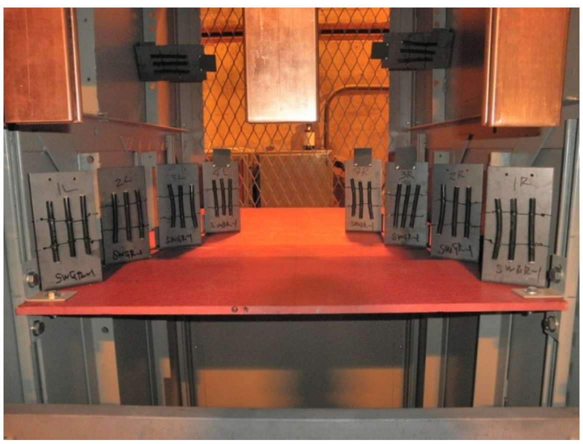
(1) Different target numbers were used for the installation before the tests ("install") and for the photographs after the test ("Photo"). "Photo" target numbers are used to report the results.
(2) Corner location may have a "corner effect" that concentrates the heat but no effects were observed in the tests.

(a) T1 on inside of door

(b) T2 from front



(c)T3- T7 from front



(d) T5, T6, T7, T8, T9 from front

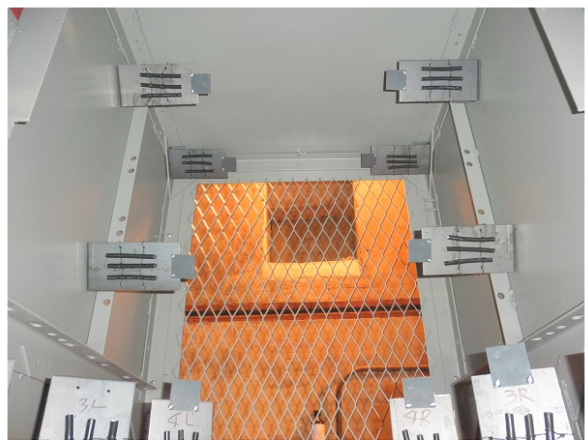
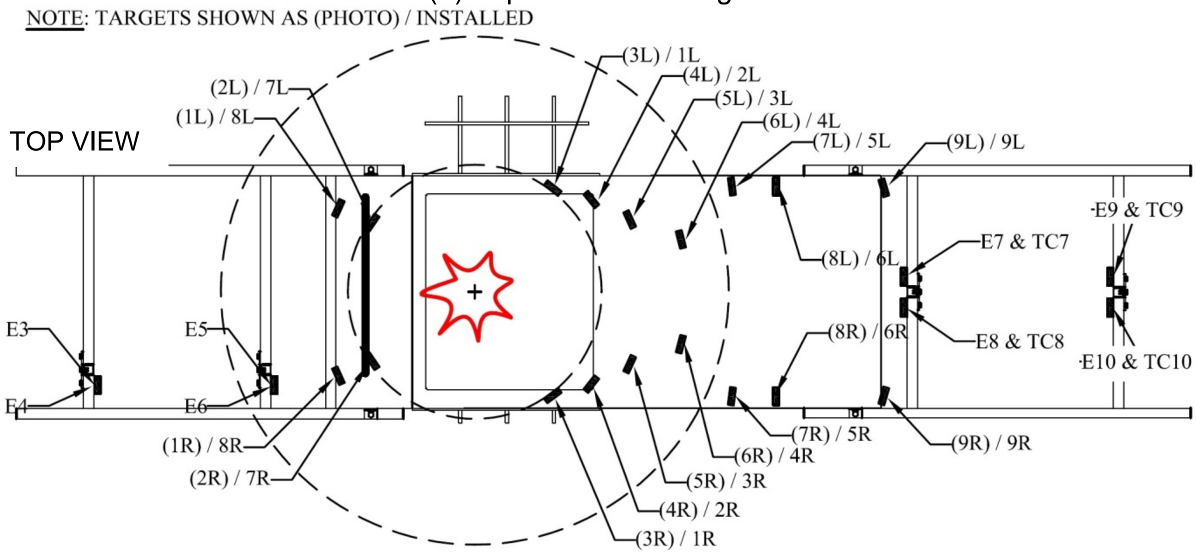


Figure 3.6-3 SWGR Internal Targets

(a) Top View of all Targets



(b) Side View of all Targets

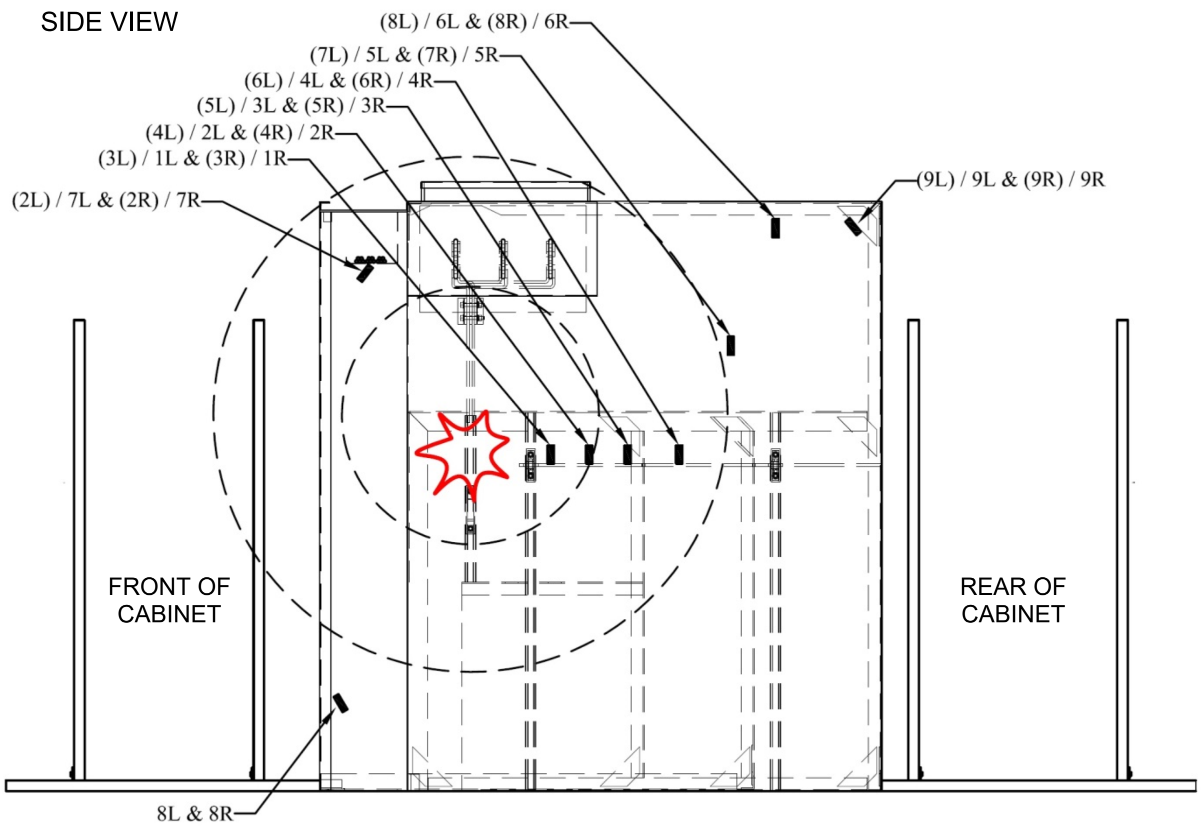


Figure 3.6-4 SWGR Tests 7 through 10 Diagram of Target Locations Showing Arc Location and 50 cm and 100 cm Radial Distances

Target numbers in Figure 3.6-4 are used for the post-test photos in Appendix F and figures. Target positions in Figure 3.6-5 using “T” and “E’ designations are used for the results tables in the “Target Damage” results sections for each test. Numerical scores for damage are shown.

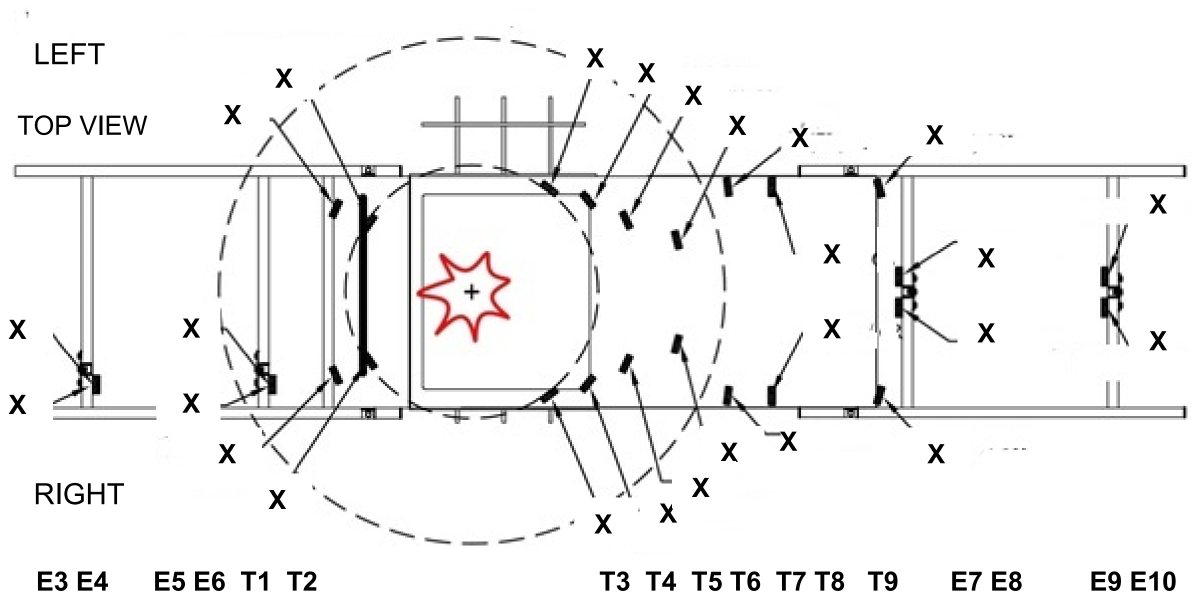


Figure 3.6-5 SWGR Target Locations for Damage Results Tables Showing Arc Location and 50 cm and 100 cm Radial Distances and Example Results (X = 1 – 6)

3.7 SWGR Tests 7 through 10 Pressure Instrumentation

Two Dynisco PT150-50 strain-gauge type pressure transducers (PRT) were used. See Appendix A for the analysis method. The pressure transducer positions are at the 12.7 mm holes in Figure 3.4-1.

3.8 SWGR Test 7 Key Observations

This test was initiated at 7.1 kV and 29.5 kA with a target arc duration of 2.8 seconds that was achieved. The resulting total energy was 88.2 MJ and power was 30 MW. The arc voltage was 897 V. The arc progression is seen in Figure 3.8-1.

Figure 3.8-1 SWGR Test 7 Arc

Photos from HD cameras inside the test cell, seen in Figure 3.8-2, indicate the distance the flames traveled and if the flames made contact with the slugs during the tests. The arc flames extended out of the front and rear cabinet openings to the instrumentation stand 0.91 m from the cabinet. Figure 3.8-2(c) and (d) show flame contact with all the targets in front of and behind the cabinet. Figure 3.8-2(e) and (f) showed the arc burned through the cabinet and contacted S2 on the right side. The IR camera image of the front of the cabinet, seen in Figure 3.8-2(g), shows the flames escaping down from the holes in the cabinet while still making contact with S2. The flame does not appear to contact S1 at the higher position.

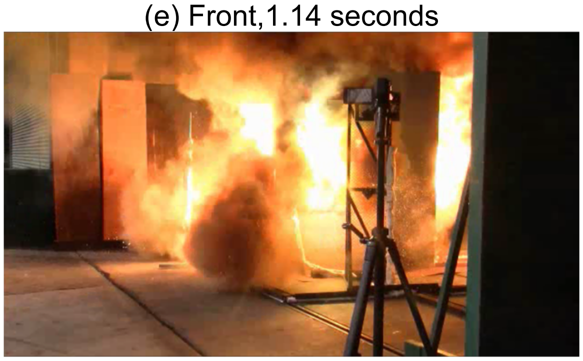
(a) Test 7 Side View- Front

(b) Test 7 Side View- Rear

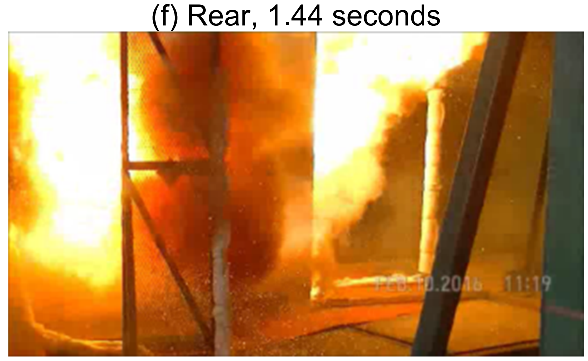
(c) Front, 0.53 seconds

(d) Rear, 0.40 seconds

(e) Front,1.14 seconds



(f) Rear, 1.44 seconds



(g) Front View FLIR, 2.17 seconds

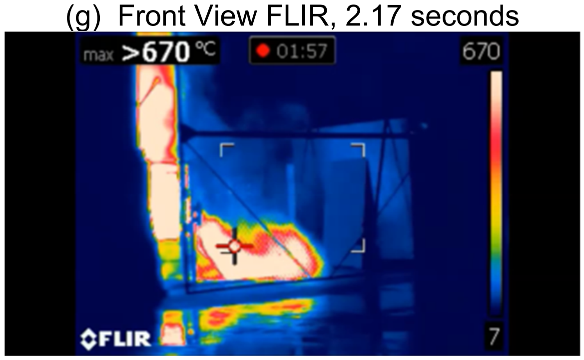


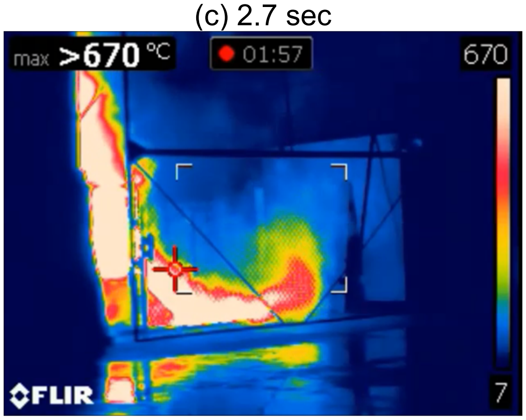
Figure 3.8-2 SWGR Test 7 Flames during Arc

Images from the IR camera are shown in Figure 3.8-3; the SWGR is on the left of the picture. The FLIR camera was on auto-scale and the maximum temperature that could be detected (670 ˚C) was within about 1 second that is typical for previous arc tests. The view is straight into the front of the SWGR. The hot plume is near the floor as seen in Figure 3.8-3(c). At 5 seconds after the arc, the maximum temperature is near the bottom, seen in Figure 3.8-3(d). The location of the plume and the temperatures indicate that the plasma and heat from the arc travel downward from the ends of the bus bars, which are pointed downward. This is discussed more in Section 4.4.

(a) Arc Start

(b) 1.6 sec; max temperature (670 ˚C)

(c) 2.7 sec



(d) 7.8 sec (5 sec after arc)

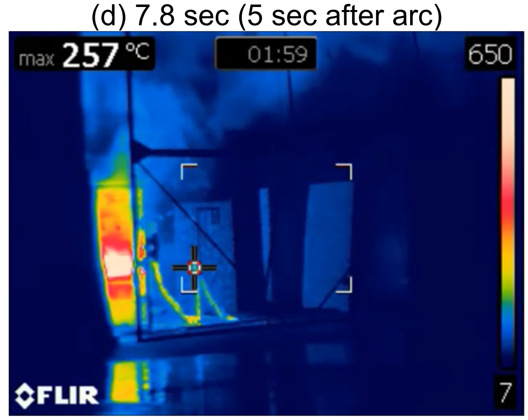


Figure 3.8-3 SWGR Test 7 Thermal Images

3.8.1 SWGR Test 7 Exterior Damage

Figure 3.8-4 shows the exterior cabinet damage. The arc attached to the cabinet panels, creating holes through the exterior panels as it burned through as shown in Figure 3.8-4(a). Charring of the panels was also seen on the exterior of the cabinet in many areas, such as the bottom panel of the front door as shown in Figure 3.8-4(b). Soot deposited on the external surfaces where smoke leaked through cracks and openings. The screens on the front and rear did not melt or fail from the flames passing through them.

(a) Right Side (b) Front

Figure 3.8-4 SWGR Test 7 Exterior Damage

3.8.2 SWGR Test 7 Interior Damage

The damage to the cables, indicated as “medium,” by the presence of charring, is shown in Figure 3.8-5. Since an ensuing fire was not observed, this damage was caused during the arc. Perhaps the open front panel allowed the arc heat to escape instead of sustaining a cable fire. Post-test resistance measurements showed no shorting failures in the CV-2 cables. Additional discussion is in Section 4.2.

(a) In-situ Damage (b) In-situ Detai: “medium” damage

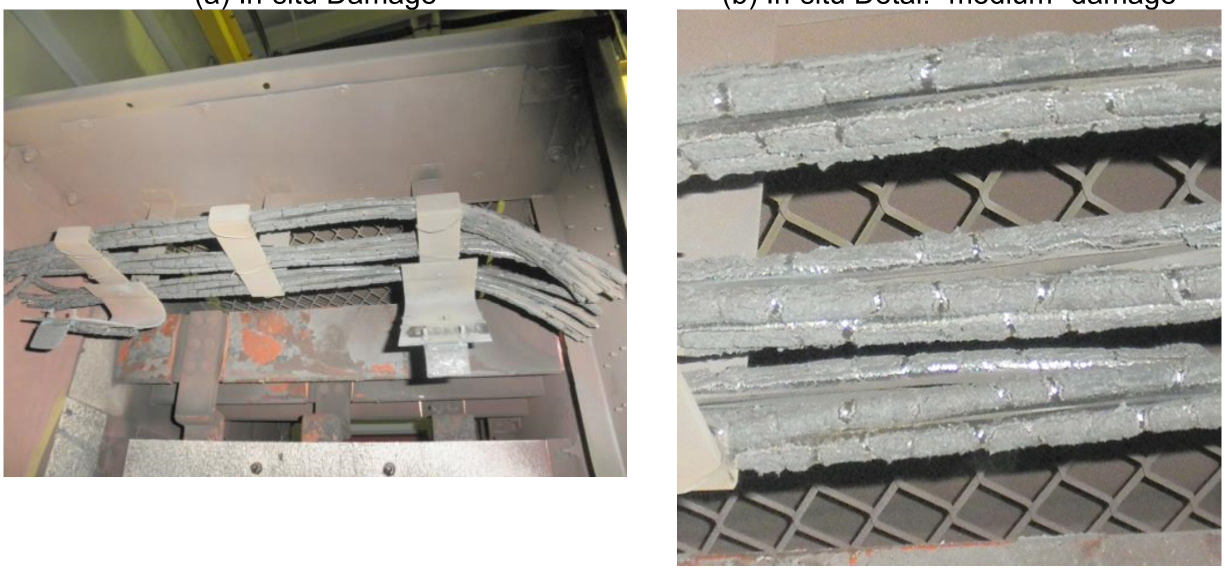
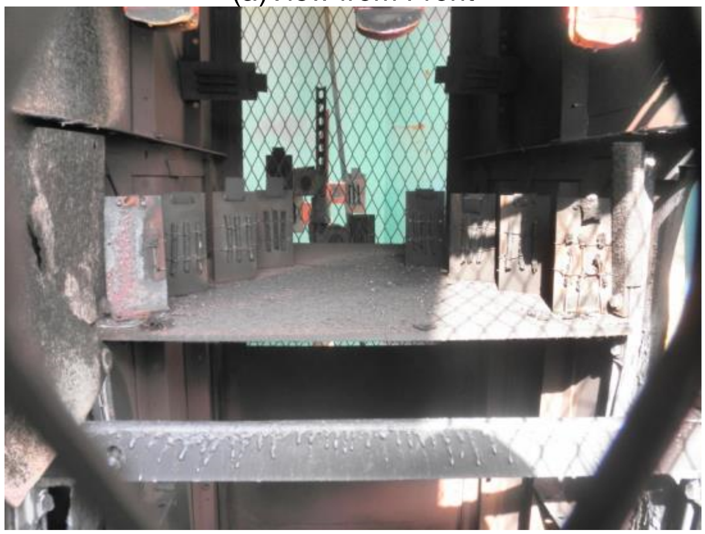


Figure 3.8-5 SWGR Test 7 Interior Cable Damage

Figure 3.8-6 shows the internal damage to the bus bars, targets on the platform, and the ground bar. The steel ground bar was intact, with minor melting, and there were holes through the wall panels, indicating perhaps that the arc attached side panels of the cabinet. The copper bus bars mass loss was 5.238 kg and the lengths changed 14-29 cm. The ground bar lost 0.583 kg of steel. The calculation details of the mass loss are in Appendix G.

As observed in previous tests, the bus bars do not burn evenly and Phase A has slightly more mass loss than Phases B and C. The ground bar loss is about 11% of the total copper bus bar loss. Ground bus bar losses were more than 20% in the other SWGR tests in this report and this probably indicates that the arc was attaching to the cabinet more in this test than other tests and less energy was applied to the ground bar.

(a)View from Front



(b) Bus Bars

(c) Ground Bar

Figure 3.8-6 SWGR Test 7 Bus Bar and Ground Bar Damage

3.8.3 SWGR Test 7 Target Damage

The results are shown in Figure 3.8-7 and Table 3-5. See Figure 3.6-5 for target locations. Detailed photographs of the target damage are in Appendix F.

Cable target Damage:

- T1 at the bottom front had more damage than T2 at the top front even though the distance from the arc was longer (86 vs. 48 cm). This is because the flames and heat shoot down from the end of the bus bars as discussed in Section 4.4.
- T3 directly in the arc plasma at the level of the arc was destroyed as in all SWGR tests.
- Internal cable damage was heavy to T1 (86 cm) in the flames below the arc, medium out to T6 (80 cm) and minor damage out to T9 (200 cm). Interior targets all had minor damage or greater. All cables that were measured passed resistance tests.
- External cable damage was mostly medium out to E10 (162 cm). There was one heavy damage at E8 (142 cm) perhaps from a strong flame strike. There was no damage at E3 (155 cm) and E4 (155 cm). All cables passed resistance tests.

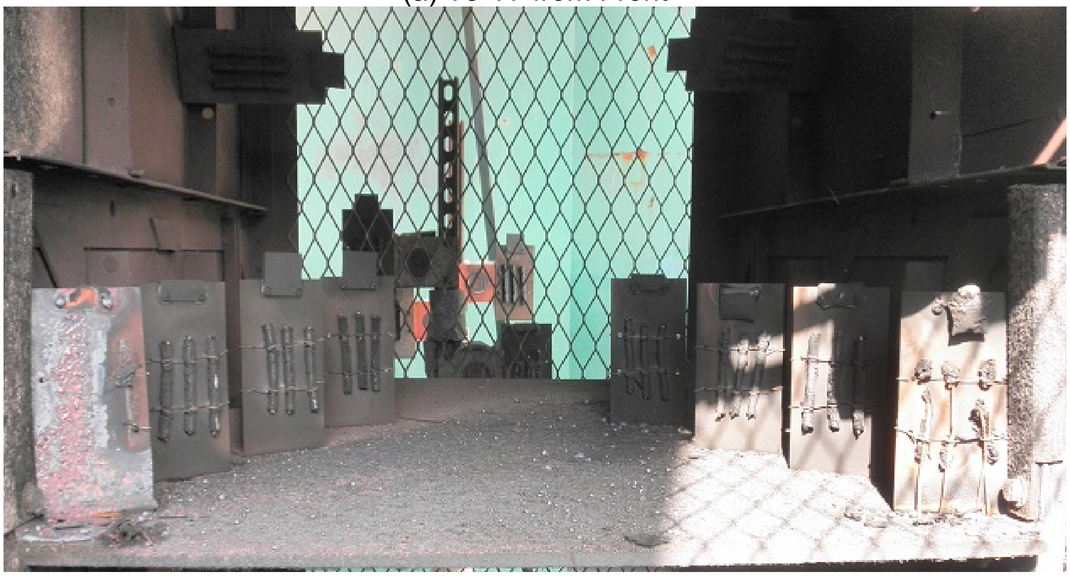
Plastic target damage:

- Internally the plastic damage was similar to cable damage where the plastic was destroyed at T1 and T3. There was heavy damage out to T6 (120 cm).
- There was one heavy damage at T4 (80 cm) that was odd because it is not the closest target. This may be related to T3 being destroyed even though it was 60 cm from the arc.
- External heavy damage was similar to the cable damage with heavy damage out to E8 (155 cm) and medium damage out to E10 (162 cm).

Other:

- There was metal coating on T3L (48 cm) in contact with the plasma similar to metal coating in the DP tests but not as severe.

(a) T3-T7 from Front



(b) E3 through E6, from front

(c) E7 and E8, from rear

Figure 3.8-7 SWGR Test 7 Target Damage

Table 3-5 SWGR Test 7 Target Damage

Target (Cm)		Damage Description		Label Temp. (˚C)	Note
		Cable	Plastic		
T1 86	L	5. heavy damage	6. destroyed	burnt	
	R	5. heavy damage	6. destroyed	burnt	
T2 48	L	4. medium damage	4. medium damage	burnt	plastic is bent forward
	R	4. medium damage	4. medium damage	burnt	plastic is bent forward
T3 48	L	6. destroyed	6. destroyed	burnt	nothing is left, target plate is coated with metal
	R	6. destroyed	6. destroyed	burnt	nothing is left
T4 55	L	4. medium damage	5. heavy damage	burnt	plastic is bent backward
	R	4. medium damage	5. heavy damage	burnt	plastic is bent backward
T5 64	L	4. medium damage	2. sooted	burnt	
	R	4. medium damage	5. heavy damage	burnt	plastic is bent forward
T6 80	L	4. medium damage	2. sooted	burnt	
	R	4. medium damage	5. heavy damage	burnt	plastic is bent backward
T7 100	L	3. minor damage	2. sooted	burnt	
	R	3. minor damage	3. minor damage	burnt	
T8 120	L	3. minor damage	3. minor damage	burnt	
	R	3. minor damage	3. minor damage	burnt	
T9 200	L	3. minor damage	2. sooted	burnt	
	R	3. minor damage	3. minor damage	160-166	
E3 155		1. none	1. none	<41	this target is used for SWGR-2
E4 155		1. none	1. none	<41	this target is used for SWGR-2
E5 91		4. medium damage	no sample	143-149	cable sample is cut off
E6 91		4. medium damage	3. minor damage	93-99	
E7 155		4. medium damage	4. medium damage	burnt	
E8 155		5. heavy damage	5. heavy damage	burnt	plastic is bent forward
E9 231		4. medium damage	4. medium damage	121-127	
E10 231		4. medium damage	4. medium damage	160-166	

3.8.4 SWGR Test 7 Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 3.8-8. Slugs S5 and S7 failed during the test. Flames made contact with S2 through S10 during the test.

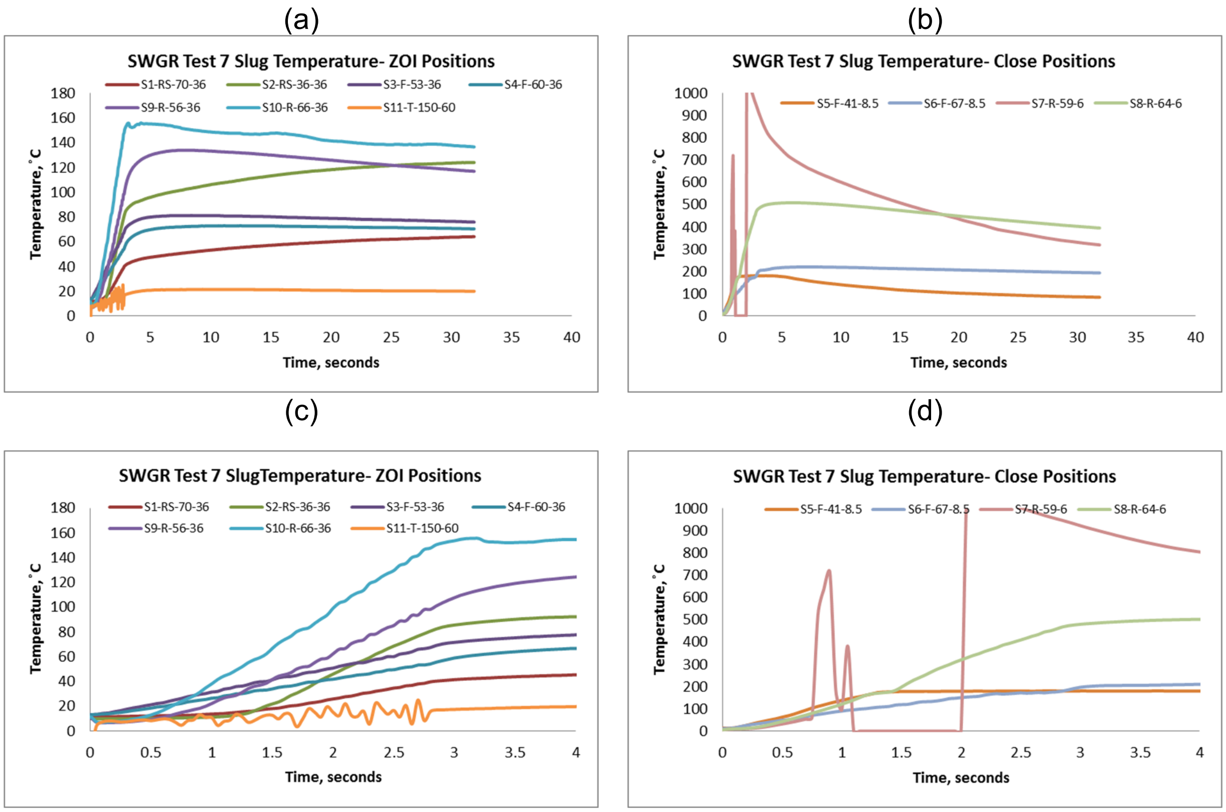


Figure 3.8-8 SWGR Test 7 Calorimetry Temperature Data

Table 3-6 shows the flux calculated using the method in Section A.1 using the temperature of the calorimeter slug before and after the arc. The flux is an average of the flux during the arc. The table shows if the slug calorimeter was hit by flames and in that case the flux is not valid.

Several TCs on the slug calorimeters failed during the test. Although the temperature and flux before the time of failure could be analyzed in all the failed cases the flux calculation was not valid because of flame contact. The flux 1.5 m above the cabinet (S11) was much lower flux than previous SWGR tests probably because the heat escaped the front and rear rather than the top vent as in previous tests in Volume 1 [3].

Table 3-6 SWGR Test 7 Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comment
S1-RS-70-36	28.0	61.35	64	none
S2-RS-35-36	70.9	156.37	124	Flame contact
S3-F-53-36	54.4	119.78	81	Flame contact
S4-F-60-36	40.9	89.86	73	Flame contact
S5-F-41-8.5	167.0	698.22	180	Flame contact Results are at 1.5 sec, when S5 failed
S6-F-67-8.5	164.4	368.02	220	Flame contact
S7-R-59-6	46.1	404.89	N/A	Flame contact Results are at 0.7 sec, when S7 failed
S8-R-64-6	449.7	1,036.63	508	Flame contact
S9-R-56-36	91.6	202.51	134	Flame contact
S10-R-66-36	140.8	313.7	156	Flame contact
S11-T-150-60	7.8	17.01	21	Flux much lower than prior SWGR tests

3.8.5 SWGR Test 7 Temperature Data

The temperatures measured by the TCs are shown in the Figure 3.8-9. These TCs were located on the external targets E7 through E10, at the rear of the cabinet. The TCs closer to the cabinet, TC7 and TC8, measured high temperatures; TC9 and TC10 measured much lower temperatures comparatively.

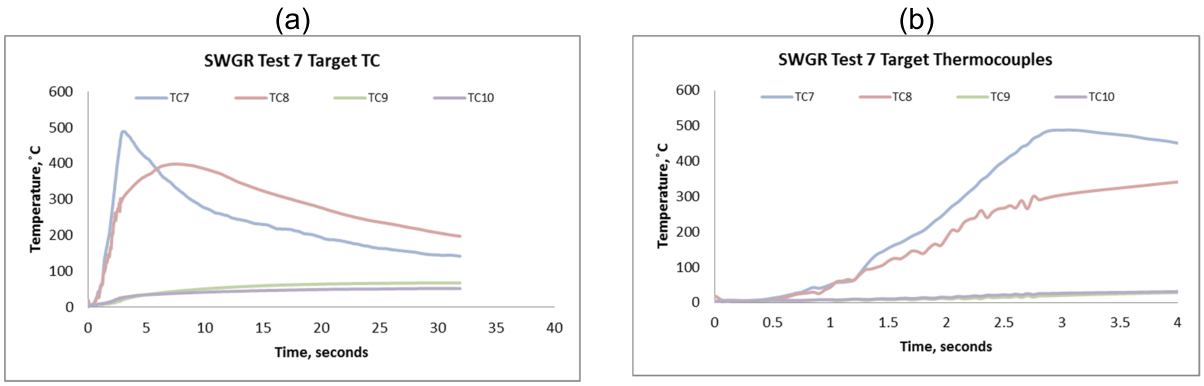


Figure 3.8-9 SWGR Test 7 Rear External Target Temperatures

Table 3-7 shows the temperatures for the TCs on the targets at the end of the arc and the maximum during the test. “Label” is the temperature indicated by the Omega temperature label on the back of the target near the TC. The labels at TC7 and TC8 were probably burned during flame contact; the cable target damage was also heavy in these locations. The TC and labels do not match very well but the reason is not clear. Perhaps the label temperatures also increase from local hot gas directly contacting them.

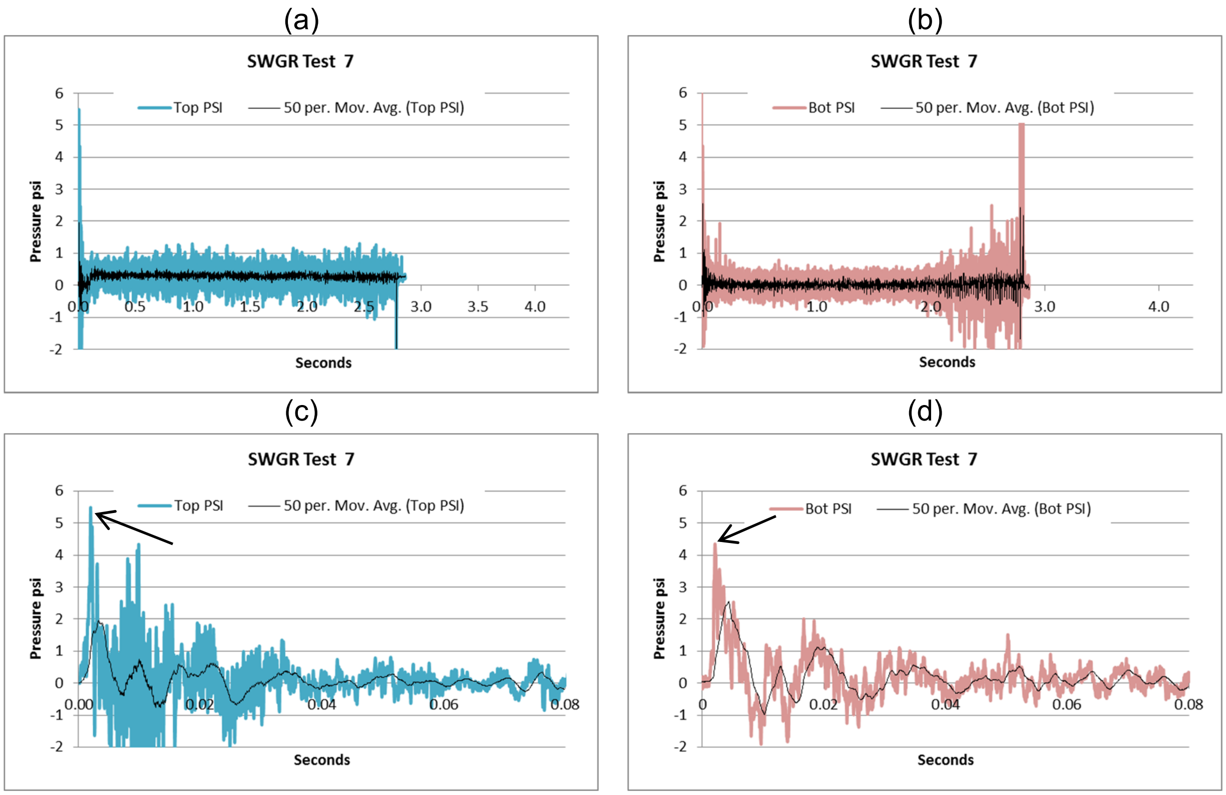
Table 3-7 SWGR Test 7 Rear External Target Temperatures

TC	Arc End (˚C)	Max T (˚C)	Label
TC7	472	489	Burnt
TC8	291	398	Burnt
TC9	20	67	121-127
TC10	26	52	160-166

Internally all labels were burnt but T9 (200 cm) that showed 166 °C. This damage is much more severe than the DP tests where some labels survived. This may be because the SWGR is totally open and there are no structures to block the flames like there are in the DP.

3.8.6 SWGR Test 7 Pressure Data

The gauge pressure curves are shown in Figure 3.8-10. The maximum pressures are indicated by the arrows in the charts. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc. PRT1 (top) has a zero-shift about 0.1 seconds after the arc starts.



PRT1 (top)
28.3 ± 0.5 kPa (4.1 ± 0.07 psi)
@ 0.0019 second

PRT2 (bottom)
27.6 ± 1.4 kPa (4.0 ± 0.2 psi)
@ 0.0022 second

Figure 3.8-10 SWGR Test 7 Pressure Data

3.8.7 SWGR Test 7 Arc Energy

The arc duration was 2.8 seconds with total energy of 88.2 MJ, seen Figure 3.8-11. The energy analysis methods are in Appendix A. The “Energy” is calculated as volts multiplied current multiplied by the time step and each time step is shown. “Energy total” is the cumulative sum of the energy in each time step.

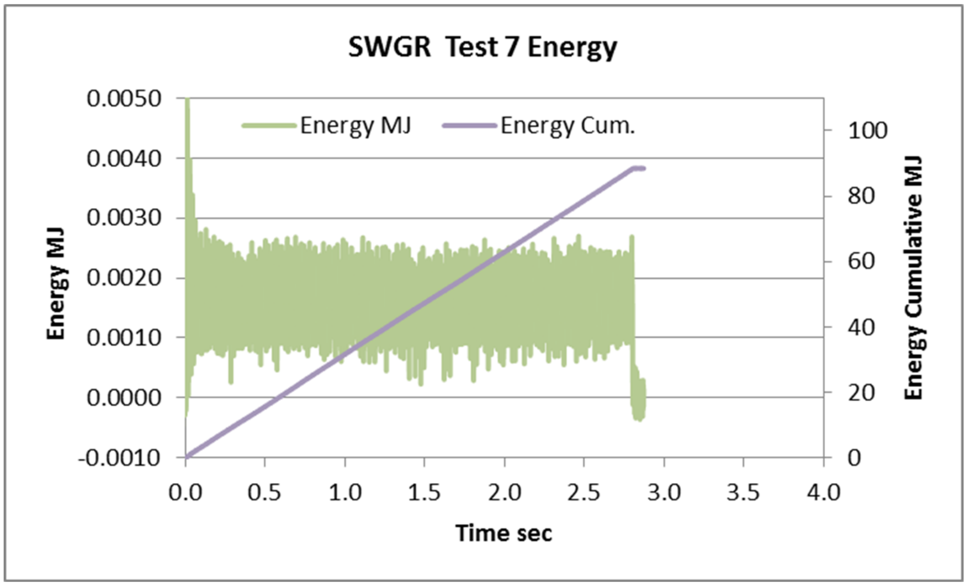


Figure 3.8-11 SWGR Test 7 Arc Energy

3.9 SWGR Tests 8 through 10 Changes

In Test SWGR 7, the arc appeared to attach to the side panels, burning large holes in the right panel and smaller holes on the left panel. To prevent this in the remaining tests SWGR Tests 8, 9, and 10, red board was added to the inside of the panels, as shown in Figure 3.9-1. It was reasonably effective in SWGR Test 8 but more careful fitting in SWGR Tests 9 and 10 proved to be more effective. The red board also helps to force the arc to attach to the ground bar rather than the walls for better voltage control.

For SWGR Test 8, the ground bar was set 15 cm from the ends of the bus bars as a one-off test, as shown in Figure 3.9-1. See Section 3.3 for more discussion. As expected, the arc voltage was lower than the other SWGR tests in this report, which had 30 cm gaps. However, SWGR Test 7 cannot be directly compared because it was arcing to the sidewall that was closer than the ground bar.

Figure 3.9-1 Red Board Added for SWGR Test 8, 9, 10

3.10 SWGR Test 8 Key Observations

This test was initiated at 7.1 kV and 29.5kA, with a target duration of 3.5 seconds with a total energy of 89.1 MJ, and power of 22 to 32 MW. The arc voltage was 816 V. Figure 3.10 -1 shows the observed arc sequence.

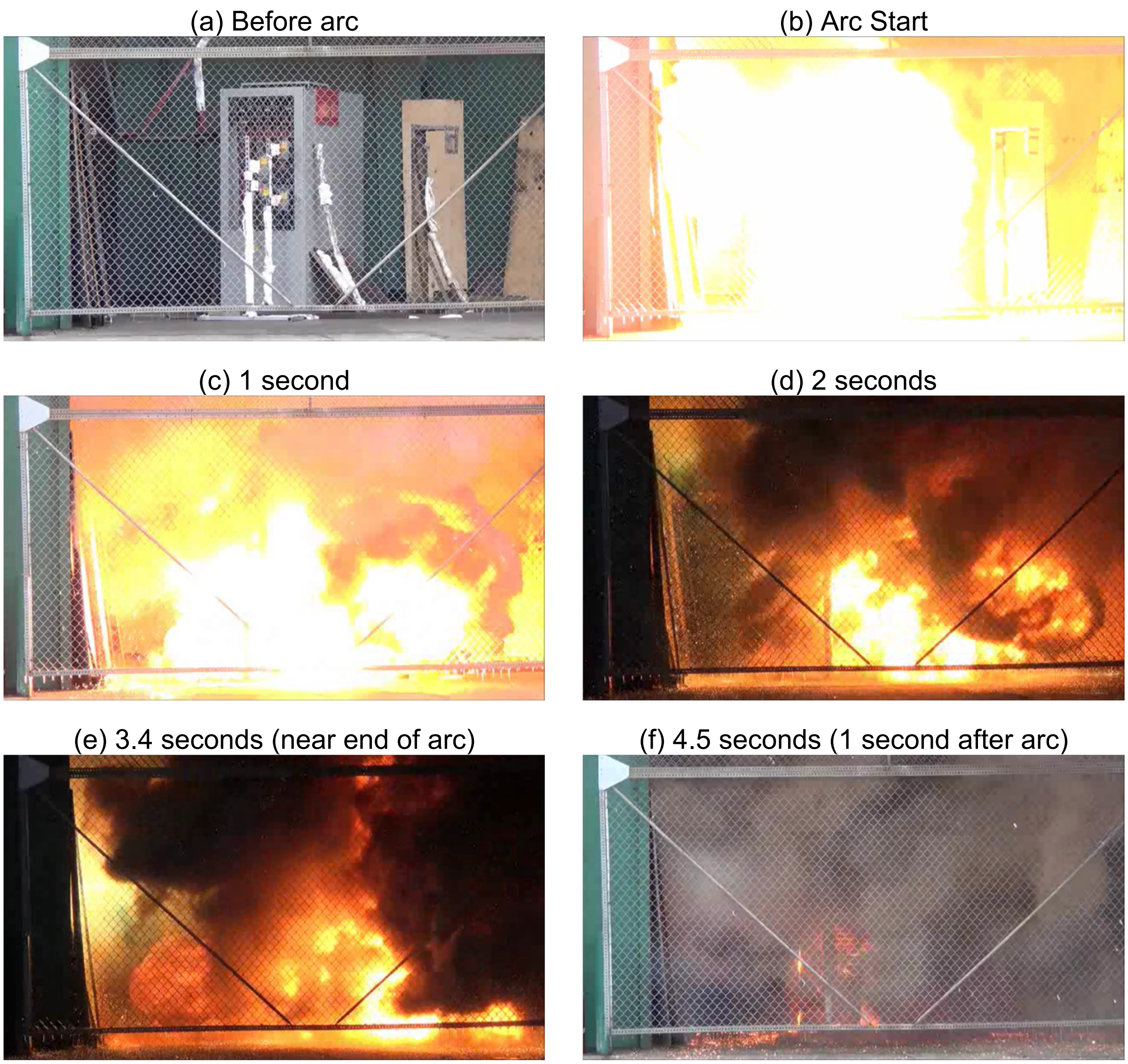


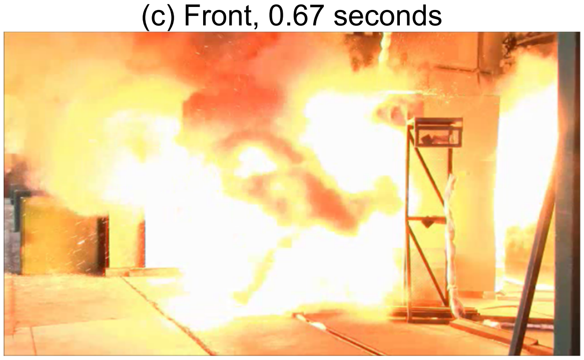
Figure 3.10-1 SWGR Test 8 Arc

Photos from HD cameras inside the test cell, seen in Figure 3.10-2, indicate the distance the flames traveled, and if the flames made contact with the slugs during the tests. Figure 3.10-2(c) and (d) show flame contact with all the targets in front of and behind the cabinet. Figure 3.10-2(e) and (f) show flames approached S1 and S2 on the side but does not appear to make contact.

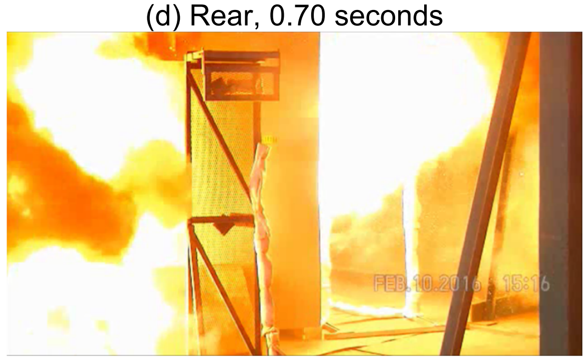
(a) Test 8 Side View, Front

(b) Test 8 Side View, Rear

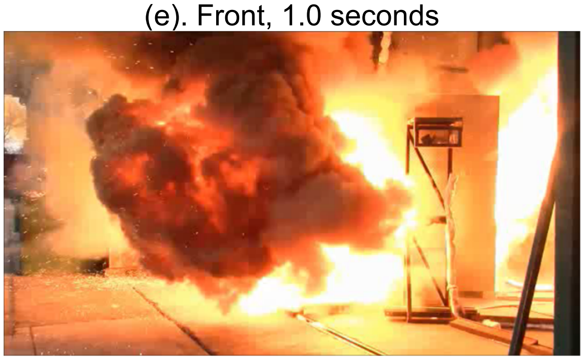
(c) Front, 0.67 seconds



(d) Rear, 0.70 seconds



(e). Front, 1.0 seconds



(f) Rear, 0.93 seconds

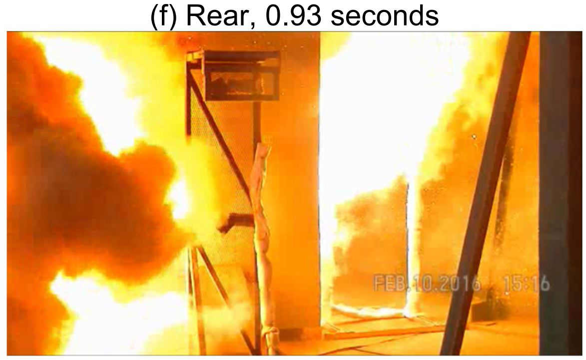


Figure 3.10-2 SWGR Test 8 Flames during Arc

Images from the IR camera are shown in Figure 3.10-3. These images are from the NRC FLIR SC6700 camera, set to a fixed maximum temperature of 60 ˚C (140 ˚F) and without auto-scale, the images are overexposed during the arc.

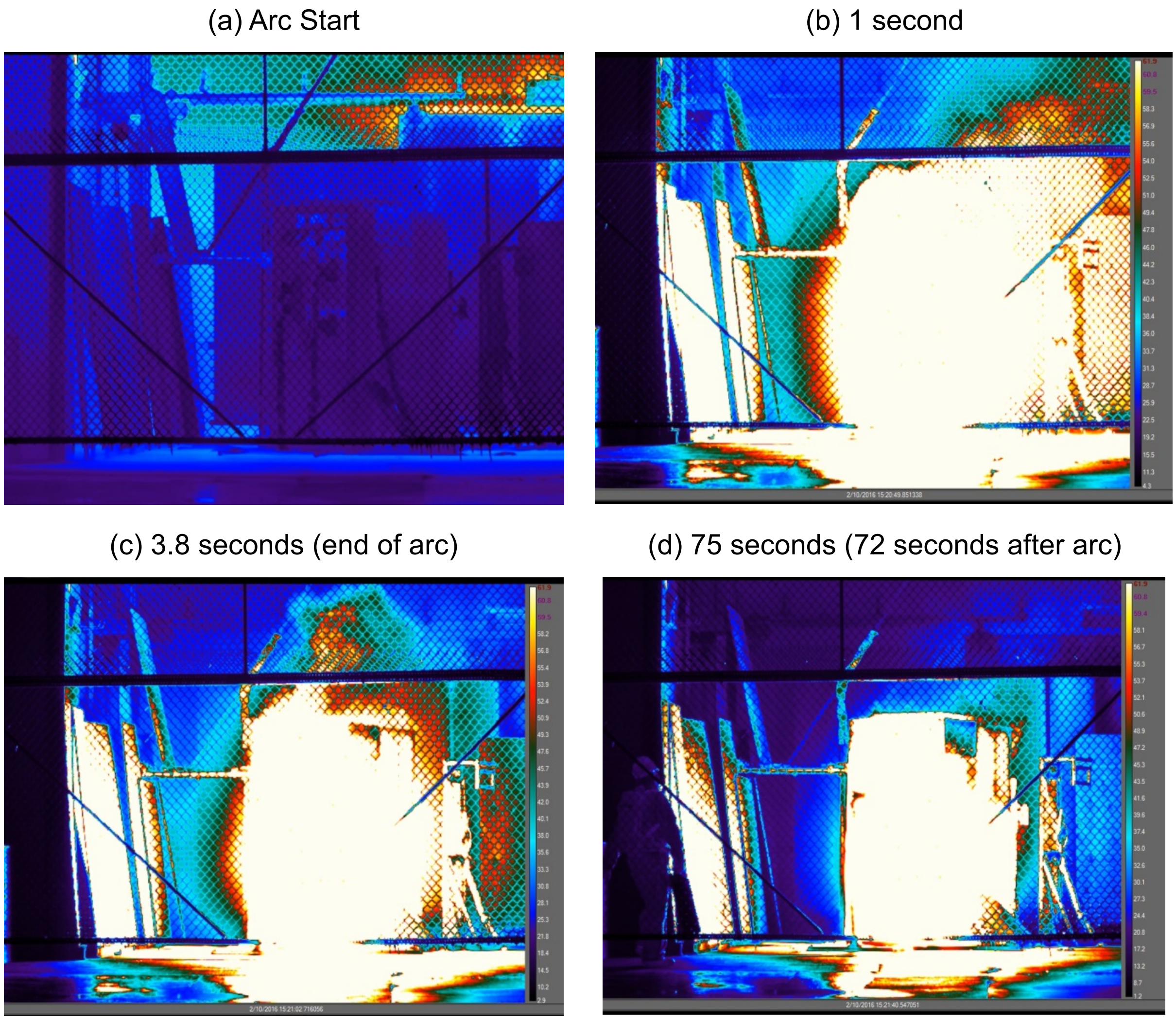


Figure 3.10-3 SWGR Test 8 Thermal Images

3.10.1 SWGR Test 8 Exterior Damage

The major exterior cabinet damage was holes in the panels where the arc attached and burned through, as shown in Figure 3.10-4(a). There was a similar hole on the left side. However, the damage was less than in SWGR Test 7 even though the energy was comparable. This indicates that the additional red board on the walls in SWGR Test 8 was somewhat effective but needed more improvements. There was external charring in many areas such as the bottom panel of the front door as shown in Figure 3.10-4(b). There were various soot deposits on the external surfaces where smoke leaked through cracks and openings. The screens on the front and rear did not melt or fail from the flames passing through them.

(a) Right Side (b) Front

Figure 3.10-4 SWGR Test 8 Exterior Damage

3.10.2 SWGR Test 8 Interior Damage

Charring of the cables indicates “medium” damage, shown in Figure 3.10-5. Since an ensuing fire was not observed, this damage was presumably caused during the arc. Perhaps the open panel allowed the arc heat to escape and the cable fire could not be sustained. Post-test resistance measurements showed no CV-2 cables had shorting failures. Additional discussion is in Section 4.2.

(a) In-situ Damage (b) In-situ Detail: “medium” damage

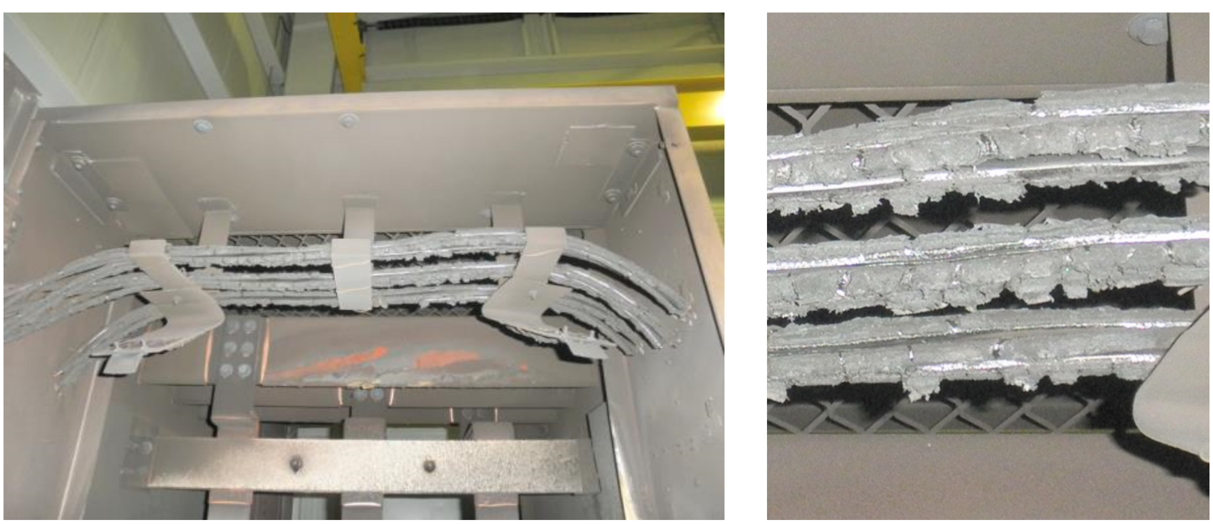


Figure 3.10-5 SWGR Test 8 Cable Damage

Figure 3.10-6 shows the internal damage to the bus bars, targets on the platform, and the ground bar. The ground bar was dislodged and fell to the floor (Figure 3.10-6(b)) causing the arc to attach to the panels (despite the red board); this was also indicated by the holes in the cabinet side panels. The ground bar, located 15 cm from the copper bus bar, lost 1.89 kg of steel. The mass loss calculations are detailed in Appendix G. Although SWGR Tests 7 and 8 had similar energy, more steel was consumed in Test 8 than Test 7, because the ground bar was closer to the bus bars.

The bus bars lost a total of 3.8 kg of copper and the lengths changed 12-30 cm. An average of 27 cm of copper bus bar was burned for each bus and the steel angle bracket was burned.

The ground bar lost about 36% of the total copper bus bar loss.

(a) Bus Bars and Targets

(b) Detached Ground Bar

(c) Bus bars (large melted slugs circled in red)

(d) Ground Bar

Figure 3.10-6 SWGR Test 8 Bus Bar and Ground Bar Damage

3.10.3 SWGR Test 8 Target Damage

The results are shown in Figure 3.10-7 and Table 3-8. See Figure 3.6-5 for target locations. Detailed photographs of the target damage are in Appendix F.

Cable Damage:

- T1 at the bottom front had more damage than T2 at the top front even though the distance from the arc was longer (86 vs. 48 cm). This is because the flames and heat shoot down from the end of the bus bars as discussed in Section 4.4
- T3 directly in the arc plasma at the level of the arc was destroyed as in all SWGR tests.
- Internal cable damage was heavy to T1 (86 cm) in the flames below the arc, medium out to T9 (200 cm) that was further out than SWGR Test 7. There were two points with minor damage T7 (100 cm) and T8 (120 cm). All cables that were measured passed resistance tests.
- External cable damage was at least medium for all targets out to E10 (231 cm). There was one heavy damage at E5 (91 cm) perhaps from a strong flame strike.

Plastic damage:

- Internally the plastic damage was similar to cable damage where the plastic was destroyed at T1 (86 cm) and T3 (48 cm). There was heavy damage out to T1 (86 cm) and medium damage out to T8 (120 cm).
- External damage for plastic was "minor" which is less than the cable damage that was "medium". There was one heavy damage out to E5 (91 cm perhaps related to the heavy cable damage at that point) and minor damage for all other points out to E10 (231 cm).

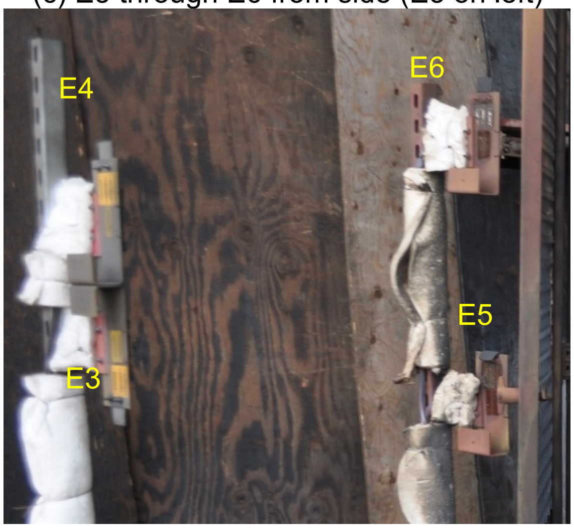
Other:

- There was minor metal coating on T3L (48 cm) in contact with the plasma similar to metal coating in the SWGR Test 7 but not as severe. See Figure 3.10-7(b).

(a) T3 -T6 from front

(b) Target T3L

(c) E3 through E6 from side (E3 on left)



(d) E7 through E10 from rear

Figure 3.10-7 SWGR Test 8 Target Results and Target Numbers: Observations

Table 3-8 SWGR Test 8 Target Damage

Target (Cm)		Damage Description		Label Temp. (˚C)	Note
		Cable	Plastic		
T1 86	L	5. heavy damage	5. heavy damage	burnt	
	R	5. heavy damage	6. destroyed	burnt	
T2 48	L	4. medium damage	4. medium damage	burnt	
	R	4. medium damage	4. medium damage	burnt	
T3 48	L	6. destroyed	6. destroyed	burnt	all the samples are gone, minor metal coating
	R	6. destroyed	6. destroyed	burnt	all the samples are gone, minor metal coating
T4 55	L	4. medium damage	5. heavy damage	burnt	plastic is bent forward
	R	4. medium damage	4. medium damage	burnt	
T5 64	L	4. medium damage	3. minor damage	burnt	
	R	4. medium damage	4. medium damage	burnt	
T6 80	L	4. medium damage	2. sooted	burnt	
	R	4. medium damage	3. minor damage	burnt	
T7 100	L	4. medium damage	3. minor damage	burnt	
	R	3. minor damage	3. minor damage	burnt	
T8 120	L	4. medium damage	4. medium damage	burnt	
	R	3. minor damage	3. minor damage	burnt	
T9 200	L	4. medium damage	3. minor damage	154-160	
	R	4. medium damage	3. minor damage	160-166	
E3 155		4. medium damage	3. minor damage	160-166	
E4 155		4. medium damage	3. minor damage	160-166	
E5 91		5. heavy damage	5. heavy damage	burnt	plastic is bent backward
E6 91		4. medium damage	3. minor damage	burnt	
E7 155		4. medium damage	3. minor damage	burnt	
E8 155		4. medium damage	3. minor damage	burnt	
E9 231		4. medium damage	3. minor damage	burnt	
E10 231		4. medium damage	3. minor damage	116-121	

3.10.4 SWGR Test 8 Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 3.10-8. The thermocouples on S5 and S7 failed during the test. Flames made contact on S3 through S10. Additional unknown failures were observed in S5, S8, and S9 during the arc.

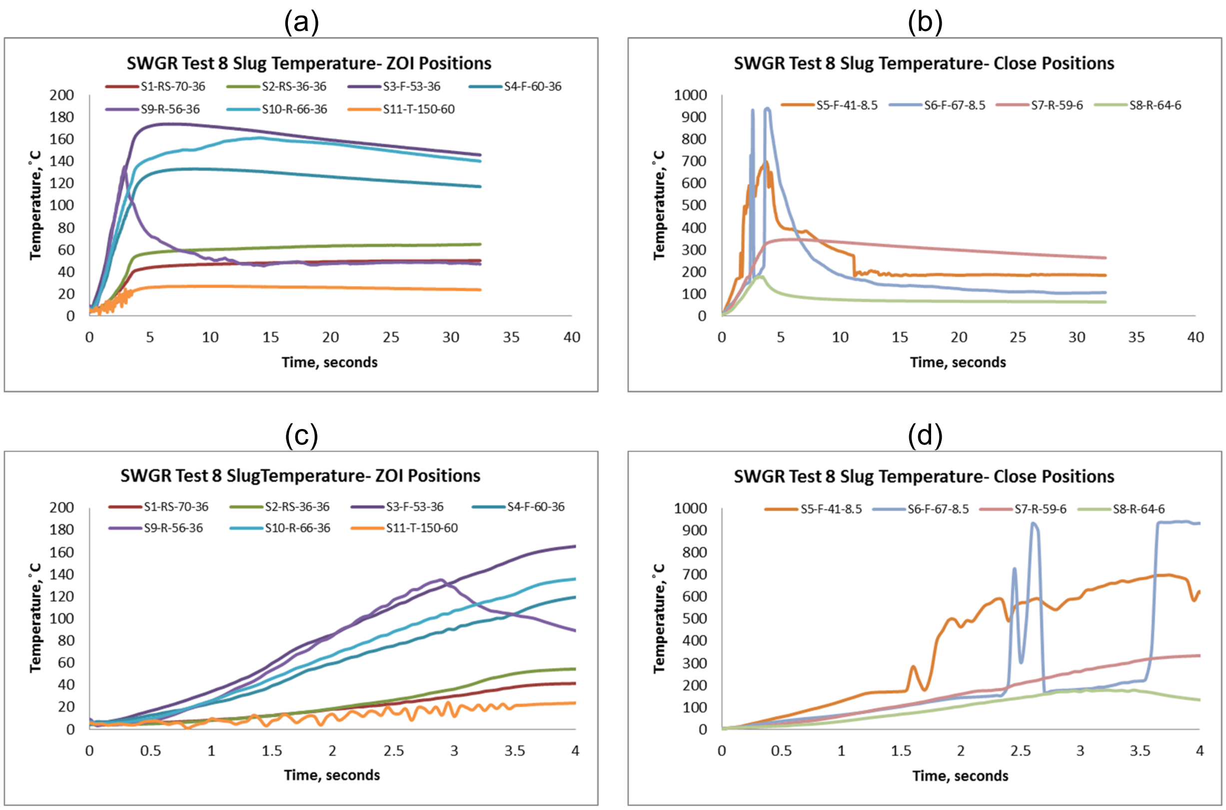


Figure 3.10-8 SWGR Test 8 Slug Calorimetry Temperature Data

Table 3-9 shows the flux results based on the method in Appendix A using the change in temperature (ΔT) between the start and end of the arc. Like SWGR Test 7, the flux measured 1.5 m above the cabinet (S11) was a much lower flux than previous SWGR tests that resulted in much higher energy. The maximum slug temperatures are also shown to indicate the maximum temperature a metal object could reach during the arc.

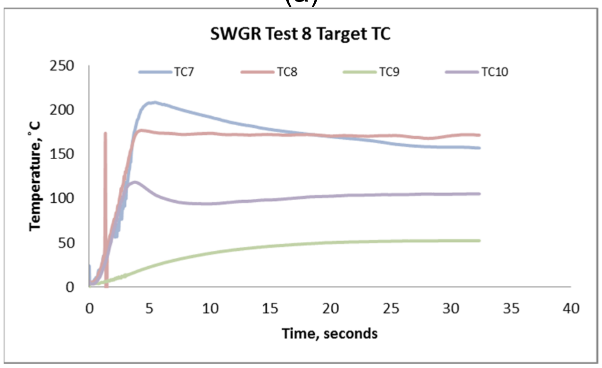
Table 3-9 SWGR Test 8 Flux Results

Slug	ΔT (˚C)	Flux (kW/m²)	Max T (˚C)	Comments
S1-RS-70-36	33.2	58.63	50	58.6 kW/m²
S2-RS-36-36	46.2	81.75	65	81.7 kW/m²
S3-F-53-36	148.4	267.0	174	Flame contact
S4-F-60-36	98.1	175.18	133	Flame contact
S5-F-41-8.5	139.9	793.11	698	Flame contact S5 failed at 1.2 seconds, evaluated at 1.1 sec
S6-F-67-8.5	213.4	387.38	939	Flame contact
S7-R-59-6	307.2	563.46	346	Flame contact
S8-R-64-6	90.8	295.85	171	Flame contact S8 failed at 1.95 sec, evaluated at 1.9 sec
S9-R-56-36	80.0	170.39	102	Flame contact S9 failed at 2.85 sec, evaluated at 2.8 sec
S10-R-66-36	116.7	208.96	161	Flame contact
S11-T-150-60	17.0	29.94	27	29.9 kW/m²

3.10.5 SWGR Test 8 Temperature Data

The temperatures measured by the TCs are shown in the Figure 3.10-9. These TCs were located on the external targets E7 through E10, at the rear of the cabinet. Although the resulting energy was similar, the temperatures measured by TC7 and TC8 are not as high as seen in SWGR Test 7. The unusually low temperature at TC9 indicates an error or fault - perhaps the TC detached from the plate.

(a)



(b)

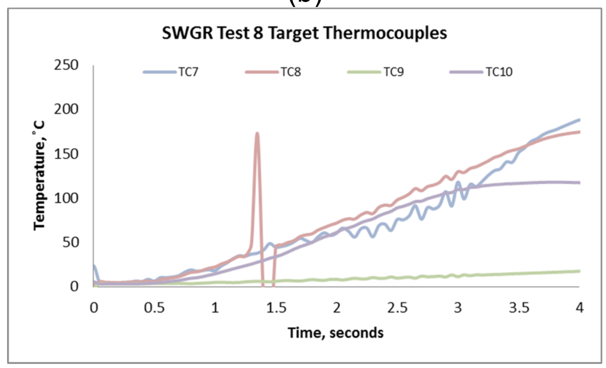


Figure 3.10-9 SWGR Test 8 Rear External Target Thermocouple Data

Table 3-10 shows the temperatures for the TCs on the targets at the end of the arc and the maximum during the test. “Label” is the temperature indicated by the Omega temperature label on the back of the target near the TC. The labels at TC7, TC8 and TC9 were probably burned during flame contact. TC10 and the corresponding label showed agreement.

Table 3-10 SWGR Test 8 Rear External Target TC Results

TC	Arc End (˚C)	Max (˚C)	Label
TC7	152	208	Burnt
TC8	156	177	Burnt
TC9	15	52	Burnt
TC10	117	118	116-121

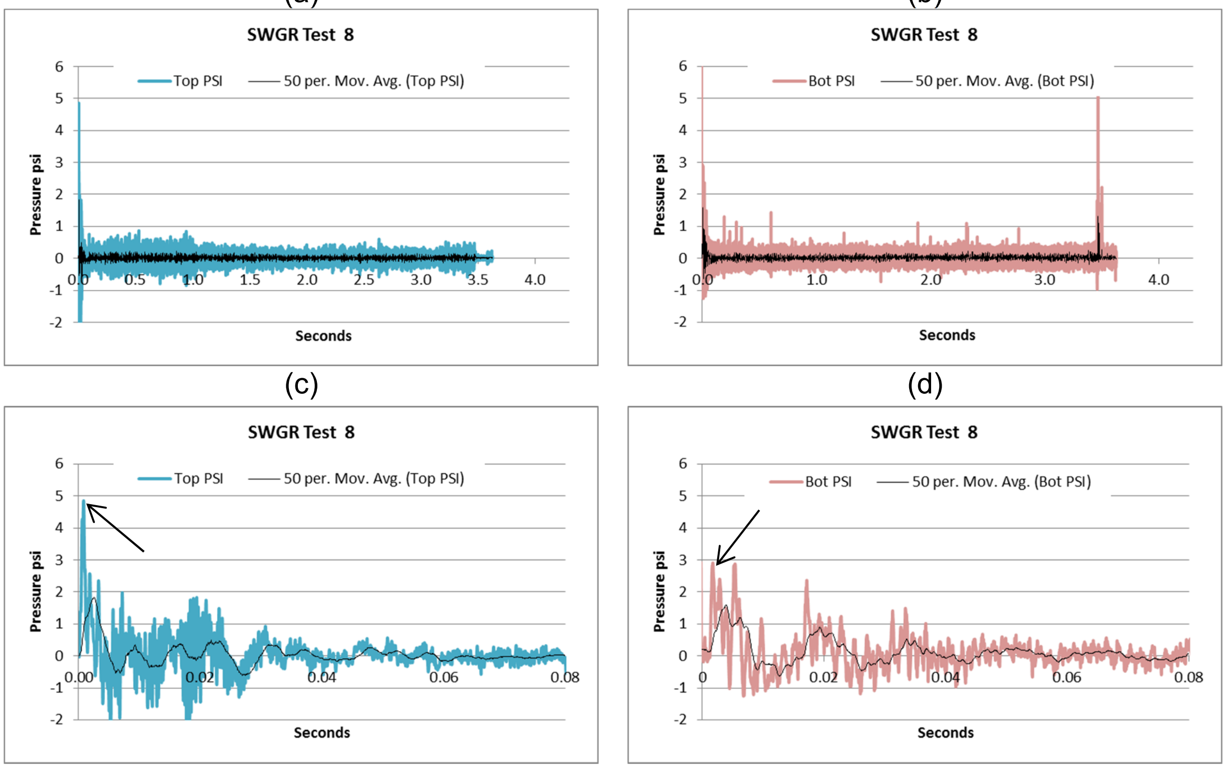
Most of the external temperature labels were burnt but in the front E3 (155 cm) and E4 (155 cm) indicated 166 °C. In the rear E10 (231 cm) indicated 121 °C. All locations had flame contact.

Internally all the temperature labels were burnt but T9 (I200 cm) that showed 166 °C similar to SWGR Test 7.

3.10.6 SWGR Test 8 Pressure Data

The gauge pressures during the arc are shown in Figure 3.10-10. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc.

(a) (b)



PRT1 (top)
27.6 ± 1.4 kPa (4.0 ± 0.2 psi)
@ 0.0008 second

PRT2 (bottom)
19.38 ± 1.0 kPa (2.8 ± 0.15 psi)
@ 0.0017 second

Figure 3.10-10 SWGR Test 8 Pressure Data

3.10.7 SWGR Test 8 Arc Energy

The arc duration was 3.5 seconds with total energy of 89.1 MJ, and the power was 20 to 35 MW, seen in Figure 3.10-11. The energy analysis methods are in Appendix A. The "Energy" is calculated as volts multiplied current multiplied by the time step and each time step is shown. "Energy Total" is the cumulative sum of the energy in each time step.

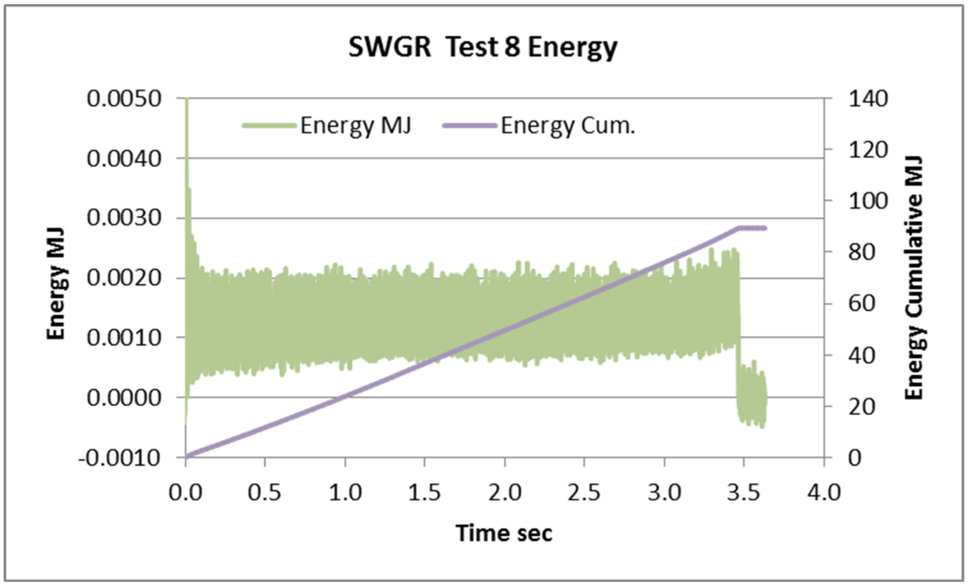


Figure 3.10-11 SWGR Test 8 Arc Energy

3.11 SWGR Test 9 Key Observations

This test was initiated at 7.1 kV and 29.5 kA and a target arc duration of 4 seconds with a total energy of 137.3 MJ and a power of 30 to 35 MW. The arc voltage was 966 V; the gap was larger, 30 cm, than the previous test at 15 cm (the ground bar was reset after SWGR Test 8). Figure 3.11-1 shows the arc sequence observed with the HD camera. Figure 3.11-1(f) was taken long after the arc while waiting for the smoke to clear.

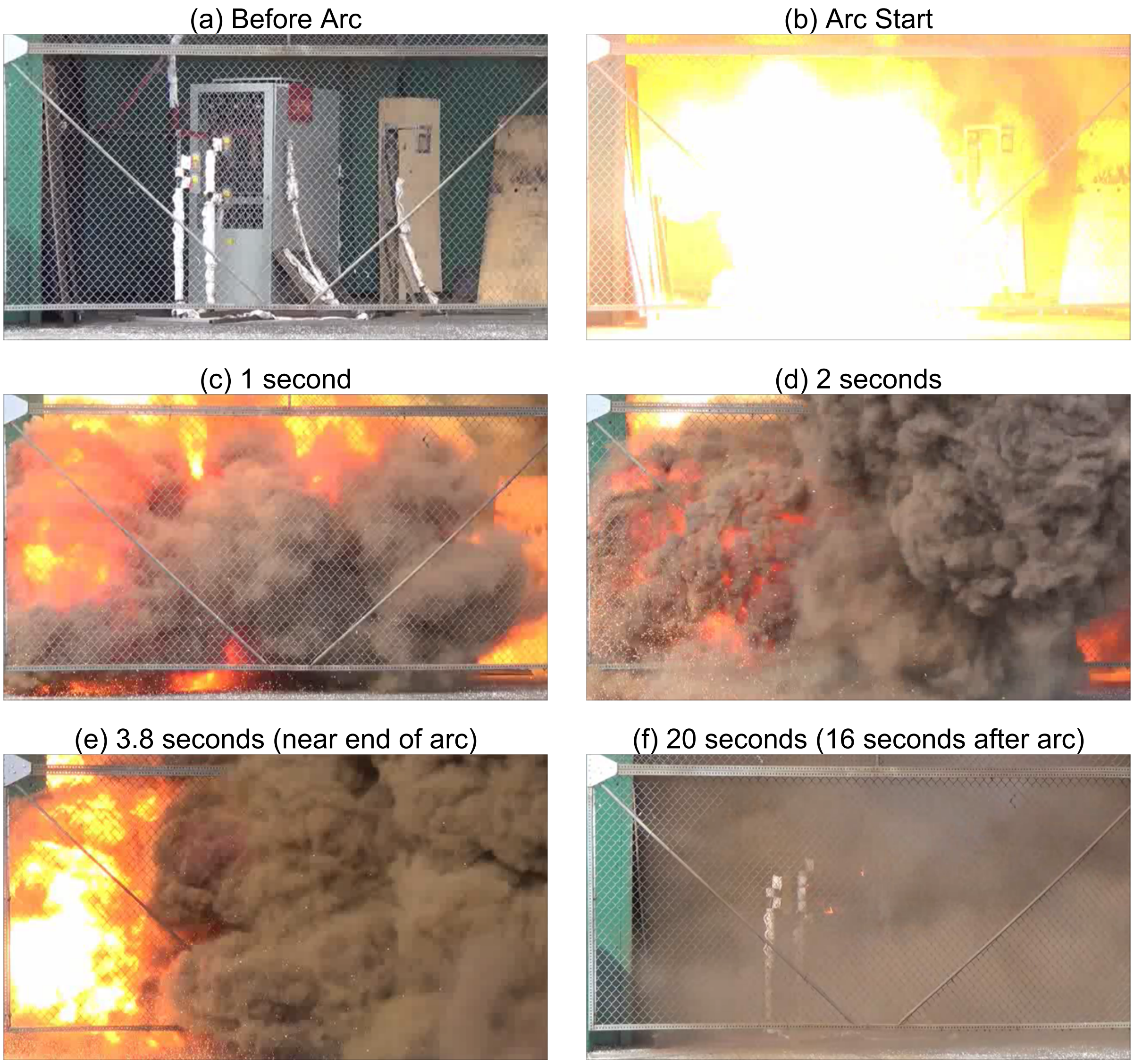


Figure 3.11-1 SWGR Test 9 Arc

Photos from HD cameras inside the test cell, seen in Figure 3.11-2Figure 3.10-2, indicate the distance the flames traveled, and if the flames made contact with the slugs during the tests. Figure 3.11-2(c) and (d) show flame contact with all the targets in front of and behind the cabinet. Figure 3.11-2(e) and (f) show flames approached S1 and S2 on the side but does not appear to make contact.

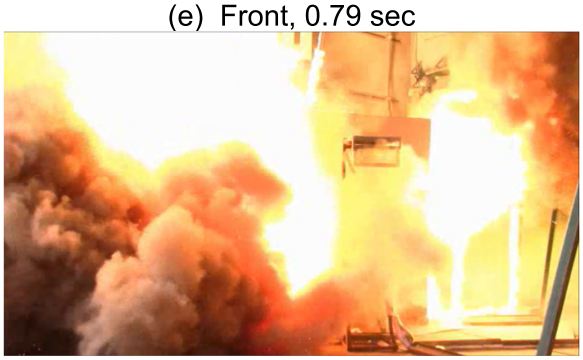
(a) Test 9 Side View- Front

(b) Test 9 Side View- Rear

(c) Front, 0.46 sec

(d) Rear, 0.50 sec

(e) Front, 0.79 sec

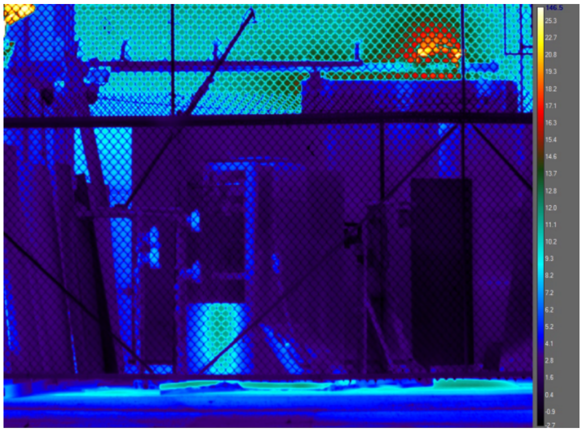


(f) Rear, 0.79 sec

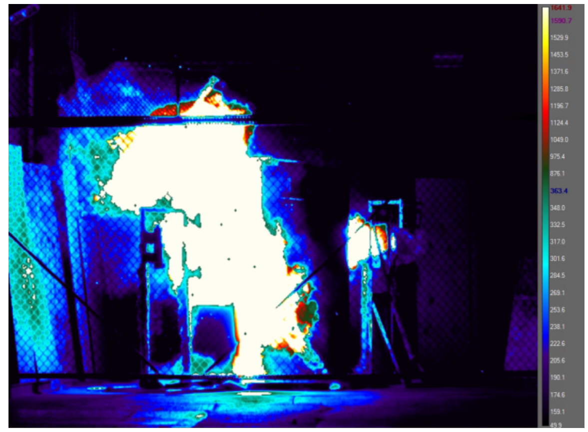
Figure 3.11-2 SWGR Test 9 Flames during Arc

Images from the IR camera, NRC FLIR SC6700, are shown in Figure 3.11-3. The FLIR camera was on auto-scale and the maximum temperature that could be detected (1545 ˚C) was within about 1 second that is typical for previous arc tests.

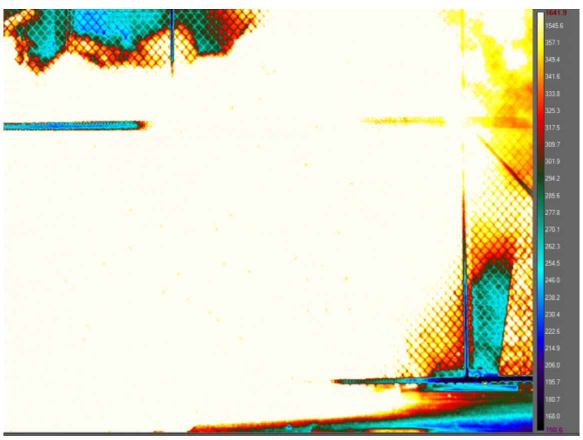
(a) Arc Start



(b) 012 sec, max temperature (1590 C)



(c) 2.1 sec (1545 ˚C max temp)



(d) 3.7 sec (0.6 sec after arc,
max temp 354 C)

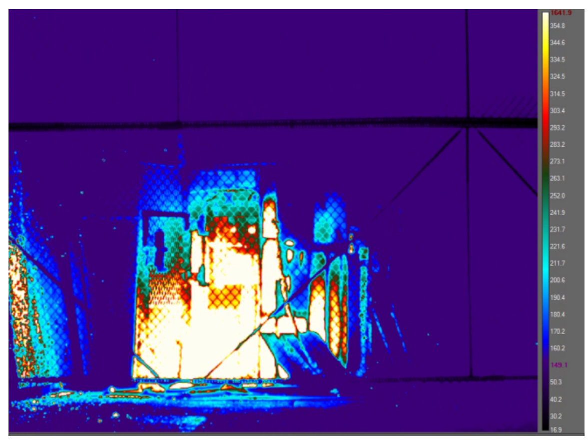


Figure 3.11-3 SWGR Test 9 Thermal Images

3.11.1 SWGR Test 9 Exterior Damage

The exterior panel damage consisted of holes in the panels where the arc attached and burned through, as shown in Figure 3.11-4. The damage was less than in SWGR Test 8, even though the arc duration and the energy were much higher in SWGR Test 9 (137 MJ vs. 89 MJ). This indicates that the additional red board enhancements in SWGR Test 9 were effective in preventing the arc from attaching to the interior side of the panel. There was charring on the exterior sides of the panels in many areas, such as the bottom panels of the front door as shown in Figure 3.11-4. There were various soot deposits on the external surfaces where smoke leaked through cracks and openings. The screens on the front and rear did not melt or fail from the flames passing through them.

Figure 3.11-4 SWGR Test 9 Exterior Damage

3.11.2 SWGR Test 9 Interior Damage

The charring of the cables indicates “medium” damage, shown in Figure 3.11-5. Since an ensuing fire was not observed, this damage was caused during the arc. As in previous tests, perhaps the open panel allowed the arc heat to escape instead of sustaining a cable fire. Post-test resistance measurements did not show shorting failures of the CV-2 cables. Additional discussion is in Section 4.2.

Figure 3.11-6 shows the interior damage to the bus bars, targets on the platform, and the ground bar. The mass loss for the copper bus bars was 6.78 kg, and the lengths changed 16-36 cm. As described earlier, the ground bar was at 30 cm from the ends of the vertical bus bars. The ground bar remained intact with severe melting on the top surface – indicating that the arc attached to the ground bar, as planned. Some of the red board peeled back but appeared to be effective protecting the cabinet sidewalls during the arc. The ground bar lost 1.27 kg of steel, which is about 20% of the copper bus bars. These losses were less than in SWGR Test 8 that had a lower energy because the ground bar in SWGR Test 8 was much closer to the bus bars. Mass loss calculations are detailed in Appendix G.

(a) In-situ Damage (b) In-situ Detail: “medium” damage

Figure 3.11-5 SWGR Test 9 Cable Damage

(a) Front View: Bus Bars, Ground Bar, and Targets

(b) Bus Bars

(c) Ground Bar

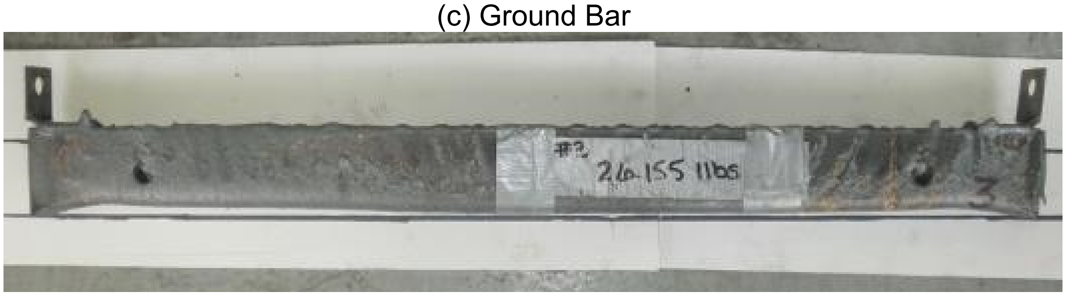


Figure 3.11-6 SWGR Test 9 Bus Bar and Ground Bar Damage

3.11.3 SWGR Test 9 Target Damage

The results are shown in Figure 3.11-7 and Table 3-11. See Figure 3.6-5 for target locations. Detailed photographs of the target damage are in Appendix F.

Cable Damage:

- T1 at the bottom front had more damage than T2 at the top front even though the distance from the arc was longer (86 vs. 48 cm) but the difference was less than SWGR Tests 7 and 8 perhaps because the longer duration increased the damage at T2. T1 had more damage because the flames and heat shoot down from the end of the bus bars as discussed in Section 4.4.
- T3 directly in the arc plasma at the level of the arc was destroyed as in all SWGR tests.
- Internal cable damage was heavy to T1 (86 cm) in the flame below the arc. Cable damage was medium out to T9 (200 cm) that was similar SWGR Test 8. Damage was not less than medium because of the higher energy. All cables that were measured passed resistance tests.
- External cable damage was heavy out to E8 (211 cm) and at least medium for all targets out to E10 (287 cm). This was more damage than any other test from the high energy.
-

Plastic damage:

- Internally the plastic damage was similar to cable damage where the plastic was destroyed at T1 (86 cm.), T3 (48 cm), and also T4 (55 cm.). There heavy damage out to T6 (80 cm) and medium damage out to T8 (120 cm).
- External damage was similar to the cable damage and was heavy out to E7 (211 cm) and E8 (211 cm). All other points were medium damage out to E10 (287 cm).
-

Other:

- There was metal coating on T3L (48 cm) in contact with the plasma similar to metal coating in the SWGR-7 and SWGR-8 but a little more severe. Some of the T3L steel was also destroyed from the high energy. Targets E7 and E8 (211 cm) also had metal coating.
- E10 had some red dots that appear to be red epoxy from the horizontal red board bar above the targets that had a burned spot caused by the flames.

(a) T3-T7E7-E10 (through screen), from front

(b) E3 through E6 from front

(c) E7 through E10 from front

Figure 3.11-7 SWGR Test 9 Target Damage and Target Numbers: Observations

Table 3-11 SWGR Test 9 Target Damage

Target (Cm)		Damage Description		Label Temp. (˚C)	Note
		Cable	Plastic		
1 86	L	5. heavy damage	6. destroyed	burnt	one cable is gone
	R	5. heavy damage	4. medium damage	burnt	
2 48	L	5. heavy damage	3. minor damage	burnt	
	R	4. medium damage	4. medium damage	burnt	
3 48	L	6. destroyed	6. destroyed	burnt	all targets are gone, part of plate s missing, melted metal is attached
	R	6. destroyed	6. destroyed	burnt	all targets are gone, plate is coated with red metal
4 55	L	5. heavy damage	6. destroyed	burnt	plastic is gone
	R	5. heavy damage	5. heavy damage	burnt	plastic is bent forward
5 64	L	5. heavy damage	5. heavy damage	burnt	
	R	5. heavy damage	5. heavy damage	burnt	
6 80	L	5. heavy damage	5. heavy damage	burnt	
	R	5. heavy damage	5. heavy damage	burnt	
7 100	L	4. medium damage	4. medium damage	burnt	
	R	4. medium damage	4. medium damage	burnt	
8 120	L	4. medium damage	4. medium damage	burnt	
	R	4. medium damage	4. medium damage	burnt	
9 200	L	4. medium damage	3. minor damage	204-210	
	R	4. medium damage	3. minor damage	204-210	
E3 239		4. medium damage	4. medium damage	burnt	
E4 239		4. medium damage	4. medium damage	burnt	
E5 160		5. heavy damage	4. medium damage	burnt	

Table 3-11 SWGR Test 9 Target Damage (continued)

Target (Cm)	Damage Description		Label Temp. (˚C)	Note
	Cable	Plastic		
E6 158	5. heavy damage	4. medium damage	burnt	
E7 211	5. heavy damage	5. heavy damage	burnt	plastic is bent backward; bottom of sample plate is coated with metal
E8 211	5. heavy damage	5. heavy damage	burnt	plastic is bent backward; bottom of sample plate is coated with meta
E9 287	4. medium damage	4. medium damage	71-77	
E10 287	4. medium damage	4. medium damage	71-77	plate surface has red dot

3.11.4 SWGR Test 9 Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 3.11-8. The thermocouple on S5 and S7 failed during the test. Notice the data is organized differently than previous charts because the targets and slugs were moved further from the cabinet to try to reduce flame contact. Exterior slugs at the front and rear were not exactly 0.91 m from the cabinet. Flames made contact with S3 through S10; additional unknown failures occurred at S6 during the arc.

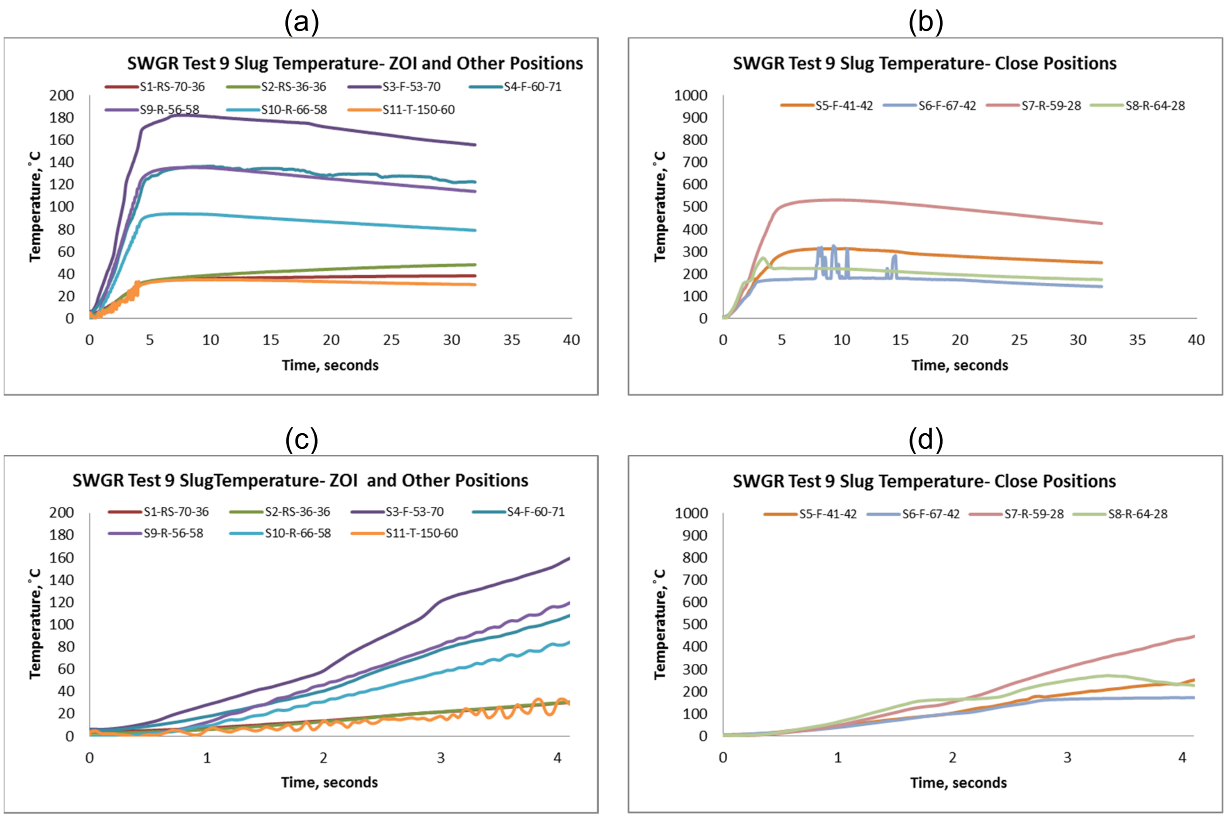


Figure 3.11-8 SWGR Test 9 Calorimetry Temperature Data

Table 3-12 shows the flux results based on the method in Appendix A using the change in temperature (ΔT) between the start and end of the arc. The flux is an average of the flux during the arc. The table shows if the slug calorimeter was hit by flames and in that case the flux is not valid. Like SWGR Test 7, the flux measured 1.5 m above the cabinet (S11) was a much lower flux than previous SWGR tests in Volume 1 [3] even though the energy was higher in Test 7.

The thermocouple on S6 failed during the test and the temperature and flux at the time of failure could be analyzed. However, the S6 flux was not valid because of flame contact.

Table 3-12 SWGR Test 9 Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comments
S1-RS-70-36	26.1	39.33	38	39.3 kW/m^2
S2-RS-36-36	28.1	42.34	48	42.3 kW/m^2
S3-F-53-70	153.6	236.36	182	Flame contact
S4-F-60-71	103.0	157.24	136	Flame contact
S5-F-41-42	244.6	380.93	313	Flame contact
S6-F-67-42	156.3	348.94	326	Flame contact Failed at 2.85 sec, evaluated at 2.8 sec
S7-R-59-28	445.4	706.50	531	Flame contact
S8-R-64-28	225.4	349.79	228	Flame contact
S9-R-56-58	119.8	183.07	135	Flame contact
S10-R-66-58	84.1	127.80	94	Flame contact
S11-T-150-60	27.4	41.26	35	41.2 kW/m^2

3.11.5 SWGR Test 9 Temperature Data

The temperatures measured by the TCs are shown in the Figure 3.11-9. These TCs were located on the external targets E7 through E10, at the rear of the cabinet. The unusually low temperatures at TC9 and TC10 indicates an error or fault - perhaps the TC detached from the plate. Additionally, TC 7 has an unknown error that starts at about 1 second.

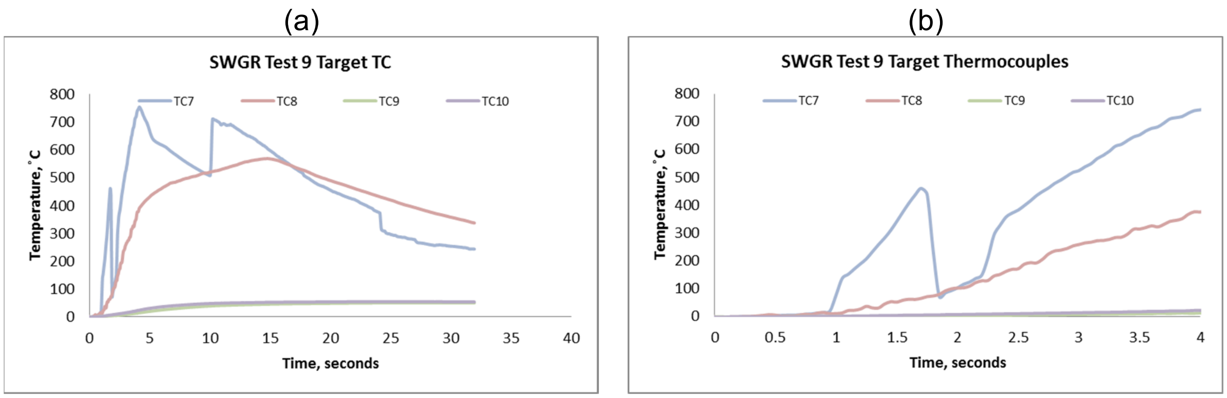


Figure 3.11-9 SWGR Test 9 Rear External Target Temperatures

Table 3-13 shows the temperatures for the target TCs at the end of the arc and the maximum during the test. "Label" is the temperature indicated by the Omega temperature label on the back of the target near the TC. The labels at TC7 and TC8 were probably burned during flame contact. The agreement between TC9 and TC10 with the corresponding label was not as good as in SWGR Test 7.

Table 3-13 SWGR Test 9 Rear External Target Temperatures

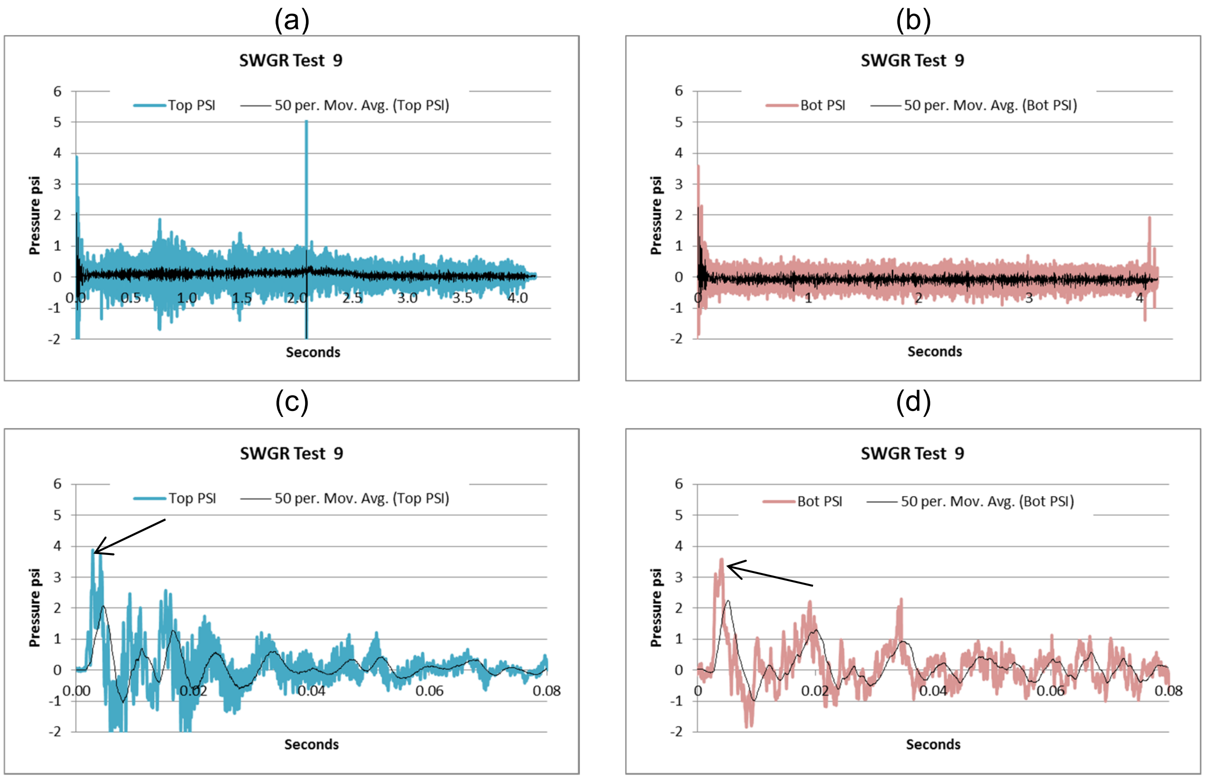
TC	Arc End ˚C	Max ˚C	Label
TC7	N/A	78 (1)	Burnt
TC8	389	750	Burnt
TC9	14	50	71-77
TC10	23	54	71-77

(1) Temperature at failure at about 1 second.

Internally all the labels were burnt but T9 (200 cm) that showed 210 ˚C (SWGR Test 8 with less energy showed 166 ˚C at T9). Externally most labels were burnt to 211 cm but E9 (287 cm) and E10 (287 cm) indicated 77 ˚C. All locations had flame contact.

3.11.6 SWGR Test 9 Pressure Data

The gauge pressures during the arc are shown in Figure 3.11-10. The maximum pressures are indicated by the arrows in the charts. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc. There was a noise spike of unknown cause in PT1at about 2.1 seconds.



PRT1 (top)
21.4 ± 0.5 kPa (3.1 ± 0.07 psi)
@ 0.0027 second

PRT2 (bottom)
21.4 ± 1.4 kPa (3.1 ± 0.2 psi)
@ 0.0039 second

Figure 3.11-10 SWGR Test 9 Pressure Data

3.11.7 SWGR Test 9 Arc Energy

The arc duration was 4 seconds with total energy of 137.3 MJ, and power of 30 to 35 MW, seen in Figure 3.11-11. The energy analysis methods are in Appendix A. The "Energy" is calculated as volts multiplied current multiplied by the time step and each time step is shown. "Energy Total" is the cumulative sum of the energy in each time step.

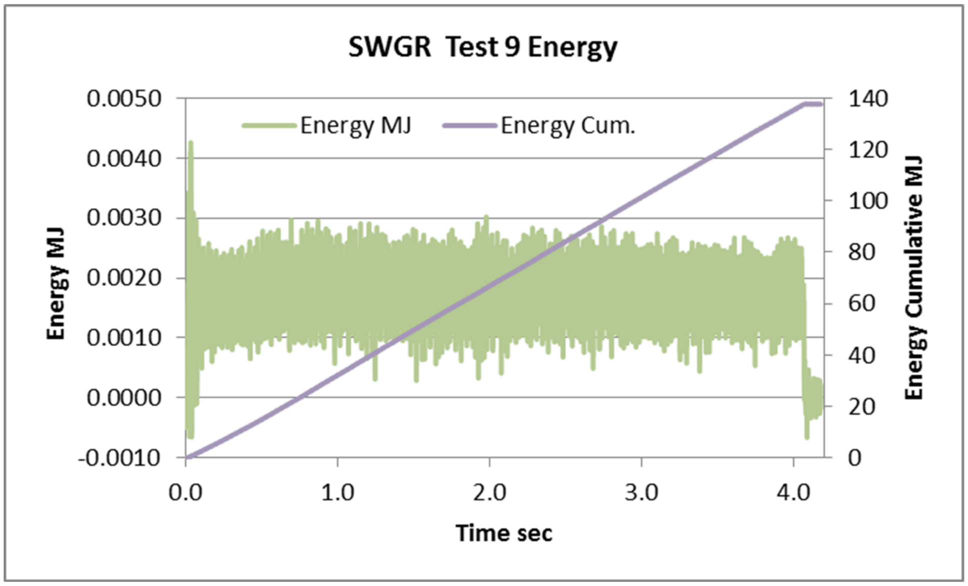


Figure 3.11-11 SWGR Test 9 Arc Energy

3.12 SWGR Test 10 Key Observations

This test was initiated at 7.1 kV and 29.5 kA and a target arc duration of 0.8 seconds with a total energy of 24.02 MJ and a power of 30 MW. The arc voltage was 949 V for the 30 cm gap. The arc sequence is shown in Figure 3.12-1.

(a) Before Arc
(b) Arc Start
(c) 0.2 second
(d) 0.5 second
(e) 0.7 second (near end of arc)
(f) 9 seconds (8.2 seconds after arc)

Figure 3.12-1 SWGR Test 10 Arc

Photos from HD cameras inside the test cell, seen in Figure 3.12-2, indicate the distance the flames traveled, and if the flames made contact with the slugs during the tests. Figure 3.12-2(c) show flame contact with S3 and S4. Flames did not escape at the rear of the cabinet and the flames did not reach as far over the cabinet in Tests 7 through 9.

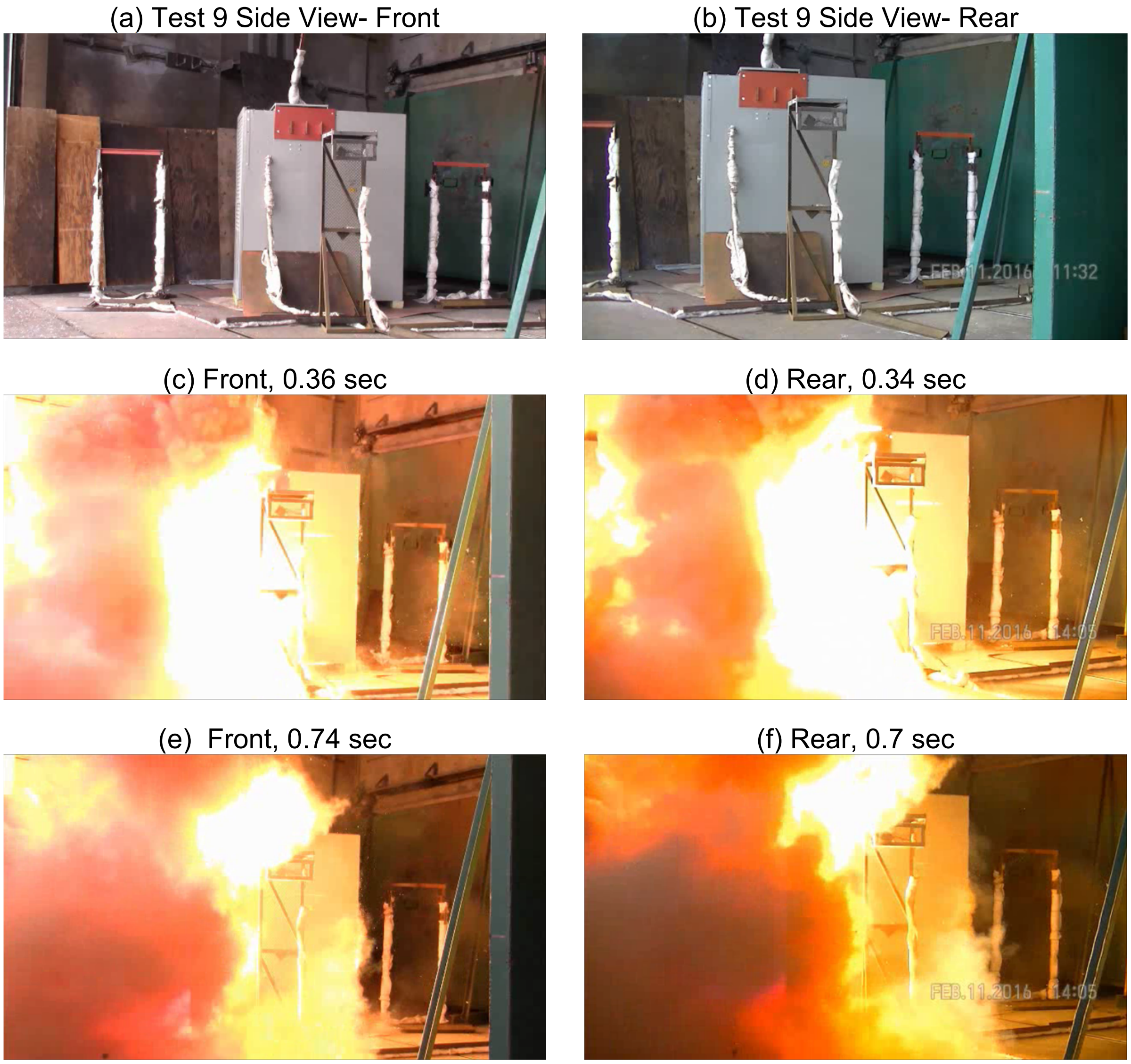
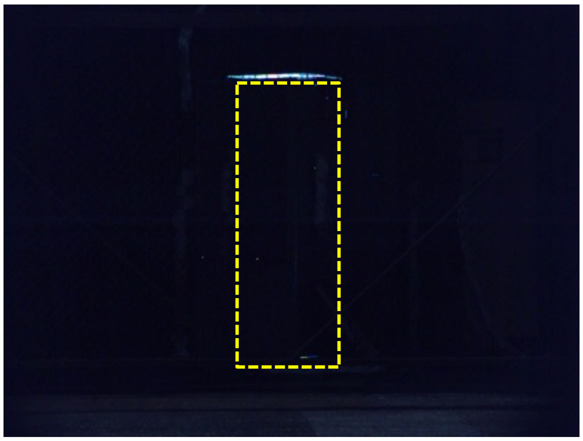


Figure 3.12-2 SWGR Test 10 Flames during Arc

During the arc, the door opened, blocking S5 and S6 from a view of the arc, as seen in the HS video in Figure 3.12-3. This explains why the values for S3 and S4 are higher even though they are both further from the arc than S5 and S6. In Figure 3.12-3(b), the door is open at the bottom but attached with a bolt on the top right. In Figure 3.12-3(c), the door is swinging open and hits the support with S5 and S6. In Figure 3.12-3(d), the door is completely open.

(a) Arc Start

(Door is outlined in yellow)



(b) 0.073 sec bolt holding top right corner

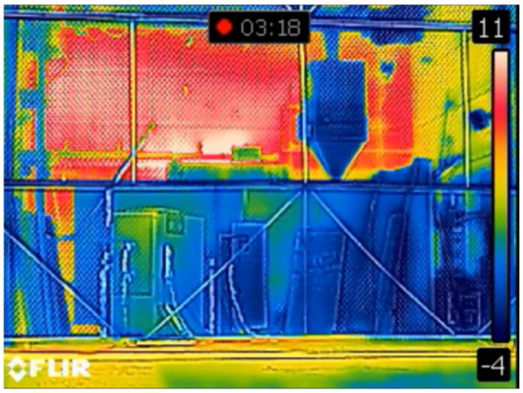
(c) 0.138 second door hits S5 and S6

(d) 0.175 second door open S5 and S6

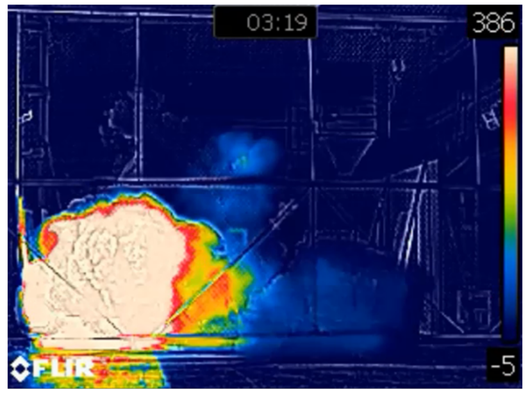
Figure 3.12-3 SWGR Test 10 High Speed Images of Door Opening

Images from the IR camera are shown in Figure 3.12-4. The IR camera was on auto-scale and the maximum temperature that could be detected (639 ˚C) was within about 1 second that is typical for previous arc tests. The IR camera measured a maximum temperature of 639 ˚C, which is less than the maximum it can measure (670 ˚C).

(a) Arc Start

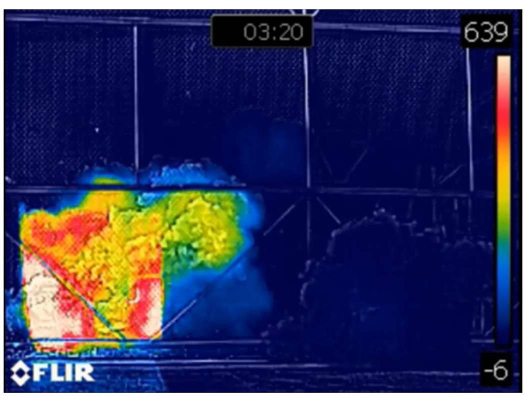


(b) 0.7 sec (just before arc end)



(c). 1.03 sec max temperature achieved,

639 C



(d) 5 sec (4.2 sec after arc)

Front door open

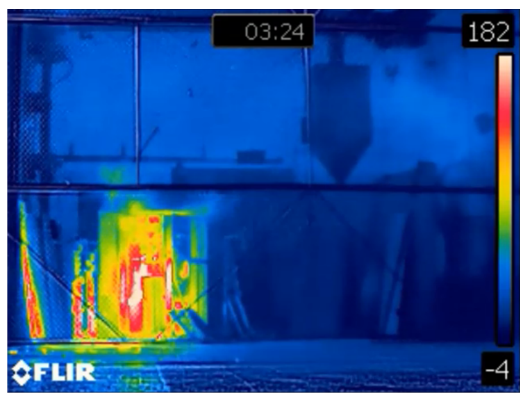


Figure 3.12-4 SWGR Test 10 Thermal Images

3.12.1 SWGR Test 10 Exterior Damage

There was no burn through the door or the side panels for the tests, as shown in Figure 3.12-5. The test was both a low duration and low energy output.

(a) Front Door (b) Right Side

Figure 3.12-5 SWGR Test 10 Exterior Damage

3.12.2 SWGR Test 10 Interior Damage

The charring of the interior cables, as shown in Figure 3.12-6, indicates “medium” damage. Since an ensuing fire was not observed, this damage was caused during the arc. Post-test resistance measurements showed CV-2 cables did not have shorting failures. Additional discussion is in Section 4.2.

(a) In-situ damage (b) In-situ Detail: “medium” damage

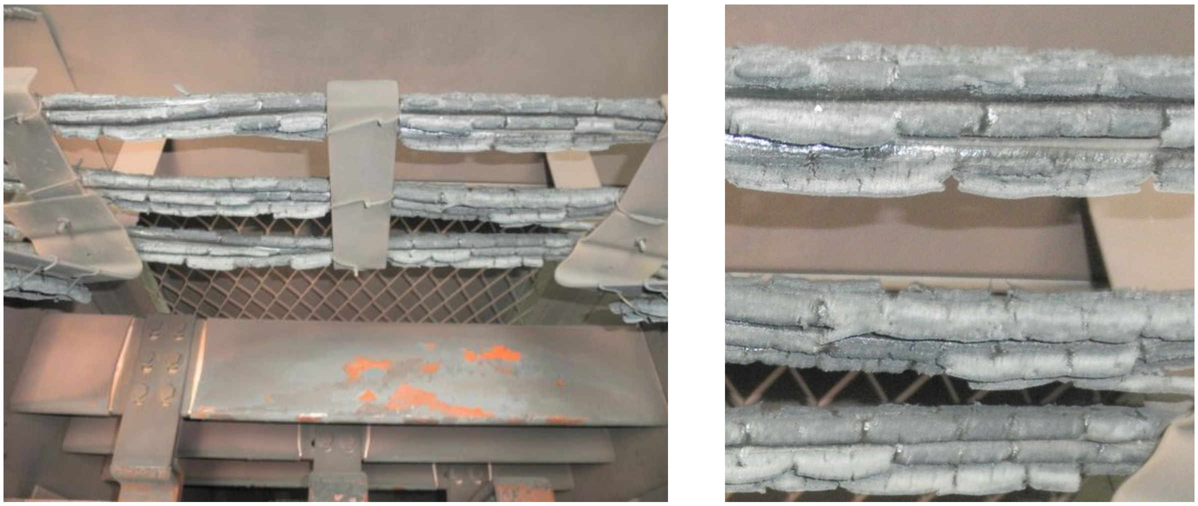


Figure 3.12-6 SWGR Test 10 Cable Damage

The damage to the bus bars is shown in Figure 3.12-7. The mass loss of the copper bus bars was 0.672 kg and the lengths changed 3-6 cm. The ground bar, which was located 30 cm from the ends of the vertical bus bars, remained in place but had minor melting because the arc duration was short. All of the interior red board remained intact. The mass loss of the steel ground bar was 0.173 kg, which is about 16% of the copper bus bar loss.

The conditions were similar to SWGR Test 9, but Test 10 was a shorter arc with less energy. The shorter duration arc explains why the mass loss was less for this test than SWGR Tests 7 through 9. See Appendix G for details on the calculations.

(a) Bus bars, ground bar, and targets

(b) Bus bars (melted metal slugs circled in red)

(c) Ground Bar

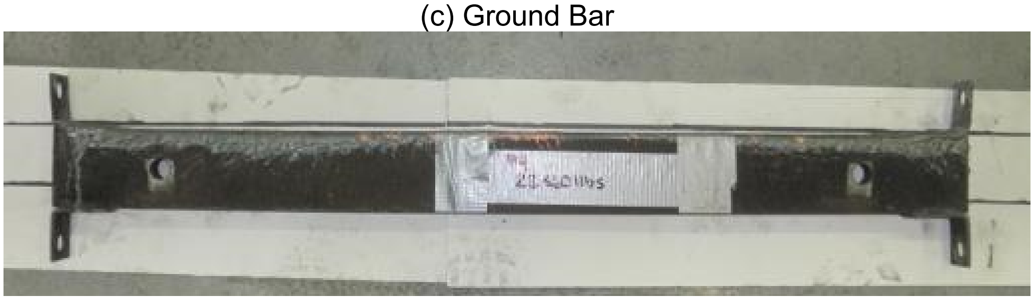


Figure 3.12-7 SWGR Test 10 Bus Bar and Ground Bar Damage

3.12.3 SWGR Test 10 Target Damage

The results are shown in Figure 3.12-8 and Table 3-14. See Figure 3.6-5 for target locations. Detailed photographs of the target damage are in Appendix F.

SWGR Test 10 was a “closed cabinet” with no openings in the front or rear. However, the front door opened at the start of the arc. The energy was intentionally much lower than the other SWGR tests. Damage is less than SWGR Tests 7 through 9 because the arc energy is much lower. The observations are in Table 4.4-6. The summary observations are:

Cable Damage:

- Internal cable damage was much lower than SWGR Test 7-9. Except for T3 in the plasma that was destroyed, the damage was medium or minor. T1 (86 cm) and T2 (48) in the front had minor damage and were similar in Test 10.
- T3 directly in the arc plasma at the level of the arc was destroyed as in all SWGR tests even with the short duration and lower energy.
- Internal damage was heavy medium to T6 (80 cm) then minor out to T8 (120 cm). T9 (200 cm) only had sooting. -All cables that were measured passed resistance tests.
- External cable damage was lower than previous tests. There was only one minor at E3 (152 cm) and all other damage was none or sooted. Large flames and did heat did not escape from the closed panels but there was some lost from the open door.

Plastic damage:

- Internally the plastic damage was similar to cable damage but T3 was not destroyed. Damage was minor out to T7 (100 cm) and sooted for T8 (120 cm) and T9 (200 cm).
- External damage was low with either sooting or none. There were two sooted points, E5 (91 cm) and E3 (150 cm). All other were “none”.

Other:

- Minor metal coating on the outside edges of Targets 3L and 3R.

(a) T3- T6 from front

(b) E3-E6 from front

(c) E7-E10 from rear (no damage)

Figure 3.12-8 SWGR Test 10 Target Results and Target Numbers: Observations

Table 3-14 SWGR Test 10 Target Damage

Target (cm)		Damage Description		Label Temp. (˚C)	Note
		Cable	Plastic		
T1 86	L	3. minor damage	No data	burnt	plastic is missing
	R	3. minor damage	3. minor damage	burnt	
T2 48	L	3. minor damage	3. minor damage	116-121	
	R	3. minor damage	3. minor damage	77-82	
T3 48	L	6. destroyed	4. medium damage	burnt	1 cable is gone, minor metal coating
	R	6. destroyed	4. medium damage	burnt	2 cables are gone, minor metal coating
T4 55	L	4. medium damage	3. minor damage	burnt	
	R	3. minor damage	3. minor damage	burnt	
T5 64	L	4. medium damage	3. minor damage	burnt	
	R	4. medium damage	3. minor damage	burnt	
T6 80	L	3. minor damage	3. minor damage	>260	
	R	4. medium damage	3. minor damage	>260	
T7 100	L	3. minor damage	3. minor damage	143-149	
	R	3. minor damage	3. minor damage	154-160	
T8 120	L	3. minor damage	2. sooted	77-82	
	R	3. minor damage	2. sooted	88-93	
T9 200	L	2. sooted	2. sooted	<41	
	R	2. sooted	2. sooted	<41	
E3 150		3. minor damage	2. sooted	160-166	
E4 150		1. none	1. none	<41	
E5 86		2. sooted	2. sooted	160-166	
E6 86		1. none	1. none	<41	
E7 211		1. none	1. none	<41	
E8 211		1. none	1. none	<41	
E9 287		1. none	1. none	<41	
E10 287		1. none	1. none	<41	

3.12.4 SWGR Test 10 Calorimetry Data

Temperatures measured at the slug locations are shown in Figure 3.12-9. The door opened during the test, blocking the arc from S5 and S6, resulting in lower-than-expected temperature measurements. Flames made contact with S3 and S4, resulting in high temperature measurements.

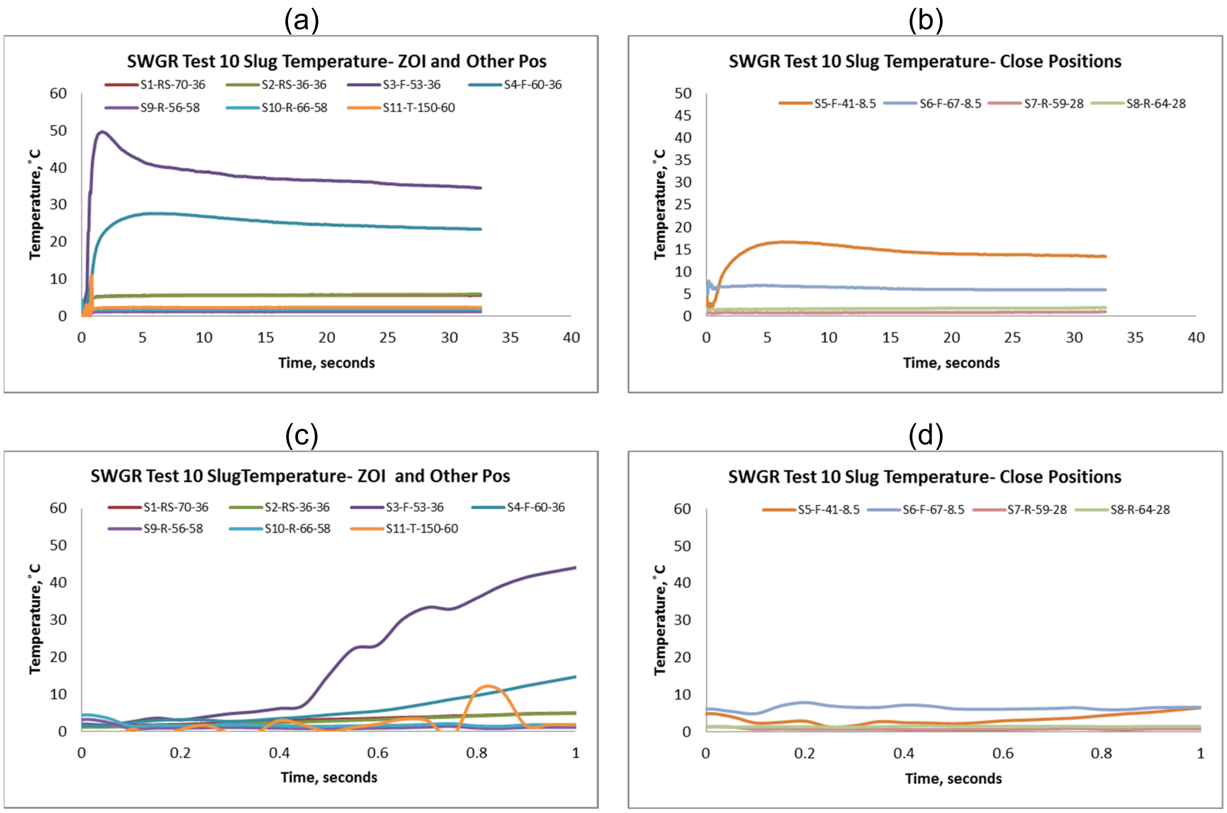


Figure 3.12-9 SWGR Test 10 Calorimetry Temperature Data

Table 3-15shows the flux calculated using the method in Section A.1 using the temperature of the calorimeter slug before and after the arc. The flux is an average of the flux during the arc. The table shows if the slug calorimeter was hit by flames and in that case the flux is not valid. The flux measured 1.5 m above the cabinet (S11) is much higher than other SWGR tests in this report and comparable to previous SWGR tests in Volume 1. It is likely that the closed cabinet forced more heat to escape the top of the cabinet.

Table 3-15 SWGR Test 10 Flux Results

Slug	ΔT (˚C)	Flux (kW/m^2)	Max T (˚C)	Comments
S1-RS-70-36	2.7	20.46	6	20.5 kW/m^2
S2-RS-35-36	3.1	23.49	6	23.5 kW/m^2
S3-F-53-36	37.7	287.30	50	Flame contact
S4-F-60-36	9.1	69.03	28	Flame contact
S5-F-41-8.5	2.2	16.68	17	Slugs are blocked by the open door as shown in Figure 3.12-3 and cannot see the flames or arc.
S6-F-67-8.5	1.0	7.58	7	
S7-R-59-28	0.0	0	1	Cabinet was closed with a plate- no flux reached the rear of the cabinet during the short duration 24 MJ arc.
S8-R-64-28	0.0	0	2	
S9-R-56-58	0.0	0	1	
S10-R-66-58	0.0	0	2	
S11-T-150-60	10.6	80.39	11	80.4 kW/m^2

3.12.5 SWGR Test 10 Temperature Data

The temperatures measured by the TCs are shown in the Figure 3.12-10. These TCs were located on the external targets E7 through E10, at the rear of the cabinet. Since the thermocouples were not exposed to heat, the measurements are low.

(a) (b)

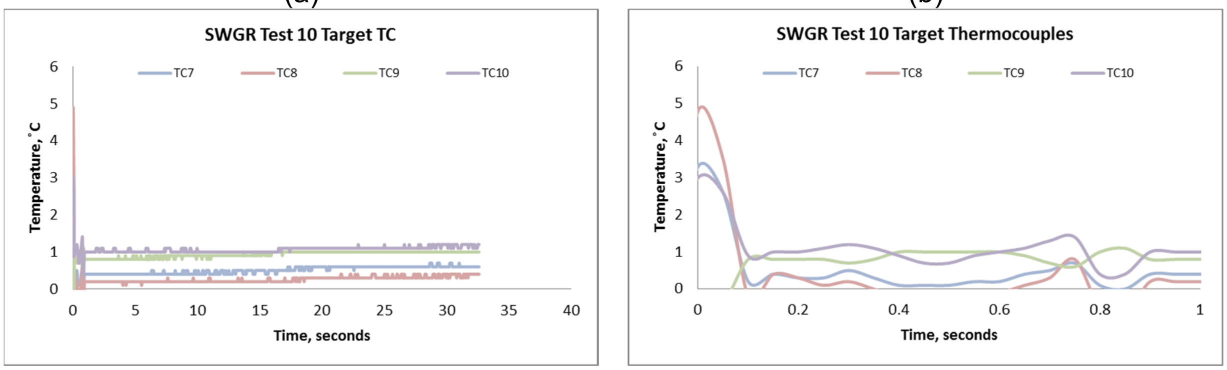


Figure 3.12-10 SWGR Test 10 Rear External Target Temperatures

Table 3-16 shows the temperatures for the target TCs at the end of the arc and the maximum during the test. "Label" is the temperature indicated by the Omega temperature label on the back of the target near the TC.

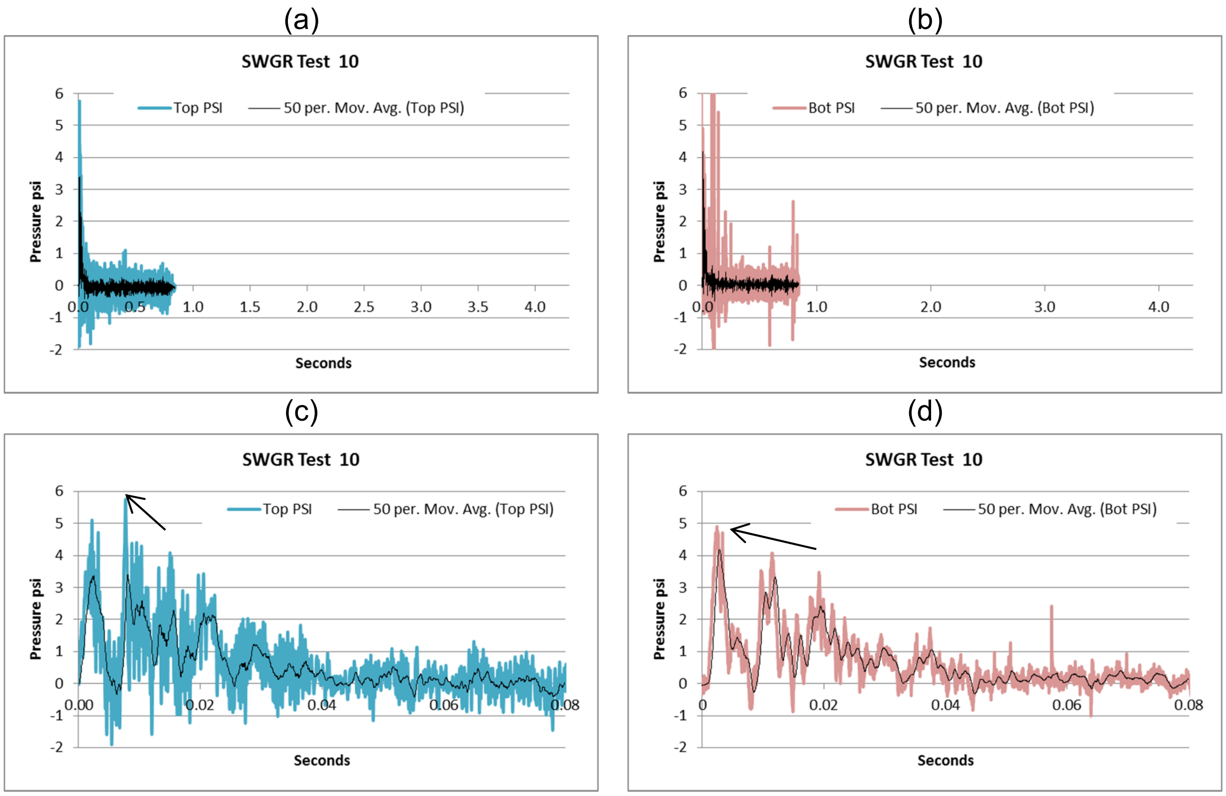
Table 3-16 SWGR Test 10 Rear External Target Temperatures

TC	Arc End (˚C)	Max (˚C)	Label
TC7	0	1	<41
TC8	-1	0	<41
TC9	1	1	<41
TC10	0	1	<41

The internal labels were burnt at T1 (30 cm) and in the range where the cable damage was medium out to T5 (100 cm). Temperature generally decreased with distance from the arc as expected. Externally all labels survived and were less than the minimum measurable 41 ˚C with two points showing 166 ˚C at E3 (150 cm) and E5 (91 cm).

3.12.6 SWGR Test 10 Pressure Data

The gauge pressures during the arc are shown in Figure 3.12-11. The maximum pressures are indicated by the arrows in the charts. The pressure analysis methods are in Appendix A and involved picking the maximum near the start of the arc then including a nominal uncertainty for the noise in the signal just before the arc.



PRT1 (top)
13.9 ± 0.5 kPa (4.8 ± 0.07 psi)
@ 0.0076 second

PRT2 (bottom)
33.1 ± 1.4 kPa (4.8 ± 0.2 psi)
@ 0.0024 second

Figure 3.12-11 SWGR Test 10 Pressure Data

3.12.7 SWGR Test 10 Arc Energy

The arc duration was 0.8 seconds with total energy of 24.02 MJ, and power of 30 MW, seen in Figure 3.12-12. The energy analysis methods are in Appendix A. The “Energy” is calculated as volts multiplied current multiplied by the time step and each time step is shown. “Energy Total” is the cumulative sum of the energy in each time step.

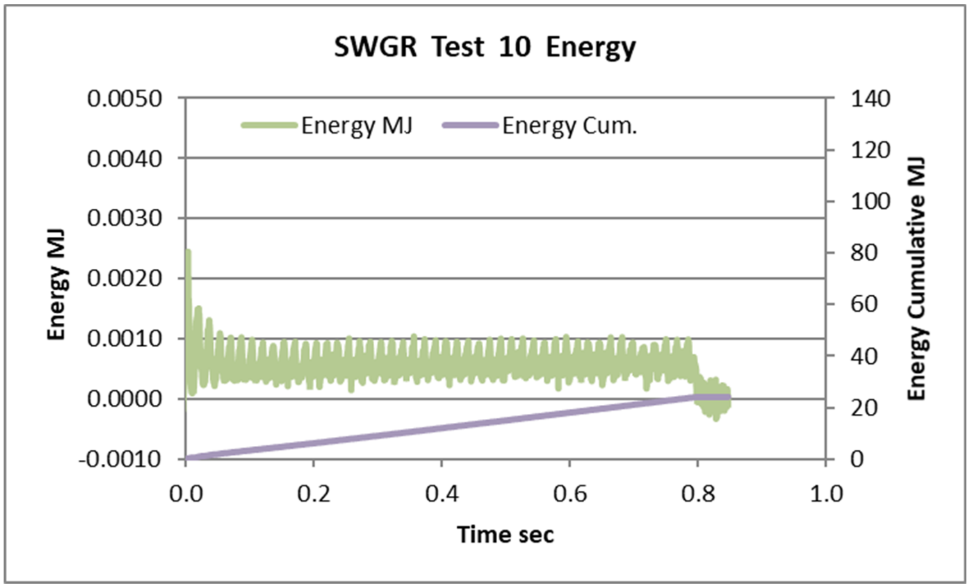


Figure 3.12-12 SWGR Test 10 Arc Energy

3.13 SWGR Tests 7 through 9: Summary of Electrical Conditions

Table 3-17 shows the electrical conditions measured by KEMA.

Table 3-17 SWGR Tests 7 through 9 Electrical Results (1)

Test	OCV (kV)	Phase	Sym (kA)	Sym @End (kA)	Peak (kA)	Curr. Dur. (sec)	Arc Energy (MJ)	Freq @End (Hz)		Phase Arc Volts
7	7.1	A	25.7	22.9	68.4	2.801	33.80	50.2		A-N 551
		B	26.2	23.5	60.5		32.10			B-N 582
		C	25.6	22.8	45.8		23.30			C-N 421
		AVG	25.8	23.1			Σ88.2			AVG L-L 897
8	7.1	A	25.4	22.7	67.4	3.471	35.20	49.8		A-N 546
		B	26.1	23.6	59.0		32.40			B-N 478
		C	25.6	22.3	47.1		21.50			C-N 389
		AVG	25.7	22.8			Σ89.1			AVG L-L 816
9	7.1	A	25.1	23.3	71.7	4.062	51.40	44.6		A-N 583
		B	26.9	24.1	59.0		52.80			B-N 635
		C	24.4	23.4	49.1		33.10			C-N 456
		AVG	25.5	23.6			Σ137.3			AVG L-L 966
10	7.1	A	25.7	25.2	68.2	0.804	9.51	57.3		A-N 585
		B	25.7	26.5	59.2		8.51			B-N 675
		C	25.3	25.2	46.7		6.0			C-N 383
		AVG	25.6	25.6			Σ24.02			AVG L-L 949

(1) See Table 2-15 for abbreviations and acronyms used in this table.

3.14 SWGR Tests 7 through 9 Qualitative Summary

1. Ensuing Fires: There were no tests causing sustained ignition of cables. Perhaps the open panels in SWGR Tests 7 through 10 and the open front door in SWGR Test 10 allowed the residual arc heat to escape. Although the CV-2 cables did not fail based on resistance testing, all showed “medium” damage based on the damage criteria in Section 1.4. The cable damage was similar over the broad range of arc energies and this is discussed more in Section 4.1.

2. Damage: The damage was consistent with previous tests in Volume 1. However, the arc in SWGR Test 7 attached to the sidewall rather than the ground bar and caused large holes through the exterior panels. There were also breaches in the panels in SWGR Test 8. Red board was added to prevent the arcing to the walls in SWGR Tests 9 and 10. Other damage was similar to previous SWGR tests. Cable/plastic target damage and bus bar damage are discussed in the results sections for each test.

a. Bus Bar Damage
   - The bus bars burned as expected with mass losses consistent with the arc energy. The ground bar mass loss was highest for SWGR Test 8 where the bar was only 6 inches from the ends of the bus bars (Tests 7, 9, and 10 were nominally 12 inches). See Appendix G.

b. Cable Target Damage:
   - Cables on the targets were destroyed at all T3 (48 cm) targets that were in the arc plasma. Cables were also destroyed at T9 the Test 9 (highest energy) 86 cm in the front below the arc.
   - The bottom front targets had more damage than the top front even though the distance from the arc was longer (86 vs. 48 cm). This is because the flames and heat shoot down from the end of the bus bars as discussed in Section 4.4. Evaluation of arc damage needs to consider the direction of the plasma from the end of the bus bars.
   - Internal cable damage was heavy out to 86 cm in the front below the arc from the arc due to the high energies of Test 9. At the level of the arc cable damage was heavy to 80 cm from the arc. Medium damage was out to 200 cm. The cabinet did not have major internal obstructions that stopped the heat and flame like the DP cabinets.
   - External cable damage was heavy out to 211 cm that is outside the ZOI but all cables passed resistance tests.

c. Plastic Target Damage:
   - Similar to the cables, plastic samples on the targets were destroyed at T3 and at the T1 position below the arc in the higher energy Tests 7-9.
   - Internal heavy plastic damage was seen out to 80 cm from the arc.
   - External heavy damage was seen out to 211 cm from the arc. Medium damage was out to 287 cm.
   - Plastic melted and partly pyrolized but did not appear to burn freely in any case.

d. Temperature labels:
   - Internally most of the temperature labels were burned. This is much more severe than the DP tests where some labels survived. This may be because the SWGR is totally open and there are no structures to block the flames like there are in the DP.
   - Externally most all of the labels were burnt from heavy flame contact out to 211 cm from the arc. So, it was not possible to compare label data with the TC data near Targets E7-E10.

e. Other:
    - Metal coating and sputter was observed in all SWGR Tests but only Target 3L in SWGR Test 9 with the highest energy had heavy metal coating. Metal coating on SWGR Test 8, Target 8 at 211 cm was the maximum distance from the arc for all the tests.

3. Calorimetry: It was difficult to make direct flux measurements of the arc because of flame impingement. The measurement at 1.5 m above the cabinet (S11) in Test 3 were the only calorimeter results that could be compared throughout the Volume 1 [3] and FY15 tests and are shown in Table 3-18. For SWGR Tests 7 through 9, the flux was much lower even with higher energy because the heat and flames in these tests escaped through the open cabinet front door and rear panel rather than through the vent at the top of the cabinet. Slug 11 in the FY15 did not have a good view of the radiation from the flames as it did in previous tests. For SWGR Test 10 where the front and rear panels were closed, more heat and flames escaped from the top and S11 measured the highest flux, closer to the values in SWGR Test 3 in Volume 1. SWGR Test 3 was selected for comparison because it had the most similar conditions to the FY15 tests.

Table 3-18 SWGR Top Calorimeter Flux Compared to Previous Tests

SWGR Test	Energy (MJ)	FLUX (kW/m^2)	ΔT (˚C)	Flux Ratio FY15 SWGR Test/ SWGR Test 3
SWGR Test 3 (2013)	59.9	107.3	51.2	-
SWGR Test 7	88.3	17.0	7.8	0.16
SWGR Test 8	89.1	29.9	17.0	0.27
SWGR Test 9	137.3	41.2	27.4	0.38
SWGR Test 10	24.0	80.5	10.6	0.75

4. Temperature: The TC on the external cable/plastic targets in the rear of the cabinets appeared to work but had inconsistent agreement with the temperature labels. Temperatures measured by the more reliable TC's behaved as expected with maximum temperature as high as 489 ˚C and 750 ˚C in Tests 7 and 9, respectively, at measurements closest to the arc. Test 9 had higher energy and therefore higher temperature and there was also additional flame contact. Test 8 had lower maximum temperature than expected (208 ˚C maximum); the reason is unclear. In all tests the maximum temperatures occurred within 5 seconds after the arc quenched. Test 10 with a closed rear panel had only 1 ˚C temperature change.

5. Pressure: The measured pressures were higher than previous SWGR tests. This is because in previous tests the arc was in a separate compartment that had small vents for the flow to get to the front of cabinets where the Pressure Transducers (PRT) were located. In the current tests, there were no internal structures, so the shock wave from the arc ignition could travel directly and quickly to the PRT. As discussed in Section 2.13 the high pressure indicates the pressure is from the arc shock wave that is not affected by the cabinet ventilation (open or closed).

6. Arc Energy and Power: Arc energies and power were higher than previous tests in Volume 1 because of the higher arc voltage.

7. Arc Voltage: Pretest calculations to set the arc voltage appeared to be wrong because the wrong arc gap was assumed in the analyses of previous SWGR tests. So, the position of the ground bar was too far from the bus ends and the arc voltage was in the range of 900-1000 volts rather than the target 600 volts. Arc voltage slowly increased in all tests that supports the theory that the arc gap increases as the bus material is consumed and the arc voltage increases.

8. Arc Observations: The arc was successfully viewed in SWGR Test 9 using the HS camera and IR filters as discussed in Section A.5. The arc was also observed in SWGR Test 8 but not directly. In Test 8, it appears the interface of the exterior panels opened slightly during the arc creating a slit that acted like a slit camera and projected the arc onto the metal wall in the rear of the test cell. The reflection of the arc light off the metal wall was detected by the HS camera with the filter. The direct view of the arc was too high intensity to see the arc but the slit reduced the intensity that was further reduced by the reflection from the metal wall. Note the slit causes an inverted image that has not been corrected in Figure 3.11-1.

   The figures show the frame number for the videos and the frames are 1,850 μsec for Figure 3.11-1 and 2100 μsec for Figure 3.11-2.

   The arcs in Figure 3.11-1 and Figure 3.11-2 sweep around at 60 hz in an inverted cone shape with the point attached at the ends of the bus bard for each phase. The 60 hz electrical frequency is confirmed by Frames 95 and 99 in Figure 3.11-2 that show the bright spot associated with the positive and negative peak that would represent a half-cycle. The time difference in frames 99 and 95 is 4 frames x 2100 μs per frame = 8400 μs for a half cycle or 16,800 μs for a full cycle which is approximately 60 hz (59.52 hz).

   The plasma discharge and arc point downward from the ends of the bus bars. This video clarifies that the arc is between the bus bars and the ground bar and not bus-to-bus as commonly believed. The ground bar where the arc from each phase attaches completes the 3-phase circuit.

9. External conditions: SWGR Test 9 had the maximum slug calorimeter temperature for all tests for the front S5 location at 1.04 m from the front of the cabinet (close to the NUREG/CR-6850 postulated ZOI) that was 313℃ that decreased to less than 200℃ in about 60 seconds (see Figure 3.11-8, the time to recovery is based on extrapolation from 32 seconds). As discussed in Section 4.1, the maximum distance for metal sputtering was to Target E8, 365 cm from the arc. Based on video reviews the flame extended to 353 cm from the front of the cabinet.

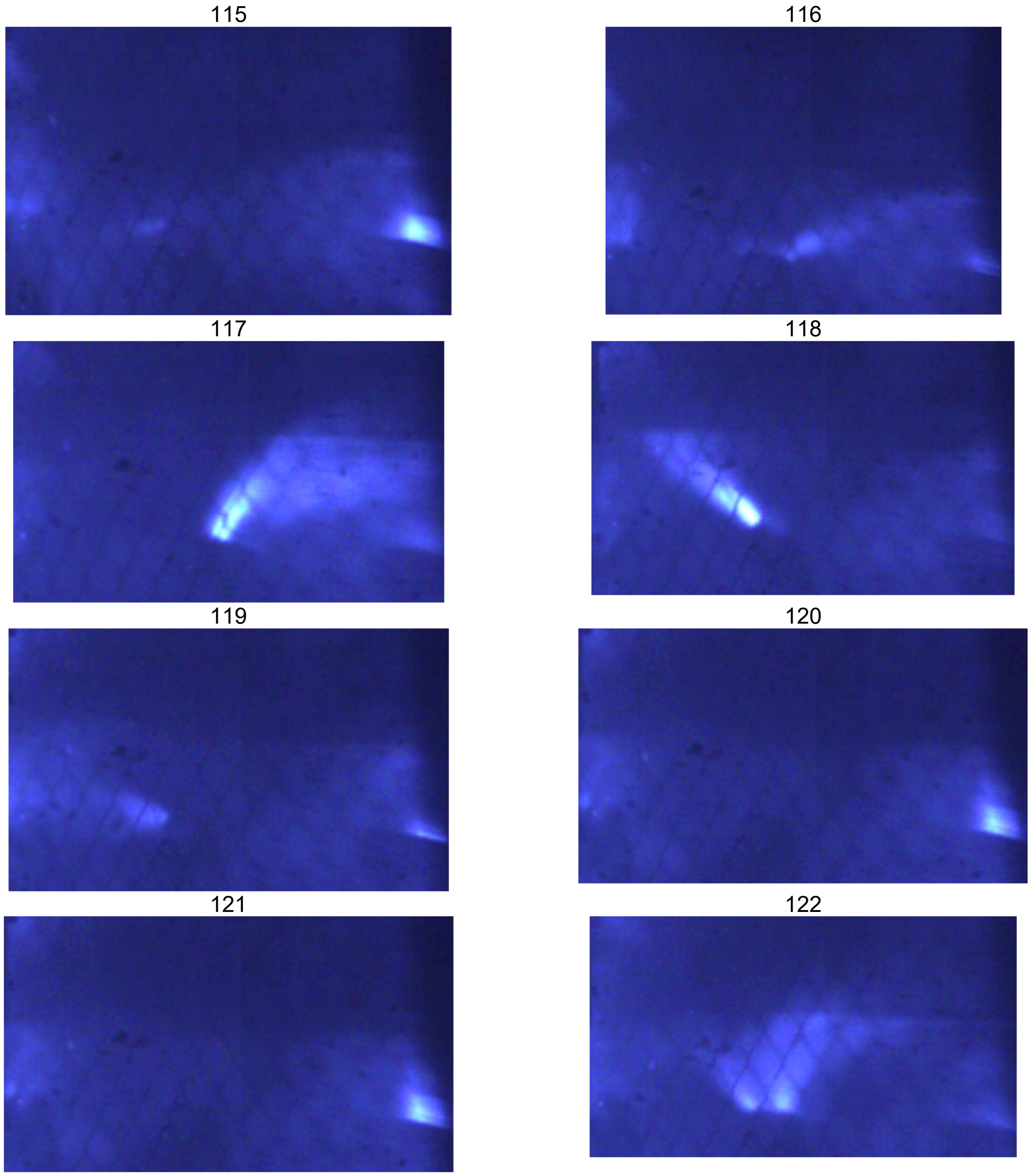


Figure 3.14-1 SWGR Test 8 Arc Observation by HS Camera Frame

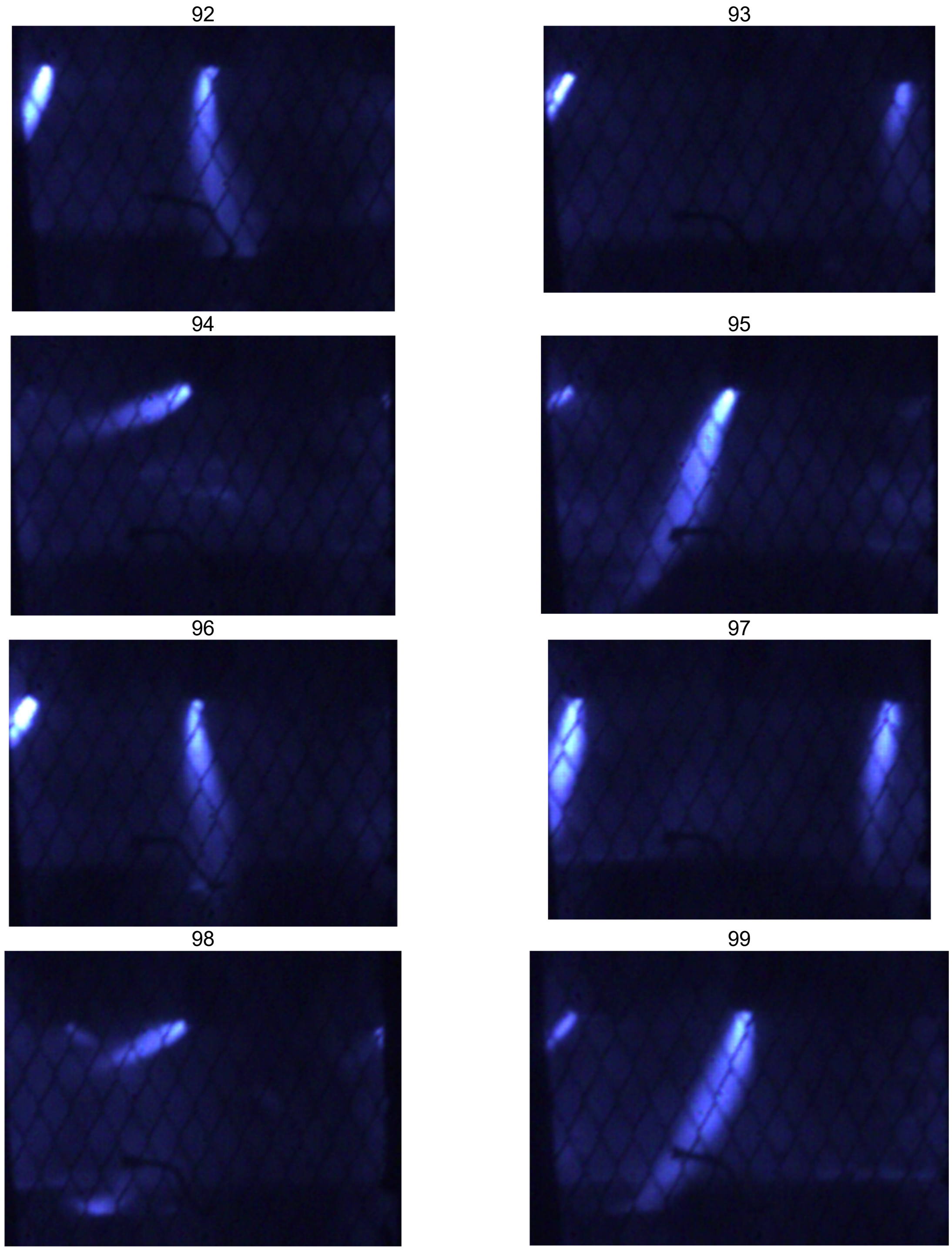


Figure 3.14-2 SWGR Test 9 Arc Observation by HS Camera Frame

4 OBSERVATIONS

This section discusses observations and insights within the NRC ZOI from NUREG/CR-6850, Appendix M. Currently, this zone is identified to be 0.91 m from the sides of the cabinet and 1.5 m above the cabinet.

4.1 Test Observations in Near Region

The key observations within 0.91 m from the sides of the cabinets are shown in Table 4-1. The maximums for the slug temperatures, flame distance, and metal sputter occurred for DP Test 9 and SWGR Test 9 that had the highest arc energies. The table has these parameters:

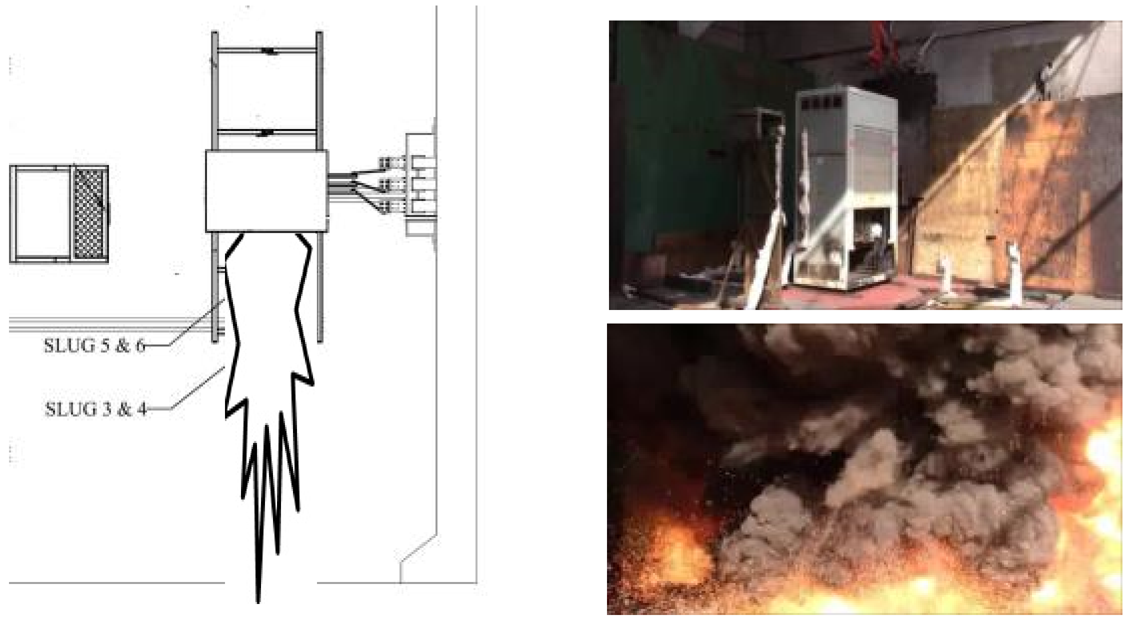
- The "Maximum. Slug Temperature" shows the maximum temperature achieved by the slug calorimeter as a bounding temperature that may be achieved by an object at that distance.
- The "Maximum Flame Distance" is the maximum distance the flames extended from the cabinet openings based on the photos in Figure 4.1-1. Since the arc was close to the front of the cabinet, flames extended furthest in this direction. In both tests the flames extended further than 0.91 m).
- The "Maximum. Metal Sputter Distance" is the maximum distance from the arc where metal coating was observed on a cable/plastic target. Hot metal and embers can cause external fires or other damage. See Section 4.5.

Table 4-1 Arc Effects 0.91 m from Cabinet

Parameter	DP Test 9	SWGR Test 9
Arc Energy MJ	66.8	137.3
Maximum Slug Temperature at 0.91 m		
Position	S6 Front	S5 Front
Max. Temperature ℃	902℃	313℃
Maximum Flame Distance		
Position	Front	Front
Distance (cm from cabinet)	193 cm	353 cm
Maximum Metal Sputter Distance		
Position	E6 Front	E8 Rear
Distance (cm from arc)	330 cm	365 cm

(1) Based on extrapolation of cooling curve from 32 seconds

(a) DP Test 9 Maximum flame



(b) SWGR Test 9 Maximum flame

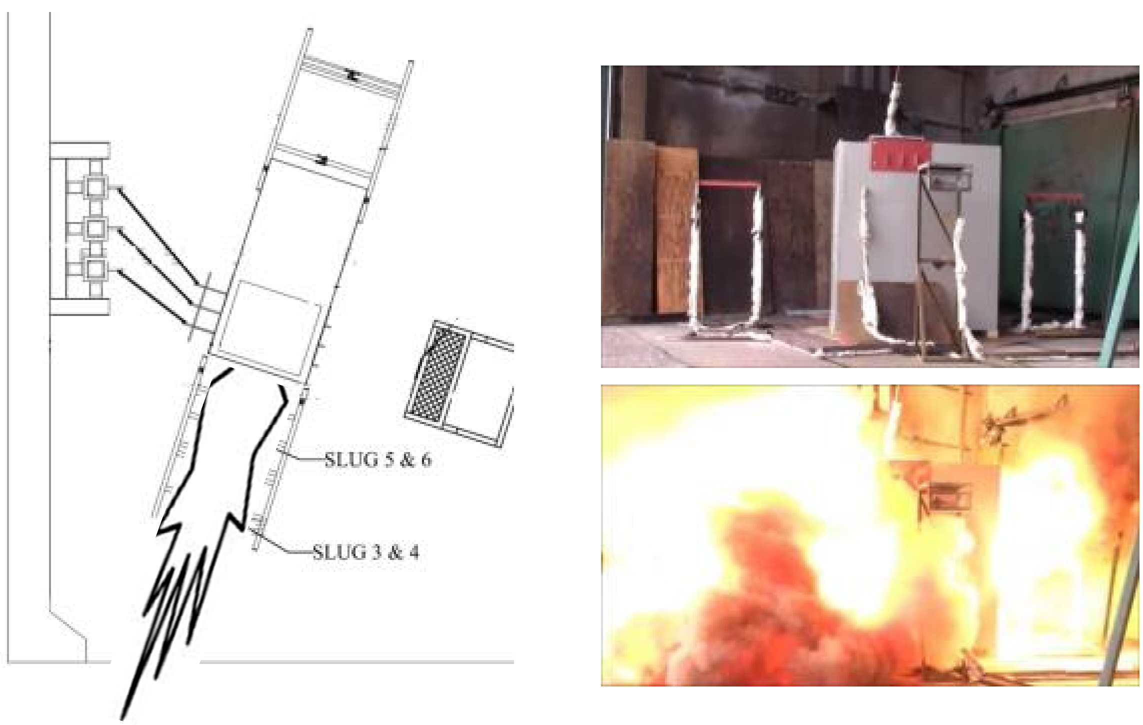


Figure 4.1-1 Maximum Flame Distance

4.2 Cable Damage Observations

The key insight from the S/NRA/R FY15 (February 2016) tests is that arc flames easily reach past 0.91 m from the open cabinets. This condition simulates a panel being lost during a HEAF event (a worst-case condition). However, the 2016 cable damage results indicate that cables are resistant to failure from heavy damage during strong flame and plasma contact. This includes cables on the targets and the interior cables in the top front of cabinets. Table 4-2 shows the cable failures for the interior and exterior cable targets based on post-test conductor to conductor manual resistance measurements. The table includes results for cables that had "minor" to "heavy" damage and were probably contacted by flames. "Destroyed" cables are also listed but these were typically missing insulation and the conductors were assumed to be failed by conductor-to-conductor shorting and were not resistance tested.

Only 1 cable sample failed by conductor-to-conductor shorting in the 387 cables tested with minor to heavy damage. It is somewhat surprising that the one failure was for a cable with only "medium" damage. For the targets, the table shows that as the energy increases the number of cables in the higher damage categories increases as expected.

The interior cable bundles inside the SWGR cabinets (see Figure 4.2-1) had 0 failures for the 70 cables tested that had minor to heavy damage. Photographs of the interior cable damage are in the "Interior Damage" subsection for each test in Chapters 2 and 3. It is interesting that all of the internal cables had similar damage for arc energies ranging from 24-137 MJ as shown in Figure 4.5-1. Like the internal cables, damage for both the T2 targets at the internal cable location was also "medium" for all the SWGR Tests except SWGR Test 9, T2L was "heavy". The reason that the damage was the same for all arc energies is not clear. Perhaps the flux at this position above the arc is very low for all tests because the heat and flames are projected downward from the ends of the bus bars as discussed in Section 4.4.

Notice that these results are for cables that behave like thermoset (TS) materials and the results may be different for thermoplastic (TP) materials that were not tested.

Table 4-2 Target and Interior Cable Resistance Test Results

Test	Energy (MJ)	Number of Cables Damaged by Damage Category							
		Cable/plastic Targets				Interior Cable-Bundles			
		Minor	Medium	Heavy	Destroy	Minor	Medium	Heavy	Destroy
DP 7, 7A	Σ4.9	12	0	0	0	10	0	0	0
DP 8	39.7	6	39	3	0	0	0	0	10
DP 9	66.8	6	27 (1)	15	6	0	0	0	10
SWGR 7	88.2	18	42	28	6	0	15	0	0
SWGR 8	89.1	3	66	9	6	0	15	0	0
SWGR 9	137.3	0	33	35	6	0	15	0	0
SWGR 10	24.0	33	12	0	0	0	15	0	0
Total	-	78	219	90	24	10	60	0	0
Failed	-	0	1	0	4 (2)	0	0	0	20 (2)

(1) The failed cable was on Target E6. Failure for cables is manually measuring zero resistance conductor-to-conductor with an ohmmeter

(2) Destroyed cables are assumed to be failed by conductor-to-conductor shorting and were not resistance tested post test. Destroyed cables were within 50 cm of the arc.

(a) SWGR Test 7: 88.2 MJ, medium damage

(b) SWGR Test 8: 89.1 MJ, medium damage

(c) SWGR Test 9: 137.3 MJ, medium damage

(d) SWGR Test 10: 24.0 MJ, medium damage

Figure 4.2-1 SWGR Test Interior Cable Bundle Damage

4.3 <u>Plastic Damage</u>

There were no ignitions of the PVC plastic targets within 0.91 m in the FY15 tests. The plastic targets melted and partly pyrolyzed but did not appear to burn freely in any internal or external location, including locations close to the cabinet.

4.4 <u>Arc Directional Effects</u>

In the SWGR tests 7 through 10, the internal T1 targets within with the fire plume at the bottom of the cabinet in the front always had more damage than the T2 targets at the top of the cabinet even though the bottom target T1 was further from the arc (86 cm. vs. 48 cm.) These results indicate that the position of the bus bar ends and the direction of the discharged plasma and heat may have a large effect on the damage.

It appears the plasma and heat were directed downward from the end of the bus bars toward T1 as shown figuratively in Figure 4.4-1a. The IR image in Figure 4.4-1b that shows the plume escaping the cabinet near the floor is additional evidence of the flames and heat are directed downward in the SWGR tests. Additional IR images in the SWGR test results sections also show the effect.

These results indicate that the position of the bus bar ends and the direction of the discharged plasma and heat may have a large effect on the damage. The ZOI distances and damage criteria may need to include “directional effects” that consider the direction of the discharged plumes that are forcefully pushed away from the ends of bus bars.

(a) Downward Plasma/Heat Motion (b) Test Evidence SWGR Test 7

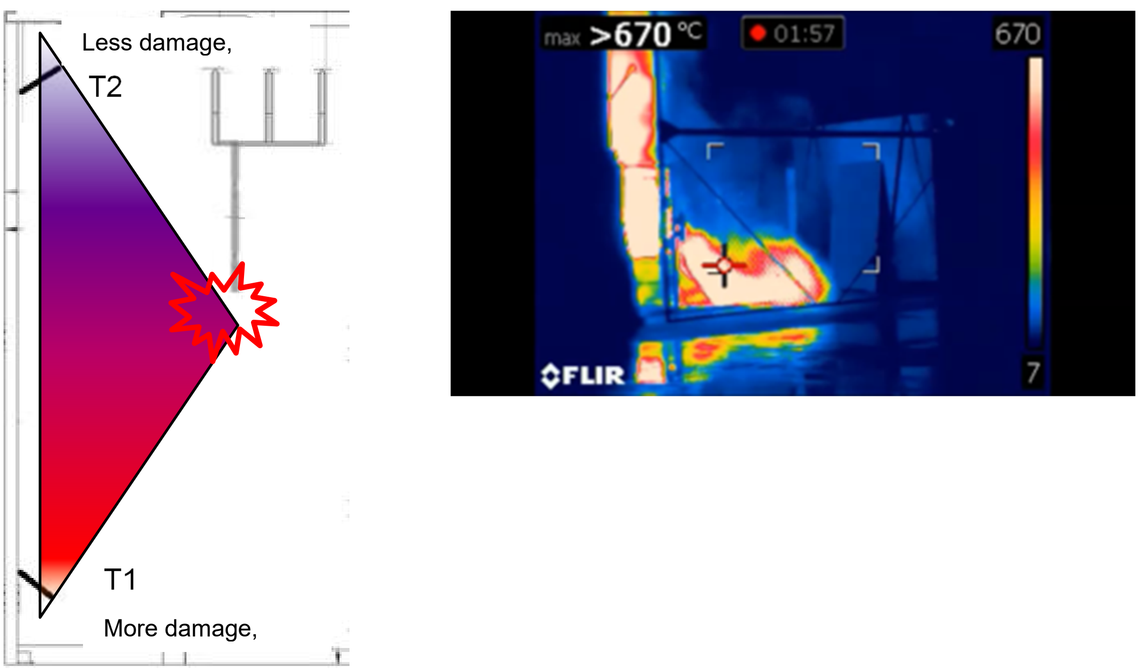


Figure 4.4-1 Downward Plasma and Heat Direction

4.5 Metal Sputtering and Coating

The arcs created metal vapor that coats the targets up to 211 cm from the arc. The metal coating of nearby items can result in shorting of electrical equipment, the consequences of which may be worse than the consequences of a fire. During the arc, metal is sputtered from the busbars and steel cross bar behind the bus bars in the DP tests and the bus bars and steel ground bar in the SWGR tests. Metal coating was observed on the cable/plastic targets, the interior of the cabinet, the exterior concrete floor, and the slug calorimeter mounts. Typical observations are in Figure 4.5-1.

- Figure 4.5-1a shows the heaviest coating observed in all tests in DP Test 8 where the coating on Target T2L near the arc has a coating 1-2 mm thick that could be removed from the target as a solid piece that is shown below the target in the figure.
- Figure 4.5-1b shows heavy coating in SWGR Test 9 Target T3L near the arc. The metal target was very hot as indicated by the loss of some of the target metal. The sputtered metal coating flowed from the hot target and formed a large metal mass to the right of the target as shown in the figure.
- Figure 4.5-1c shows the lighter coating on external targets in this case for SWGR Test 9 Target E8 that was 211 cm from the arc and was the maximum distance metal sputter was observed on a target.
- Figure 4.5-1d shows metal that coated the lower Unistrut mount in front of the cabinet in DP Test 9. The metal coating had been removed from the Unistrut surface and placed on the concrete floor for the photograph.
- Figure 4.5-1e through 4.5-1f show the sputter inside of the cabinets that is composed of small droplets of molten metal up to about 4 mm diameter that are scattered on the inner surfaces.

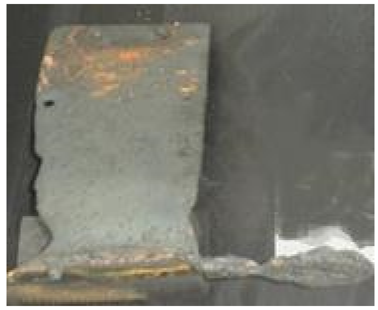
Sputtered metal (splatter) is also shown on many of the DP and SWGR cable/plastic targets in Appendix F. The observations are summarized in Table 4-3. Internal DP coatings close to the arc were more severe than SWGR probably because the ground bar in the SWGR was below the red board instrument mount where the targets were located, and the red board blocked some of the sputtered metal. Also, the metal bar in the DP where the arc attached was at the height of the targets and in direct view very close to the metal bar.

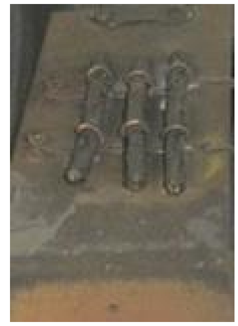
The key observation is that other external failures such as shorting in nearby electrical equipment should be included in addition to fires. The consequences of a short may be worse than the consequences of a fire. NRC guidance in NUREG/CR-6850 requires the assumption of worst-case failure modes and also for the effects of smoke that is similar to metal sputter.

(a) DP Test 8 Target T2L

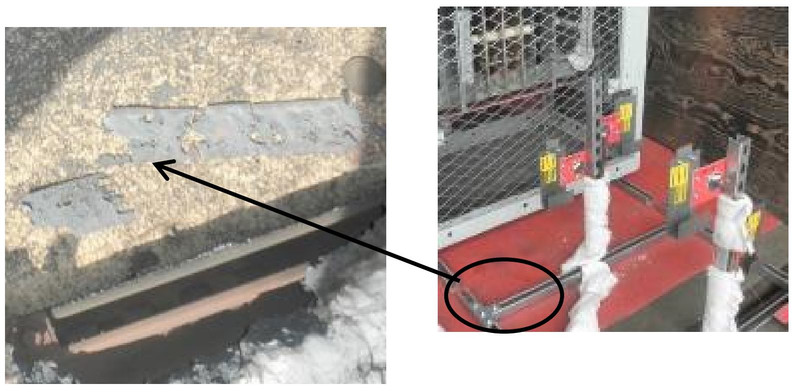
(b) SWGR Test 9 Target T3L

(c) SWGR Test 9 Target E8





(d) Coating Outside DP Test 9



(e) SWGR Test 7 (from rear)

(f) SWGR Test 8 Metal on floor (from rear)

(g) Metal sputter SWGR Test 9 (from front)

Figure 4.5-1 Metal Sputtering and Coating

Table 4-3 Metal Sputter on Cable/Plastic Targets

Test	Observation
DP 7, 7A	No coating, no steel burning or sputter
DP 8	Heavy internal coating to 48 cm at arc level External coating out to E8 (62 cm)
DP 9	Heavy internal coating to 48 cm at arc level External coating out to E6 (109 cm)
SWGR 7	Metal internal coating on to 80 cm on instrument mount No external coating
SWGR 8	Minor metal coating to 48 cm at arc level No external coating
SWGR 9	Minor metal coating on 48 cm at arc level (heavier than SWGR 7 and SWGR 8) External coating out to E7, E8 (211 cm)
SWGR 10	Minor coating on outer edges of Targets 3L and 3R (48 cm) No external coating (cabinet was closed)

5 REFERENCES

1. “Responses to the Tohoku-Pacific Ocean Earthquake and Tsunami at the Onagawa Nuclear Power Station and Tokai No. 2 Power Station”, Japan Nuclear Safety Instifiute available at http://www.genanshin.jp/english/archive/disastersitereaction/data/report_OnTk.pdf (as of 2020-04-28).

2. NUREG/CR-6850 and EPRI 1011989, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 1: Summary and Overview and Volume 2: Detailed Methodology.” Electric Power Research Institute, Palo Alto, CA and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES) Rockville, MD, September 2005.

3. NUREG/IA, NUREG/IA-0470, Volume 1, “Nuclear Regulatory Authroity Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena.” U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES) Rockville, MD, August 2016.

4. IEEE C.37.20.7, “IEEE Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal Arcing Faults,” 2007 Edition, Institute of Electrical and Electronics Engineers, New York, New York.

5. IEEE 1584, “IEEE Guide for Performing Arc-Flash Hazard Calculations”, 2002 Edition, Institute of Electrical and Electronics Engineers, New York, New York.

6. OECD Fire Project – Topical Report No. 1, Analysis of High Energy Arcing Fault (HEAF) Fire Events”, NEA/CSNI/R(2013)6, Organization for Economic Cooperation and Development, June 2013.

7. ASTM F1959, “Standard Test Method for Determining the Arc Rating of Materials for Clothing”, 2012 Edition, ASTM International, West Conshohocken, Pennsylvania.

8. Lopez, C., Wente, W.B., Figueroa, V.G., “Evaluation of Select Heat and Pressure Measurement Gauges for Potential Use in the NRC/OECD High Energy Arc Fault (HEAF) Test Program”, Sandia National Laboratories, Albuquerque, New Mexico, January 2014.

9. Putorti. A., Melly, N.B., Bareham, S., Praydis Jr, J., “Characterizing the Thermal Effects of High Energy Arc Faults.” 23rd International Conference on Structural Mechanics in Reactor Technology (SMiRT 23) – 14th International Post-Conference Seminar on Fire Safety In Nuclear Power Plants and Installations, September, 2015.

APPENDIX A
MEASUREMENTS

The measurements and instruments are in Table A-1. The number is the number of instruments per test. Note that items 5b Cable/Plastic Targets, 7 Weight, and 8 Resistance are new items not used in previous tests.

A.1 Thermocouples and Slug Calorimeter Measurements

A.1.1 Slug Calorimetry

For heat flux KEMA uses slug calorimeters that comply with ASTM F1959 [7]. ASTM F1959 has the procedure to convert temperature of the slug thermocouple measurement to total heat energy and KEMA uses this in their data acquisition system. The slug is a small copper plate with a TC for temperature measurement. Slug calorimeters can only be used in external positions because the TC wires may cause internal shorting hazards and is not safe.

The conclusion from previous tests is that slug calorimeters appear to be a good way to measure heat flux during the arc. ASTM F1959 is used to test protective clothing materials where the arc energy is measured by slug calorimeters that are directly exposed to the arc. A KEMA slug calorimeter is shown in Figure A-1. The slug calorimeters on the sides were on metal screen, vertical panels as in previous tests. However, these panels block the view of the arc and block heat so for calorimeters in front of the open panels the slugs are mounted on vertical Unistrut. Unistrut is 1 5/8-inch steel channel beams used to make metal stands to support mechanical or electrical items as shown in the test drawings. Note that ASTM F1959 specifies insulation board for mounting however the slug calorimeters in the tests used plywood or red board that should provide suitable insulation to reduce conduction losses.

The method in ASTM F1959, Section 11.10.5 calculates the total energy:

Total Heat Energy, $$Q = \frac{mass \times \overline{C}p \times (Temp_{final} - Temp_{initial})}{area} \quad (1)$$

Where:

Q	=	Total heat energy per unit area[1];
mass	=	Mass of the copper slug; listed as "mass" in ASTM F1959, kg (nominal 18 g);
$\overline{C}_p$	=	Specific heat capacity specified in ASTM F1959 (kJ/kg·°K)[2];
Temp	=	Temperature (°K);
area	=	Exposed area of the slug (12.57 cm^2).

[1] This is ASTM F1959 nomenclature; the total heat energy received at the surface of the panel as a direct result of an electric arc.

[2] This is the average specific heat, c_p, over the temperature range using formula specified by ASTM F1959 that is included in the calculations but the effect is small over the observed temperature ranges in the tests.

Table A-1 Measurements for the FY15 Tests

Instrumentation	Number	Notes/ Comment
1. Temperature		
1a. Thermocouples	4	Type K on targets E7-E10 to compare to the temperature labels.
1b. Plate thermometers (PT)	0	No NRC/NIST PT.
1c. Passive temperature labels	4 sets 1 set/target	All sides of cabinets. DP 24 targets, SWGR 26 targets.
2. Pressure		
2a. Pressure transducers Internal External	2 0	Dynisco LDA415 piezoelectric pneumatic transducers, 0-50 psi by KEMA, similar positions as previous tests. No useful data from past tests.
3. Calorimetry		
3a. Slug calorimeters	11	ASTM F1959. Similar locations to March 2015 tests.
3b. Oxygen calorimeters for HRR, combustion products, and smoke	0	NIST hood not used.
4. Video and Photography		
4a. Visible light high-speed photography	1	Various speeds by KEMA- an IR filter was added to view the arc itself.
4b. Infrared photography	0	The thermal conditions can be captured with a regular Thermal Imaging camera in Item 4c.
4c. Thermal imaging camera	2	FLIR PM 350 provided by SwRI. FLIR SC6700 proved by NRC.
4d. Video and photos	1 SET	The tests were videotaped in High Definition (HD). One HD camera will have an IR filter to view the arc. Still photos are provided for the test setup before/after.
5. Other		
5a. IEEE C37.20.7 indicators to capture debris	0	No useful data from past tests. Blocks view of arc so not used.
5b. Cable/plastic targets	DP 24 SWGR 26	Measures cable damage and plastic damage at various positions. Measures temperature with Item 1c.
6. Current /Voltage Waveform Measurement	1 set	Appropriate selection of current transformers, shunts or Rogowski coils to be decided in Test Planning with appropriate transient recorders.
7. Weight	1 set	Weights of the copper bus bars before and after the tests.
8. Resistance	Each target	Measure the cable conductor resistance after the test.

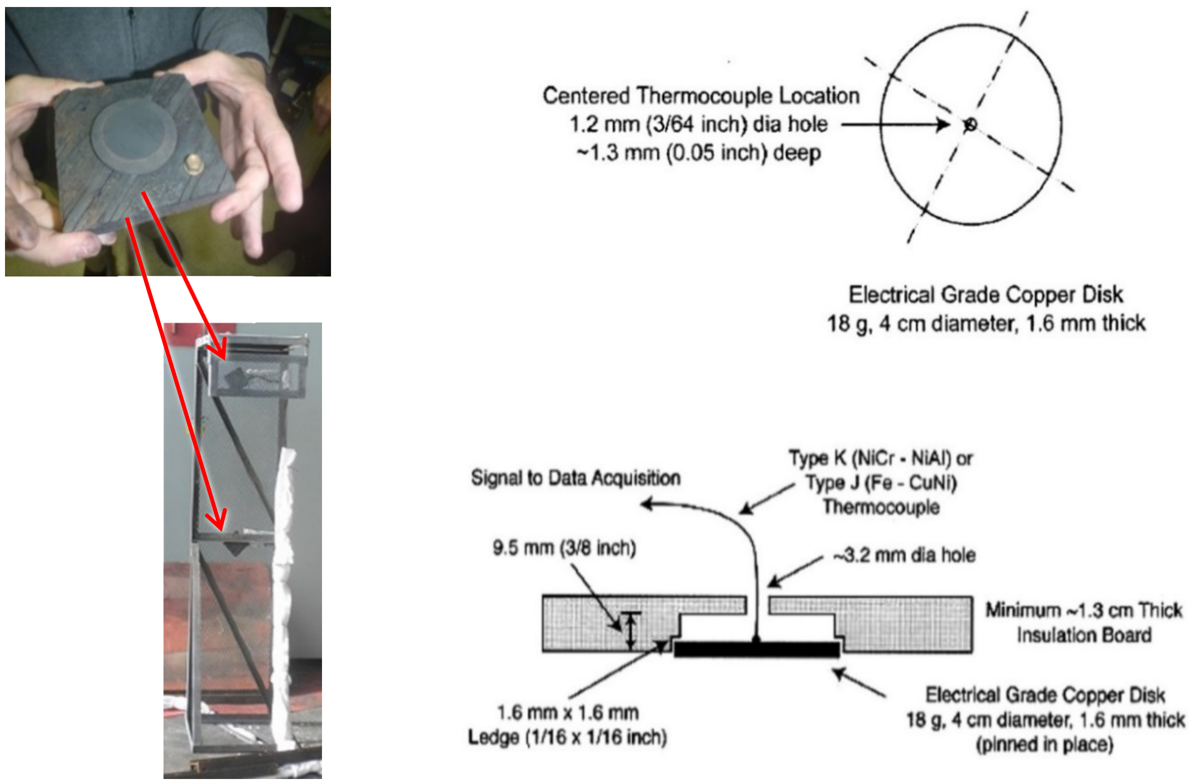


Figure A-1 ASTM F1959 Slug Calorimeters

ASTM F1959 does not prescribe a method to evaluate heat flux. For the heat flux analysis of the HEAF tests, the energy is divided by the time between $Temp_{final}$ and $Temp_{initial}$:

$$\dot{Q} = \frac{Q}{\Delta t} \qquad (1)$$

$\dot{Q}$ = heat flux (W/m^2);
Δt = Time associated with ΔT_{slug} (s)

For the analysis of the S/NRA/R HEAF tests, the reported flux is the average over the arc duration (Δt is approximately the arc duration) based on the ΔT_{slug} caused by an unknown combination of radiation and convection heat transfer. The flux analysis assumes the flux is predominantly radiation during the arc because the convection would be low during the short time of the arc at the ZOI distances (results where the arcs are impacted by flames and convection may be significant, and are not included in the analysis as discussed in this section). Radiation sources viewed by the slug calorimeters include the flames and plasma that are escaping the cabinet and, in some cases, the arc itself if a panel is lost or the arc burns though a cabinet wall. The effects of re-radiation or convection from the back of the slug, conduction to the slug mount and other effects are assumed to be negligible. With the assumption that the dominant flux is via radiation heat transfer, the $1/\varepsilon$ factor is included to account for the emissivity:

$$\dot{Q}_c = \frac{Q}{\Delta t} = \frac{m\bar{c}_p \Delta T_{slug}}{A \Delta t} \frac{1}{\varepsilon} \qquad (2)$$

Where:

$\dot{Q}_c$ = Incident heat flux (W/m^2) corrected for absorptivity;
m = Mass of the copper slug; listed as “mass” in ASTM F1959, kg (nominal 18 g);
$\overline{c}_p$ = Specific heat capacity specified in ASTM F1959 (kJ/kg·°K);
ΔT_{slug} = Slug Temperature difference over time (K);
A = Exposed area of the slug (12.566 cm^2);
Δt = Time associated with ΔT_{slug} (s);
ε = Emissivity/absorptivity of the coating/paint (~0.9)

An emissivity of 0.9 is assumed in accordance with the paint specified in ASTM F1959. However, the slug calorimeter’s copper surfaces appeared greyish in some cases and this creates uncertainty in the measurements because the emissivity is not known. The heat energy and the heat flux are indirectly proportional to the emissivity. That is, if the actual emissivity is assumed to be 0.85 to 0.95 the assumption of 0.90 has an uncertainty of ± 5.5%.

For ASTM F1959 Formula (1), the slug calorimeters are 30.5 cm from a completely exposed high energy arc, and the slugs are engulfed in flames and convection heat transfer effects are significant and ASTM does not include emissivity explicitly in the formula. Note that for cases where convection is negligible that heat fluxes analyzed using ASTM F1959 Formula (1) without the 1/ε would be lower by a factor of 1.11 so including the emissivity in (2) above is conservative relative to the ASTM method.

For this method, the $Temp_{final}$ is just after the arc extinguished and the $Temp_{initial}$ was just before the arc initiated. This method is not impacted by electrical noise and temperature spikes during the arc. The results of the slug calorimeter temperature are shown with a straight line that indicates the start and end of the arc and represents the time, Δt, and temperature ΔT used for the flux calculation as shown for DP Test 1 in Figure A-2. The ASTM F1959 results are reported for flux in the various results tables in this report. Usually the flux reported is the maximum flux which for Figure A-2 was Slug S8.

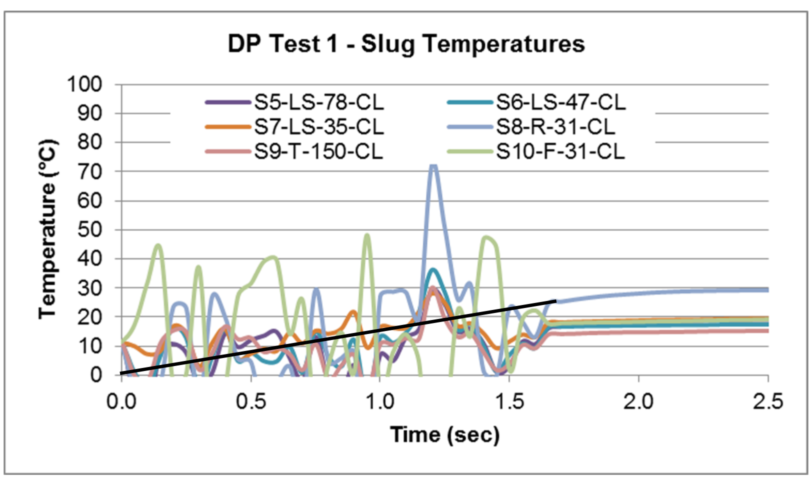


Figure A-2 Typical Slug Calorimeter Temperature Results

Most of the results have large variations of the indicated temperature with time. Some of these variations are from Electromagnetic Interference/Radio Frequency Interference (EMI/RFI) noise that is evident in Figure A-2 because negative temperatures are not physically possible. Noise is usually worse if the slug is near the power supply and the noise was usually different for all the slug calorimeters. Other variations are from rapidly varying arc flux or flames escaping the cabinet intermittently through vents or loss of cabinet integrity such as cabinet burn-through, or dislodged and bent cabinet panels that cause the slug to heat and cool.

In some cases, the temperature spikes were very large where the flames contacted the slug calorimeter. If the calorimeter was contacted by flames as indicated by a large spike and review of videos, the data was not used to calculate the flux and this is noted in the results. These cases indicate that radiation may not be the dominant heat transfer mode. Some of the spikes in the calorimeter temperatures are noise but these do no effect the start and end temperatures over the arc interval used for the Formula (2) ASTM F1959 flux calculation because the Δt is between the arc start and arc end.

The flux values that are reported are only for the time during the arc. After the arc quenches, the flux from the arc and residual heat in the cabinet is very small and the decreasing temperature of the slug indicates a negative flux using Formula (2). However, this flux is a measure of the slug calorimeter cooling; not of the cabinet conditions. If an ensuing fire occurs, the slug will eventually heat up, but at this point the slug response is some complicated mix of low radiation heat transfer from the warm cabinet wall the slug is viewing, convective heat transfer from the cabinet to the local air, and the convective heat transfer from the air to the slug. Therefore, it can be assumed that the results are valid during the arc itself because the arc duration is short and the temperature response at the slug is primarily related to heat conditions caused by the arc and the associated escaping flames and plasma.

In cases where using Formula (2) is not useful for flux measurement because there is flame contact, the slug temperature measurements provide a qualitative indication of the temperature that a small metal object at the NUREG/CR 6850 ZOI boundary could attain during the test. The slug's small copper disk with high emissivity provides a conservative estimate of a typical metal object that would typically have much lower thermal inertia and lower emissivity. This is true during the arc, after the arc, and also in cases where the slug calorimeter is contacted by flames. Therefore, the slug temperatures as well as the flux results are presented in this report. For example, an increasing slug temperature response after the arc is a qualitative indicator of an ensuing fire. The reported maximum slug temperatures are immediately after the arc to avoid noise spikes and indicate the maximum temperature a copper object could achieve from the arc heat.

A.1.2 Passive Temperature

Irreversible passive temperature indicators (called "temperature labels" or "labels"), Omega Engineering, Model No. TL-E- ****-30, where **** is the temperature range) are placed on the sides of the cabinets for each test. The indicators show the maximum temperature measured by a permanent color change. In some cases, near the arc high temperatures will destroy the gauges. The labels are shown in Figure A-3 have a range from room temperature to >204 ˚C in 6 ˚C increments.

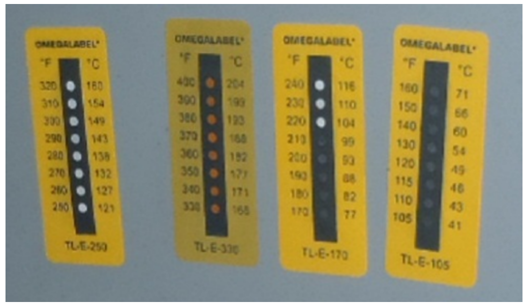


Figure A-3 Passive Temperature Label Set

The cable/plastic targets each have a set of temperature labels as discussed later. Also as discussed later, the temperature labels on the targets near the arc may be damaged by the flames and arc plasma.

The results from the tests are in Table A-2 Temperature Label Results.. The results are inconsistent and many labels are burned from the high energy in these tests and heat leaks through cracks in the cabinets. The only conclusion is that the temperature can vary greatly within just 50 cm because of the strong local effects of the arc.

Table A-2 Temperature Label Results.

Test	Front	Rear	Right	Left
DP -9	>204	burnt	>204 middle	>60 middle
DP-8	>206	<41	<41	<41
SWGR-7	burnt	>260	>241	>77
SWGR-8	burnt	>260	>138 rear	60-77 rear >121 middle
SWGR-9	burnt	burnt	>204 middle	>204
SWGR-10	>60	>49	>46	<41

A.1.3 Thermocouples

Type K thermocouples (TC) were used to measure the temperatures of the cable/plastic Targets E7-E10. These temperature readings are compared to the results from the temperature labels discussed in the previous section. The agreement was inconsistent and the TCs are judged to be more reliable.

A.2 Pressure Measurements

The Dynisco PT150-50 strain-gauge type Pressure Transducers (PRT) were connected to the cabinets by a reinforced rubber tube and then placed inside a PVC pipe for protection, as shown in various figures in the main text. The PRTs were not attached to the cabinet and moved and flexed the tube during some tests and this may have caused some very small pressure effects in the tubing and electrical effects in the cable. However, such effects were not specifically identified. Since the tubing was not filled with incompressible fluid, the compression of the air may have some effect on the time constant of the pressure response but this is not considered in the analysis.

Figure A-4 shows a typical gauge pressure history for SWGR Test 4 in March 2014, Arc 1 where PRT1 was on Cabinet 7 and PRT2 was on Cabinet 8. Moving point averages were used to show the general trend of the response and remove some the noise and pressure effects. The data acquisition frequency was 20 kHz so 50-point averaging covers 0.0025 seconds and is an effective filter. The pressure transducers use strain gauges in bridge circuits that have high frequency response but the frequency response is limited by the mechanical limitations of the internal components and the manufacturer reports a minimum frequency response of 2 kHz but a typical response of 7 kHz depending on the connection to the item being measured. The minimum should allow measurements every 0.0005 seconds and this is adequate to measure the peaks that typically occur in the range of 0.010 to 0.025 seconds. The reported peak pressures were from the un-averaged data because the averaging artificially reduces the amplitudes of the highest peak pressure.

(a) (b)

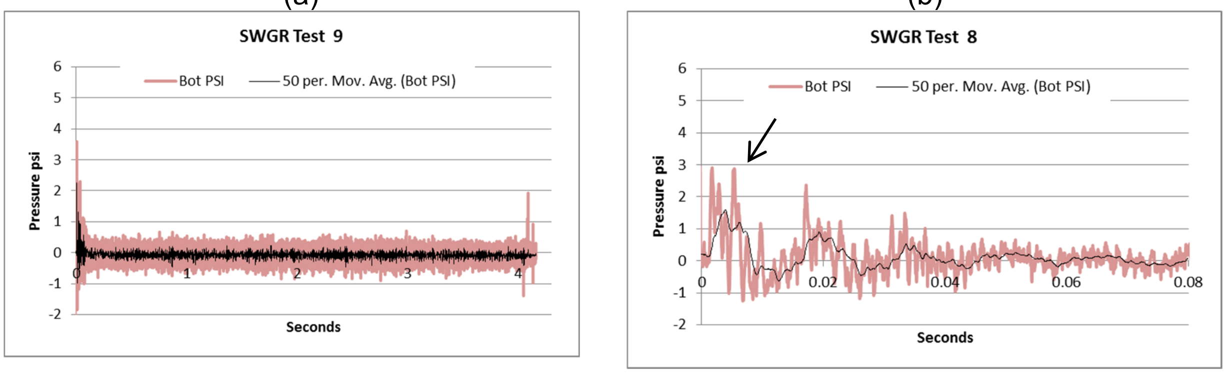


Figure A-4 Typical Pressure Results with Noise.

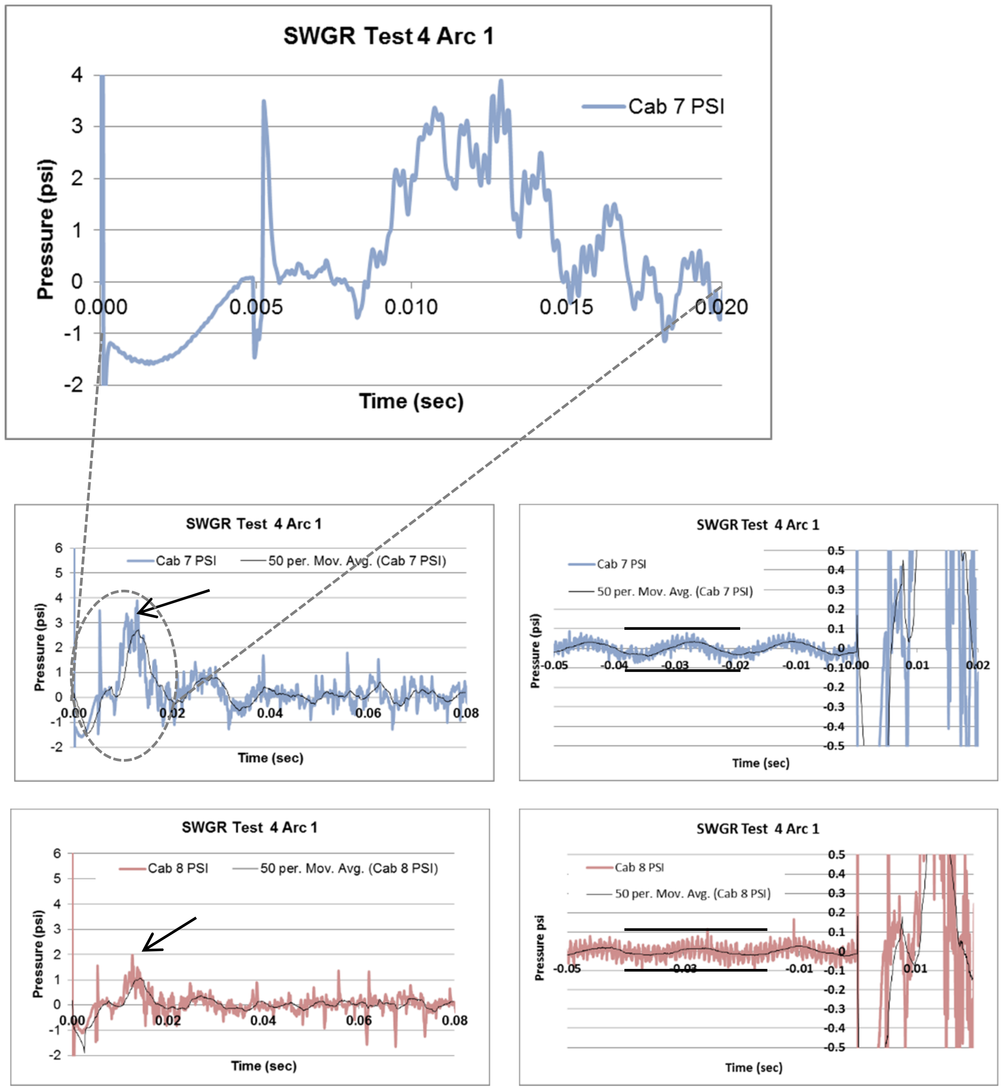
The pressure often had spikes as the arc first forms and later quenches. The spikes were probably caused by rapidly changing magnetic field effects as the start and stop of the arc causes unstable and unbalanced current in the 3-phase power in the nearby bus bars and conductors.

The time for the maximum pressures for all tests ranged from 0.0008-0.0167 seconds after the arc imitated. Noise spikes could be distinguished from pressure by expanding the time-scale and observing the response width because noise spikes are extremely narrow as shown in Figure A-52 for SWGR Test 4 in March 2014, Arc 1 but the behavior was the same in the FY15 tests. The noise spike at 0.005 seconds is very narrow compared to the peak pressure at 0.0129 seconds. The initial negative spike down also indicates that this is a noise spike.

Note that the pressures are typically very low so electrical noise in the result was estimated and included as a pressure uncertainty. Figure A-5 shows a typical pressure analysis to understand the electrical noise in the circuits. The plus/minus (±) uncertainty is based on the peak-to-peak un-averaged noise before the arc. The results before the arc initiated were reviewed to manually select the peak-to-peak noise level including the higher frequency noise that is filtered by the 50-point moving average. This peak-to-peak value was used as a conservative uncertainty.

The high frequency noise is considered when evaluating the maximum pressure as shown in Figure A-6. This example shows there is a high frequency noise (around 3.8 kHz) that occurs on many of the pressure results. The origin is not known. The noise is filtered by the 50-point moving average but the averaging reduces the indicated maximum pressure and delays the time of the maximum pressure as shown in the figure. However, a trendline with a 10-point moving trendline is only delayed about 0.5 ms and the maximum is not greatly reduced. The maximum pressure that is reported is selected as the mid-point of the peak-to-peak values in the cycle that includes the maximum measured pressure. As shown in the figure, the maximum measured pressure in SWGR Test 7 was 5.5 psi but 4.1 psi is reported; this is about a 25% reduction. So, it is important to consider the high frequency noise using this manual method. The maximum pressure and the time are manually recorded directly from the EXCEL chart. Figure A-7 and Figure A-8 show the detailed results.

The PRT measurement uncertainty is not included in the analysis because the only measurements that are reported are the peak pressure relative to the pressure at the start of the arc and the peak pressure that occurs from the initial shock wave within about 0.020 seconds after the start of the arc. It is assumed that the PRT accuracy did not change during this short interval and accuracy is not included in the uncertainty. The manufacturer lists the accuracy as ±0.5% of the full-scale range which is ±0.25 psi for the 50-psi full scale range for the PRT150-50 and includes linearity, hysteresis, and repeatability. There are other factors that could affect the results such as movement of the PRT and flexing of the tube that connects the PRT to the cabinet but these also occur after the peak pressure and are not considered. The entire pressure data history is shown in the charts for interest, but only the peak pressure is reported.



SWGR Test 4
Arc 1
Pressure 1
(Cab 7)
23.4 ± 0.7 kPa
(3.4 ± 0.1 psi)
@0.0129 sec
(12.9 ms)

SWGR Test 4
Arc 1
Pressure 2
(Cab 8)
12.4 ± 0.7 kPa
(1.8 ± 0.1 psi)
@0.0126 sec
(12.6 ms)

Figure A-5 Typical Pressure Results and Uncertainty Estimate

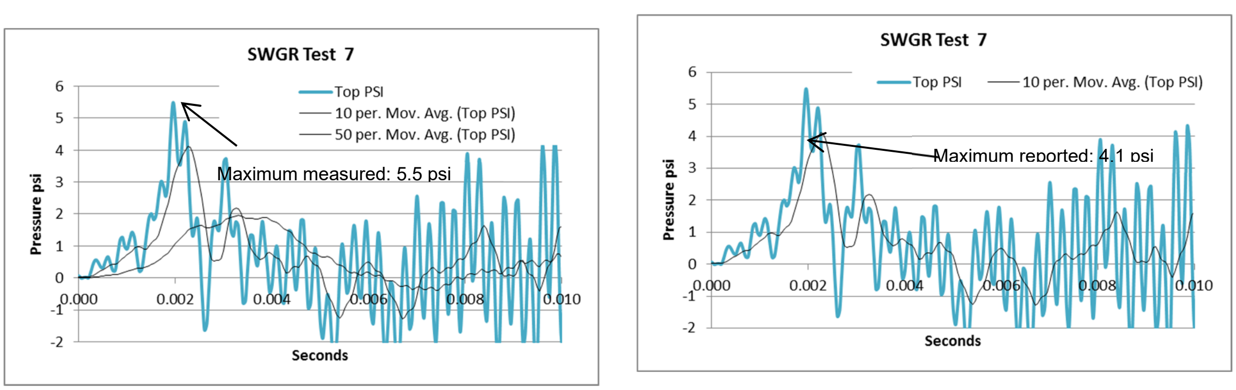


Figure A-6 High Frequency Noise Analysis

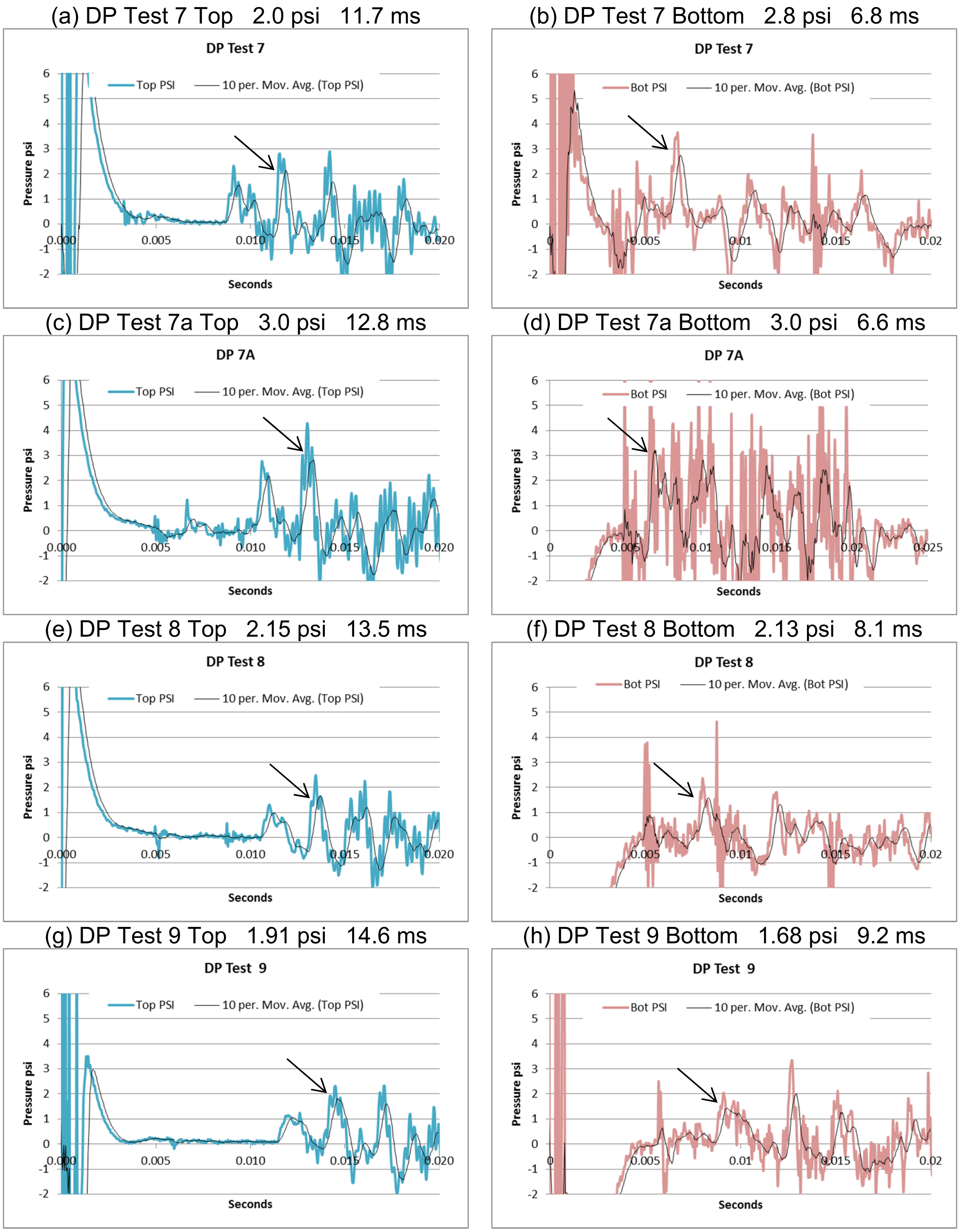
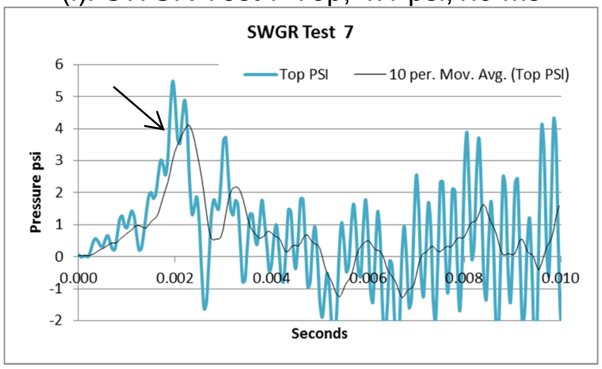
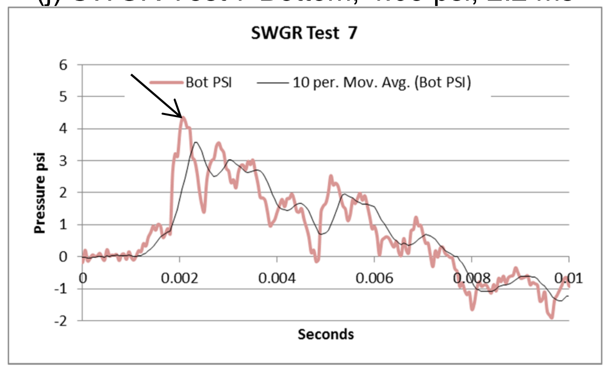


Figure A-7 Maximum Pressure Analysis- DP Tests

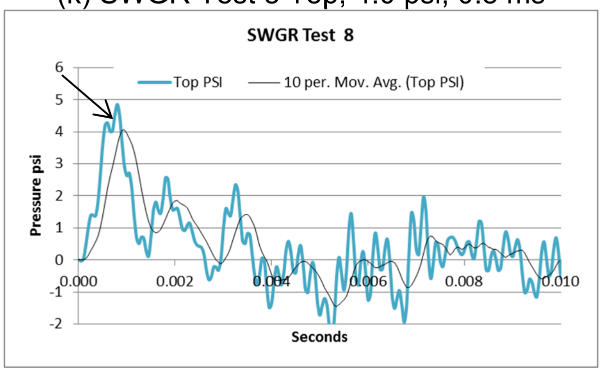
Note trendlines are 10 point moving average, not 50 (i). SWGR Test 7 Top, 4.1 psi,1.9 ms



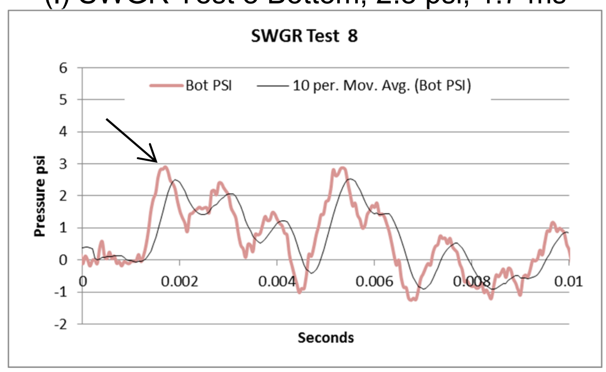
(j) SWGR Test 7 Bottom, 4.03 psi, 2.2 ms



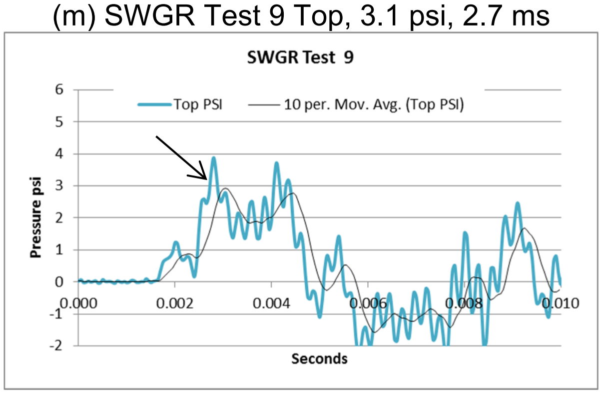
(k) SWGR Test 8 Top, 4.0 psi, 0.8 ms



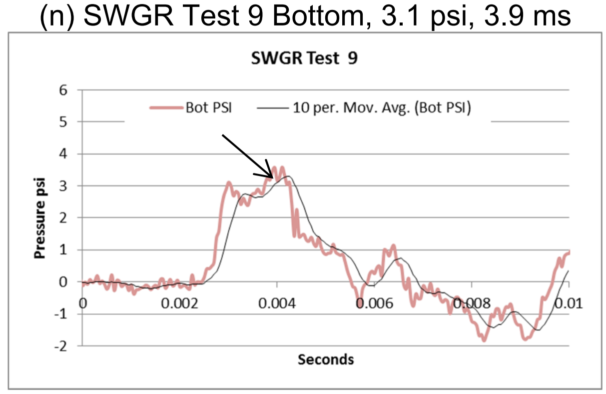
(l) SWGR Test 8 Bottom, 2.8 psi, 1.7 ms



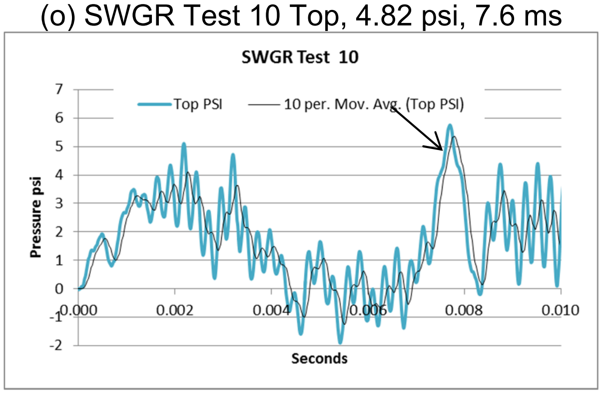
(m) SWGR Test 9 Top, 3.1 psi, 2.7 ms



(n) SWGR Test 9 Bottom, 3.1 psi, 3.9 ms



(o) SWGR Test 10 Top, 4.82 psi, 7.6 ms



(p) SWGR Test 10 Bottom, 4.79 psi, 2.4 ms

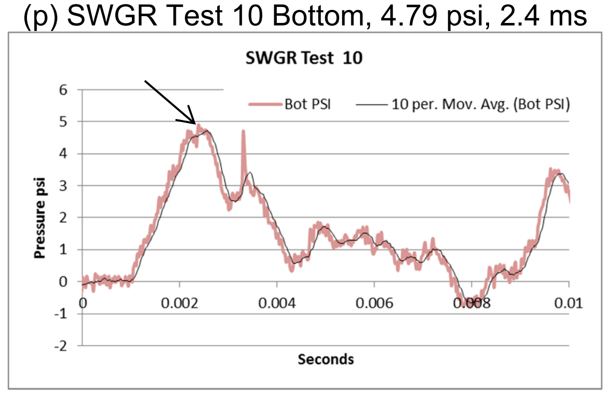


Figure A-8 Maximum Pressure Analysis- SWGR Tests

Note the SWGR Bottom data has much lower high frequency noise than other pressure measurements.

A.3 Energy Measurements

Total arc energy, Q_{tot}, is a key parameter that characterizes the strength of the arc and the potential for damage and ability to cause an ensuing fire in the cabinet or externally. An EXCEL worksheet is used to calculate the energy for the June 2013 SWGR Test 2, shown in Table A-3. The currents and voltages for each phase, a, b, and c (Columns C-H) are multiplied to give the power in each phase (Columns J-K). The powers from each phase are added and then multiplied by the time step (0.00005 seconds) to give energy in Column M. The energy for each step is added to a cumulative total (referred to as "Qtot" or "Energy Total" in this report) in Column N. The resulting graph, as shown in Figure A-9 Test 2 Arc Energy Result, is just for the time of the arc.

The cumulative energy should be a smooth line, linear with time that shows the KEMA power system provided a steady energy for the test. Discontinuities or spikes in the Q_{tot} line indicate the arc was not steady and also could indicate re-strikes.

Table A-3 SWGR Test 2 Arc Energy Calculation.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
time	Time adj	A CURRENT	A-N VOLT.	B CURRENT	B-N VOLT.	C CURRENT	C-N VOLT.		a	b	c	Energy MJ	Energy Cum.
0.0632	0	1992	1002	3828	233.6	2852	-35.94		99.7992	44.71104	-5.12504	0.000139385	0.00017
0.06325	5E-05	-234.4	35.94	39.06	8.984	78.13	35.94		-0.42122	0.017546	0.1404	-2.6327E-07	0.00017
0.0633	1E-04	-117.2	-26.95	0	-8.984	117.2	17.97		0.157927	0	0.105304	2.63231E-07	0.00017
0.06335	0.00015	312.5	-148.2	-78.12	-13.48	585.9	-8.984		-2.31563	0.052653	-0.26319	-2.5262E-06	0.00017
0.0634	0.0002	273.4	-71.87	-1289	-40.43	898.4	8.984		-0.98246	2.605714	0.403561	2.02681E-06	0.00017
0.06345	0.00025	390.6	-17.97	-1641	-40.43	1133	-22.46		-0.35095	3.317282	-1.27236	1.69397E-06	0.00017
0.0635	0.0003	625	-8.984	-2187	17.97	1406	13.48		-0.28075	-1.96502	0.947644	-1.2981E-06	0.00017
0.06355	0.00035	898.4	58.4	-2578	35.94	1719	40.43		2.623328	-4.63267	3.474959	1.46562E-06	0.00017
0.0636	0.0004	1211	-26.95	-3242	-40.43	2031	26.95		-1.63182	6.553703	2.736773	7.65865E-06	0.00018
0.06365	0.00045	1484	26.95	-3828	8.984	2422	-4.492		1.99969	-1.71954	-0.54398	-2.6383E-07	0.00018
0.0637	0.0005	1719	58.4	-4258	35.94	2695	26.95		5.01948	-7.65163	3.631513	9.99367E-07	0.00018
0.06375	0.00055	1953	4.492	-4883	-8.984	2930	0		0.438644	2.193444	0	2.63209E-06	0.00018
0.0638	0.0006	2266	4.492	-5547	13.48	3125	40.43		0.508944	-3.73868	6.317188	3.08745E-06	0.00019
0.06385	0.00065	2539	0	-5977	-8.984	3438	8.984		0	2.684868	1.54435	4.22922E-06	0.00019
0.0639	0.0007	2930	-4.492	-6523	-22.46	3711	71.87		-0.65808	7.325329	13.33548	2.00027E-05	0.00021
0.06395	0.00075	3164	-31.45	-7031	-4.492	3945	53.91		-4.97539	1.579163	10.63375	7.23752E-06	0.00022
0.064	0.0008	3516	31.45	-7656	-13.48	4180	44.92		5.52891	5.160144	9.38828	2.00773E-05	0.00024
0.06405	0.00085	3711	-8.984	-8125	31.45	4492	17.97		-1.66698	-12.7766	4.036062	-1.0407E-05	0.00023
0.0641	0.0009	4063	31.45	-8750	-8.984	4570	-22.46		6.389068	3.9305	-5.13211	5.18746E-06	0.00023
0.06415	0.00095	4336	4.492	-9297	-35.94	5000	44.92		0.973866	16.70671	11.23	2.89106E-05	0.00026
0.0642	0.001	4766	-4.492	-9844	-8.984	5117	62.89		-1.07044	4.421925	16.09041	1.94419E-05	0.00028
0.06425	0.00105	5078	13.48	-10270	17.97	5391	76.37		3.422572	-9.2276	20.58553	1.47805E-05	0.00029
0.0643	0.0011	5391	-13.48	-10820	-35.94	5469	8.984		-3.63353	19.44354	2.456675	1.82667E-05	0.00031
0.06435	0.00115	5703	22.46	-11450	22.46	5625	89.84		6.404469	-12.8584	25.2675	1.88136E-05	0.00033
0.0644	0.0012	6172	40.43	-11950	-17.97	5977	31.45		12.4767	10.73708	9.398833	3.26126E-05	0.00036
0.06445	0.00125	6367	35.94	-12540	-26.95	6016	0		11.4415	16.89765	0	2.83391E-05	0.00039
0.0645	0.0013	6719	-26.95	-12930	-4.492	6055	22.46		-9.05385	2.904078	6.799765	6.49991E-07	0.00039
0.06455	0.00135	7188	31.45	-13590	-40.43	6328	17.97		11.30313	27.47219	5.685708	4.4461E-05	0.00044
0.0646	0.0014	7500	22.46	-14060	-13.48	6563	49.41		8.4225	9.47644	16.21389	3.41128E-05	0.00047
0.06465	0.00145	7969	40.43	-14530	-4.492	6641	22.46		16.10933	3.263438	7.457843	2.68306E-05	0.00050

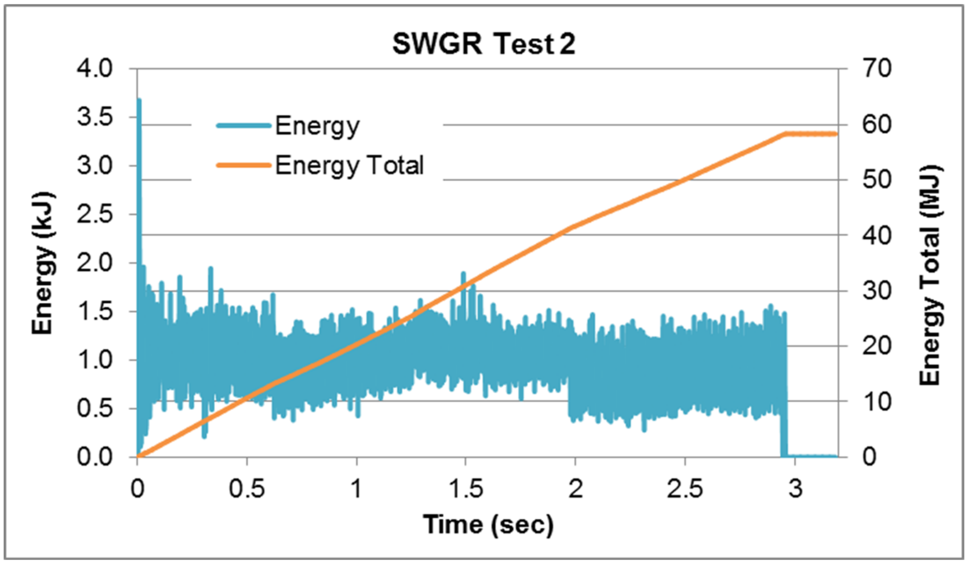


Figure A-9 Test 2 Arc Energy Result

A.4 Pictures and Video

Various cameras were used for video and photography by KEMA, SwRI, and by NRC. NRC used a FLIR SC6700 IR camera and SwRI used a FLIR T300 camera. Video cameras were in front of the test cell looking toward the test cell as shown in Figure A-10. The KEMA High-Speed (HS) Phantom V7.3 camera at 500 – 1200 frames per second was also used. Videos and photographs were provided separately on DVD. Several cameras are in a line to view the front of the cabinets. Other cameras are in the test cell at the front and rear of the cabinets.

FLIR T300

FLIR SC6700

Figure A-10 Thermal and High-Speed Cameras

For DP and SWGR Tests with open panels, the HS video of the arc using Infrared (IR) filters was used to show the arc behavior and where it attaches. The initial results for DP Tests 7 and 8 and SWGR Test 7 were poor because of over-exposures. Using trial and error a 970 nanometer IR pass filter with slow exposure times worked for DP Test 9 and SWGR Tests 8 and

9. In SWGR test 8, the exposure was too high, but the light from the arc leaked though a small opening in the cabinet that acted like a slit and projected the light from the arc onto the metal panel at the rear of the test cell. The HS camera with the IR filter was able to view the reflection of the arc from the metal panel.

Several HD video cameras were placed around the tests to observe the flames from the arc. These were used to see contact with the slug calorimeters.

The SwRI FLIR T300 and the NRC FLIR SC6700 Thermal Imaging camera were used as in past tests. These cameras were set to various temperature ranges and the exact position/view and ranges for the cameras will be decided before the test. However, the best results in the past were by using auto-scaling.

APPENDIX B
KEMA TEST LABORATORY

KEMA Laboratories Chalfont ("KEMA") performed the S/NRA/R HEAF tests at their lab facilities in Chalfont, Pennsylvania shown in Figure B-1. The large KEMA G2 - 2250 MVA, 16 kV, variable frequency generator was used for the tests.

Test Cell 7 in Figure B-1 through Figure B-3 has a U.S. "Medium Voltage" (Japanese "High Voltage") supply bus for the SWGR 7.1 kV arc (on the left) and a low voltage supply bus for the 480 V and 600 V DP arc.

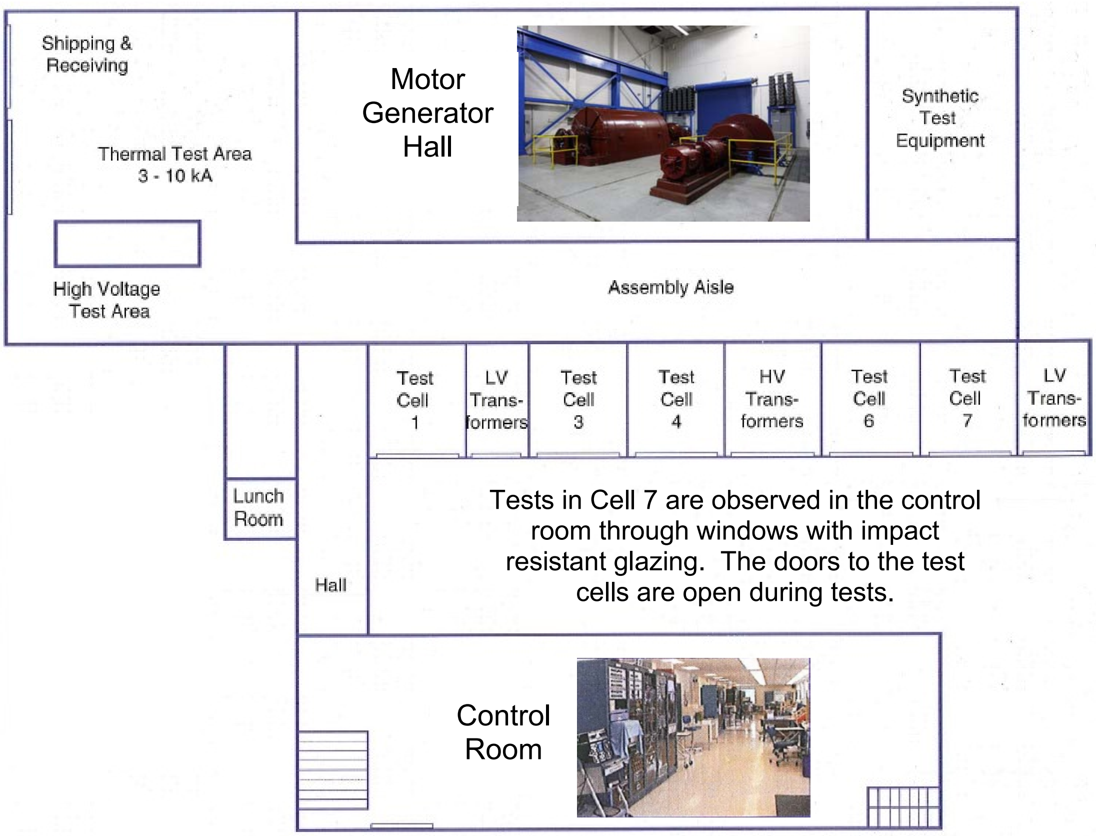


Figure B-1 KEMA Powertest Facility

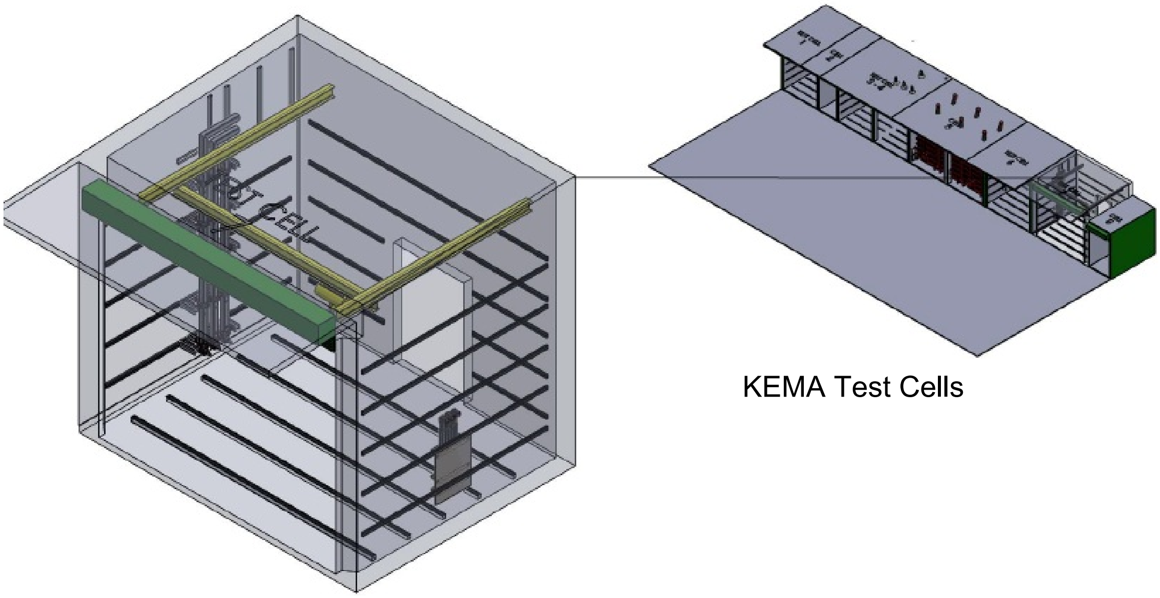
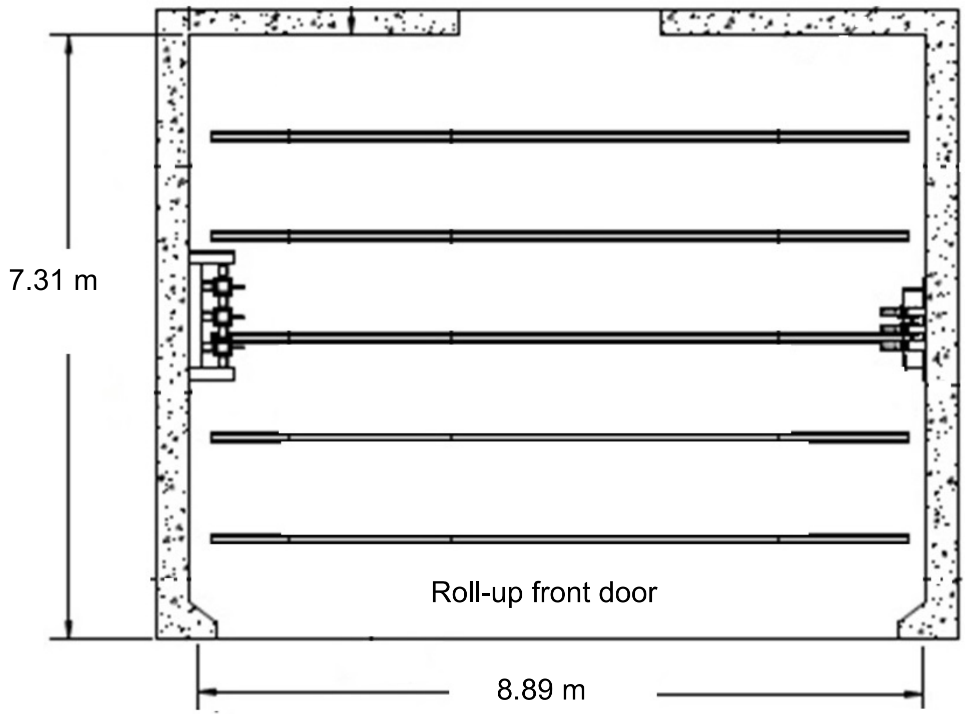


Figure B-2 KEMA Test Cell 7 Arrangement

A 324-inch roll up door opens to view the tests from the Control room and also to bring in large test items. The medium voltage (MV, >1,000 volt) supply is on the left and the low voltage supply (<1,000 volts) is on the right.

(a) Top View



(b) From Front

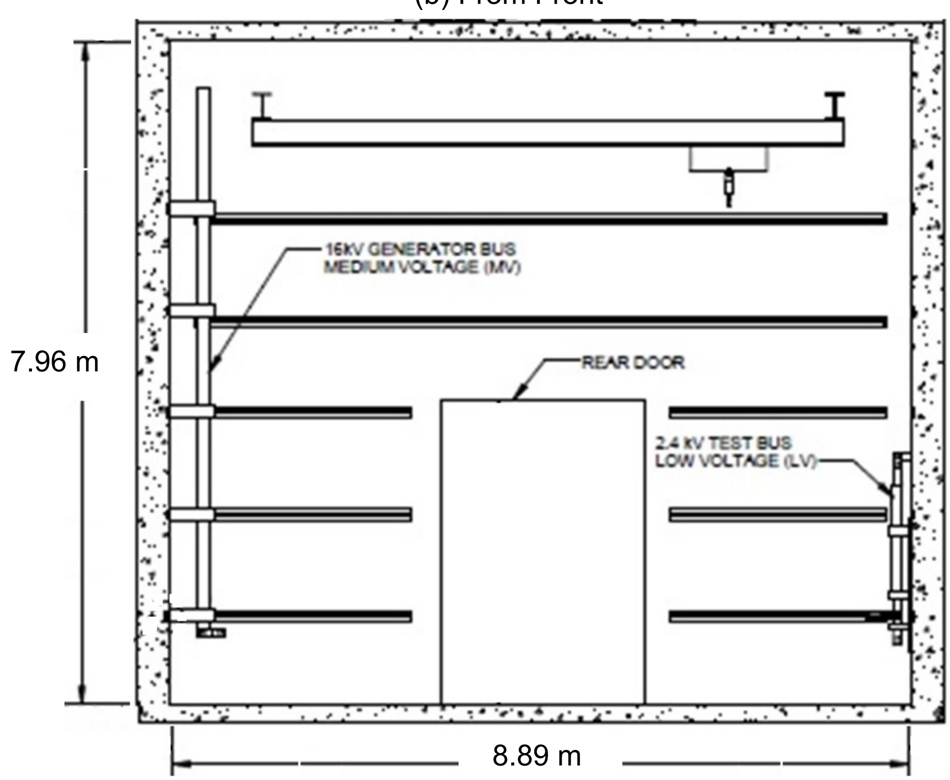
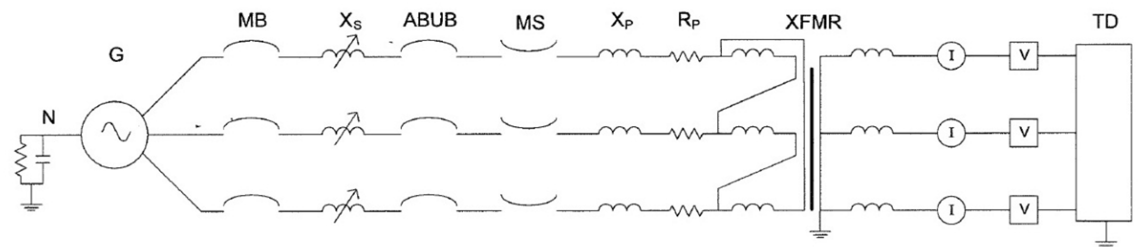


Figure B-3 KEMA Test Cell 7 Details

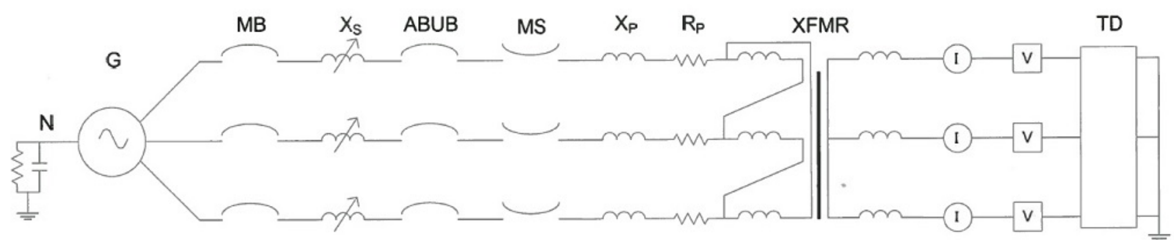
KEMA adjusted the generators and electrical components in Figure B-4 to get a stable supply that can repeat the exact conditions for voltage and current. There is a trade-off between the stability/repeatability and the target current/voltage. S/NRA/R approved the target test conditions in a test plan and accepted the final KEMA settings based on calibration runs as the tests progressed. KEMA adjusted the equipment and operation of their electrical system to try to meet the target arc current and voltage. In the delta circuit, the SWGR cabinet is grounded to earth. In the wye circuit the DP cabinet is grounded to the wye neutral.

The current measuring equipment included a GE JVM5 Potential Transformer, a 20/1 Voltage Divider in the KEMA circuit at the generator, 3 coaxial shunts manufactured by Compton, and 3 additional voltage dividers for each phase in the KEMA circuit.

(a) Delta Circuit Used for SWGR



(b) Wye Circuit used for DP tests



N	Neutral
G	Generator
MB	Master Breaker
X_s	Station Reactance
ABUB	Auxiliary Back Up Breaker
MS	Making Switch
X_P	Primary Reactance
XFMR	Transformer
R_P	Primary Resistance
TD	Test Device
V	Voltage Measurement
I	Current Measurement

Figure B-4 KEMA Electrical System Setup

APPENDIX C
CABLE PROPERTIES

This appendix shows the properties for the cables and plastic used in the cable/plastic targets (CCV) and the cables used in the bundles (CV-2).

The properties of the cables are in Table C-1. The Fire Properties for future modeling is from the draft fire data handbook being prepared by S/NRA/R. There are more S/NRA/R data and property measurements for CCV than any other type of cable. So, CCV is used for the targets where modeling may be used later to understand the flux and observations. CV-2 is used for the cable bundles because CV-2 and CV-4 were used for the cable bundles in previous tests. The cable materials are in Figure C-1.

Table C-1 Cable Properties

Property	CV-2	CCV-8	Basis
Physical Properties			
Number of Conductors	2	8	Physical counting
Conductor area, mm^2	2	2	Vendor specification
Outer Diameter, mm	10.5	14	Vendor specification
Mass per length, kg/km	120	290	Total weight measurement
Combustible, %	69	50	Insulation weight by measurement
Fire Properties			
Average Heat Release Rate (HRR), kW/m^2	257	222	Cone calorimeter @50 kW/m2
Heat of Combustion, MJ/kg	24	27	Cone calorimeter @50 kW/m2
Ignition time (s)/ Temperature (˚C)	435 / 366	870 / 469	Penlight Tests
Failure time (s)/ Temperature (˚C)	467 / 532	902/ 539	Penlight Tests
Critical Heat Flux (CHF), kW/m^2	8.5	14.5	Cone calorimeter bracketing tests

Table C-1 and Figure C-1 show the CCV-8 cable with eight conductors. The CCV cable on the targets is CV-2 cable with two conductors because the smaller CV-2 will be easier to ignite. However, except for extreme conditions near the arc plasma, the cables on the targets did not ignite.

Based on previous tests the CV and CCV cable behave like thermoset (TS) cables and char when they are burned. They do not melt like thermoplastics (TP).

CV-2- for bundles Jacket/Sheath: Japan Industrial Standard (JIS) Flame Retardant Vinyl (Polyvinylchloride, PVC) First Wrapping: No Shield: None Fill: Yes Insulation: Cross-Linked Polyethylene (XLPE) Conductor: Stranded	
CCV - for Cable/Plastic targets Sheath: Heat Resistant Vinyl (PVC) First Wrapping: Thin, Clear, Cellophane-Like Plastic Shield: None Fill: None Insulation: Cross-Linked Polyethylene (XLPE, clear) Conductor: Stranded	

Figure C-1 Cable Materials

The cables cannot contain lead. These cables were used in previous tests at KEMA.

APPENDIX D
SHORT CIRCUIT CURRENT CALCULATIONS

As discussed in Section 1.2.1 the bolted fault current that is the maximum feasible fault current for an electric circuit was used as the short circuit current in the tests. The bolted fault current was based on the well-known “infinite bus” short circuit calculation (or “bolted short”) from textbooks as described below.

D.1 DP Test Current

The feed circuit in Japan is not specified. The schematic assumed for the DP and MCC in a typical NPP plant is in Figure D-1. A 480 V, 3 kA, bus feeds the DP. A 480 V, 600 A, DP MCCB feeds the MCC.

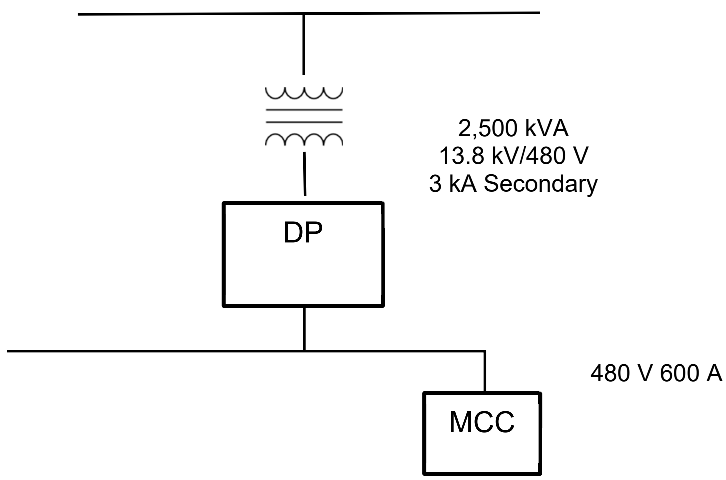


Figure D-1 Circuit Assumed for DP and MCC Tests

The calculated maximum, bolted, three phase short circuit current that could occur for a 480 V secondary bus of a 2,500 kVA transformer with a percent impedance of 5.75% is:

SCA2 = (FLA2 * 100%) / Z%
FLA2 = kVA three-phase / (Sqrt(3) * kV_{LL})
FLA2 = 2,500 kVA / (1.732 * 0.480 kV_{LL})
FLA2 = 3.007 kA
SCA2 = (3007 * 100%) / 5.75%
SCA2 = 52.296 kA (nominal 53 kA was specified for the tests)

Where:
SCA2 = bolted short circuit amperes on the secondary bus (short circuit amps)
FLA2 = transformer secondary full load current rating (full load amps)
kV_{LL} = line-to-line voltage in kV
Sqrt(3) = square root of three which is 1.732

Z% = transformer nameplate percent impedance, 5.75% is a conservative lowest value in typical industrial circuits

D.2 SWGR Test Current

The calculated maximum, bolted, three phase short circuit current that could occur at the 6.9 kV secondary bus of a 26 MVA transformer with a percent impedance of 9.5 percent is nominally 23 kA.

SCA2 = (FLA2 * 100%) / Z%
FLA2 = kVA three-phase / (Sqrt(3) * kVLL)
FLA2 = 26,000 kVA / (1.732 * 6.9 kVLL)
FLA2 = 2.176 kA
SCA2 = (2.176 * 100%) / 9.5%
SCA2 = 22.9 kA; a nominal 23 kA was specified as the symmetric current

APPENDIX E
CABLE/PLASTIC TARGETS

E.1 Description

The cable/plastic targets were attached to the interior cabinet walls and measurement platforms. The purpose of the targets was to evaluate damage of cable samples and plastic samples at various positions. The cable/plastic target is shown in Figure E-1.

Temperature labels were used to measure the temperature inside the cabinets (TC cannot be used on or in the cabinet for safety from possible shorting). Temperature labels were placed on the back of the cable/plastic target to record the maximum temperature. TCs were added to external Targets E7-E10 in the rear of the cabinet to compare to the temperature labels. Temperature labels are on the back of the target to protect them from direct flame.

The cable samples were 10 cm long and had 3 cables Figure E-1. The cables were CCV that has well-known properties from previous S/NRA tests as discussed in Appendix C.

The plastic samples were 5 x 5 cm PVC because it is commonly used and the properties are known. PVC that was 0.125 inch-thick (3.18 mm) and 0.063 inch-thick (1.60 mm) were tested.

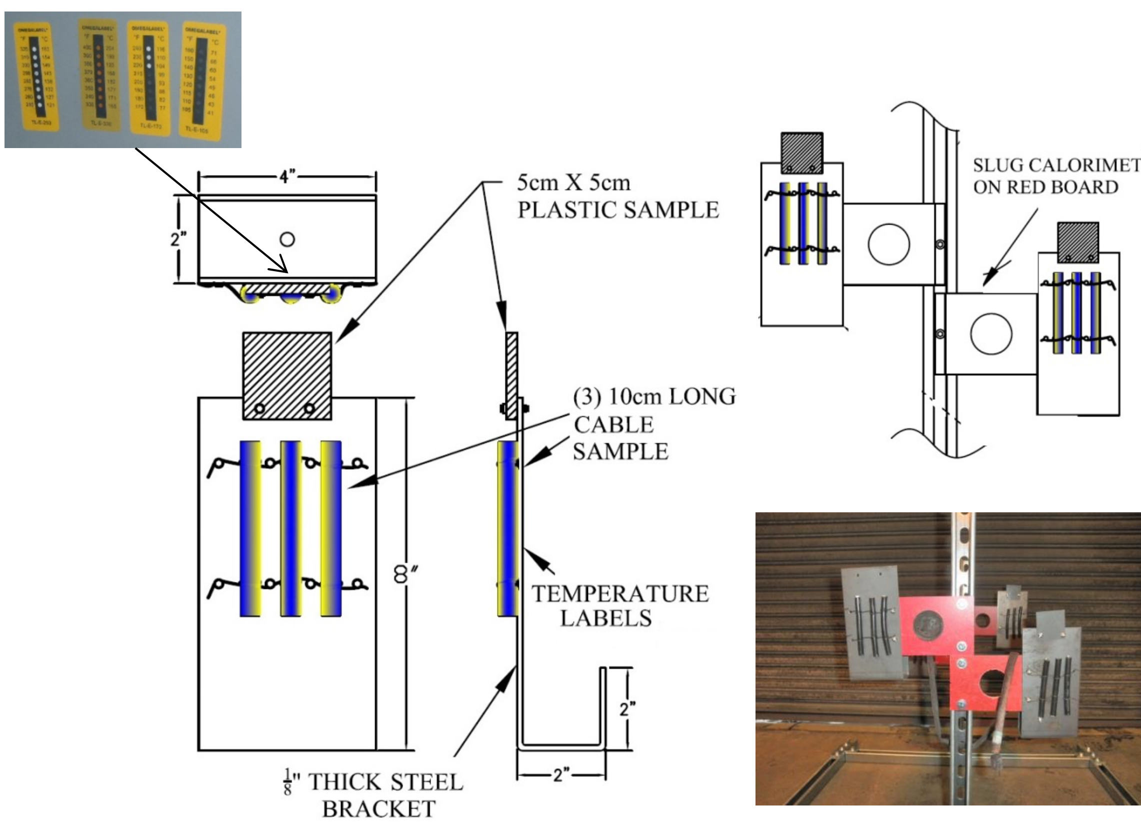


Figure E-1 Cable/plastic Targets

E.2 Presentation of Results

Results for the targets are presented in tables in the "Cable/Plastic Targets" sections in the main text for each test. An example result table is in Table E-1. The information is organized in the left column by:

- Name of the cabinet tested: The cabinet name is used. For the DP, Cabinet DP-1 was used with DP Test 7, DP Test 7A, and DP Test 9. Cabinet DP-2 was used for DP Test 8. For SWGR, SWGR Cabinets 1-4 are for SWGR Tests 7-9.
- Target, Line 1: Target numbers that are shown in figures in Sections 1.4 (DP) and 2.6 (SWGR). The internal targets are numbers and the position on the left side (L) or right side (R) of the cabinet. The external target numbers are preceded by an "E" and have the same number of the external slug calorimeter where they are located. For example, E6 is the target located to the left of slug calorimeter S6. Internal targets are noted by "T".
- Target, Line 2: The distance in cm. to the arc center is shown below the number. T= Internal, E= external.

The damage information in the table includes:

- Damage description, Cable: Describes the damage using the numerical score from Table E-2 and Figure 1.4-1.
- Damage description, Plastic: Same as cable in Table E-1. The plastic is sometimes bent where it partially melted and this is in the "Note" part of the table
- Label Temperature: The highest temperature indicated by the temperature label. The labels have a range. These are burnt in many cases with high target damage and flame contact.
- Note: Description of the appearance of the target, condition of the plastic (such as "bent"), if a cable fails an electrical resistance continuity test. Metal coating is noted (usually for targets within 60 cm).

Table E-1 Example of Target Observations

Target (cm)		**Damage Description**		**Label Temp. (˚C)**	**Note**
		Cable	Plastic		
T1 86	L	6. destroyed	6. destroyed	burnt	all the targets are gone, plate is coated with metal
	R	5. heavy damage	5. heavy damage	burnt	one cable is gone, plastic is bent forward, plate is coated with metal
T4 55	L	5. heavy damage	5. heavy damage	177-182	plastic is bent forward
	R	4. medium damage	4. medium damage	160-166	
T8 120	L	2. sooted	2. sooted	43-46	
	R	2. sooted	2. sooted	82-88	
E3 239		4. medium damage	4. medium damage	71-77	left cable is failed
E4 239		4. medium damage	4. medium damage	burnt	

Table E-2 (repeated here from Table 1-3 for convenience) shows the numerical scores and the type of damage. In some cases, the results can be “no sample”; for example, plastic samples were not used on the right side (R) targets in the first DP test.

Note that some targets were not damaged and were reused.

Table E-2 Target Damage Descriptions

Identifier	Damage Description	Types of Damage
1	None	No damage; cable and plastic the same as installed and can be reused. Usually low temperatures. May look slightly brown from minor copper minor deposition. No smoke soot. May be reused
2	Sooted	No damage to cable or plastic. Soot from smoke from other combustibles or copper covers the cable. The cable jacket color is dull and the letters on the cable are hard to see.
3	Minor damage	Light charring or discoloration of the target and cables, minor charring.
4	Medium damage	Charring of cables; plastic bent slightly.
5	Heavy damage	Deep charring of cable. Cables may be missing; plastic samples may be missing. This usually occurs for targets within 50 to 100 cm of arc. Plastic is bent over metal target mount. Orange steel after cool down indicates high heat.
6	Destroyed	Cable or plastic samples are no longer attached. This usually occurs for targets within 40 cm of the arcs, on long duration arcs. Bright orange steel indicates very high heat.

APPENDIX F
TARGET DAMAGE INFORMATION

This appendix shows additional details of the damage in the “Cable/Plastic Targets” sections in the main text for each test. The detailed results show figures of the top view of the DP or SWGR with the numerical score for each target location as in Figure F-1 (see Section E.2 for description of the numerical scoring). For targets that are arranged vertically, the numerical scores are presented in a horizontal line as shown in Figure F-1. The top view figures are from Figure 2.6-4 for the DP and Figure 3.6-5 for the SWGR.

This appendix also shows the post-test photos of the cable/plastic targets. The labels in the photos show the FY15 test numbers that start at 1 and the position in Figure 2.6-3 for the DP and Figure 3.6-4 for the SWGR. The test numbers used in the report are shown in the figure titles.

F.1 DP Tests

F.1.1 DP Test 7 and 7A

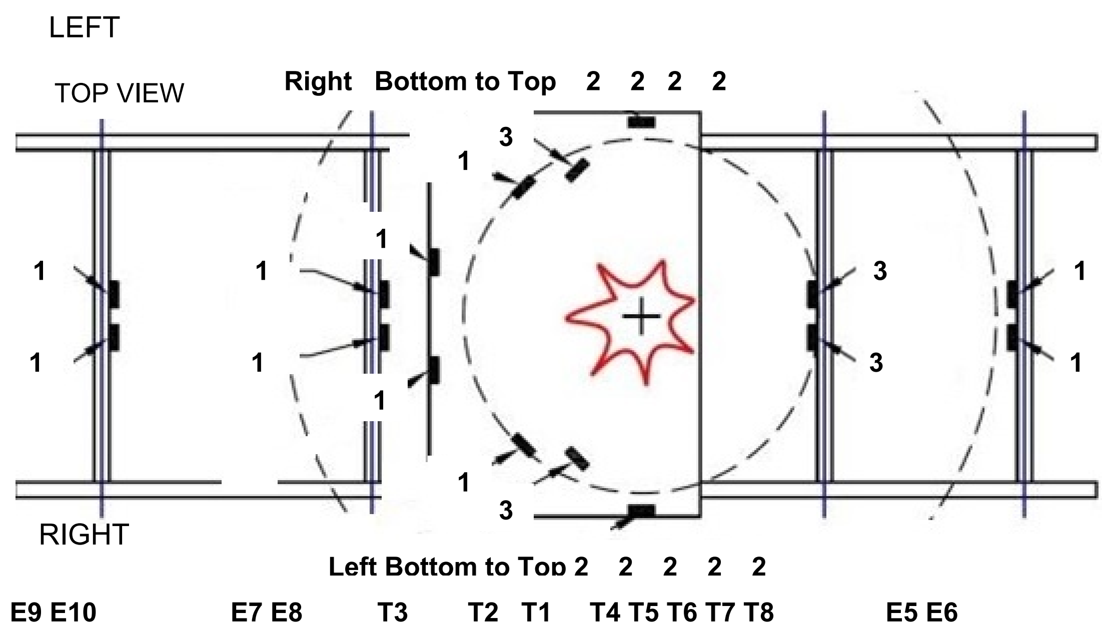


Figure F-1 DP Test 7, 7A Detailed Target Damage

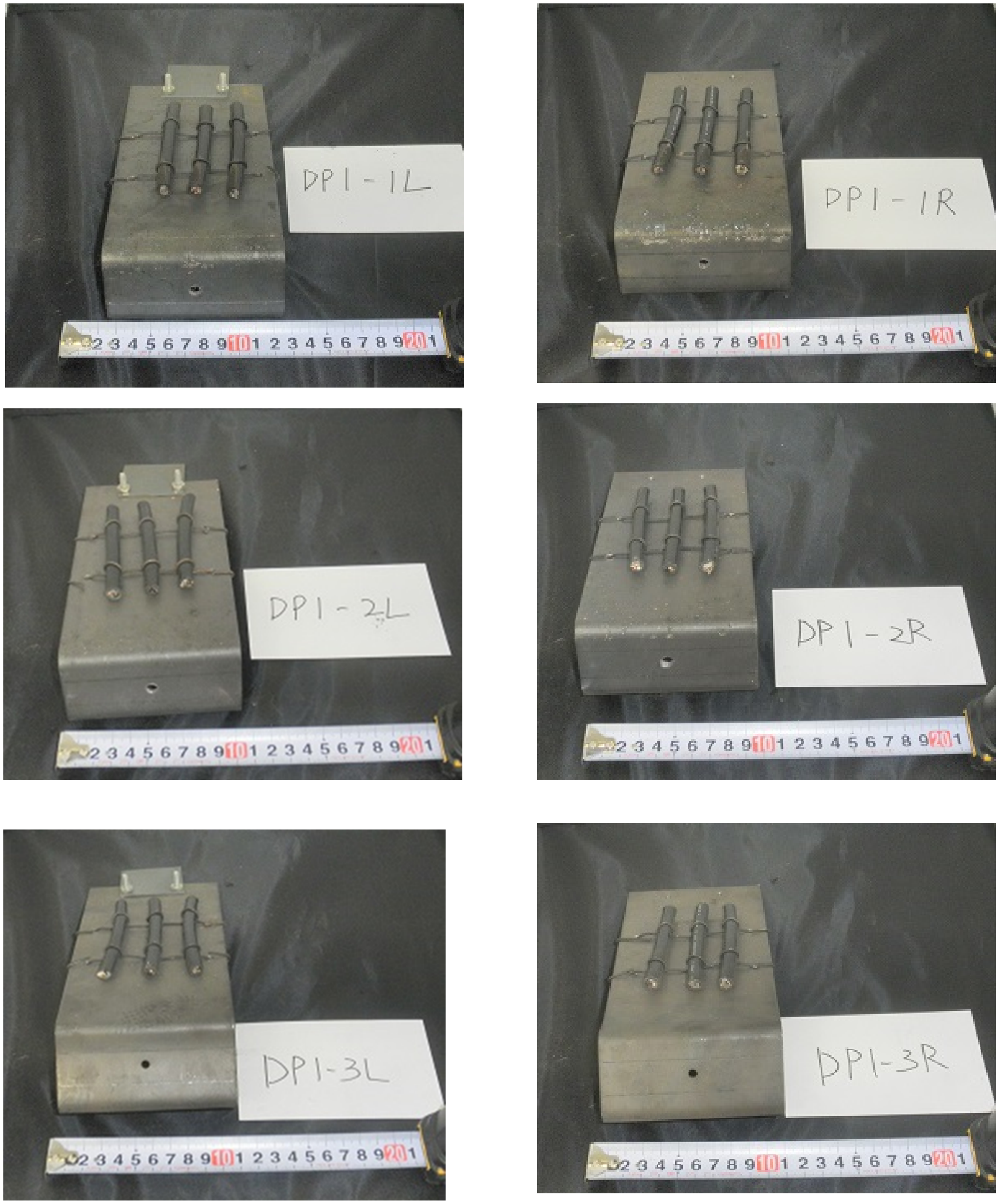


Figure F-2 DP Tests 7 and 7A Target Damage

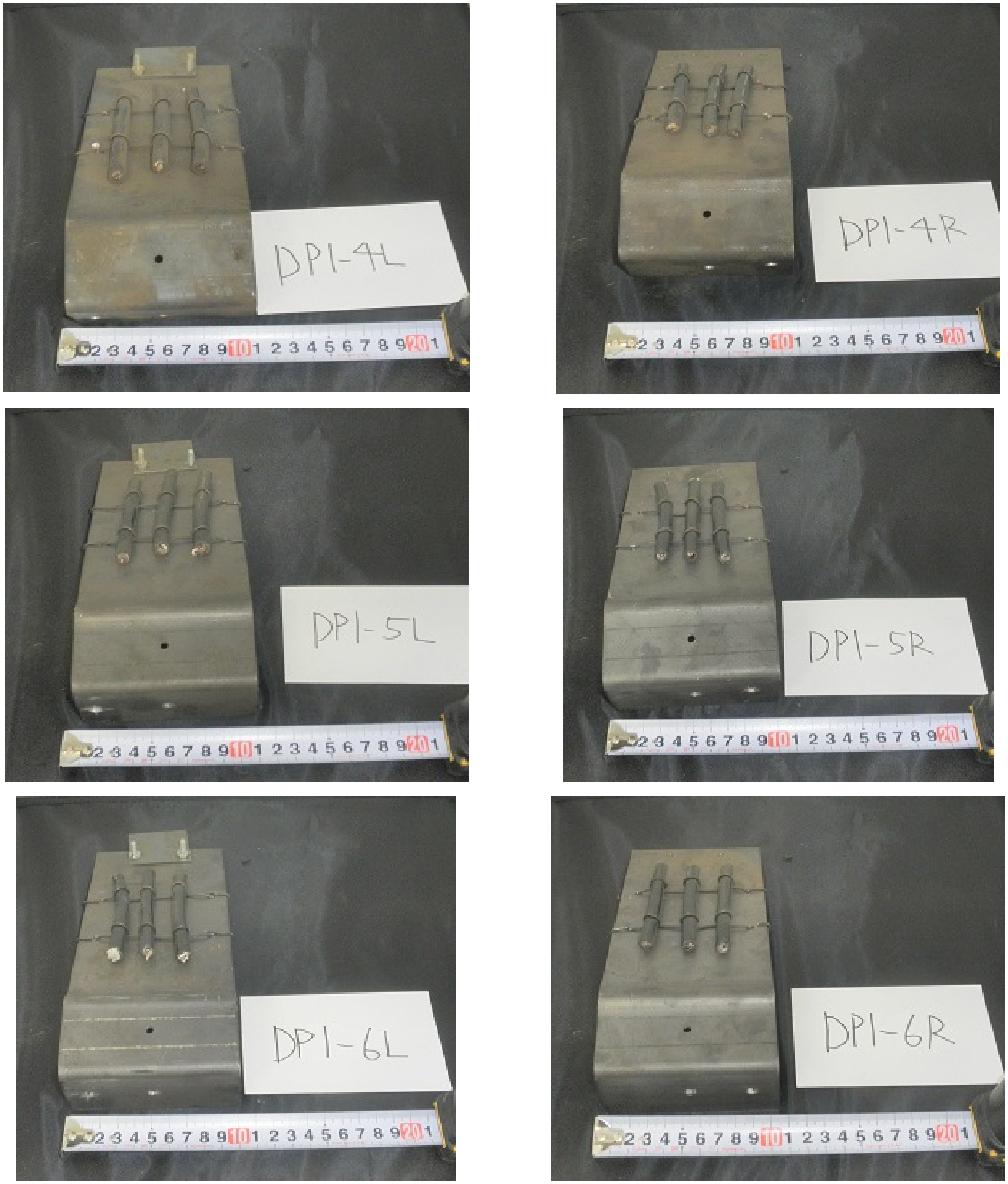


Figure F-2 DP Tests 7 and 7A Target Damage (continued)

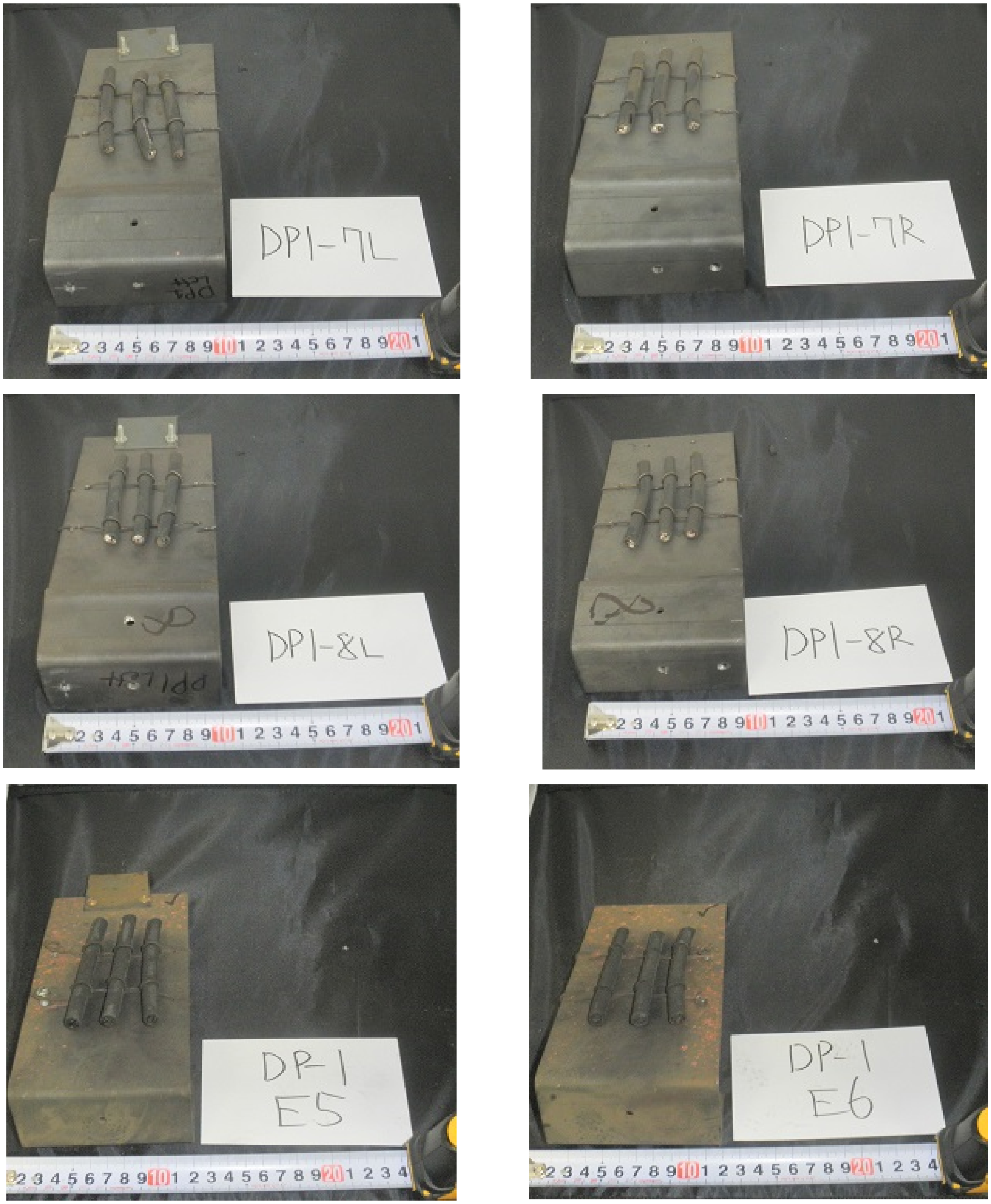


Figure F-2 DP Tests 7 and 7A Target Damage (continued)

F.1.2 DP Test 8

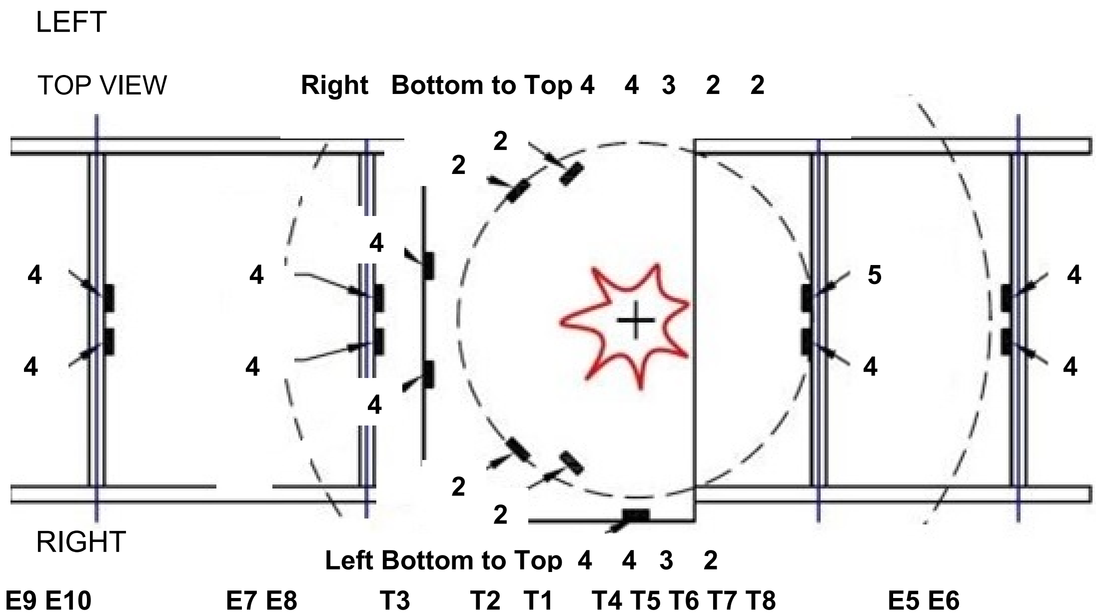


Figure F-3 DP Test 8 Target Damage

Figure F-4 DP Test 8 Detailed Target Damage

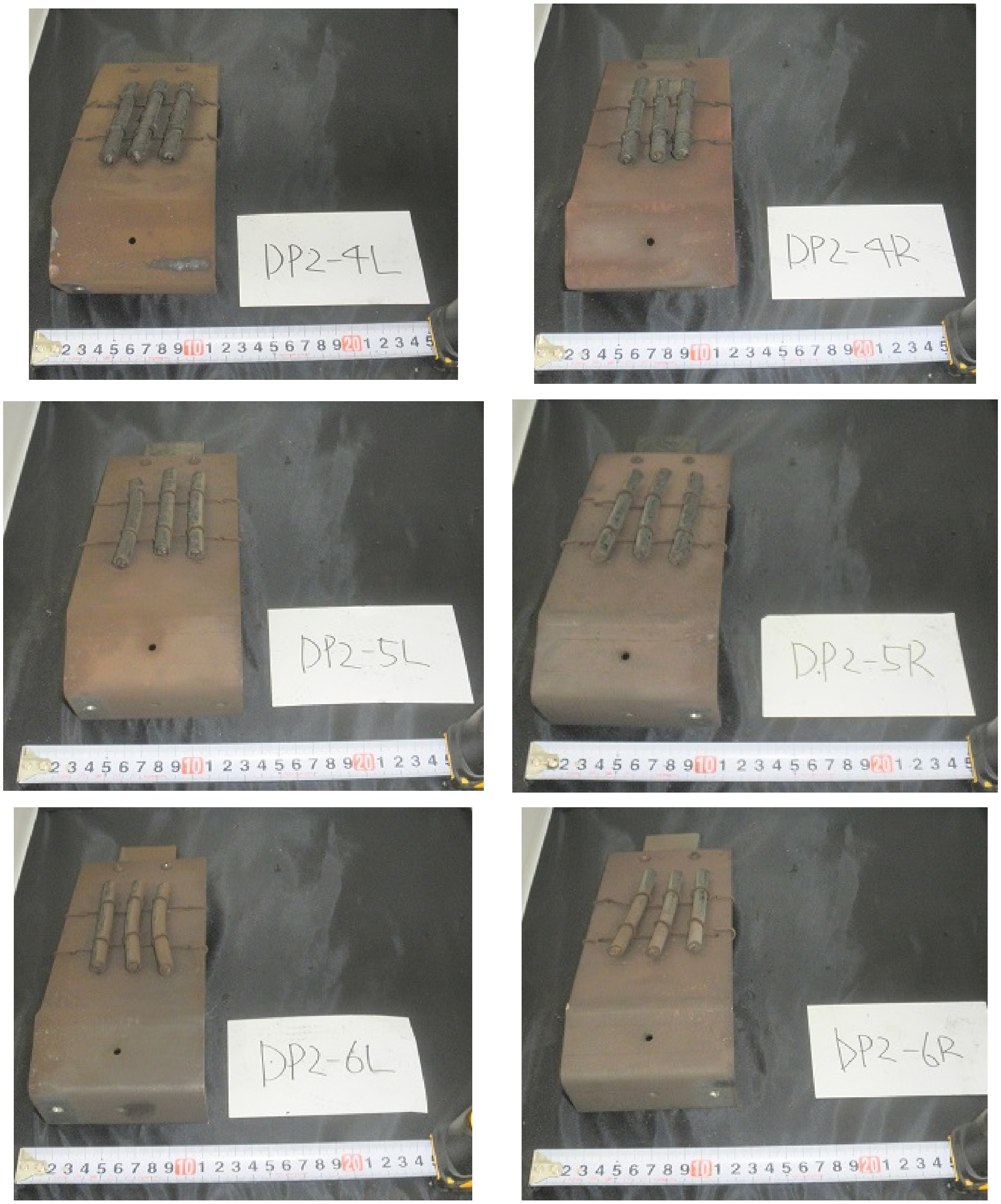


Figure F-4 DP Test 8 Detailed Target Damage (continued)

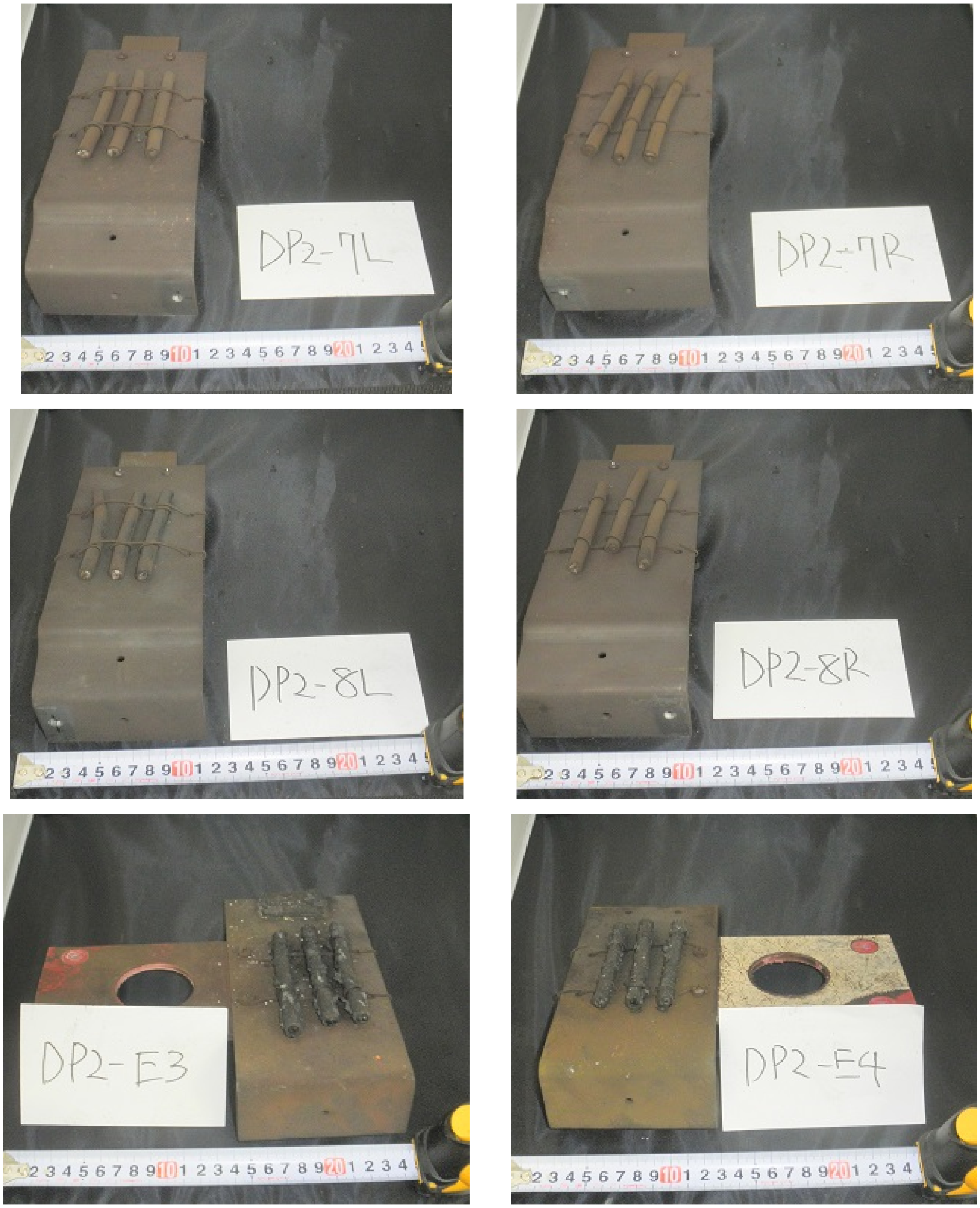


Figure F-4 DP Test 8 Detailed Target Damage (continued)

Figure F-4 DP Test 8 Detailed Target Damage (continued)

F.1.3 DP Test 9

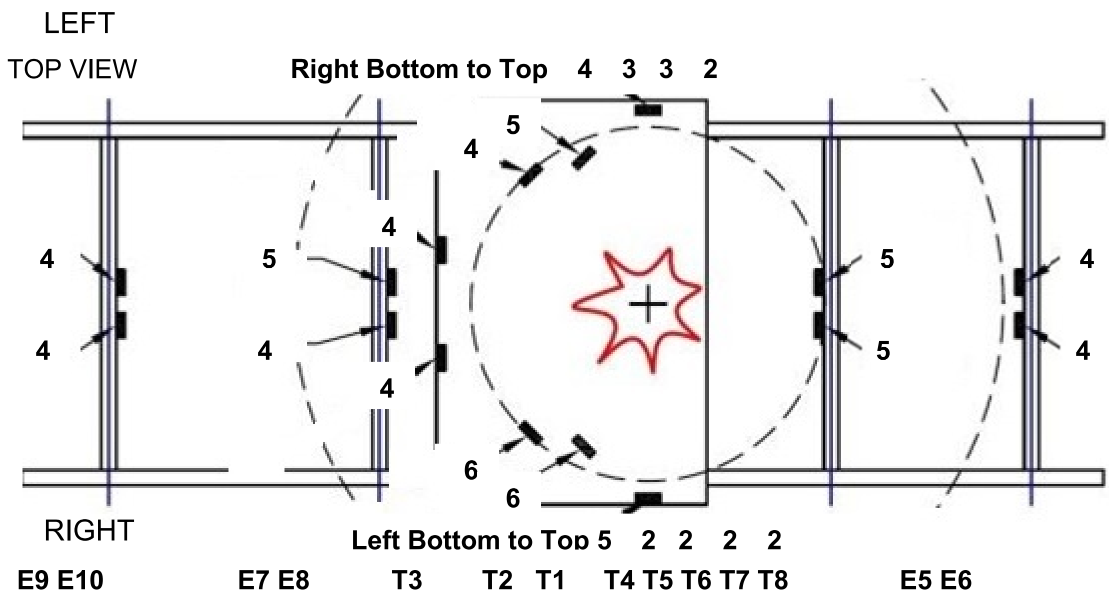


Figure F-5 DP Test 9 Target Damage Detail

Figure F-6 DP Test 9 Detailed Target Damage

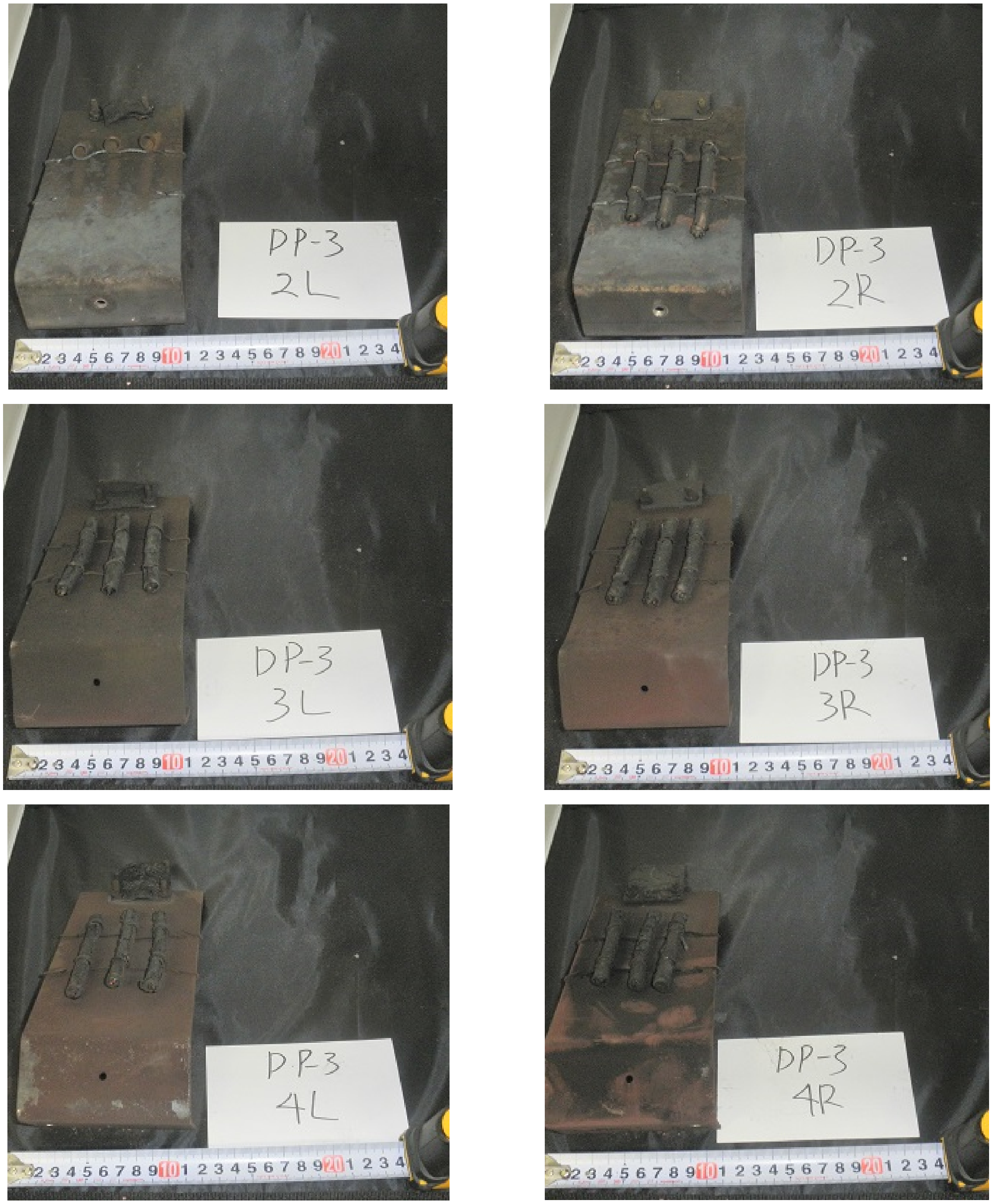


Figure F-6 DP Test 9 Detailed Target Damage (continued)

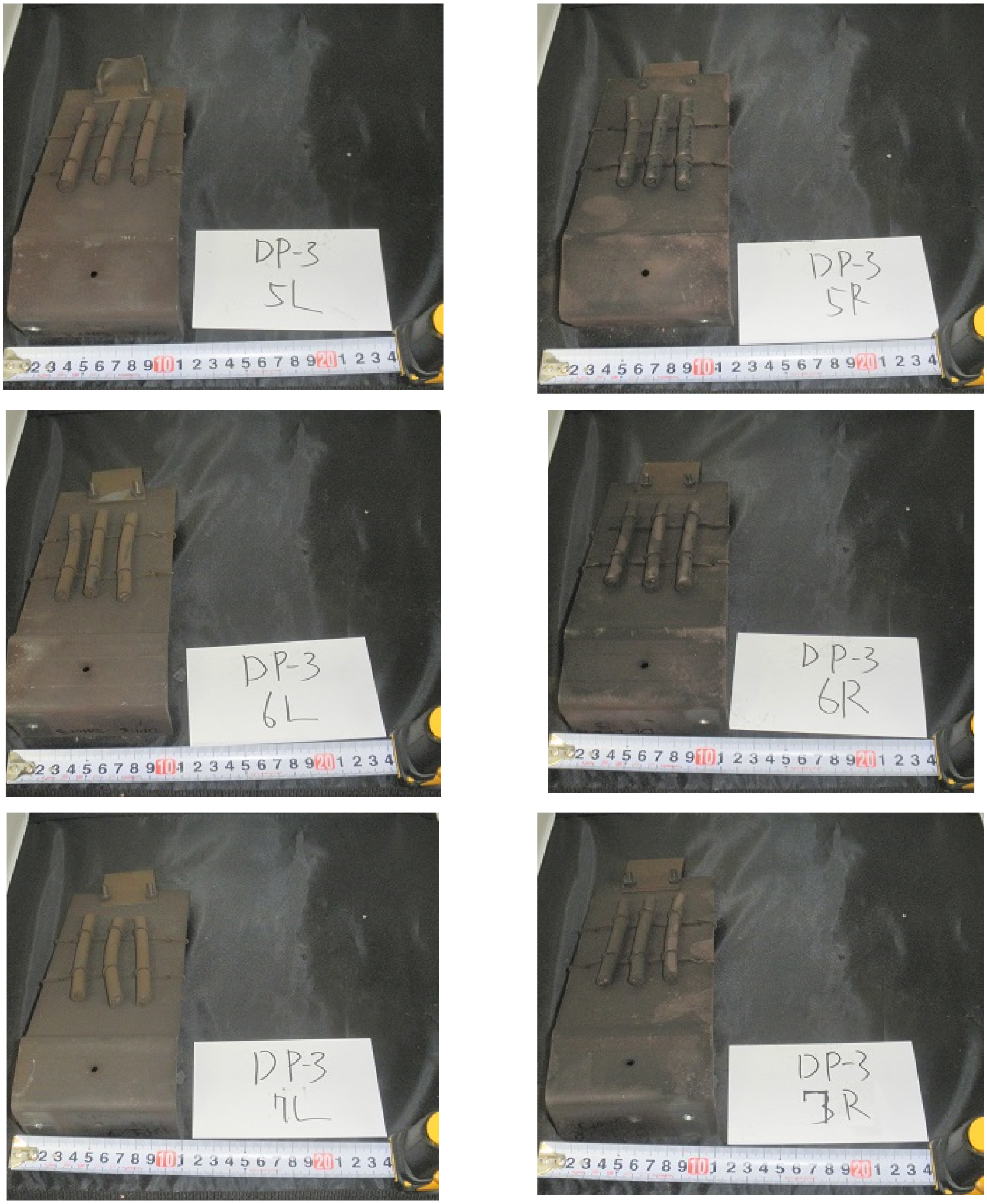


Figure F-6 DP Test 9 Detailed Target Damage (continued)

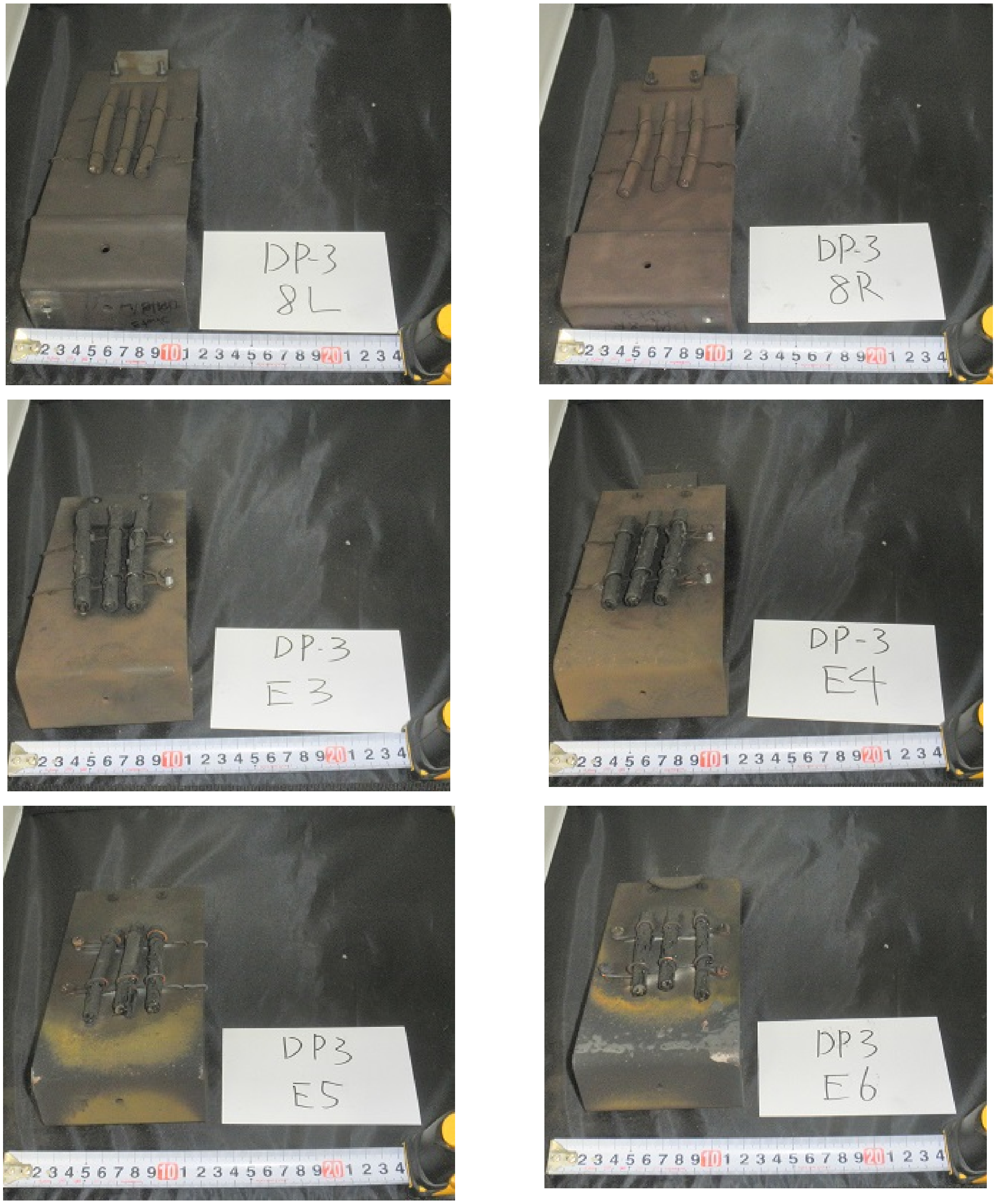


Figure F-6 DP Test 9 Detailed Target Damage (continued)

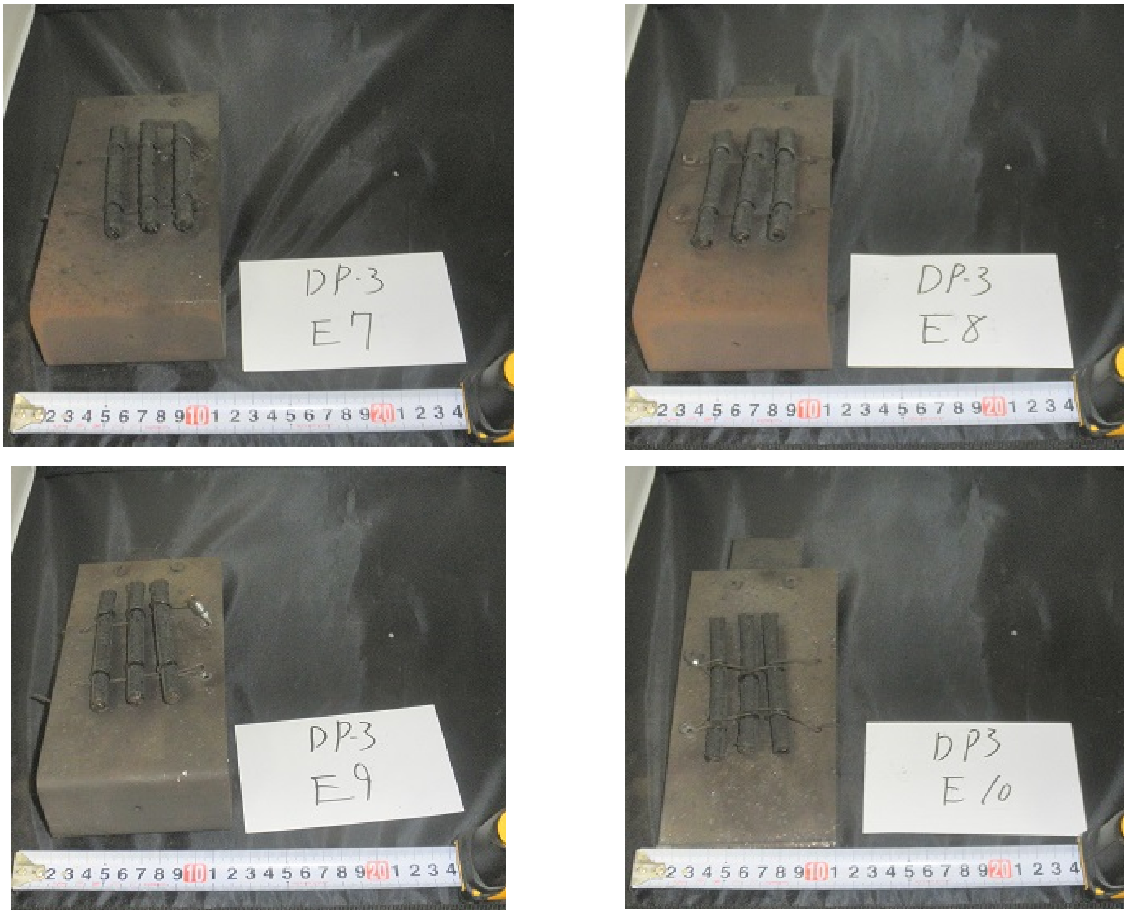


Figure F-6 DP Test 9 Detailed Target Damage (continued)

F.2 SWGR Tests

F.2.1 SWGR 7

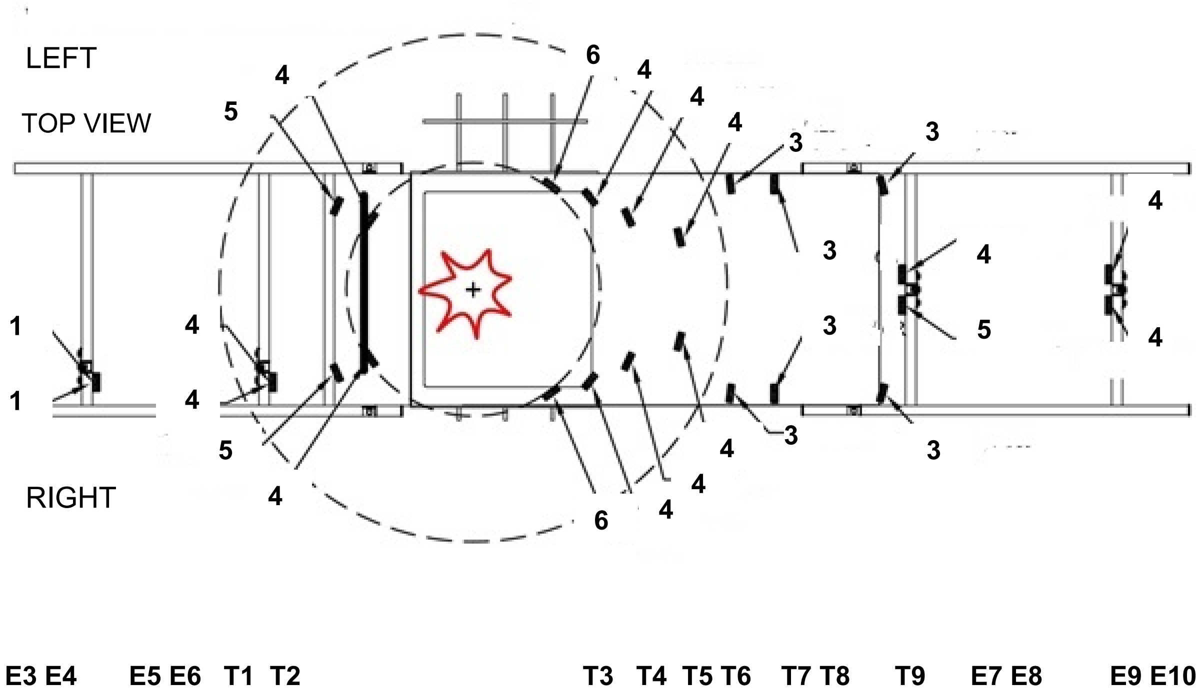


Figure F-7 SWGR Test 7 Target Damage Diagram

Figure F-8 SWGR Test 7 Detailed Target Damage

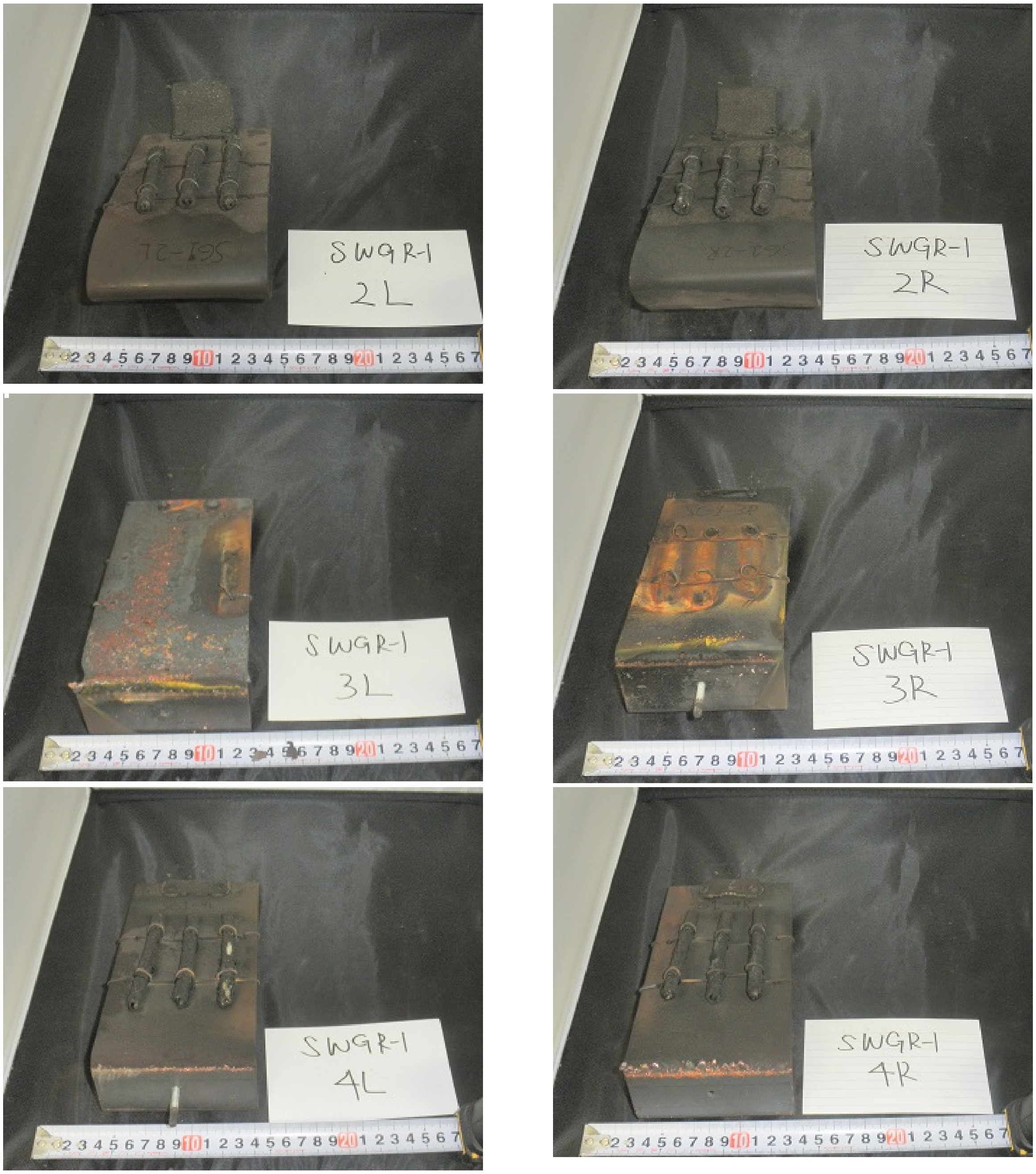


Figure F-8 SWGR Test 7 Detailed Target Damage (continued)

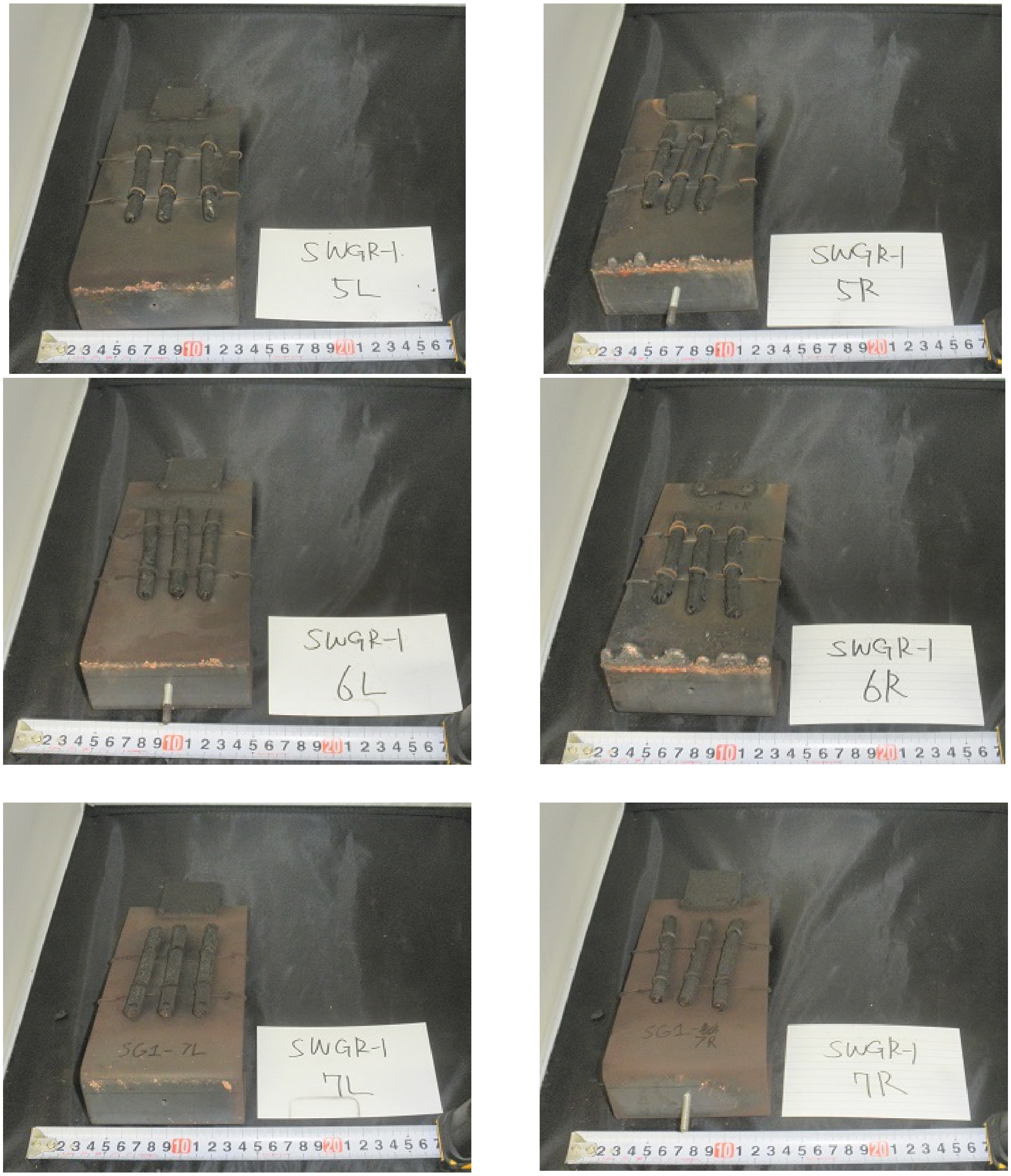
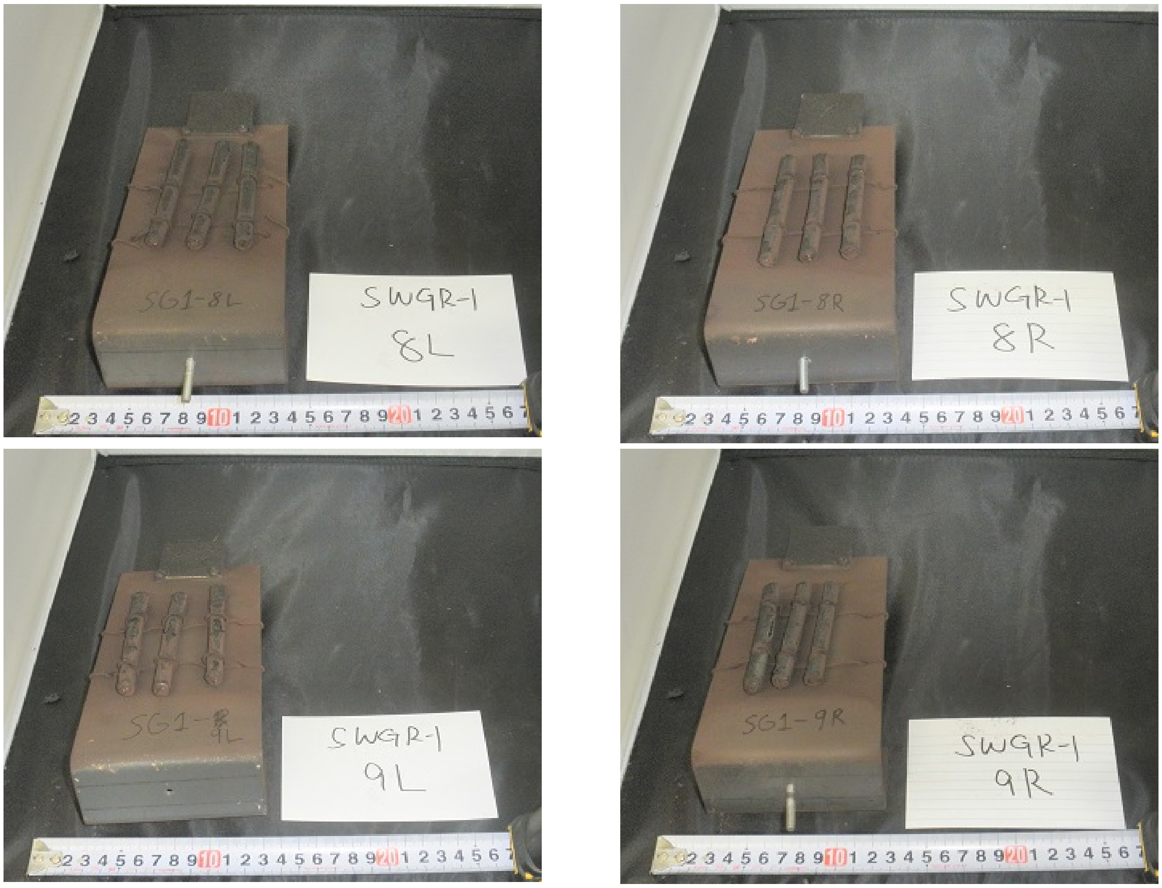


Figure F-8 SWGR Test 7 Detailed Target Damage (continued)



E3 No dmage- reused   E4 No damage reused

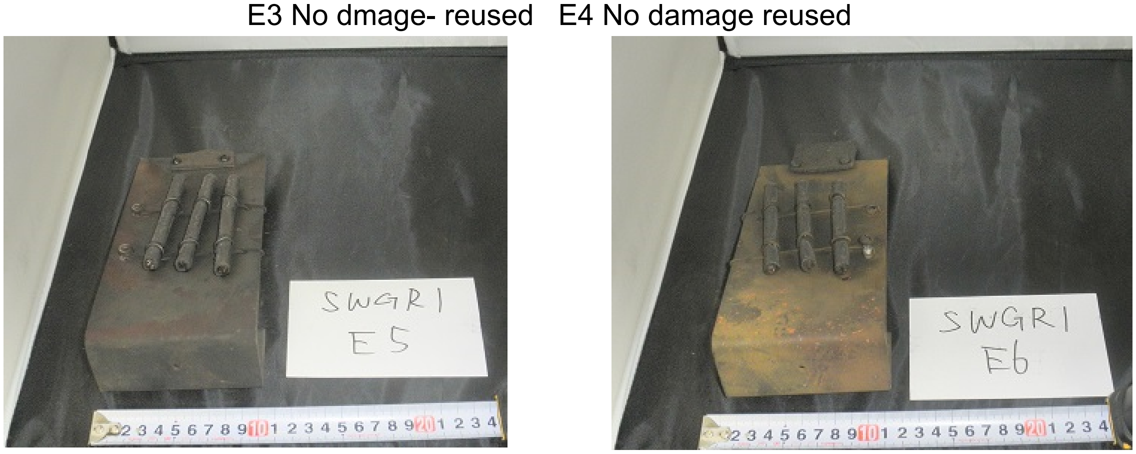


Figure F-8 SWGR Test 7 Detailed Target Damage (continued)

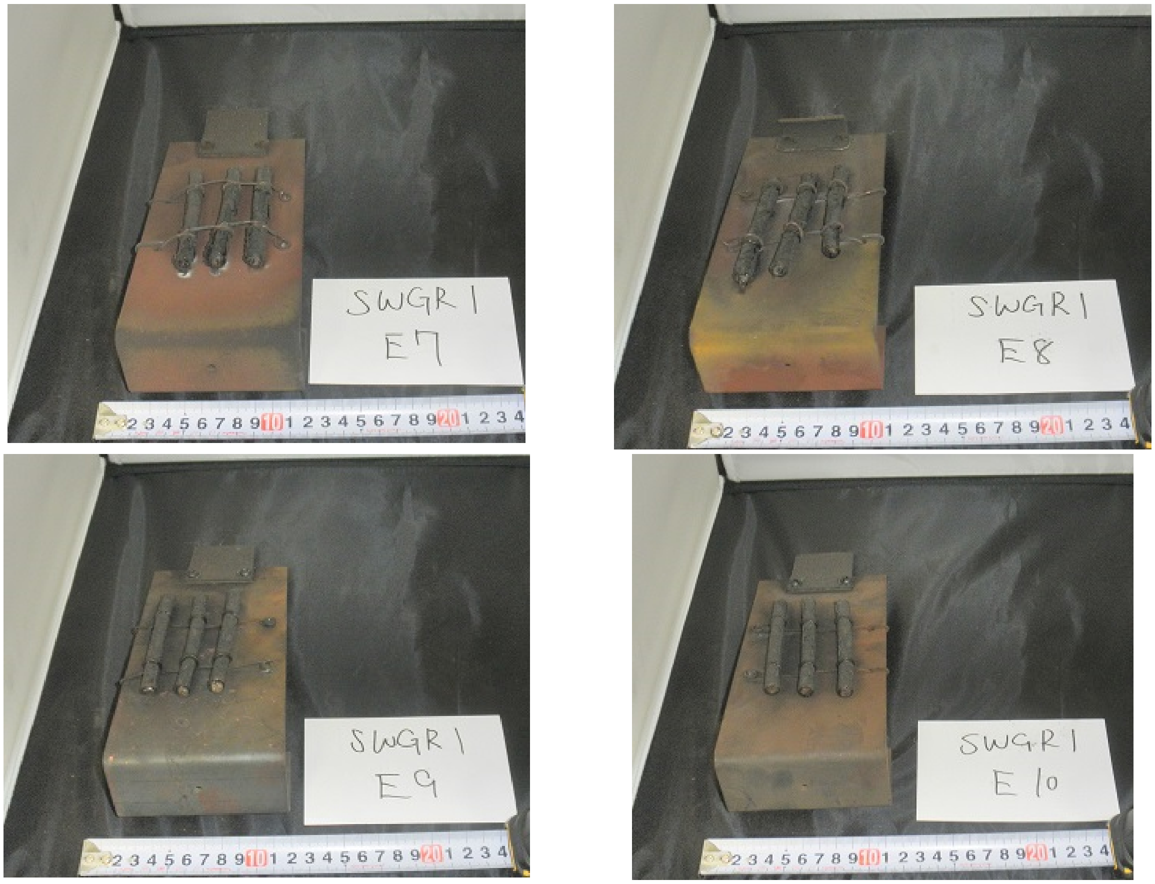


Figure F-8 SWGR Test 7 Detailed Target Damage (continued)

F.2.2 SWGR 8

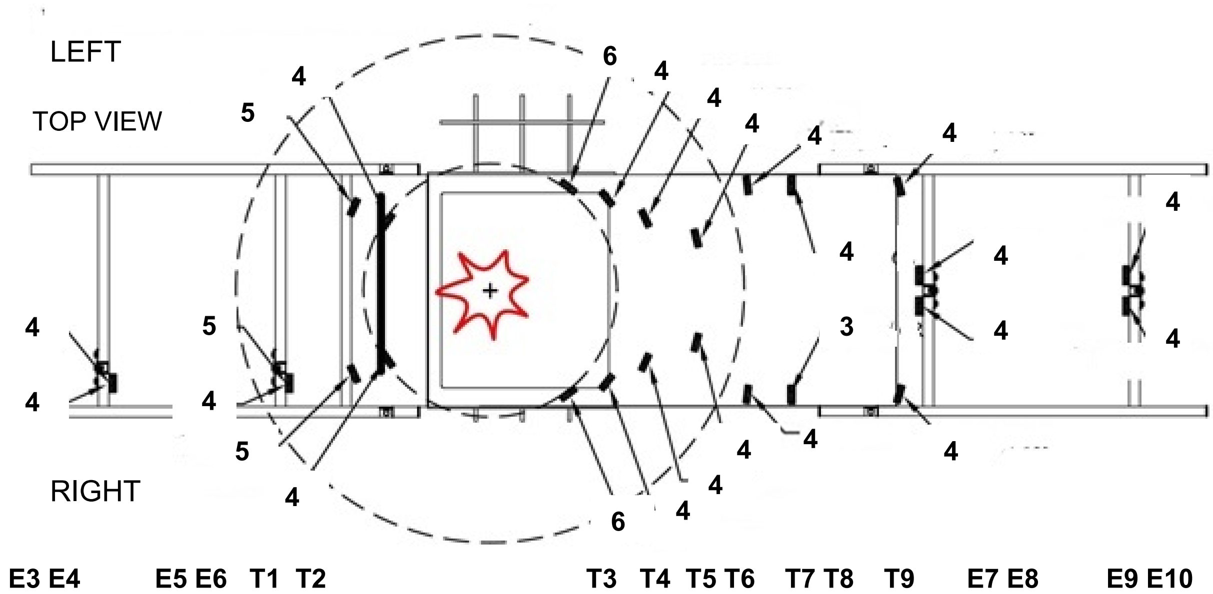


Figure F-9 SWGR Test 8 Target Damage Diagram

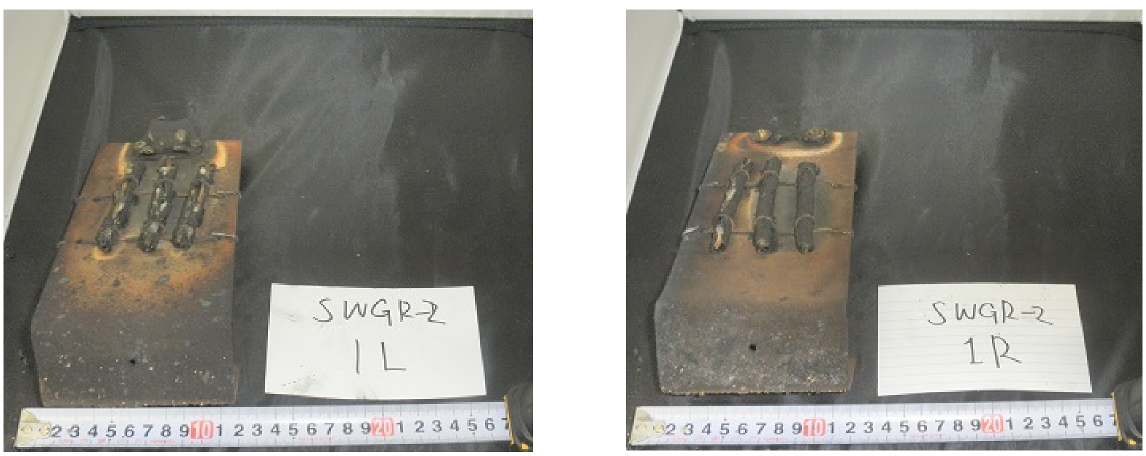


Figure F-10 SWGR Test 8 Detailed Target Damage

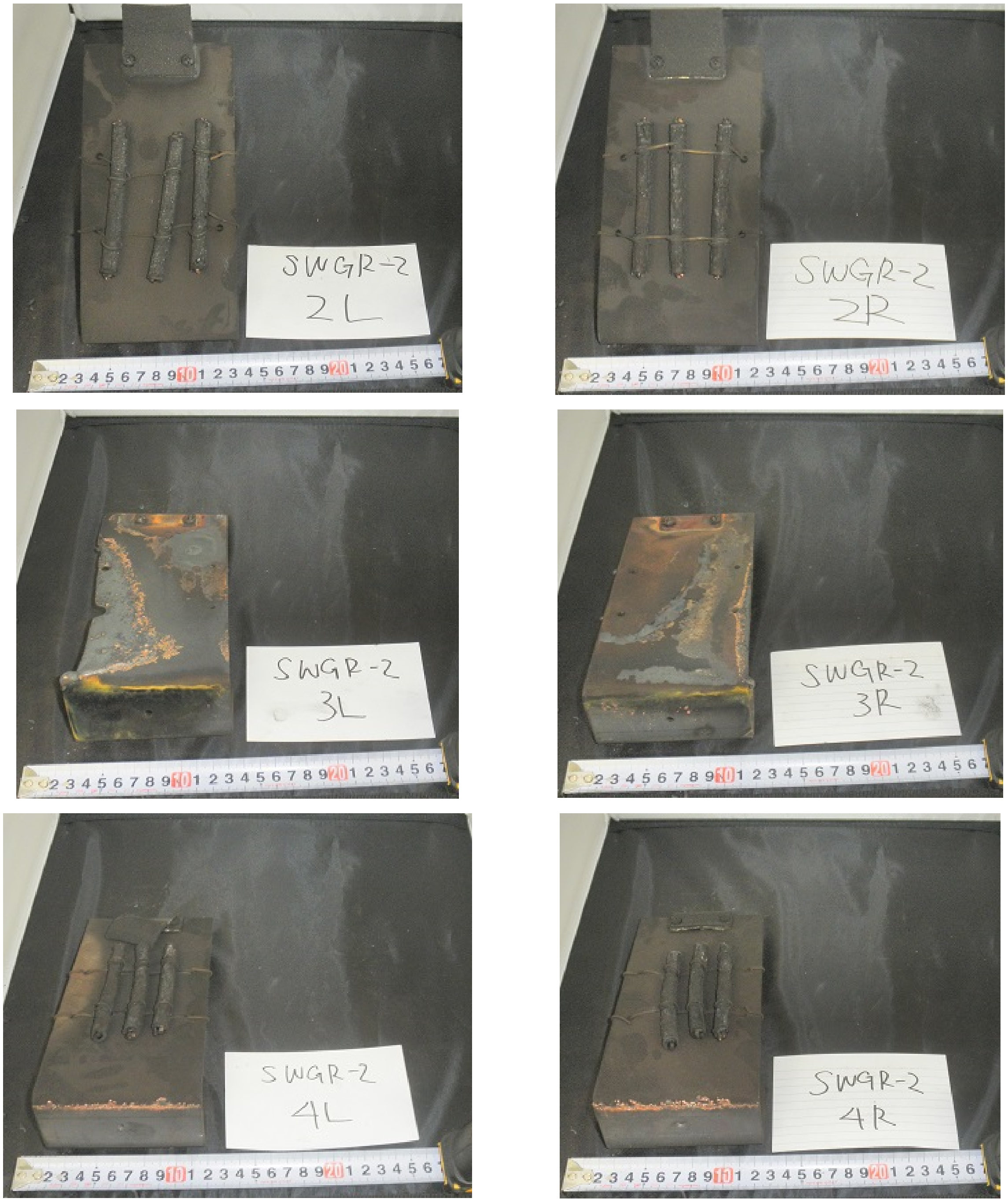


Figure F-10 SWGR Test 8 Detailed Target Damage (continued)

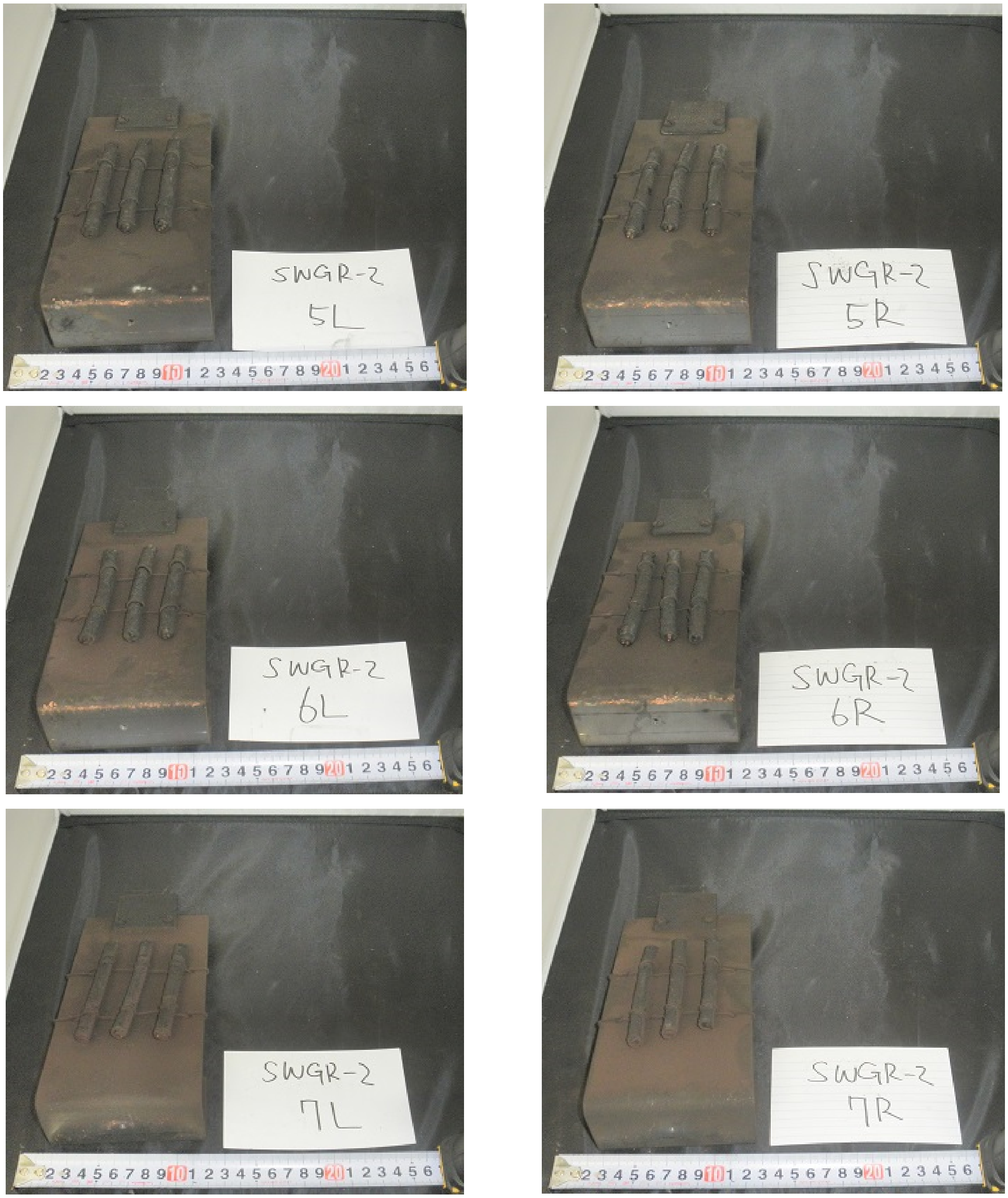


Figure F-10 SWGR Test 8 Detailed Target Damage (continued)

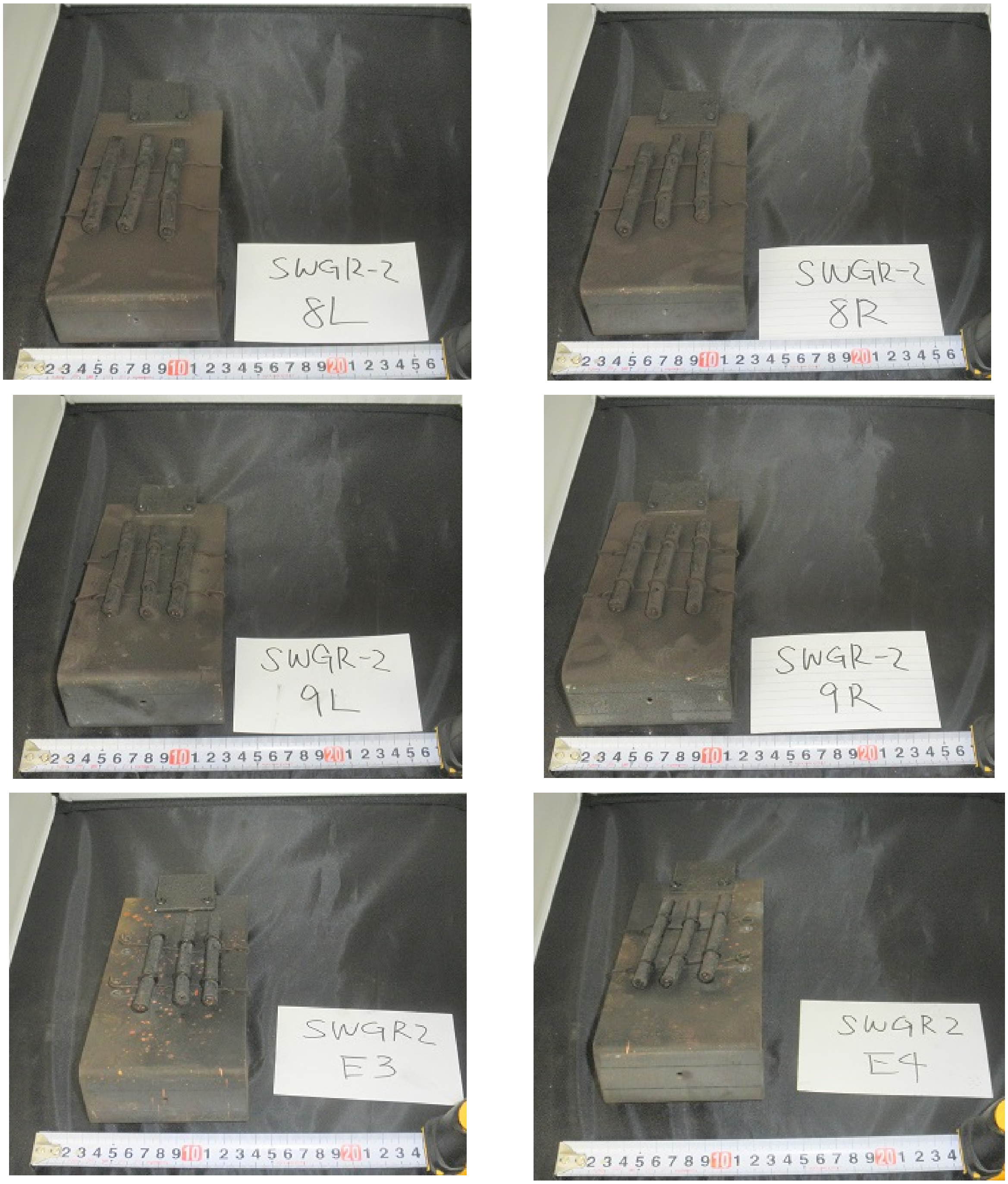


Figure F-10 SWGR Test 8 Detailed Target Damage (continued)

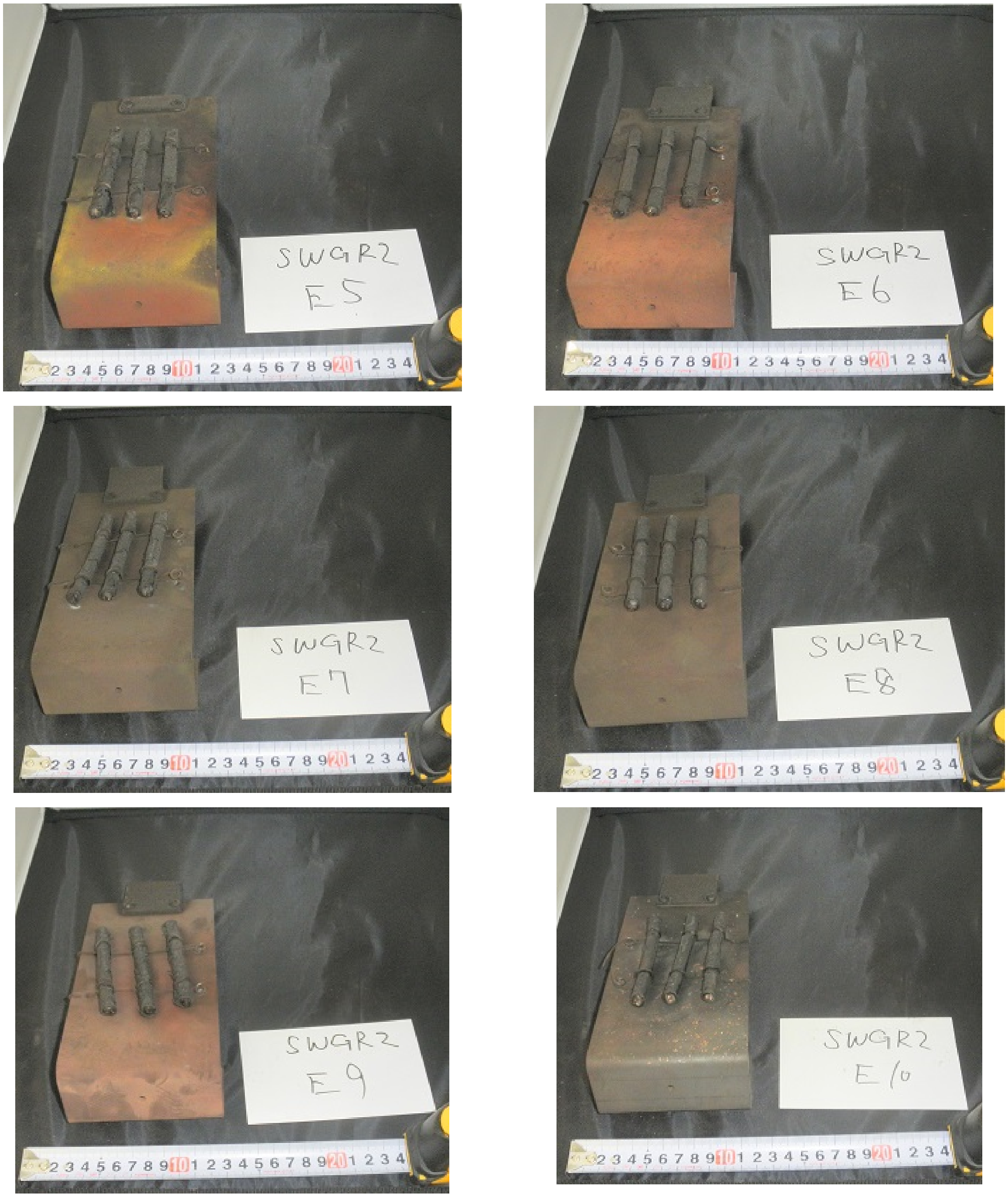


Figure F-10 SWGR Test 8 Detailed Target Damage (continued)

F.2.3 SWGR 9

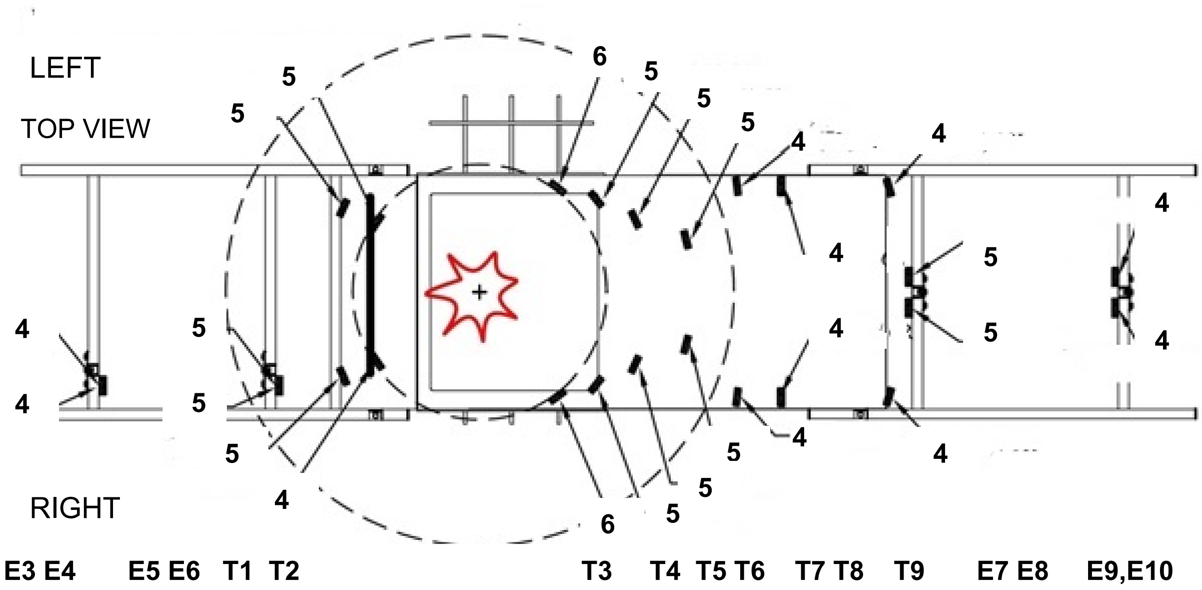


Figure F-11 SWGR Test 9 Target Damage Diagram

Figure F-12 SWGR Test 9 Detailed Target Damage

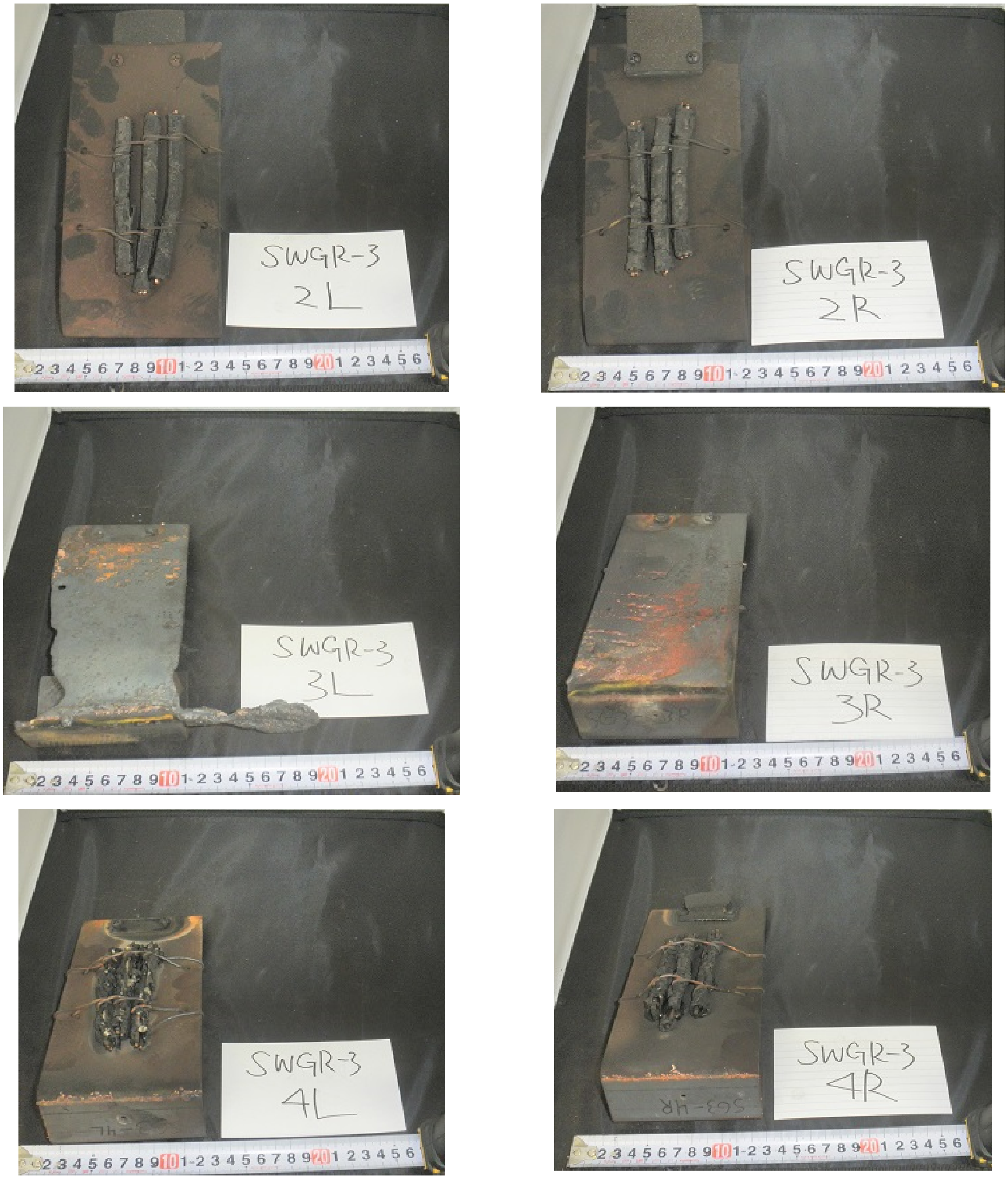


Figure F-12 SWGR Test 9 Detailed Target Damage (continued)

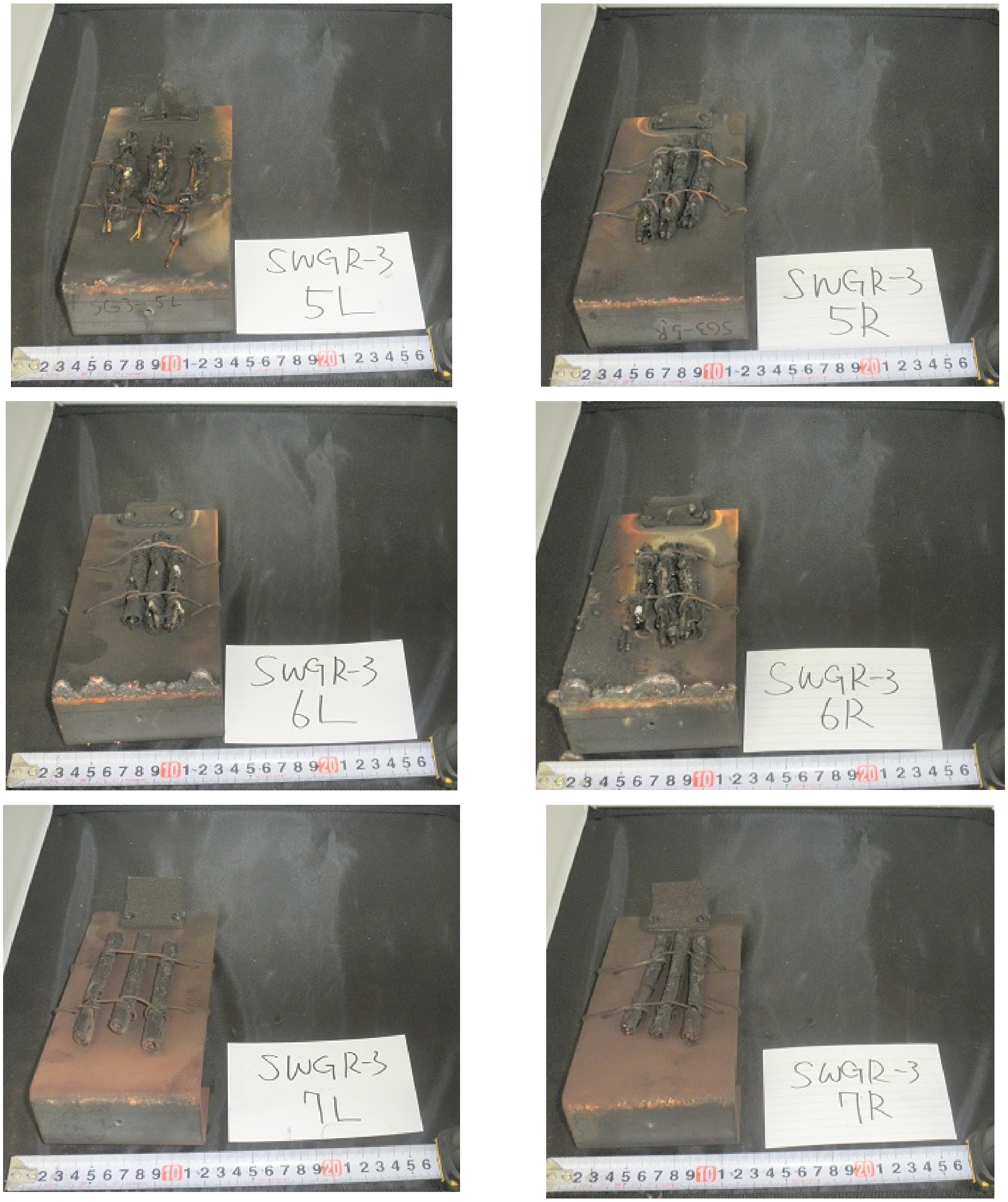


Figure F-12 SWGR Test 9 Detailed Target Damage (continued)

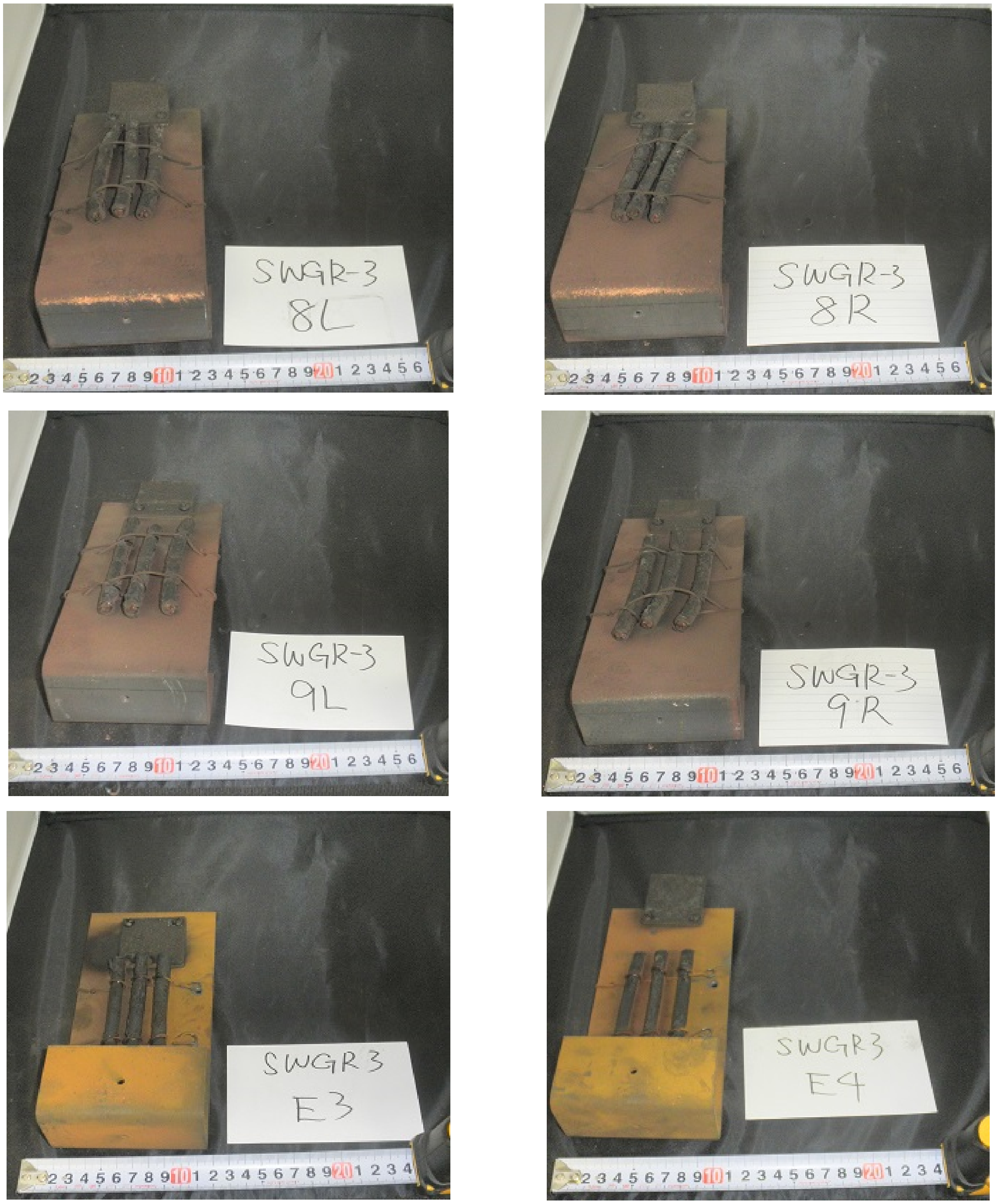


Figure F-12 SWGR Test 9 Detailed Target Damage (continued)

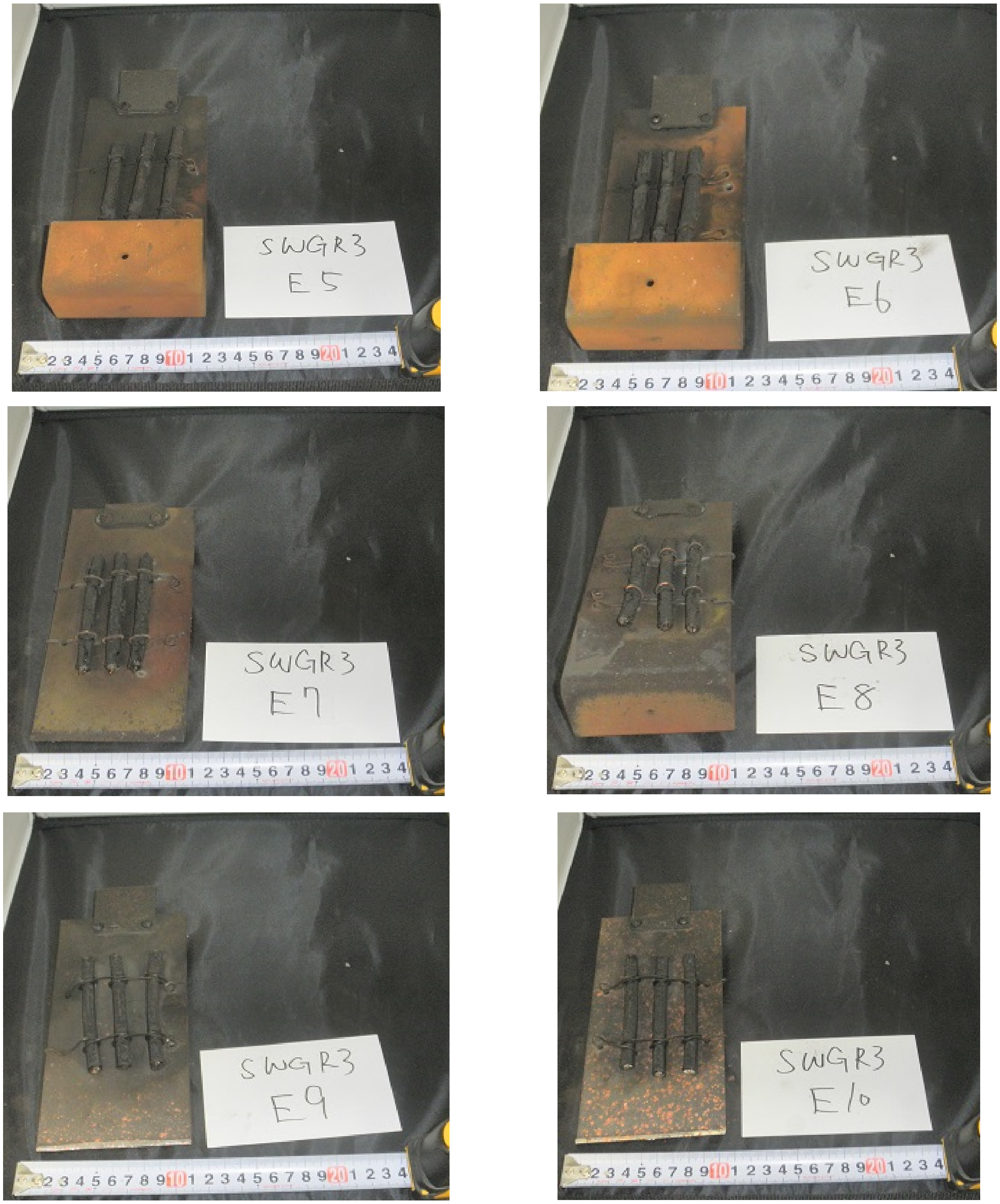


Figure F-12 SWGR Test 9 Detailed Target Damage (continued)

F.2.4 SWGR 10

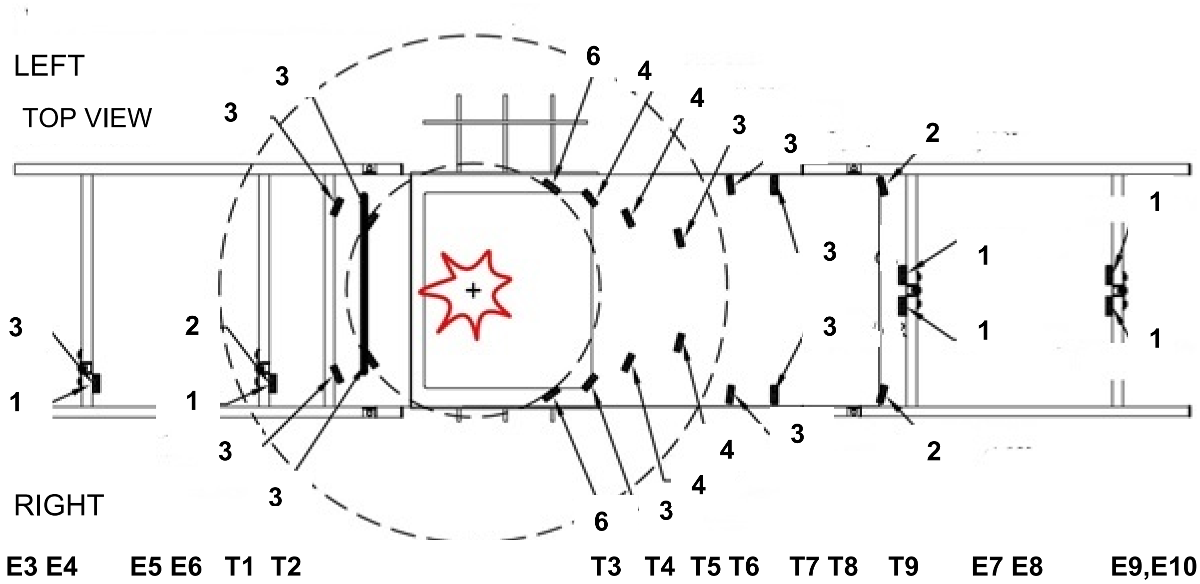


Figure F-13 SWGR Test 10 Target Damage Diagram

Figure F-14 SWGR Test 10 Detailed Target Damage

Figure F-14 SWGR Test 10 Detailed Target Damage (continued)

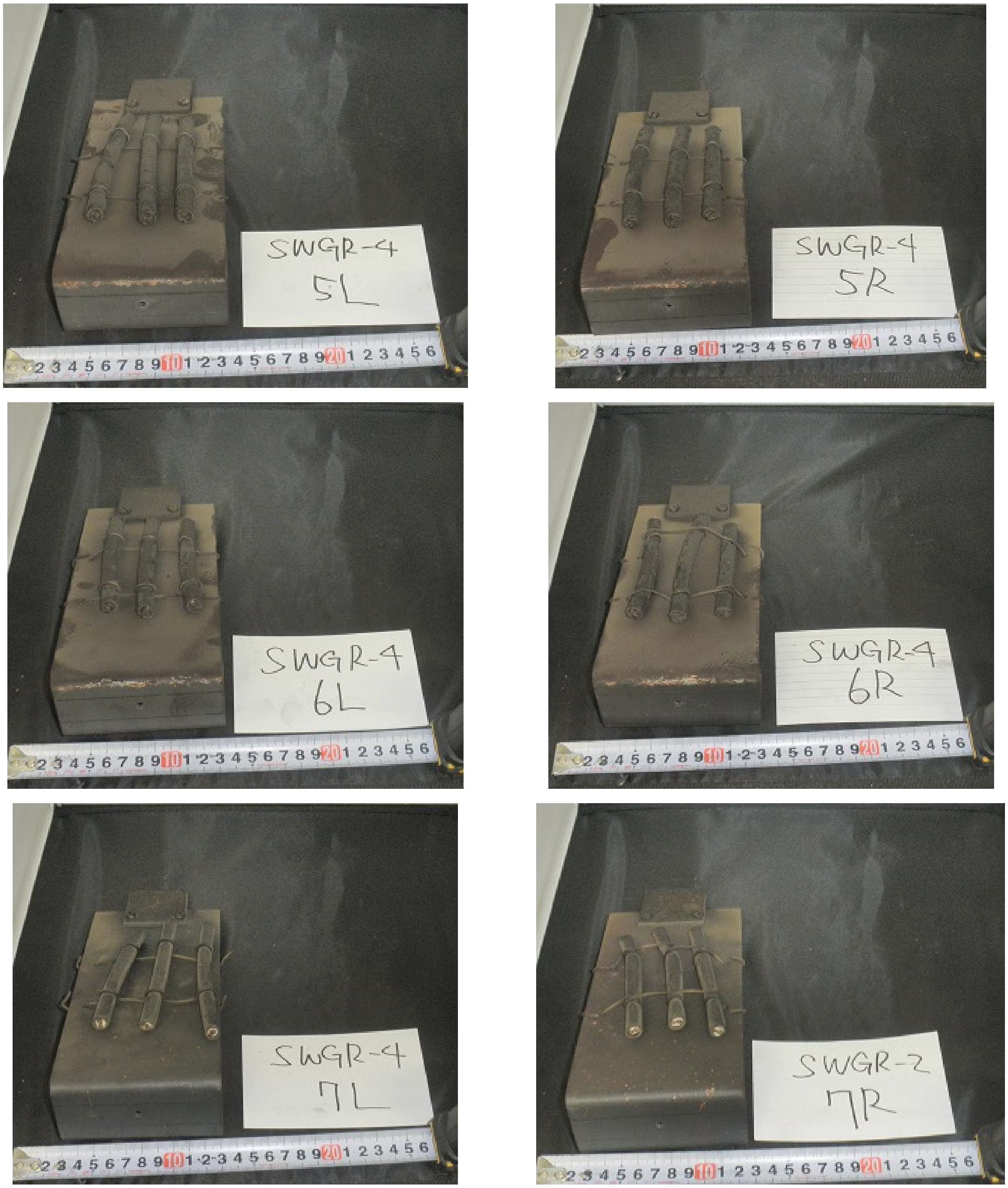


Figure F-14 SWGR Test 10 Detailed Target Damage (continued)

Figure F-14 SWGR Test 10 Detailed Target Damage (continued)

Figure F-14 SWGR Test 10 Detailed Target Damage (continued)

APPENDIX G
BUS BAR MASS LOSS CALCULATIONS

G.1 DP Tests

This section discusses the mass losses for the vertical bus bars for the DP tests. The photos of the damage are in the internal damage section in the main text for each test. The photos show the DP bus bars marked as DP Cabinet 1 or Cabinet 2. Cabinet 1 was used for DP Tests 7, 7A, and 9 and Cabinet 2 was used for Test 8. DP Tests 7 and 7A had short arcs with minor damage and Cabinet 1 was re-used for Test 9. The copper mass loss in Tests 7 and 7A (to use as the starting mass for Test 9) was estimated by calculation because the bus bars were not removed and weighed after DP Tests 7 and 7A.

The overall DP configuration is in Figure 2.3-1. The DP bus bar configuration is shown in Figure 2.4-1 and Figure G-1. Each phase has two copper bus bars that are stacked together and treated as one bus bar. The phases are A, B and C from left to right.

As a quick check of the results as "reasonable", the measured mass loss is compared to a calculation based on the bus length lost during the test. This check is done because the results for Test 10 did not appear reasonable and the check was a way to identify any other odd results. The bus bars are 0.25 inches (6.4 mm) thick so two bus bars stacked together are 0.5 inches thick (12.8 mm) and are 4 inches wide. The mass loss for each inch lost is 1 in. lost x 4 in. wide x 0.5 total thickness x 0.324 lb/in^3 for copper = 0.65 lb/in-lost or 116 g/cm-lost. If the lost area includes holes, the value is perhaps 5% less. Based on measurement uncertainty, the range of mass/length lost should be within 10% of the 116 g/cm to be considered "reasonable". All the DP tests met this "reasonable" criterion.

Measurement uncertainties are discussed in Section G.2 .

G.1.1 DP Tests 7 and 7A

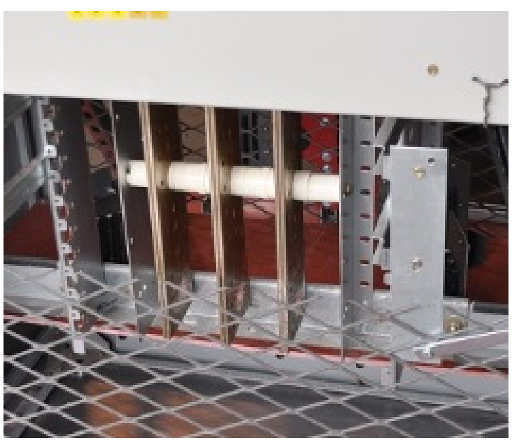
The bus bar damage is shown in Figure 2.8-9. Table G-1 shows the estimated mass losses. There was little damage because of the very low arc energies. The results meet the "reasonable" criterion.

Table G-1 DP Test 7 and 7A Estimated Mass Loss

DP Test 7 and 7A	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase total	31.4	31.27	0.130	59	0.5	116
B Phase total	31.4	31.27	0.130	59	0.5	116
C phase Total	31.4	31.27	0.130	59	0.5	116
			Total	177	1.5	116
			avg. length lost		0.5	

(a) Front View with panels removed

(b) Arc position front view



(c) Arc position rear view

Figure G-1 DP Bus Bar Configuration

G.1.2 DP Test 8

The bus bar damage is shown in Figure 2.9-6. The mass losses are shown in Table G-2. The results meet the "reasonable" criterion.

Table G-2 DP Test 8 Mass Loss

DP Test 8	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase total	31.4	29.095	2.305	1048	9.5	110
B Phase total	31.4	29.510	1.890	859	7.0	123
C phase Total	31.4	29.725	1.675	761	7.0	109
			Total	2668	23	114
			avg. length lost		8	

G.1.3 DP Test 9

The bus bar damage is shown in Figure 2.11-6. The mass losses are in Table G-3. The results are described as “estimated” because the bus bars are reused from Tests 7 and 7A and the initial weight after Tests 7 and 7a are not known. The results meet the “reasonable” criterion.

Table G-3 DP Test 9 Estimated Mass Loss

DP Test 9	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase total	31.27	27.425	3.845	1748	16.6	105
B Phase total	31.27	27.770	3.500	1591	15.4	104
C phase Total	31.27	28.180	3.090	1405	12.8	110
			Total	4744	45	106
			avg. length lost		15	

G.2 <u>SWGR Tests</u>

This section discusses the mass loss for the vertical bus bars and ground bar for the SWGR tests. The top horizontal bus bars did not have any damage or mass loss during the tests and mass changes are not reported.

The photos in the main text show the SWGR bus bars marked as SWGR Cabinet 1 through Cabinet 4 that correspond to SWGR Tests 7-10. The SWGR bus bar configuration is shown in Figure G-2. For SWGR Tests 7, 9, and 10 the arc gaps were 11.8 inches that provided an arc voltage was 897-966 volts. SWGR Test 8 had a 6-inch arc gap and the arc voltage was 816 volts.

Each phase had two copper bus bars that were called “front” and “rear” and have a 0.375-inch space between them. The phases are A, B and C from left to right in Figure G.2-1. The bus bars are 0.375 inches (6.35 mm) thick and 3-inches (76.2 mm) wide. The bus bars have polymer insulation on them but this was removed before weighing after the test. The bus bar weight from the manufacturer was measured before the polymer insulation was installed.

As a quick check of the results as “reasonable”, the measured mass loss is compared to a simple calculation based on the bus length lost during the test. The mass loss for each inch lost is 1 in. lost x 3 in. wide x 0.375 thickness x 0.324 lb/in^3 for copper = 0.365 lb/in lost or 65 grams/cm lost. So, the actual measured mass lost is compared to 65 g/cm lost for the quick check.

There are many uncertainties in bus bar mass loss calculations:

a. Most of the uncertainty is because the check using the 65 g/cm assumes that the only copper mass lost is from the rectangle shown in Figure G-2. This rectangle is based on the width of the bus bar and the length that was lost based on the length before the arc minus the length after the arc. After the arc, the longest bus bar length is recorded as shown in Figure G-2. However, this simple rectangle does not account for the material lost because the bus bar does not burn evenly. For example, in Figure G-2, the triangle shape of material lost is not included in the 65 g/cm check. This uncertainly also applies to any material lost above the rectangle like the irregular shapes at the end of the bus bars.

b. Another uncertainty is that only the front bus bar length was measured in-situ after the test. Therefore, the analysis assumes that the same length was lost on the front and rear bus bars but there may be small differences.

c. Another uncertainty is some of the material from the simple rectangle is not lost because it melts and moves between the bus bars and forms a slug that sticks to the bus bars. This slug is weighed with the bus bar it stuck to so the weight is too high and the weight difference before and after the arc is too low. As shown in the Test 10 results later, this slug may also cause a bus bar to weigh more after the test than before the test and the mass loss is negative (-).

d. In some tests there may not be large slugs between the bus bars but there was coating of the copper from the material in the rectangle sputtering onto the bus bars above the arc. This uncertainty is probably small.

e. The bus bars have rounded edges and the simple calculation assumes square edges.

f. The mass for any holes is not considered (this applies more for the DP tests).

These measurement uncertainties can cause the check to 65 g/cm to be uncertain by 10% or so. For tests where the total mass loss is large like SWGR Tests 7-9, the uncertainties above will usually be within the 10%. However, when the mass loss is small the uncertainties above may exceed 10%. For example, in Figure G-2 for Test 10, the triangle mass is about 21% of the total mass loss and this must be included in the check.

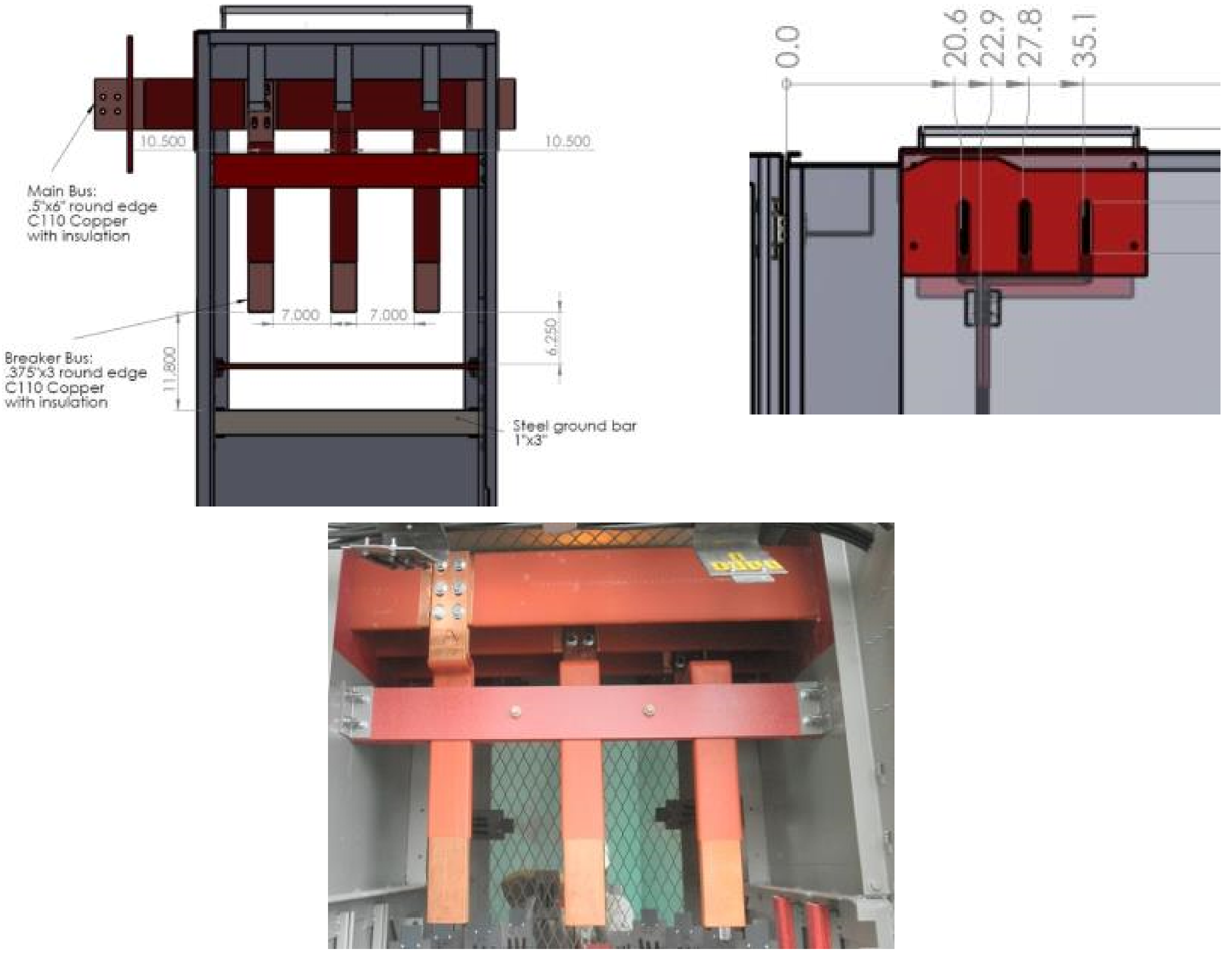


Figure G-2 SWGR Bus Bar Configuration

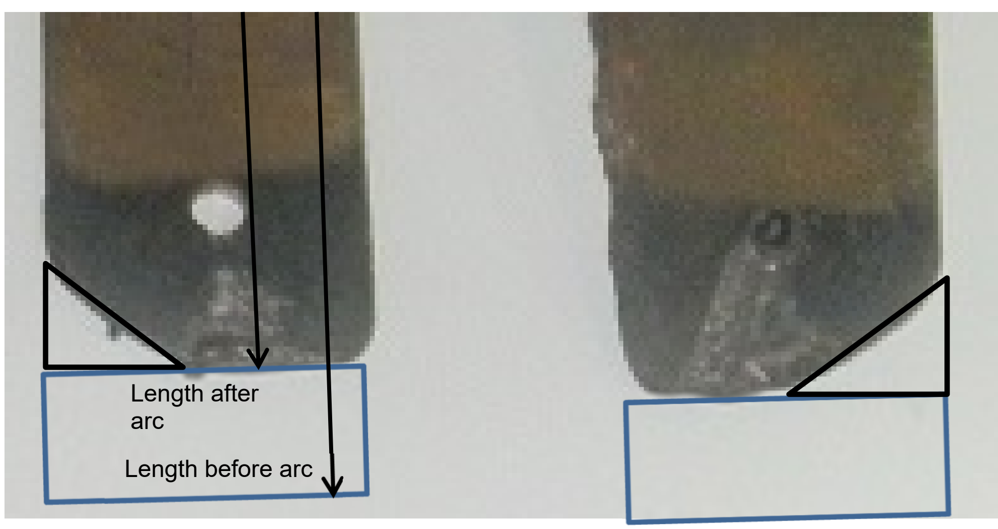


Figure G-3 Bus Bar Length Measurement Example

G.2.1 SWGR Test 7

The bus bar damage is shown in Figure 3.8-6. Table G-4 shows the mass losses. The results meet the “reasonable” criterion.

Table G-4 SWGR Test 7 Mass Loss

SWGR 1 Test 7	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase Front	9.963	8.055	1.908	867	14.0	62
A Phase Rear	9.913	8.010	1.903	865	14.0	62
A Phase total	19.876	16.065	3.811	1732	27.9	62
B Phase Front	10.888	9.090	1.798	817	13.7	60
B Phase Rear	10.938	9.085	1.853	842	13.7	62
B Phase total	21.826	18.175	3.651	1660	27.3	61
C Phase Front	13.463	11.550	1.913	870	14.6	60
C Phase Rear	13.513	11.365	2.148	976	14.6	67
C phase Total	26.976	22.915	4.061	1846	29.2	63
			Total	5238	84	62
			avg. length lost		28	

	before lb	after lb	lugs missing number	lug correction lb	change lb	change g
Ground bar	28.8	24.680	2	0.14	1.260	583

G.2.2 SWGR Test 8

The bus bar damage is shown in Figure 3.10-6. Table G-5 shows the mass losses. The results do not meet the reasonable criteria for the Phase C front and rear because a large slug of copper is attached to bus bar C Front a s shown in the figure. Phase A rear caused the Phase A had similar slugs. These slugs are also indicated by the large differences in the mass lost for the front and rear bus bars (198 grams in Phase A and 248 grams in Phase C). Note the results are reasonable for the Phase A total and Phase C total mass loss that includes the front and rear bus bars. So, it seems the transfer of copper between the front and rear bus bar pieces explains the unreasonable result of each piece.

Table G-5 SWGR Test 8 Mass Loss.

SWGR 2 Test 8	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase Front	9.963	7.625	2.338	1063	14.8	72
A Phase Rear	9.913	8.010	1.903	865	14.8	59
A Phase total	19.876	15.635	4.241	1928	29.5	65
B Phase Front	10.888	9.145	1.743	792	12.4	64
B Phase Rear	10.938	9.070	1.868	849	12.4	69
B Phase total	21.826	18.215	3.611	1641	24.8	66
C Phase Front	13.463	11.835	1.628	740	14.0	53
C Phase Rear	13.513	11.340	2.173	988	14.0	71
C phase Total	26.976	23.175	3.801	1728	27.9	62
			Total	5297	82	64
			avg. length lost		27	

	Before lb	After lb	Lugs Missing number	Lug Correction lb	Change lb	Change g
Ground bar	28.8	24.790	2	0.14	4.150	1886

G.2.3 SWGR Test 9

The bus bar damage is shown in Figure 3.11-6. Table G-6 shows the mass losses. The results meet the "reasonable" criterion.

Table G-6 SWGR Test 9 Mass Loss

	Before lb	After lb	Change lb	Change g	Length chng cm	mass/length g/cm
A Phase Front	9.963	7.375	2.588	1176	17.8	66
A Phase Rear	9.913	7.285	2.628	1195	17.8	67
A Phase total	19.876	14.66	5.216	2371	35.6	67
B Phase Front	10.888	8.535	2.353	1070	16.5	65
B Phase Rear	10.938	8.645	2.293	1042	16.5	63
B Phase total	21.826	17.18	4.646	2112	33.0	64
C Phase Front	13.463	11.245	2.218	1008	15.9	64
C Phase Rear	13.513	11.340	2.173	988	15.9	62
C phase Total	26.976	22.585	4.391	1996	31.8	63
			Total	6479	100	65
			avg. length lost		33	

	Before lb	After lb	Lugs Missing number	Lug Correction lb	Change lb	Change g
Ground bar	28.8	26.155	2	0.14	2.785	1266

G.2.4 SWGR Test 10

The bus bar damage is shown Figure 3.12-7. Table G-7 shows the mass losses. The initial results did not meet the "reasonable" criterion. Corrections were made in Table G-8 as described below. There were also other odd results as discussed below.

There are some negative values because large slugs of melted copper were between the bus bars on Phase A and Phase B as shown in Figure 3.12-7 and Figure G-4. On Phase A the slug was with the rear bus bar so the rear bus bar mass was higher after the test than before the test. On Phase B the slug was with the front bus bar so the rear bus bar mass was higher after the test than before the test.

The results for SWGR Test 10 are different from the longer arcs in SWGR Tests 7 -9 because the mass lost/ length lost ratios are all outside the "reasonable" range of 65± 10% g/cm-lost. The differences of front-rear pairs are caused by the melted copper between the bus bars. However, unlike Phase A and Phase C in SWGR Test 8, the total for the mass/length are also well below the 65 g/cm check value. In SWGR Test 10, the overall mass losses were lower than other tests so the errors from the uncertainties are much higher than 10%. Therefore, the uncertainties discussed above were evaluated as shown in Table G-8. For simplicity, the uncertainties are corrected for the total mass loss for each phase not for each front and rear bus bar.

The corrections are for slugs in all phases and for the triangles in Phase A and Phase C. Note that the Mass/length in the final column are within 10% of the 65 g/cm check value. Figure G-2 shows an example of the rectangles for the mass lost based on the length change for the simple 65 g/cm check. The triangles are additional mass lost that is not in the 65 g/cm check.

The uncertainty caused by the slug between the bus bars is accounted for as shown in the Column 3, "Slug", of Table G-8. The slugs were not weighed so the masses of the slugs are not known. However, they can be estimated based on the difference of the bus bar changes since we would assume that if the slug was not on one of the bus bars, the bus bar mass changes would be the same. For example, for Phase A, the difference is 118 grams ([222 – {-15}]/2). Notice if the 118 is subtracted from the 222 and added to the -15 that the mass loss in both bus bars would be 103 grams. The slug mass of 118 gams is added to the Total Corrected grams. The slug mass for Phases A and B are 108 grams and 40 grams respectively. Note that these slug masses are 36%, 28%, and 11% of the total mass lost and were a significant contributor to the uncertainty and one reason the reasonable 65 g/cm ± 10% was not achieved.

The mass in the triangles in Figure G-4 above the rectangular shape where the main mass losses occur are not included in the simple 65 g/cm check. Corrections were made in Table G-8 for the triangular-shaped losses in Phases B and C   Phase A was within10% of 65 g/cm with the correction for the slug above and the corrections for the triangles was not performed. The corrections are calculated using the area of the triangles scaled from the photos in the figures then the masses are added to the Corrected Change in Table G-8. For Phase B the corrections were 70 grams (32 grams for the front bus bar and 38 grams for the rear bus bar) and 79 grams (35 grams for the front bus bar and 44 grams for the rear bus bar). Note that these triangle masses are 18% and 22% of the total mass lost and are a significant contributor to the uncertainty.

Table G-7 SWGR Test 10 Mass Loss

	Before lb	After lb	Change lb	Change g	Length chng cm	Mass/length g/cm
A Phase Front	9.963	9.475	0.488	222	2.7	82
A Phase Rear	9.913	9.945	-0.032	-15	2.7	-5
A Phase total	19.876	19.42	0.456	207	5.4	38
B Phase Front	10.888	10.890	-0.002	-1	2.9	0
B Phase Rear	10.938	10.465	0.473	215	2.9	75
B Phase total	21.826	21.355	0.471	214	5.7	37
C Phase Front	13.463	13.100	0.363	165	3.0	55
C Phase Rear	13.513	13.325	0.188	85	3.0	28
C phase Total	26.976	26.425	0.551	250	6.0	42
			Total	672	17	39
			avg. length lost		6	

	Before lb	After lb	Lugs Missing number	Lug Correction lb	Change lb	Change g
Ground bar	28.8	28.560	2	0.14	0.380	173

Table G-8 SWGR Test 10 Mass Loss Corrections

	Change g	Slug g	Triangle g	Corrected Change g	Length chng cm	Mass/length g/cm
A Phase Front	222					
A Phase Rear	-15					
A Phase total	207	118	0	325	5.4	60
B Phase Front	-1					
B Phase Rear	215					
B Phase total	214	108	70	392	5.7	69
C Phase Front	165					
C Phase Rear	85					
C phase Total	250	40	79	370	6.0	61
Totals	672			1,087	17	63

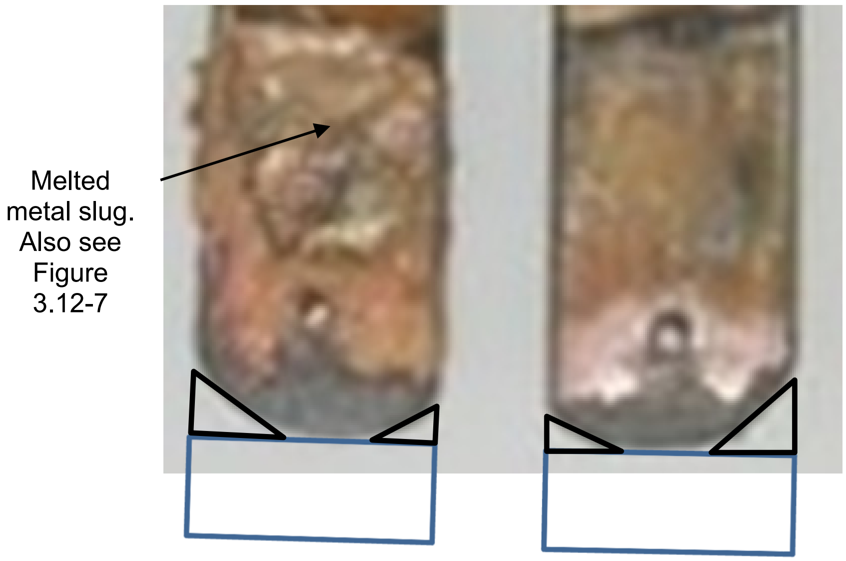


Figure G-4 SWGR Test 10 Phase B Bus Bar Mass Loss and Slug

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT (200 words or less)

A High Energy Arcing Fault (HEAF) occurred in a 6.9 kV switchgear (SWGR) in Unit 1 of the Onagawa Nuclear Power Plant (NPP)of the Tohoku Electric Power Company on March 11, 2011 during the Great East Earthquake in Japan. The Regulatory Standard and Research Department, Secretariat of the Nuclear Regulation Authority (S/NRA/R) (Japan) conducted HEAF tests by simulating the design and operating conditions of the SWGR HEAF at Onagawa NPP. Tests of 480 V Distribution Panel (DP) cabinets were also conducted to understand HEAF characteristics. This Volume 2 report discusses the electrical properties and thermal effects of HEAF tests with one arc event with arc energies from 0.6 MJ to 137.3 MJ. The test items had similar geometry to the previous tests reported in Volume 1 but internal walls and obstructions were removed and the front and rear exterior panels were removed to allow direct observations of the arc. Metal targets with samples of cables and plastics were also placed at various distances from the arc to assess ignition and damage at various distances from the arc. Bundles of cables were placed near the arc to investigate cable ignition and damage.

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