Understanding High Energy Arcing Faults

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Abstract

This report documents an experimental program designed to collect data and information to evaluate the performance of models developed to estimate the electrical high energy arcing fault (HEAF) hazard. This report covers full-scale laboratory experiments using representative nuclear power plant (NPP) three-phase electrical equipment. Equipment included medium-voltage metal-enclosed bus ducts and switchgear and low-voltage metal-enclosed switchgear. Electrical, thermal, and pressure data were recorded for each experiment and documented in this report. The experiments include five medium-voltage switchgear, two medium-voltage non-segregated bus ducts, and three low-voltage switchgear. These experiments differed from past programs in that the effects to adjacent and nearby equipment were also evaluated. The data collected supports characterization of the HEAF hazard, and these results will be used to complement the data used for HEAF hazard modeling tools and support potential improvements in fire probabilistic risk assessment (PRA) methods.

The experiments were performed at Keuring van Elektrotechnische Materialen te Arnhem (KEMA) Labs in Chalfont, Pennsylvania. The experimental design, setup, and execution were performed by staff from the NRC, the National Institute of Standards and Technology (NIST), Sandia National Laboratories (SNL) and KEMA Labs. These experiments were sponsored by member countries of the HEAF 2 international agreement under the auspices of the Organisation for Economic Co-operation and Development (OECD).

The HEAF experiments were performed between August 7 and 18, 2023. These experiments used nominal system voltages of either 0.6 kV (AC), 4.16 kV (AC) or 6.9 kV (AC). Actual arc durations of the experiments ranged from approximately 0.5 s to 8 s with fault current targets ranging from approximately 8 kA to 30 kA. Real-time electrical operating conditions, including voltage, current, and frequency, were measured during the experiments. Heat fluxes and incident energies were measured with plate thermometers and slug calorimeters at various locations around the electrical enclosures. Internal enclosure temperatures were measured using a fiberoptic system. The experiments were documented with normal and high-speed videography, infrared imaging, and photography.

Insights from the experimental series include timing information related to enclosure breach, event progression, mass loss measurements for electrodes and enclosures, peak pressure rise, along with visual and thermal imaging data to better understand and characterize the hazard. These results will be used to evaluate the adequacy of existing HEAF hazard modeling tools and for potential improvements to fire PRA methods related to HEAF.

Keywords

High Energy Arcing Fault, Arc Flash, Electrical Enclosure, Switchgear, Bus Duct, Electric Arc, Fire Probabilistic Risk Analysis, Fire Probabilistic Safety Analysis

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Executive Summary

PRIMARY AUDIENCE: Fire protection, electrical, and probabilistic risk assessment engineers conducting or reviewing fire risk assessments related to high energy arcing faults.

SECONDARY AUDIENCE: Engineers, reviewers, utility managers, and other stakeholders who conduct, review, or manage fire protection programs and need to understand the underlying technical basis for the hazards associated with high energy arcing faults.

KEY RESEARCH QUESTION: How does electrical distribution equipment physical and electrical configuration influence the HEAF hazard?

RESEARCH OVERVIEW

Operating experience has shown that high energy arcing faults (HEAFs) pose a hazard to the safe operation of nuclear facilities. Current regulations and probabilistic risk assessment methods were developed using limited information, and the inherent uncertainties required the use of safety margins to bound the hazard. The U.S. Nuclear Regulatory Commission (NRC) and its collaborative research partners have significantly advanced the understanding of HEAF phenomena, such as refinement in the areas of expected plant configurations, operational history, target fragility, source characterization, hazard modeling and associated improvements to fire PRA. The experiments documented in this report aim to provide additional data to support the Organisation for Economic Co-operation and Development (OECD) HEAF 2 member country needs and confirm risk assessment methodologies. This report documents a set of experiments performed in 2023.

A series of medium-voltage and low-voltage, metal-enclosed indoor switchgear and medium-voltage, non-segregated bus duct HEAF experiments were performed. Each experiment consisted of an arcing fault initiated within the unit on either aluminum or copper bus bars. Nominal system voltage of either 0.60 kV (AC), 4.16 kV (AC) or 6.9 kV (AC) were used, depending on equipment ratings. Fault duration targets were 4 s for medium-voltage and 8 s to 17.5 s for low-voltage experiments. Current levels ranged from 8 kA – 30 kA (AC rms). Numerous measurements were taken to characterize the environment within and surrounding the enclosure, including pressure, external heat flux, external incident energy, and internal temperature. Time-resolved electrical measurements of the fault conditions were also recorded.

This report documents the experiments performed, including the experimental methods, experimental facility, experimental devices, instrumentation, observations, and results. Videos and photometric data files are provided by laboratories contracted to the NRC, and information on accessing that information is identified. This report does not provide detailed evaluation of the results or comparisons of the results to other methods or data. Those efforts may be documented in subsequent report(s).

KEY FINDINGS

This research yields data that characterizes the effects of electrical arcing faults. The results from this research include:

- Experiments 2-37, 2-38 and 2-39 all experienced switchgear enclosure door or panel projectiles. While door opening and panel breach due to HEAF interactions have been

observed in past experiments, this is the first observation of air-borne projectiles during an experiment.

- Medium-voltage bus ducts constructed of aluminum continue to demonstrate the potential for large breach opening and as such an increased potential for direct arc exposure to external targets.
- Low-voltage switchgear demonstrated difficulty of arc sustainment. In the LV tests the arc continued to show early arc extinguishment or arc migration to locations beyond the arc initiation location.
- Damage to adjacent enclosures was observed in both low- and medium-voltage equipment. The arc migrated between adjacent enclosures and caused potential ignition of the internal components. For low-voltage experiments, post-HEAF fire migration between vertical sections was observed.

WHY THIS MATTERS

This report provides empirical evidence to assist U.S. NRC staff, OECD HEAF 2 member countries, and stakeholders who are evaluating the adequacy of current methods. The information provided will support advances in state-of-the-art methods and tools to assess the HEAF hazard in nuclear facilities. This information may also be applicable to fossil fuel and alternative energy facilities and other buildings with low- and medium-voltage electrical distribution equipment such as switchgear and bus ducts.

HOW TO APPLY RESULTS

Engineers and scientists advancing hazard and fire probabilistic risk assessment methods should focus on Section 3 of this report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may be interested in the following opportunities:

The Nuclear Energy Agency (NEA) HEAF Project conducts experiments to explore the basic configurations, failure modes, and effects of HEAF events. Primary objectives include (1) development of a peer-reviewed guidance document that could be readily used to assist regulators of participants and (2) publish joint nuclear safety project report(s) covering all experimentation and data captured. More information on the project and opportunities to participate in the program can be found online at https://www.oecd-nea.org/.

Citations

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ABBREVIATIONS AND ACRONYMS

AC	alternating current
ASTM	ASTM International
AWG	American Wire Gauge
DC	direct current
EDT	eastern daylight time
EPRI	Electric Power Research Institute
GE	General Electric
GI	generic issue
GIRP	Generic Issue Review Panel
HEAF	high energy arcing fault
IEEE	Institute of Electrical and Electronic Engineers
IN	information notice
IR	infra-red
KEMA	Keuring van Elektrotechnische Materialen te Arnhem
MD	management directive
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
NSBD	non-segregated bus duct
OECD	Organisation for Economic Co-operation and Development
PIRT	Phenomena Identification and Ranking Table
PRA	probabilistic risk assessment
PT	plate thermometer
RES	Office of Nuclear Regulatory Research
RIL	research information letter
SNL	Sandia National Laboratories
Tcap	tungsten thermal capacitance
U.S.	United States of America

1. Introduction

Infrequent events such as fires at a nuclear power plant can pose a significant risk to safe plant operations. Licensees combat this risk by having robust fire protection programs designed to minimize the likelihood and consequences of fire. These programs provide reasonable assurance of adequate protection from known fire hazards. However, several hazards remain subject to a large degree of uncertainty, requiring significant safety margins in plant analyses.

One such hazard comprises an electrical arcing fault involving electrical distribution equipment and components. While the electrical faults and subsequent fires are considered in existing fire protection programs, recent research [1, 2] has indicated that elements of the electrical fault can exacerbate the damage potential of the event. The increased damage potential could exceed the protection provided by existing fire protection features for specific fire scenarios and increase plant risk estimated in fire probabilistic risk assessments (PRAs).

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) studies fire and explosion hazards to ensure the safe operation of nuclear facilities. This includes developing data, tools, and methodologies to support risk and safety assessments. Through recent research efforts and collaboration with international partners, a non-negligible number of reportable high energy arcing fault (HEAF) events have been identified as occurring in nuclear facilities [3]. HEAF events pose a unique hazard in nuclear facilities and additional research in this area is needed to ensure that the hazard is accurately characterized and assessed for its impact on nuclear safety.

1.1. Background

In June 2013, an Organisation for Economic Co-operation and Development (OECD) / Nuclear Energy Agency (NEA) report [3] on international operating experience documented 48 HEAF events, accounting for approximately 10 % of the total fire events reported. These HEAF events are often accompanied by loss of essential power and complicated shutdowns. Existing PRA methodology for HEAF analysis is prescribed in NUREG/CR-6850 "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities Vol. 2 [4]," and its Supplement 1 [5]. To confirm these methods, the NRC led an international experimental campaign from 2014 to 2016. This experimental campaign is referred to as "Phase 1 Experimenting." The results of these experiments [6] uncovered a potential increase in the hazard severity.

In response to this new information, the NRC issued Information Notice 2017-004, "High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components (IN 2017-04)" detailing the relevant aspects of the licensee event reports and Phase 1 experiments was published in August of 2017 [2]. Additionally, RES staff proposed a potential safety concern as a generic issue (GI) in a letter dated May 6, 2016 [7]. During its review, the Generic Issue Review Panel (GIRP) determined that the pre-GI-018 no longer met the Criterion 5 of the NRC MD 6.4, concluding that the risk and safety significance of HEAFs involving aluminum cannot be adequately determined in a timely manner without performing additional, long-term research to develop the methodology for such a determination [8].

In a revised approach to resolving the knowledge gap, the NRC staff applied the BeRiskSMART framework. This approach consists of two coordinated tracks for (1) research activity in coordination with EPRI and (2) use of the NRC process LIC-504, "Integrated Risk-Informed Decision-making Process for Emergent Issues [9]," to apply best available information and NRC risk assessment tools to determine whether any regulatory action was needed. The NRC LIC-504 process was completed in July 2022, finding both increase and decreases in plant risk with a determination of no significant risk increase in total HEAF risk for the two plants evaluated [10].

Under the research approach with EPRI, the NRC developed tools to estimate the HEAF hazard [11, 12], a hazard-specific target fragility characterization [13] and an updated HEAF fire PRA method [1] to provide guidance for evaluating the risk from a HEAF. The NRC and EPRI presented their findings during a two-day public workshop held at the NRC Headquarters located in Rockville, Maryland in May 2023 [14].

Following the completion of this work, there were still several questions raised by the international member countries of the OECD HEAF 2 agreement. These include the post-HEAF fire growth and development assumptions of the ensuing fire and damage insights to equipment adjacent and near the HEAF initiation point. To fulfill the requirements of the operating agent under the HEAF 2 agreement, the NRC performed a series of experiments to help address these questions and close out the experimental campaign.

1.2. Objectives

The research objectives for this experimental series include: quantitatively characterize the thermal and pressure conditions created by HEAFs occurring in electrical enclosures (switchgear and bus ducts) along with characterizing the damage features of adjacent and nearby equipment; and document the experiments and results.

1.3. Scope

The scope of this research includes evaluating the HEAF hazard on low- and medium-voltage electrical switchgear and medium-voltage non-segregated bus ducts. This evaluation involves measurement and documentation of electrical and thermal parameters, along with physical evidence of the HEAF hazard. The results from this effort will be used to provide empirical evidence for use by the OECD HEAF 2 member countries and by NRC staff to evaluate the prediction capabilities of the recently developed hazard models [1]. Detailed data analysis for specific applications is beyond the scope of this report.

1.4. Approach

The approach taken for this work follows practices from past efforts [6, 15-18]. Specifically, the experimental device (switchgear and bus ducts) is faulted between the three phases. The laboratory provides electrical energy to the experimental device at specified parameters (system voltage, current, duration). Measurements internal and external to the test device are made using robust measurement devices fielded by the National Institute of Standards and Technology (NIST). Sandia National Laboratories (SNL) provided high-speed visual and thermal imaging and those results are presented in a separate report. Measurements were recorded, scaled, and reported. Feedback received during the developmental stage of this project was incorporated into the experimental approach. This included the arc locations, fault current magnitudes, and the durations of the experiments.

2. Experimental Method

This section provides information on methods used to perform the experiments[1], including experimental planning, overview of the experimental facility, the tested devices, and the various instruments that were used.

2.1. Experiment Planning

The original HEAF phase II matrix planned for a total of thirty-two experiments. Those experiments were selected to explore the 5 variables, namely; duration, current, voltage, conductor material and bus ducts housing material (for bus duct scenarios). In addition, replicate experiments were planned to evaluate experimental variability. The experimental matrix was separated into two distinct focus areas. The OECD/NEA driven experiments and experiments performed by the NRC with a focus on the effects of aluminum during HEAF events.

This program has evolved significantly since the international agreement was signed in 2019. The COVID-19 pandemic halted all experimental activities and preparations for a two-year period. During this time the NRC shifted all staff resources towards the NRC/EPRI working group to make analytical progress on modeling tools and methodologies which advanced the state of practice. The working group used data collected from pre-pandemic experiments and made significant advancements to update the methodology for modeling HEAFs in fire PRAs. These methods, tools, and data were made publicly available and can be accessed from the NRC HEAF homepage at https://www.nrc.gov/about-nrc/regulatory/research/fire-research/heaf-research.html.

Past work has reshaped the HEAF effort from an exploratory experimental campaign to a confirmatory one. As such, the experimental matrix is reconfigured to provide useful information and insights to the OECD/NEA member countries. The refocus of these experiments include filling data gaps and ensuring alignment with the international HEAF PIRT conducted in 2018 [19].

The significant time delay between the signing of the HEAF agreement also poses unique logistical challenges to completing the original scope of experiments. The supply chain interruption and general inflation experienced worldwide has impacted the ability to perform the same number of experiments without increasing resources. However, efficiencies gained during the performance of previous experimental series have resulted in improved and more efficient experimental methods.

The experimental plan was developed and shared with the OECD/NEA HEAF 2 member countries. Lessons learned from the Phase 1 and NRC focused generic issue experiments, results from the Phenomena Identification and Ranking Table (PIRT) exercise, information from the fire HEAF PRA update [1] and existing literature were used to develop the initial experimental plan. The experimental plan serves as a living document and has undergone several revisions over time as new information emerges. Review and feedback by the OECD/NEA were incorporated

[1] The term 'test' implies the use of a standardized test method promulgated by a standards development organization such as the International Organization for Standardization (ISO), ASTM International, Institute of Electrical and Electronics Engineers (IEEE), etc. The experiments described in this report are not standard tests and were specifically developed to examine HEAF phenomena. The term 'test' is used in some contexts to preserve continuity with previous programs or to describe facilities where standard tests are frequently performed. Standard test methods, where they exist, are used for some measurements.

into the experimental plan. The central component of the plan is the experimental matrix which specifies the key parameters for each experiment. This matrix has evolved over time and some experiments originally on the matrix have been removed, others replaced, and some added as the knowledge base has advanced. A graphical matrix for electrical enclosures is presented in Fig. 1 and Fig. 2, while the bus duct matrix is shown in Fig. 3. These figures are annotated to identify the experiment parameters, the user group interests, and year completed.

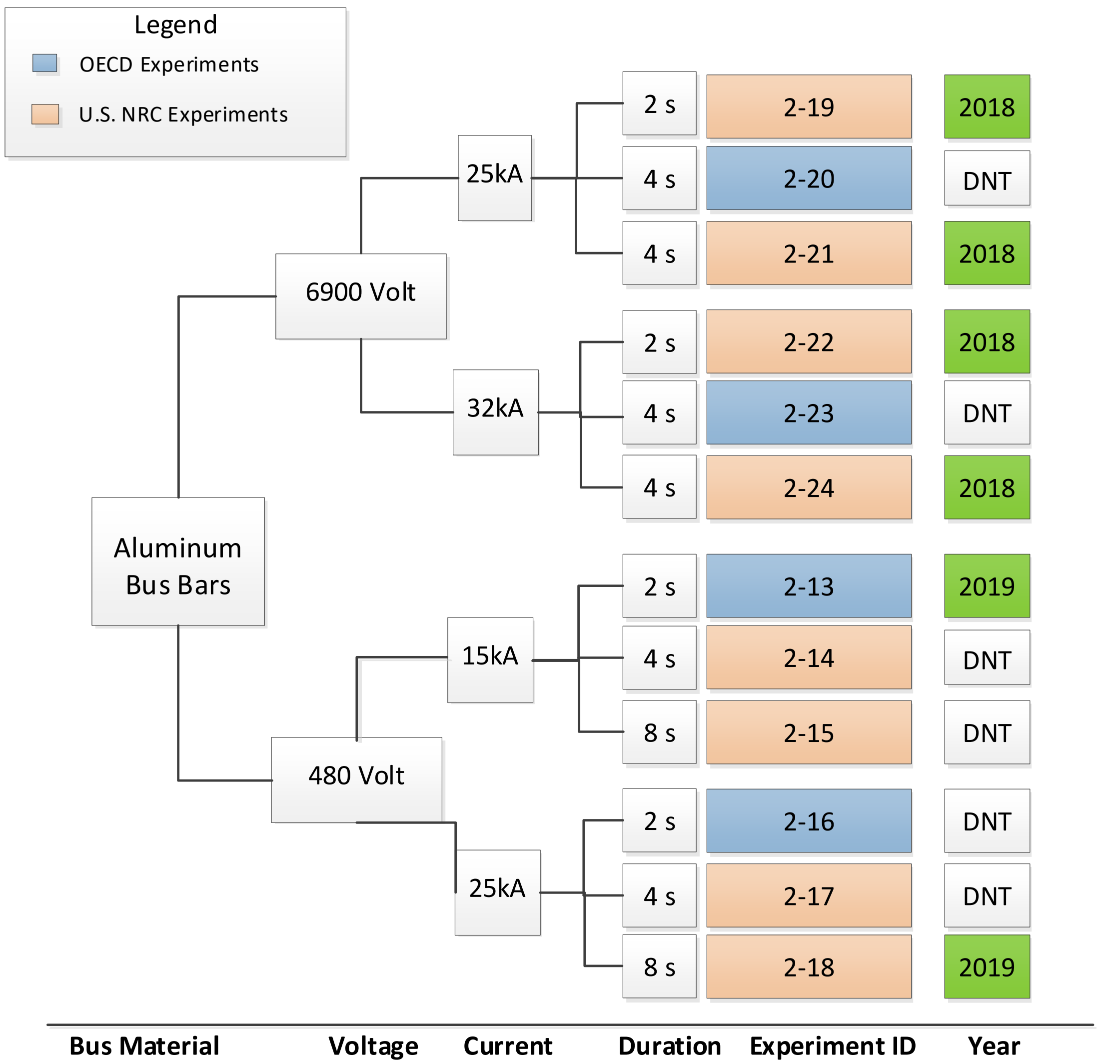

Fig. 1. Graphical Phase 2 Experimental Matrix for Electrical Enclosure – Aluminum Bus (included for completeness). These experiments are not documented in this report. (DNT, did not test)

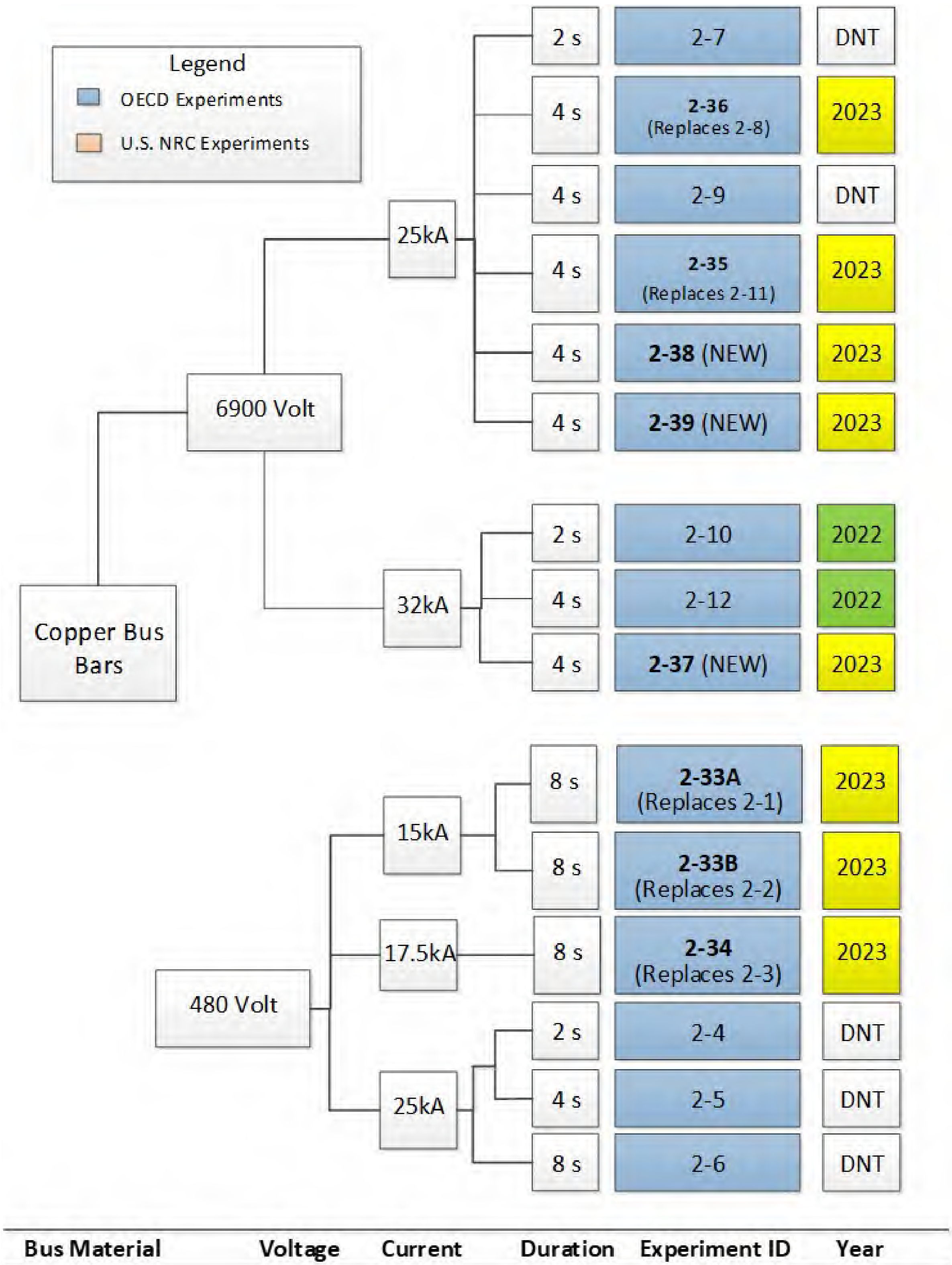

Fig. 2. Graphical Phase 2 Experimental Matrix for Electrical Enclosure – Copper Bus. Graphic shows voltage, arcing current, duration, experimental identification number and year experiment performed. (DNT, did not test)

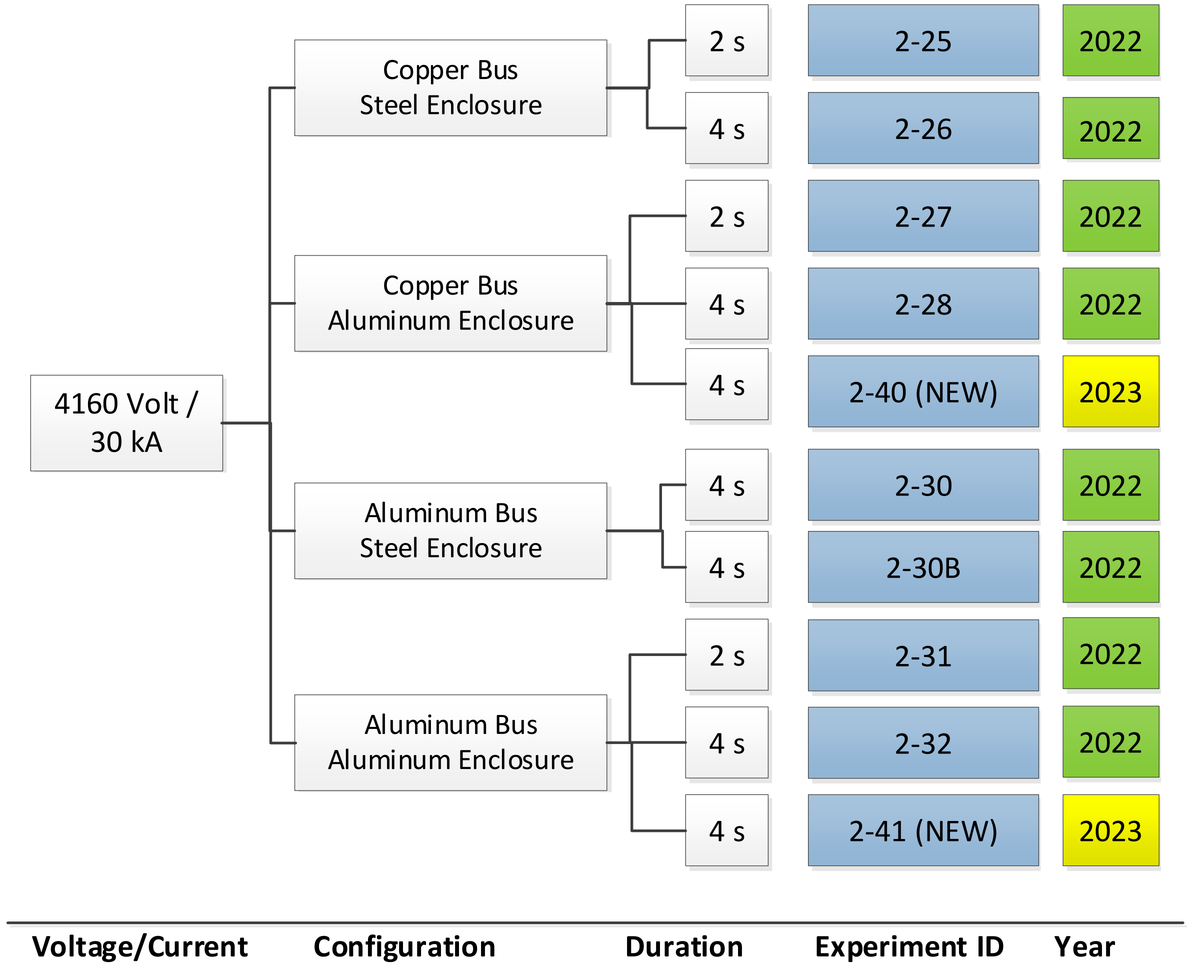

Fig. 3. Graphical Phase 2 Experimental Matrix for Non-Segregated Bus Duct. Graphic shows voltage, arcing current, duration, experimental identification number and year experiment performed.

In addition to the experimental parameters presented above, the equipment configuration differed from past campaigns. For the series of experiments documented in this report, the impact of the HEAF on adjacent enclosures and enclosures across from the source were of interest. Fig. 4, Fig. 5, and Fig. 6 present the three equipment configurations used in this experimental campaign. The "lineup" configuration supports an evaluation of the HEAF impact to equipment physically adjacent to the piece of equipment experiencing the HEAF. The "cross-aisle" configuration focuses on the impact of HEAF effluent to equipment not physically adjacent, but near the piece of equipment involved in the HEAF. Lastly, the "back-to-back" configuration was requested by OECD/NEA HEAF 2 member countries to evaluate specific configurations where equipment is placed next to each other with the enclosure backs together.

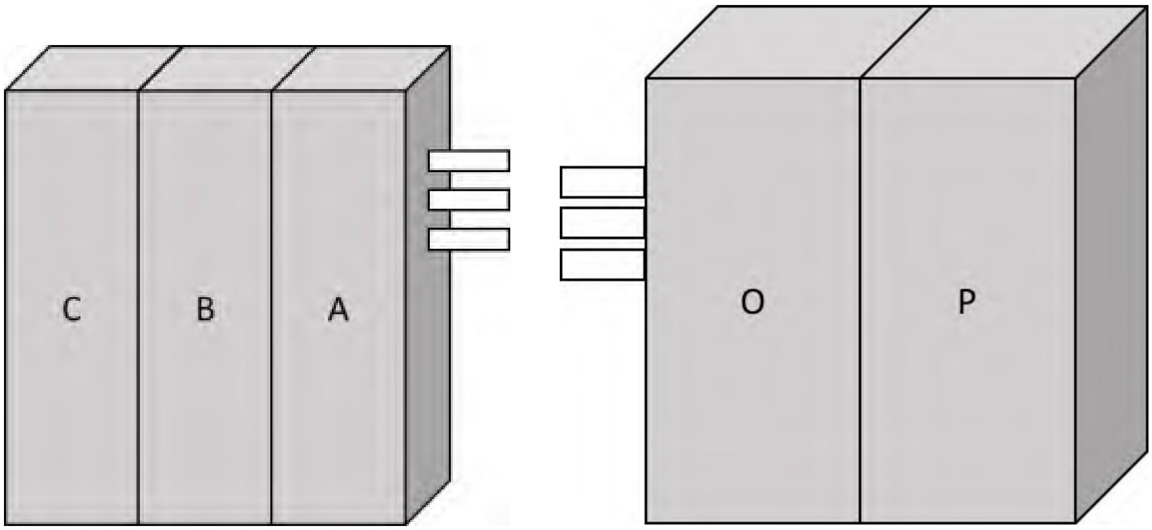

Fig. 4. Illustration of Electrical switchgear “lineup configuration” used to evaluate HEAF impact on adjacent enclosure. Low-voltage lineup configuration shown left, Medium-voltage shown right.

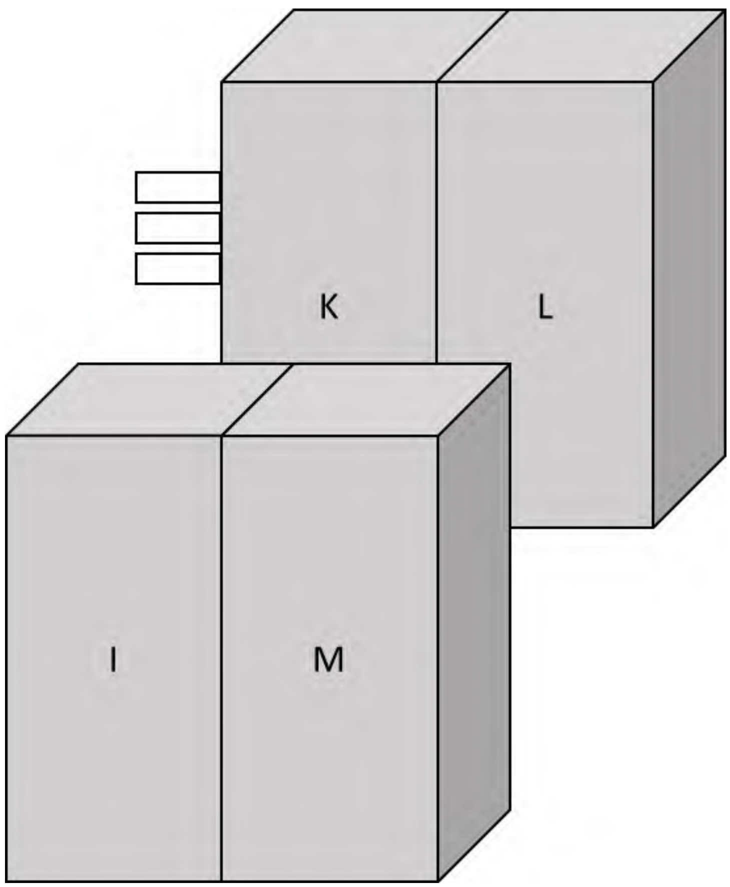

Fig. 5. Illustration of electrical switchgear "cross-aisle configuration" used to evaluate HEAF on enclosures near but not adjacent to enclosure with arc. Note that the core measurement instrumentation stands (not shown) are around the arc enclosure, and additional thermal measurement instrumentation (not shown) is included in the cross-aisle enclosure.

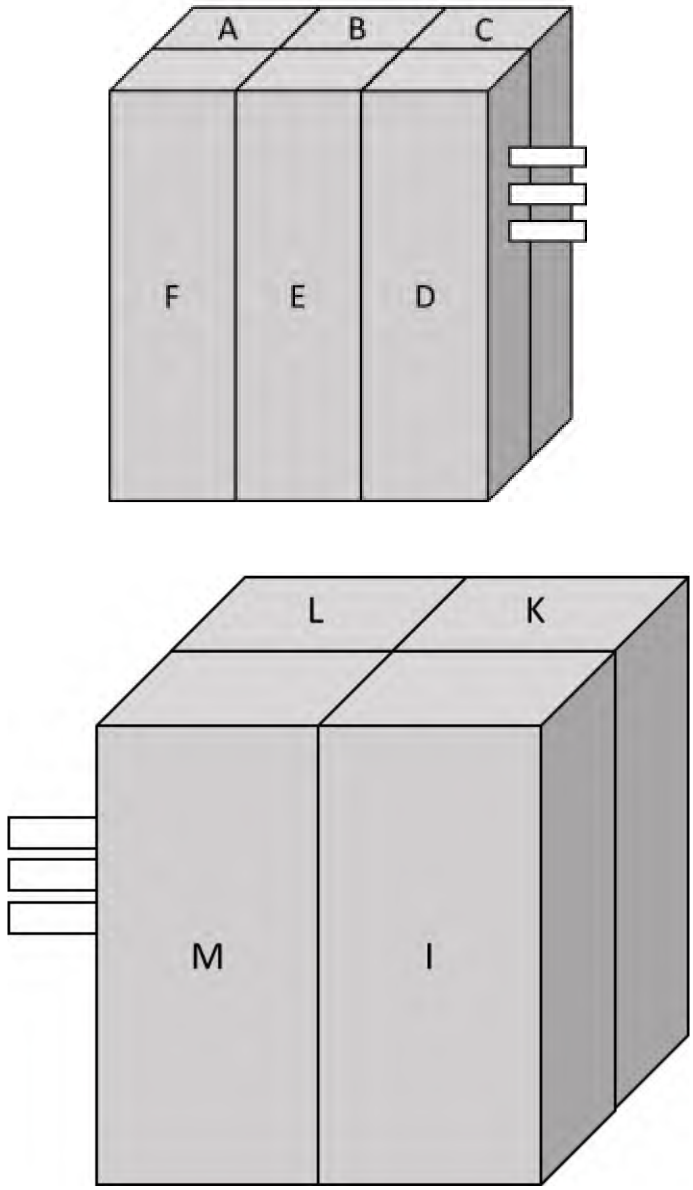

Fig. 6. Illustration of electrical switchgear "back-to-back configuration" used to evaluate HEAF on enclosures adjacent to enclosure with arc. Top image shows low-voltage configuration, bottom images shows medium-voltage configuration. Note that the core measurement instrumentation stands (not shown) are around the arc enclosure.

2.2. Experimental Facility

The full-scale experiments were performed at Keuring van Elektrotechnische Materialen te Arnhem (KEMA) Labs (referred to in the remainder of this report as “KEMA”), located in Chalfont, Pennsylvania, in August 2023. The experimental facility was chosen for its ability to meet the requirements of the program; specifically, the electrical voltages, currents, and energies needed for sustained arcing within the test enclosures and to permit fire conditions for a period after termination of the arc. KEMA provided the electrical and pressure measurements required to characterize the power supplied to the enclosures during the arcing experiments. KEMA also provided radiant energy measurements.

The test cell is a cubical space with one open side. The open side was equipped with a roll-up door for security and weather protection when not in use. The open side of the cell faces the operator control room, with a courtyard area in between. The control room is equipped with impact-resistant glazing so that the operators, clients, and guests can observe the experiments. A door in the rear of the cell leads to a protected space where NIST data acquisition equipment was located and operated.

Test cell #7 was used during this experimental series to perform the low-voltage experiments, while test cell #9 was used for medium-voltage experiments. The cell layouts are shown in Fig. 7 and Fig. 8, respectively. Detailed drawings of the facility are provided in Appendix A.1. Drawings of the cell are courtesy of KEMA.

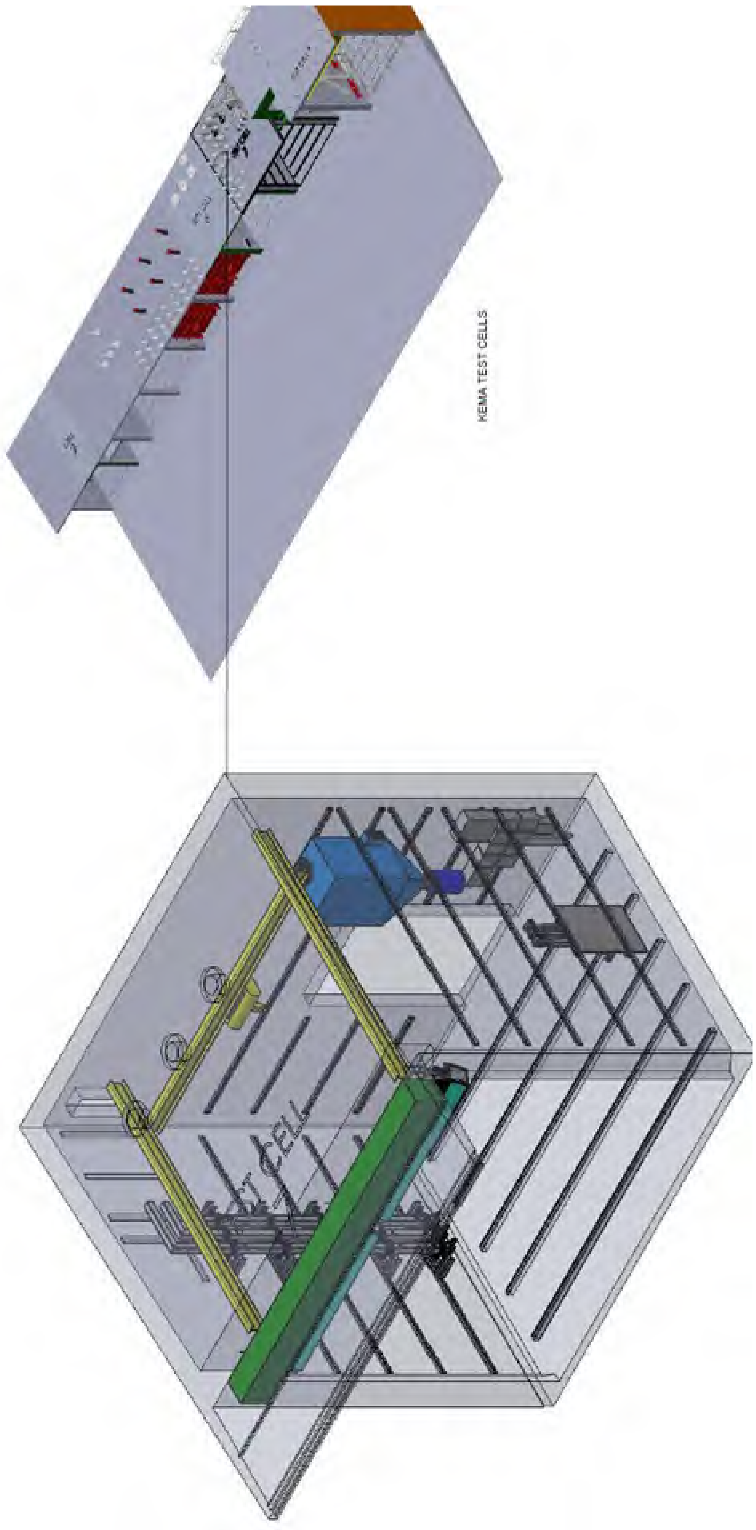

Fig. 7. Isometric drawing of Test Cell #7 (left) and location of Test Cell #7 within the KEMA facility.

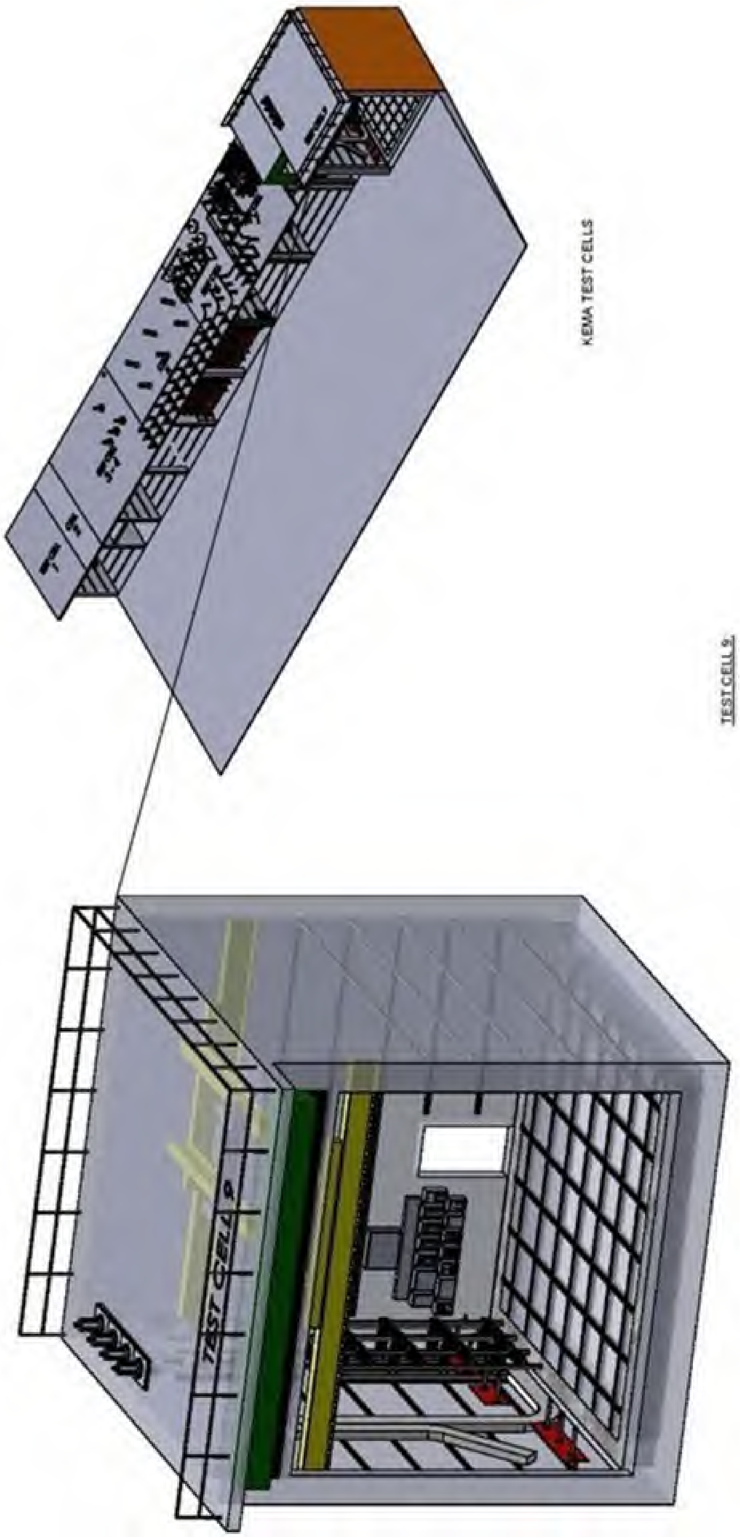

Fig. 8 Isometric drawing of Test Cell # 9 (left) and location of Test Cell #9 within the KEMA facility.

2.3. Experimental Devices

The experiment devices were sourced from several different vendors and different countries. Table 1 presents a list of the enclosures used and the experiment number, since multiple enclosures were used in an individual experiment. An asterisk indicates the experiment in which the enclosure was the device where the arc initiated. Due to the number of experiments and limited number of enclosures, several enclosures were used in multiple experiments. Effort was taken to re-use enclosures that were not damaged from previous experiments to be considerate of time and resource limitations during this experimental series.

Table 1. List of equipment used.

Enclosure ID	Country of Origin	Voltage (V)	Conductive Material	Design	Test Number
A	Germany / Netherlands	600 V	Copper	LV Load Center	2-33* 2-34
B	Germany / Netherlands	600 V	Copper	LV Load Center	2-33*
C	Germany / Netherlands	600 V	Copper	LV Load Center	2-33 2-34
D	Germany / Netherlands	600 V	Copper	LV Load Center	2-34
E	Germany / Netherlands	600 V	Copper	LV Load Center	2-34*
F	Germany / Netherlands	600 V	Copper	LV Load Center	2-34
G	Germany / Netherlands	600 V	Copper	LV Load Center	2-34
H	Germany	6 900 V	Copper	MV Switchgear	2-36*
I	U.S.	6 900 V	Copper	MV GE Horizontal Draw out type	2-37 2-38*
J	U.S.	6 900 V	Copper	MV GE Horizontal Draw out type	2-37* 2-39
K	U.S.	6 900 V	Copper	MV GE Horizontal Draw out type	2-38 2-39*
L	U.S.	6 900 V	Aluminum	MV GE Horizontal Draw out type	2-38 2-39
M	U.S.	6 900 V	Aluminum	MV GE Horizontal Draw out type	2-38 2-39
N	U.S.	6 900 V	Aluminum	MV GE Horizontal Draw out type	2-36 2-39
O	U.S.	6 900 V	Copper	MV GE Vertical Lift type	2-35*
P	U.S.	6900 V	Aluminum	MV GE Vertical Lift type	2-35
Q	U.S.	6900 V	Copper	Bus Duct	2-40
R	U.S.	4800 V	Aluminum	Bus Duct	2-41
*** Indicates Arc Initiation**					

2.3.1. Medium-Voltage Switchgear, Horizontal Draw-out Configuration, Air Circuit Breaker

The six metal-clad switchgear units were I-T-E[2] Type HK, used and refurbished from an ISO 9001-certified medium-voltage circuit breaker and electrical power distribution supplier. The units were approximately 90 cm (35 in) wide by 209 cm (82 in) long and 229 cm (90 in) high. Main buses were extended outside of the enclosure approximately 30 cm (12 in) to allow for connection to the laboratory's power supply. A grounding stab also extended outside the enclosure. Fig. 9 presents a photograph of a "lineup" configuration. Fig. 10 provides a drawing and isometric view of the enclosures.

Fig. 9. Type M-36 Metal Clad Enclosure. Enclosure "J" shown left, "I" shown right.
(note: bus bar extensions shown left, and breaker not shown)

[2] Certain commercial equipment, instruments, or materials are identified in this paper to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the U.S. Nuclear Regulatory Commission or the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for any application.

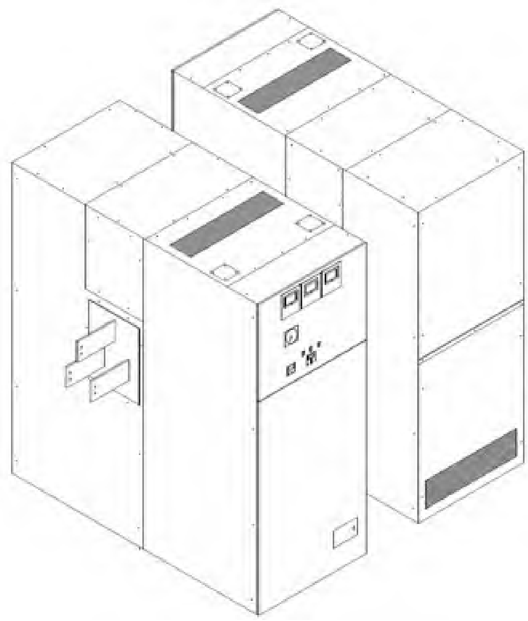

Fig. 10. Drawing of Medium-Voltage Vertical Lift Style Electrical Enclosure
(left – front view; right – rear view)

Each vertical section contained one medium-voltage circuit breaker. All breakers were GOULD I-T-E Power Circuit Breakers Type 7.5 HK 500 circuit breakers. The breaker ratings are shown in Table 2 and a photo of a breaker removed from the enclosure is shown in Fig. 11. After receipt of the equipment, the breakers were tested by the electrical contractor to ensure functionality. The breaker in the experiment enclosure was open prior to and remained open during the arc experiment. The location of the arc did not require a closed breaker. Prior to the experiments, Megger testing was performed with the breaker open to ensure the equipment was functional. A Megger test consists of applying a DC voltage across an insulator and measuring the resulting current. Ohms law allows for the measurement of the insulation resistance, typically in the megaohm range for a good insulator.

Table 2. Gould I-T-E Power Circuit Breaker Rating

Parameter	Value
Rated Max Voltage	8.25 kV
Rated Amps	1.2 kA
Frequency	60 Hz
Rated Short Circuit Amps	35 kA
Weight	485 kg (1 070 lb.)

Parameter	Value
Breaker Type	7.5 HK
Rated voltage range factor	1.2
Impulse Withstand	95 kV
Close / Latch Capability	66 kA
Date Manufactured	February 1978

Fig. 11. Photo of GOULD I-T-E 7.5 HK-500 GE Magne-blast breaker

2.3.2. Medium-Voltage Switchgear, Vertical Lift Configuration, Air Circuit Breaker

The two metal-clad switchgear units were General Electric Type M-36, used and refurbished from an ISO 9001-certified medium-voltage circuit breaker and electrical power distribution supplier. The units were approximately 92 cm (36 in) wide by 202 cm (79.5 in) long and 229 cm (90 in) high. Main buses were extended outside of the enclosure approximately 25 cm (10 in) to allow for connection to the laboratory's power supply. A shorter grounding stab also extended outside the enclosure. Fig. 12 presents a photograph of a "lineup" configuration. Fig. 13 provides a drawing and isometric view of the enclosures.

Fig. 12. Type M-36 Metal Clad Enclosure. Enclosure “O” shown left, “P” shown right.
(note: bus bar extensions shown left, and breaker not shown)

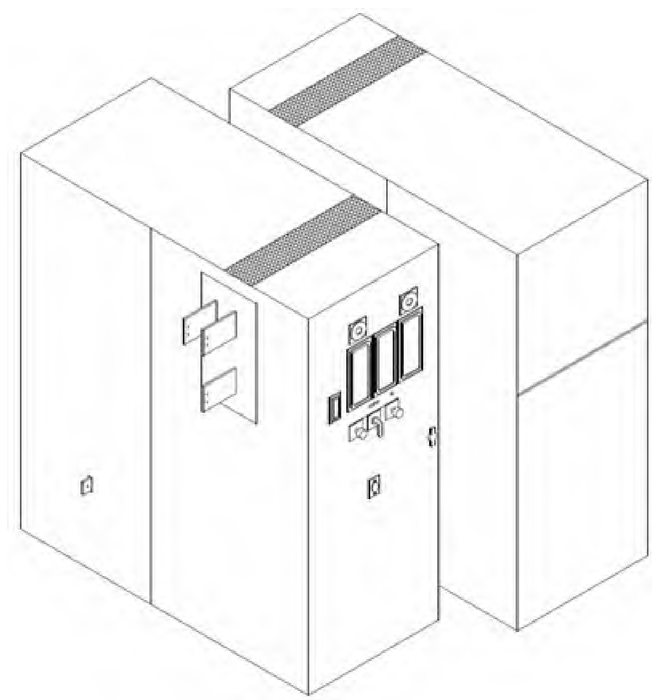

Fig. 13. Drawing of Medium-Voltage Vertical Lift Style Electrical Enclosure
(left – front view; right – rear view)

Each unit contained one medium-voltage circuit breaker. All breakers were GE Magne-blast Type AM-7.2-500 circuit breakers. The breaker ratings are shown in Table 3 and a photo of a breaker removed from the enclosure is shown in Fig. 14. After receipt of the equipment, the breakers were tested by the electrical contractor to ensure functionality. The breaker in the experiment enclosure was open prior to and remained open during arc experiment. The location of the arc did not require the breakers to be closed. Prior to the experiments, Megger testing was performed with the breaker open to ensure the equipment was functional.

Table 3. GE AM-7.2 Breaker Rating

Parameter	Value	Parameter	Value
Rated Max Voltage	8.25 kV	Breaker Type	AM-7.2-500
Rated Amps	1.2 kA	Rated voltage range factor	1.25
Frequency	60 Hz	Impulse Withstand	95 kV
Rated Short Circuit Amps	33 kA	Close / Latch Capability	66 kA
Weight	680 kg (1 500 lb.)	Date Manufactured	February 1976

Fig. 14. Photo of AM-7.2-500 GE Magne-blast breaker

2.3.3. Medium-Voltage Switchgear, Horizontal Draw-out Configuration, SF6 Circuit Breaker

One metal-clad switchgear unit was an ABB Type BA/BB, used and contributed to the program by one of the OECD/NEA HEAF 2 member countries. Limited information was provided on the equipment design and specification, which were documented in the German language. The equipment was not provided with bus conductors, and solid bars stock were procured to support experiments. The breaker was SF6 type and SF6 was removed from the devices prior to arrival in the United States. The units were approximately 63 cm (25 in) wide by 150 cm (59 in) long and 211 cm (83 in) high. Main buses were extended outside of the enclosure approximately 25 cm (10 in) to allow for connection to the laboratory's power supply. A grounding stab also extended outside the enclosure. Fig. 15 presents a photograph of a "lineup" configuration. Fig. 16 provides a drawing and isometric view of the enclosures.

Fig. 15. Type BA/BB Metal Clad Enclosure. Enclosure "H" shown left, Enclosure "N" shown right. (note: bus bar extensions and breaker not shown)

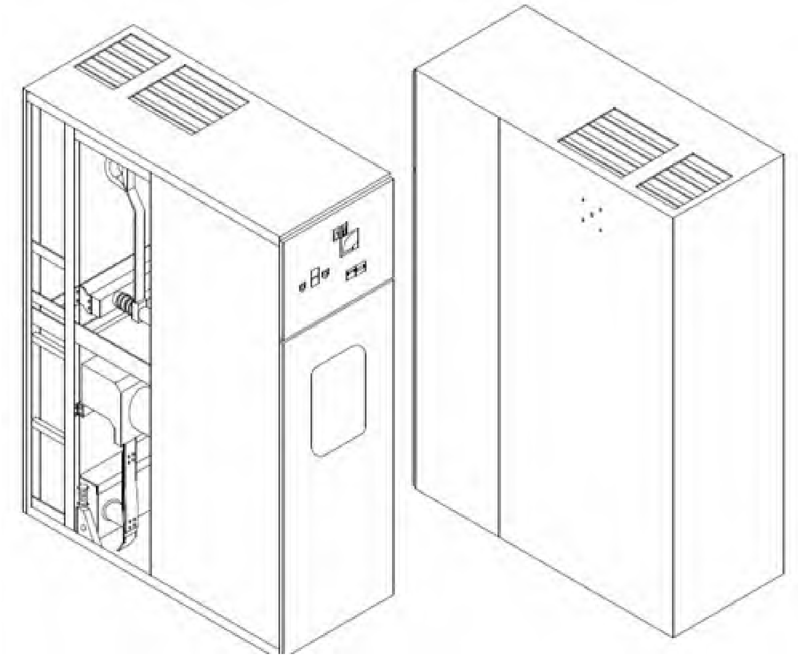

Fig. 16. Drawing of German Medium-Voltage Horizontal Draw-out Style Electrical Enclosure
(left – front view; right – rear view)

The unit contained one medium-voltage circuit breaker. The SF6 breaker was supplied by the contributing organization and no documentation was provided. The breaker was not tested for functionality due to interlocks not able to be defeated without SF6 gas. The breaker in the experiment enclosure was open prior to, and remained open during, the arc experiment. Prior to the experiments, Megger testing was performed with the breaker open to ensure the equipment was functional.

2.3.4. Low-Voltage Switchgear, Horizontal Draw-out Configuration, Air Circuit Breaker

Nine low-voltage metal-clad switchgear units were contributed to the program by OECD/NEA HEAF 2 member countries. Two of these units were previously experiments (see Appendix E). A third unit is reserved for heat release rate experiments to be performed in the future. The units were approximately 41 cm (16 in) wide by 102 cm (40 in) long and 220 cm (86 in) high. Main buses were extended outside of the enclosure approximately 25 cm (10 in) to allow for connection to the laboratory's power supply. Fig. 17 presents a photograph of a "lineup" configuration. Fig. 18 provides an isometric view of the enclosures.

Fig. 17. Photographs of the low-voltage lineup configuration.

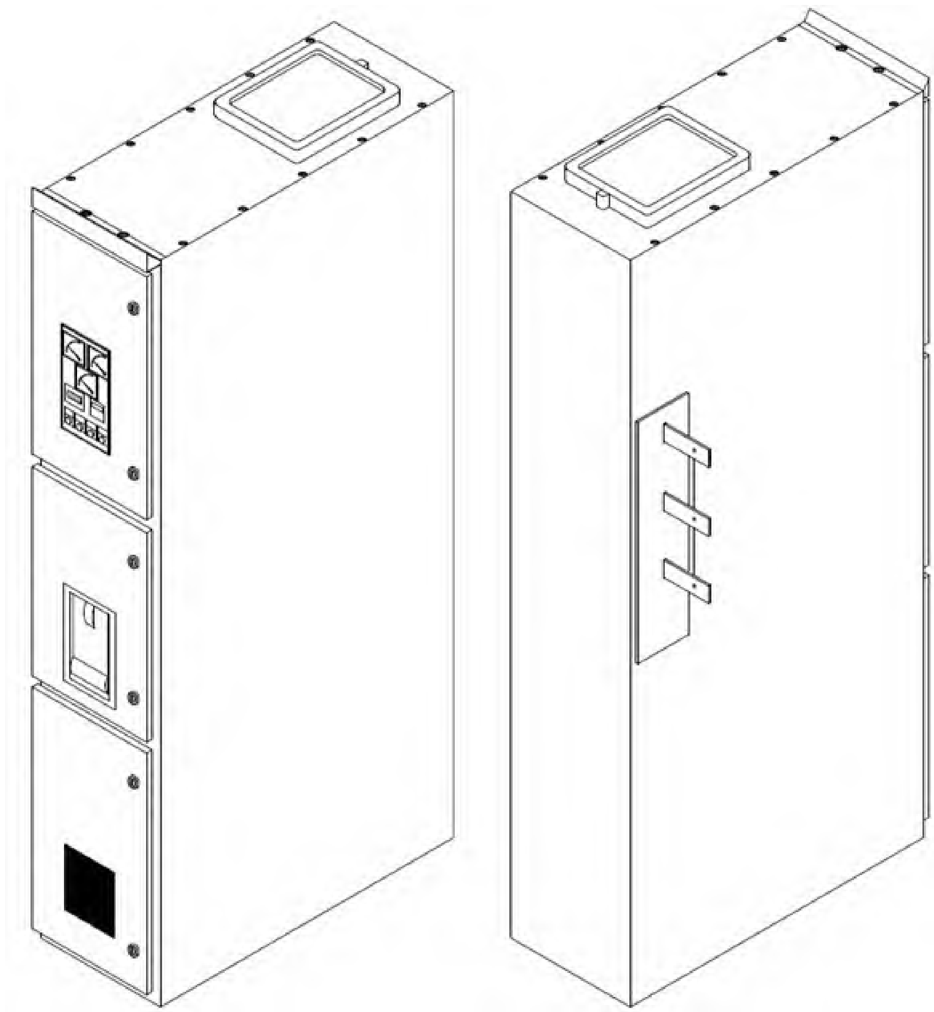

Fig. 18. Isometric drawing of low-voltage enclosure.

Each vertical section contained one low-voltage circuit breaker. All breakers were ABB. Limited information was provided with this donated equipment. The breaker nameplate is shown in Fig. 19. A photo of the breaker is shown in Fig. 20.

Fig. 19. Photo of LV breaker name plate

Fig. 20. Photo of ABB Breaker

2.3.5. Medium-Voltage Bus Duct

Two medium-voltage non-segregated bus ducts (NSBD) were acquired, all procured from a domestic vendor. Both NSBD used an aluminum duct, but their conductor materials were different. One used a copper bus, while the other had an aluminum bus. Table 4 presents the configurations. Experimental parameters (voltage, current, duration) were consistent among the two bus duct experiments.

Table 4. NSBD Configurations

Experiment #	Bus Material	Duct Material	Arc Duration	Acquired
2-40	Copper	Aluminum	4 s	New
2-41	Aluminum	Aluminum	4 s	New

Table 5. NSBD Ratings for bus conductors

RATING	COPPER	ALUMINIUM
Nominal operating voltage	4 160 V	4 160 V
Rated voltage	5 000 V	5 000 V
Continuous rating	2 000 A	2 000 A
Momentary	80 000 A (asym.) 51 613 (sym.)	80 000 A (asym.) 51 613 (sym.)
BIL rating	19 kV	19 kV
System Frequency	60 Hz	60 Hz
Enclosure Thickness	3.18 mm (0.125 in)	3.18 mm (0.125 in)
Insulation	Ceramic	Ceramic
Supports	Polyester	Polyester

2.4. Arc initiation methodology

Initiation of the arc followed the process outlined in Annex E.4 of IEEE C.37.20.7, “IEEE Guide for Experimenting Switchgear Rated Up to 52 kV for Internal Arcing Faults [20].” For medium-voltage equipment, a nominally 0.511 mm diameter (24 American Wire Gauge [AWG]) tinned copper wire was used to initiate the arc. The IEEE Guide recommends using a large wire size for low-voltage equipment to allow sufficient ionized gas to support arc sustainment. As such, a #10 AWG wire was used for all low-voltage experiments. The specific arc wire used for each experiment is presented in Section 3.

2.5. Instrumentation

Thermal, pressure, and HEAF byproduct measurements were made using a variety of instruments and techniques identified in Table 6. A full description of these instruments and their application is provided in RIL 2021-10 Experimental Results from Medium Voltage Electrical Enclosures [15] and RIL 2023-07 Experimental Results from Medium-Voltage Bus Duct and Switchgear Enclosures [18], except for the fiber optic temperature sensors.

Table 6. Experimental Measurement Instrumentation and Techniques

Measurements	Instrument / Technique
Temperature	Infrared (IR) Imaging, Plate Thermometer (PT), fiber optic sensor
Heat flux (time-varying)	Plate Thermometer (PT)
Heat flux (average)	Plate Thermometer (PT), Thermal Capacitance Slug (T_{cap} slug)
Incident Energy	ASTM F1959 Slug calorimeter (slug), Thermal Capacitance Slug (T_{cap} slug), Plate Thermometer (PT)
Pressure	Piezoelectric pressure transducer
Arc plasma / fire dimensions	Videography, IR Imaging
Surface deposit analysis	Sample collection (carbon tape / aerogels), post-experiment laboratory analysis (energy dispersive spectroscopy)
Qualitative damage	Non-energized electrical cable coupons

Temperatures inside of the electrical equipment were measured using fiber optic sensors. Fiber optic sensors were selected over the more conventional thermocouple sensors. The use of fiber adds a level of isolation between the enclosure and the data acquisition (DAQ) system, minimizing the potential for damage to the DAQ. A typical fiber optic sensor is shown in Fig. 21. It consisted of a fluorinated ethylene propylene (FEP) protected glass fiber approximately 2.3 mm in diameter (top in figure). The measurement end (right in figure) of the fiber probe was inserted into a copper connector ring and mechanically crimped (bottom in figure). The copper connector ring was approximately 9.5 mm by 15 mm by 5.0 mm thick, with a through hole of approximately 6.5 mm in diameter. The mass of the connector rings was 3.68 g ± 0.17 g (Type A uncertainty, 95% confidence interval). The fiber optic sensors had a measurement range of -40 °C to 200 °C with an uncertainty of ± 1.0 °C (per the manufacturer, 95% confidence interval). The opposite end of the fiber optic cable (left in figure) extended and connected to the data acquisition system.

The fiber optic temperature sensors passed through a hole in the top of the electrical equipment, with a typical installation shown in Fig. 22. The fiber optic cable was protected with silicone tubing, and the intersection of the sheath and the copper connector ring were wrapped with glass tape. The pass-through hole in the top of the electrical equipment was sealed with high-temperature red silicone caulk, which was allowed to cure for a minimum of approximately 12 hours before each experiment.

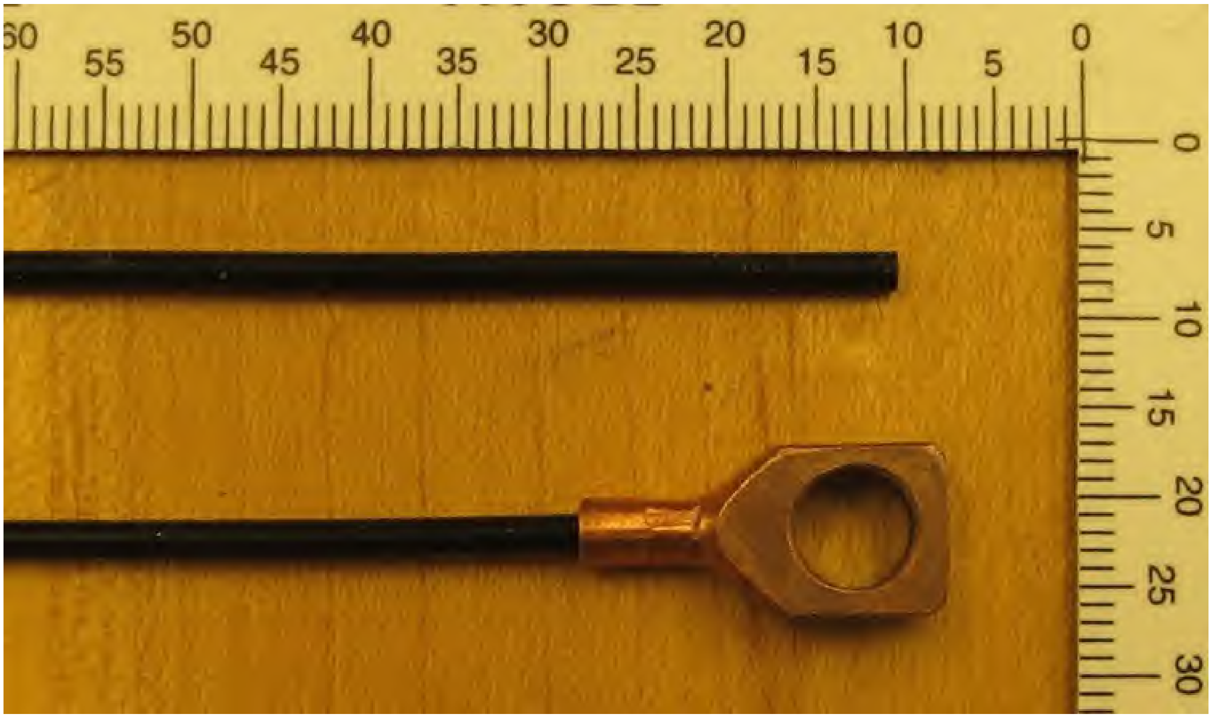

Fig. 21. Bare fiber optic temperature sensor (top), fiber optic temperature sensor with connector ring installed as used in this experimental series (bottom). Scale graduations in figure are in mm.

Fig. 22. Typical fiber optic sensor in top compartment of electrical switchgear, protected by silicone tubing and glass tape.

2.5.1. Instrument Placement – Switchgear Experiments

The thermal instrumentation devices were located on instrument racks with the face of the instruments located approximately 0.91 m (3.00 ft) from the exterior of the metal-clad enclosure. This location was selected to be consistent with historical experiments that focused on confirming the hazard zone of influence. In all medium-voltage switchgear experiments an instrumentation rack was also located above the enclosure. This instrumentation rack (Rack #3) was secured to the electrical enclosure with 90-degree angle red GPO-3 board (glass reinforced thermoset polyester) and nominal ¼ in-20 fasteners. The sensors on Rack #3 were located approximately 0.91 m (3.00 ft) from the top of the enclosure’s metal cladding. Illustration of instrumentation rack configurations are shown in Fig. 23 and Fig. 24. A photograph shows the instrumentation racks around the experimental device during setup in Fig. 25. Minor variations of instrumentation rack placement did occur among experiments and details of the exact instrument location for each experiment are presented in Appendix A. Low-voltage switchgear experiments did not use a horizontal instrumentation rack above the enclosures. The expanded uncertainty in the measurement of the distances from the instrumentation racks to the electrical enclosure is ± 13 mm (0.5 in) with a coverage factor of 2 and an estimated confidence interval of 95 percent.

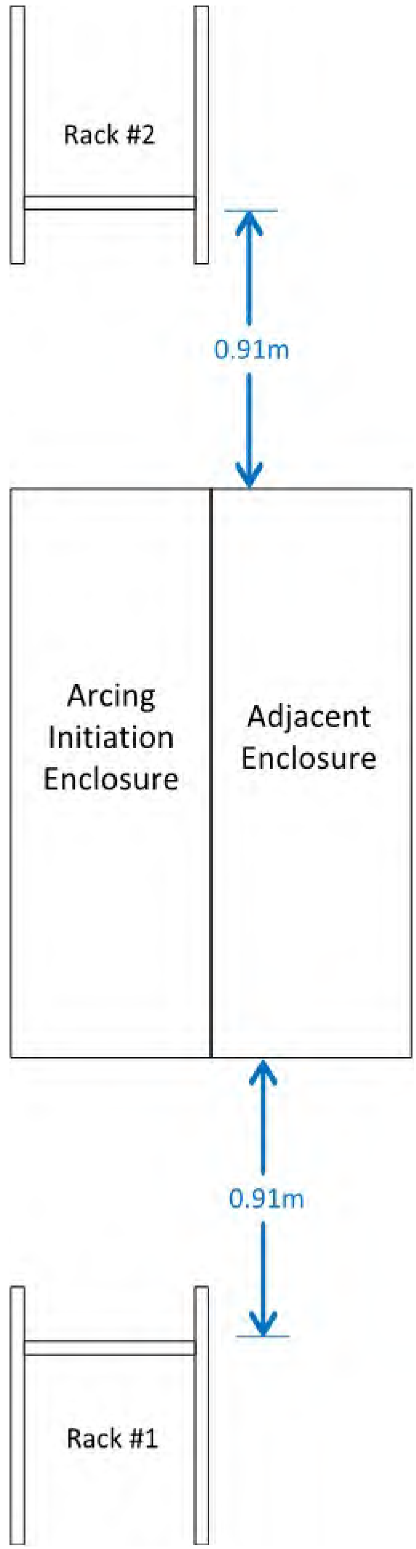

Fig. 23. Generalized plan view of instrument rack configuration around electrical enclosure. See Appendix A.3 for experiment specific instrumentation rack locations. Note that horizontal Rack #3 located above "Arcing Initiation Enclosure" is not shown, see elevation view in Fig. 24 for location.

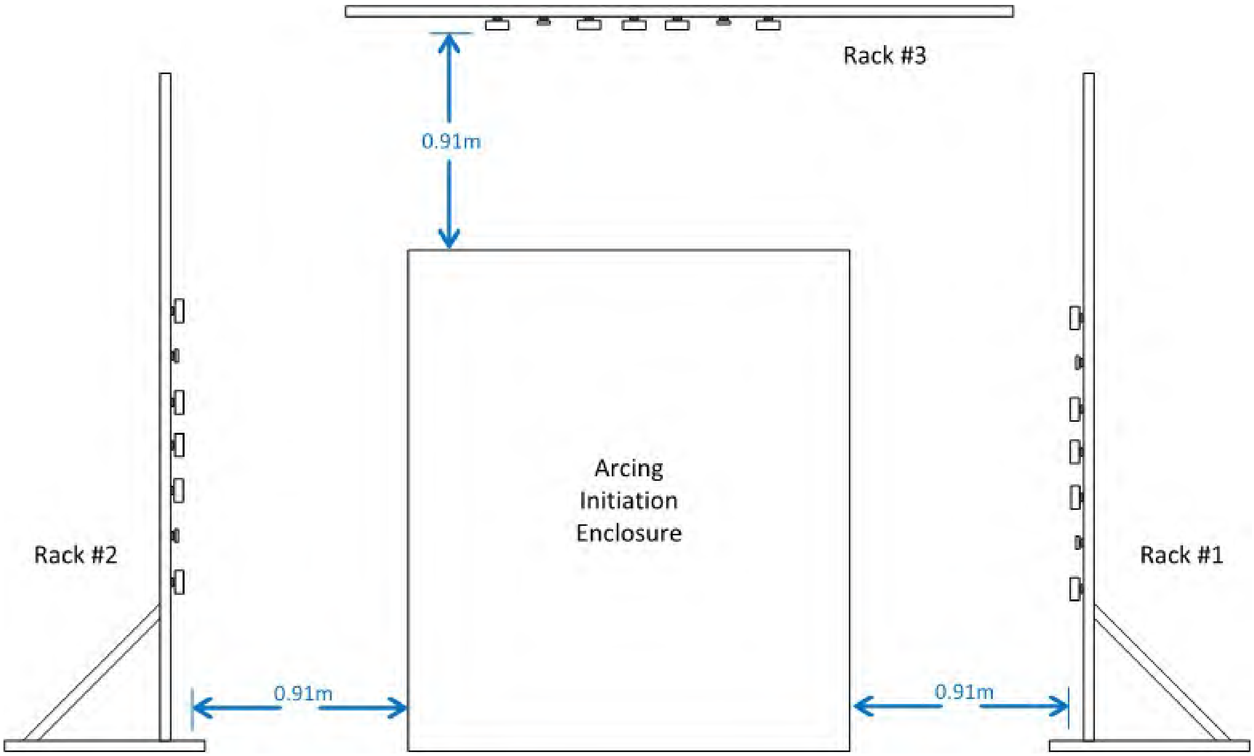

Fig. 24. Elevation view of instrument rack configuration around electrical enclosure. Enclosure doors right. Rack #3 supports not shown.

Fig. 25. Photo of instrumentation racks during experimental setup.

2.5.2. Instrument Placement - Bus Duct Experiments

Following the same scheme as the switchgear experiments, the majority of the thermal instrumentation devices were located on instrument racks with the face of the instruments located approximately 0.91 m (3.00 ft) from the exterior of the bus duct enclosure. This instrumentation rack configuration is shown in Fig. 26 and Fig. 27. Fig. 28 is a photograph showing the instrumentation racks around the experiment device. The expanded uncertainty in the measurement of the distances from the instrumentation racks to the electrical enclosure is ± 13 mm (0.5 in) with a coverage factor of 2 and an estimated confidence interval of 95 percent.

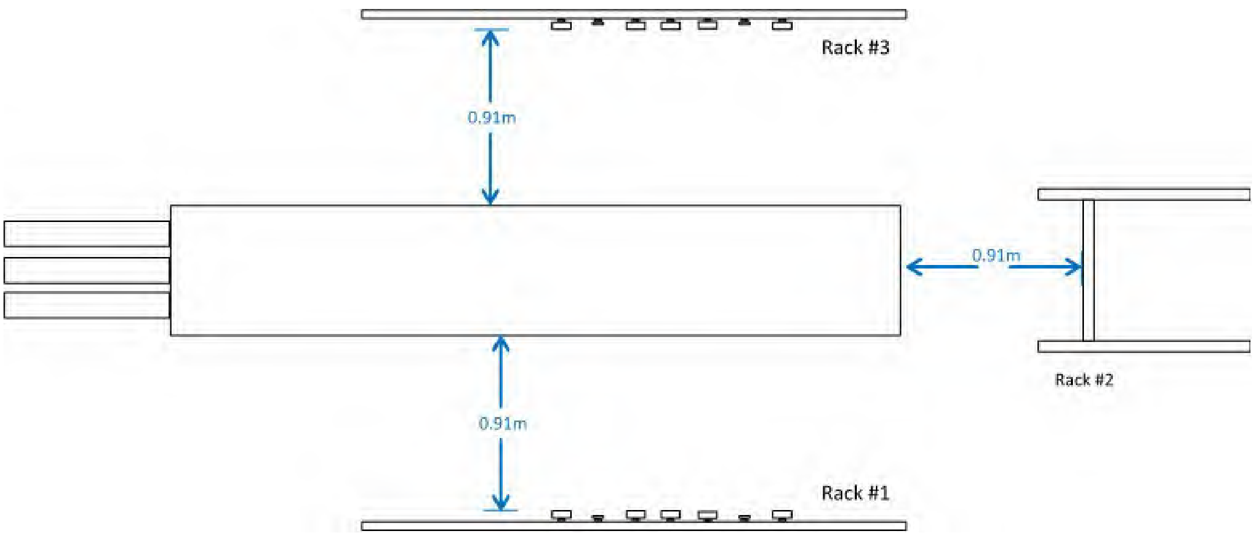

Fig. 26. Plan view of bus duct configuration. Note horizontal instrumentation Racks #4 and #5 are not shown (see next figure for placement). Rack supports not shown.

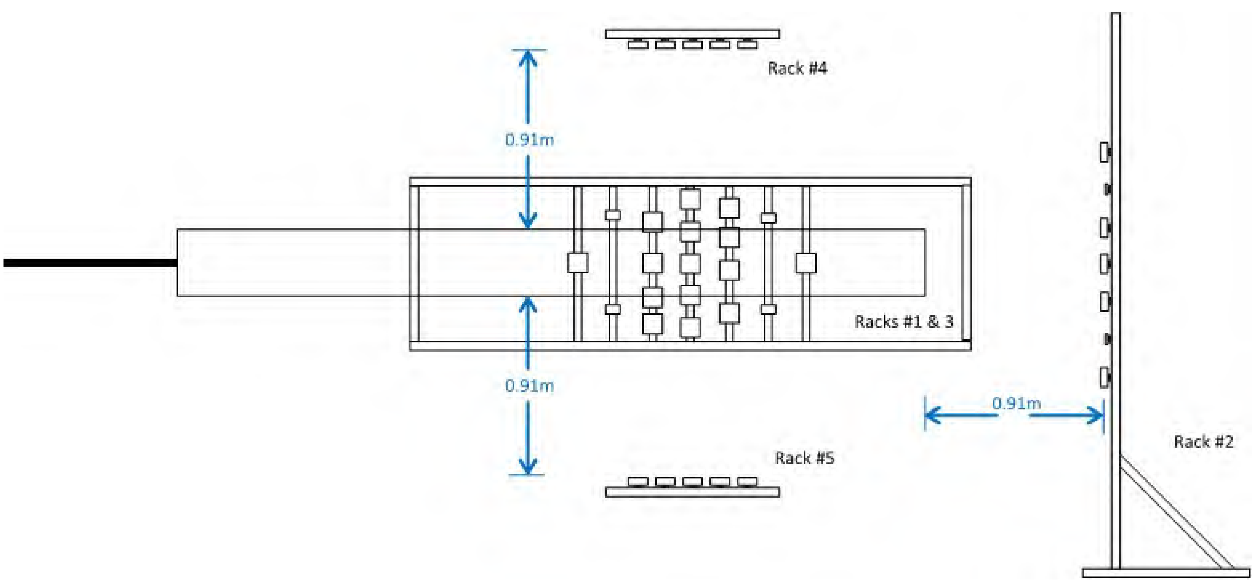

Fig. 27. Elevation view of instrument configuration. Rack supports not shown.

Fig. 28. Photo of bus duct instrumentation configuration prior to experiment

3. Experimental Results

KEMA performed calibration runs to ensure that the power circuits selected met the desired experimental parameters. The calibrations were measured at a shorting bus within the laboratory's facility, and the actual experimental conditions were slightly different because of the additional circuit length of the experimental device and its connections. The calibration experiments are presented in Table 7 with detail provided in the KEMA report (Appendix F).

Table 7. Circuit calibration parameters (measurements are ± 3 percent)

Voltage (kV)	Current Symmetrical (kA)	Current Peak (kA)	Circuit
4.19	29.8	66.2 to 88.3	S01
6.97	25.0	54.0 to 70.8	S02
0.613	14.7	29.0 to 38.8	S03
0.614	8.2	16.2 to 21.8	S04

The calibration experiments were performed for about 10 cycles to ensure stabilization of the waveform. The duration of the arc during an actual experiment was controlled by the ability to maintain the arc within the enclosure and the breaking of the circuit by the experiment laboratory's protective device(s). Provided that the arc did not prematurely extinguish, the experiment laboratory ensured that the arc duration parameter was met by automatically triggering their protective devices to open at the specified duration. Because of the laboratories desire to ensure the customer's prescribed arc duration was met, there was a delay in the opening of the circuit (breaker opening time), and as such, the actual arc durations were longer than the prescribed durations. Table 8 presents the experimental parameter variations for this series of experiments.

Table 8. Summary of Experiments

Experiment No. #	Voltage (kV)			Current (kA)		Duration (s)		Material		Notes
	System	Actual	Arc	Planned	Actual	Planned	Actual	Conductor	Enclosure	
2-33A	0.60	0.61	0.46	15	11.0	8	0.5	Copper	Steel	Switchgear, arc at secondary connection
2-33B	0.60	0.61	0.44	15	11.8	8	8.0	Copper	Steel	Switchgear, arc at breaker stab
2-34	0.60	0.61	0.45	8	6.4	17.5	4.4	Copper	Steel	Switchgear, arc at breaker stab
2-35	6.90	6.97	0.54	25	24.6	4	4.1	Copper / Aluminum	Steel	Switchgear, Vertical Lift, 2 unit
2-36	6.90	6.97	0.49	25	24.4	4	4.1	Copper	Steel	Switchgear, German, 2 unit
2-37	6.90	6.97	0.63	25	24.1	4	4.1	Copper	Steel	Switchgear, Horizontal draw-out, 2 unit
2-38	6.90	6.90	0.64	25	24.2	4	4.1	Copper/ Aluminum	Steel	Switchgear, Horizontal draw-out, 4 unit, cross-aisle
2-39	6.90	6.97	0.70	25	24.3	4	4.1	Copper	Steel	Switchgear, Horizontal draw-out, 2 unit
2-40	4.16	4.19	0.86	30	29.4	4	4.1	Copper	Aluminum	Bus duct
2-41	4.16	4.19	0.85	30	29.3	4	4.1	Aluminum	Aluminum	Bus duct

3.1. Experiment 2-33A – 600 V, 15 kA, 8 s Duration, Copper Bus, Steel Enclosure

Experiment 2-33A was performed on August 17, 2023, at 10:55 AM eastern daylight time (EDT). The temperature was approximately 26 °C (78 °F), the relative humidity was approximately 76 percent, and the atmospheric pressure was approximately 100.6 kPa. The weather was fair with a wind of approximately 5 km/h (3 mi/h) out of the southwest.

This experiment used a low-voltage “lineup” configuration consisting of Enclosures EV51 (Enclosure “A”), EV52 (Enclosure “B”), and EV53 (Enclosure “C”). The arc wire was located at the lower bus bar cable connection point in Enclosure EV53 (Enclosure “C”), which is farthest from the power supply. The arcing wire was installed between all three phases, and marked-up illustrations of the arc wire location is presented in Fig. 34.

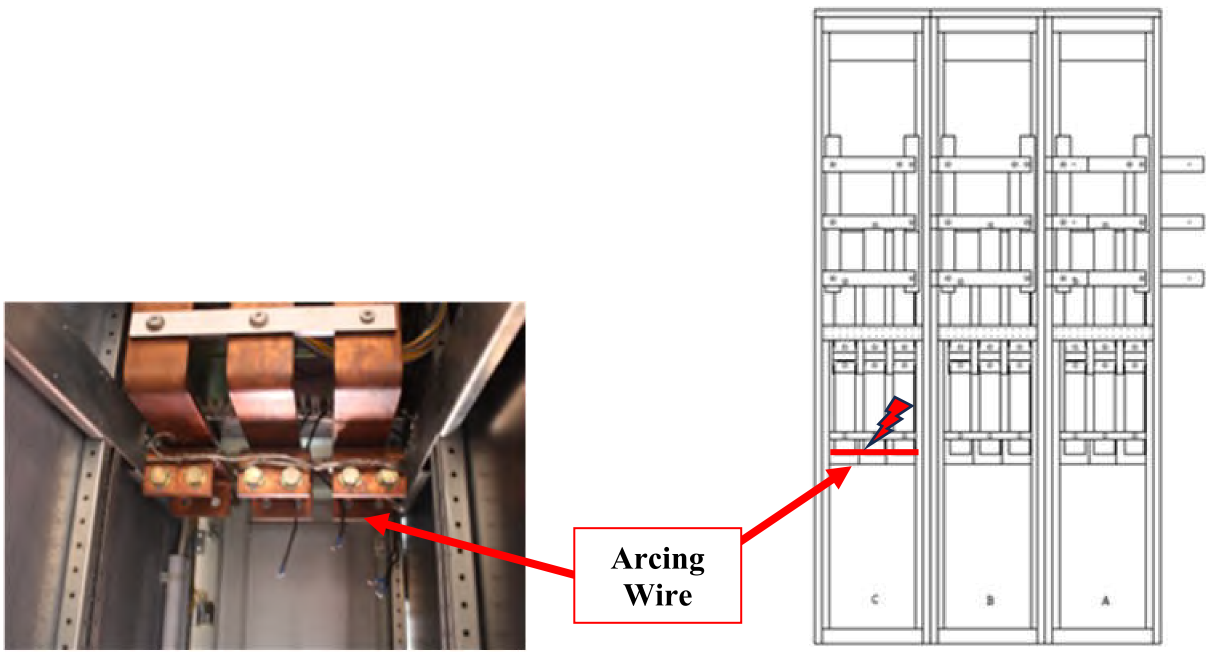

Fig. 29. Experiment 2-33A configuration. Left – photo of arcing wire (#10 AWG) installed, Right – drawing of internal bus work showing location of arc initiation.

3.1.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 9 and include an approximate time reference. Corresponding images are provided in Fig. 30, with thermography images presented in Fig. 31.

This was the first LV switchgear in this series of experiments. Scoping experiments performed in March 2023 indicated that the arc location was unlikely to be sustained. However, that experiment was a single unit and the research team was interested to observe any physical differences when a “lineup” configuration of energized equipment was used. During the experiment, the arc self-extinguished after 505 ms and did not hold for the intended 8 second duration. This was consistent with the observations from the scoping experiments (see Appendix E for more details). No visible cable damage was observed an any cable coupon on any instrument racks.

Table 9. Observations from Experiment 2-33A

Time (ms)	Observation
0	Initial light observed
316	Smoke exiting lower left cubicle
500	End of arc
633	Particle ejecta reaches left instrumentation rack

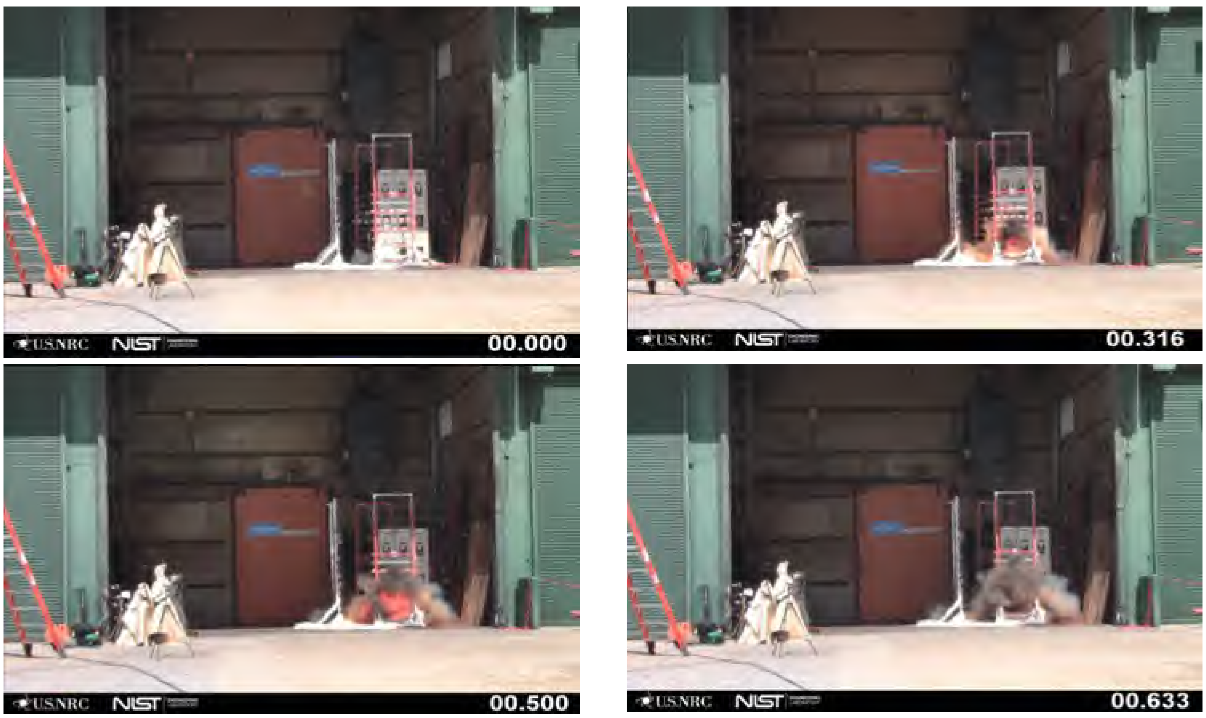

Fig. 30. Sequence of Images from Experiment 2-33A (image time stamps are in seconds).

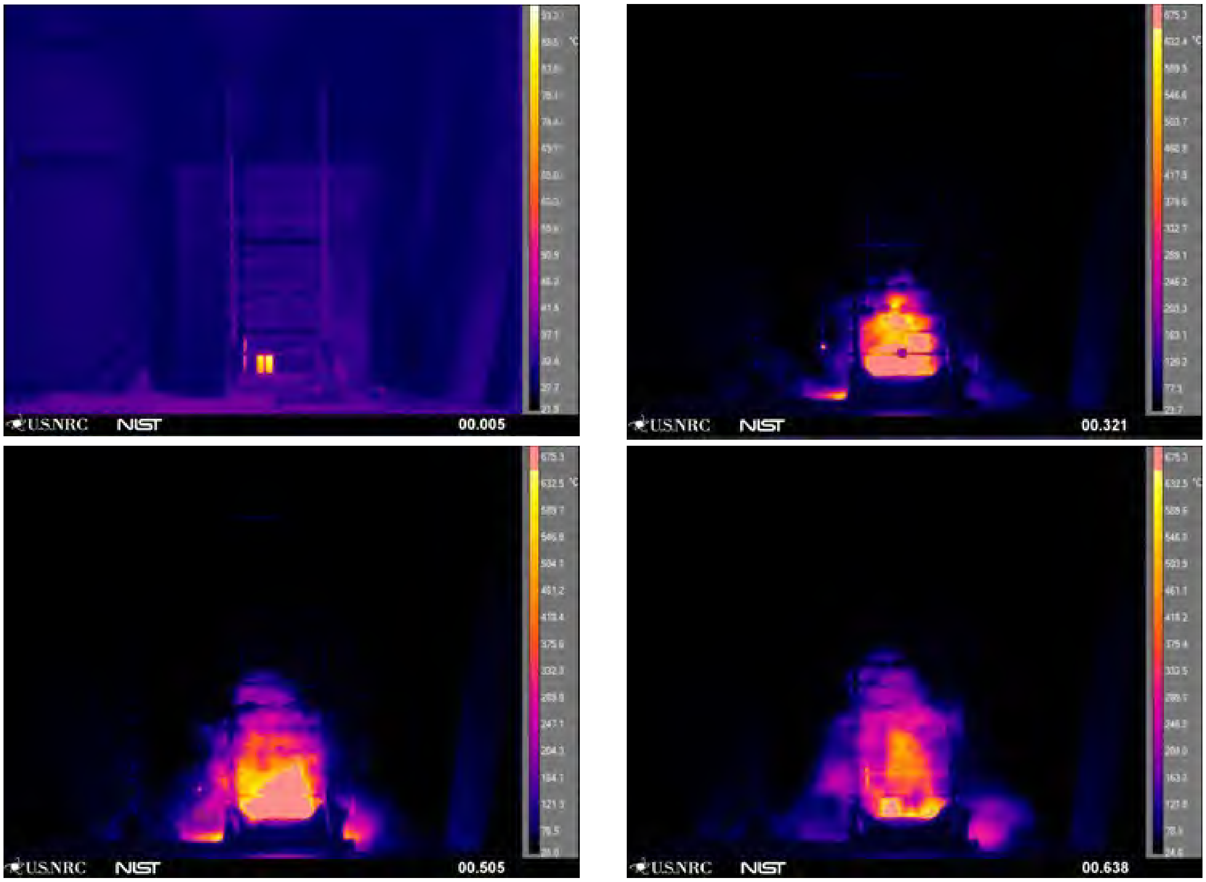

Fig. 31. Sequence of Thermal Images from Experiment 2-33A (image time stamp in seconds)

A photograph of the enclosures following the experiment is presented in Fig. 32. The enclosures did experience a breach on the exterior and internal panel on Enclosure ‘C’ (EV53). Detailed photos are shown in Appendix D. Due to the limited damage; the bus bars were not removed for mass loss weight measurements. The equipment was re-wired instead for an additional experiment as documented in Section 3.2.

Fig. 32. Enclosures Post-Experiment 2-33A. Note the external breach on the lower portions of Enclosure ‘C’.

3.1.2. Measurements

Measurements made during Experiment 2-33A are presented below. These measurements included:

- Thermal
    - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
    - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
    - Temperature – Fiber optic sensors inside of switchgear
- Pressure
    - Internal pressure
- Mass Loss
    - Pre- / Post-experimental measurements
- Electrical
    - Voltage profiles
    - Current profiles
    - Power and energy profiles

3.1.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-33A. These include PT measurements in Table 10, ASTM Slug Calorimeter measurements in Table 11, and T_{cap} slug measurements in Table 12. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 56 °C. Table 13 presents the maximum temperatures and time for the fiber optic sensors.

Table 10. Summary of plate thermometer measurements Experiment 2-33A.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %	Note
1	1	Top	13	14	8	
1	3	Mid-Right	17	20	12	
1	5	Mid-Center	42	40	20	
1	7	Mid-Left	15	21	13	
1	9	Bottom	**144**	**135**	**82**	
2	10	Top	2	1	2	Cor.
2	12	Mid-Right	4	3	2	
2	14	Mid-Center	2	1	2	
2	16	Mid-Left	1	1	1	
2	18	Bottom	6	2	1	
3	19	Top	7	7	6	
3	21	Mid-Right	19	19	16	
3	23	Mid-Center	14	13	13	
3	25	Mid-Left	8	9	8	
3	27	Bottom	23	26	22	

Note: Cor. denotes corrected value for maximum heat flux during arcing period after inspection of plotted data.

Table 11. Summary of ASTM slug calorimeter measurements, Experiment 2-33A.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder Type
1	A	Top	11.3	5.2	AG
1	B	Bottom	**30.6**	5.2	Pb-Sn
2	C	Top	2.2	92.4	AG
2	D	Bottom	1.8	89.79	Pb-Sn
3	E	Top	11.9	40.3	AG
3	F	Bottom	15.7	42.4	Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 12. Summary of T_{cap} slug measurements, Experiment 2-33A

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	8.5	4.4	33.7
1	4	Mid-Right	9.1	9.6	38.0
1	6	Mid-Left	12.0	12.8	41.4
1	8	Bottom	21.7	23.6	66.0
2	11	Top	0.8	1.0	3.7
2	13	Mid-Right	0.7	1.0	3.8
2	15	Mid-Left	0.2	0.3	3.5
2	17	Bottom	0.8	0.6	3.6
3	20	Top	2.9	3.1	20.0
3	22	Mid-Right	4.2	4.4	33.2
3	24	Mid-Left	3.4	4.0	24.0
3	26	Bottom	4.8	5.2	38.7

Table 13. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-33A

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)
61	C	5	**55.9**	90
62	B	5	45.5	140
63	A	5	42.8	202

3.1.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 33. After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear enclosure was approximately 7.7 kPa (1.1 psi) above ambient at its peak.

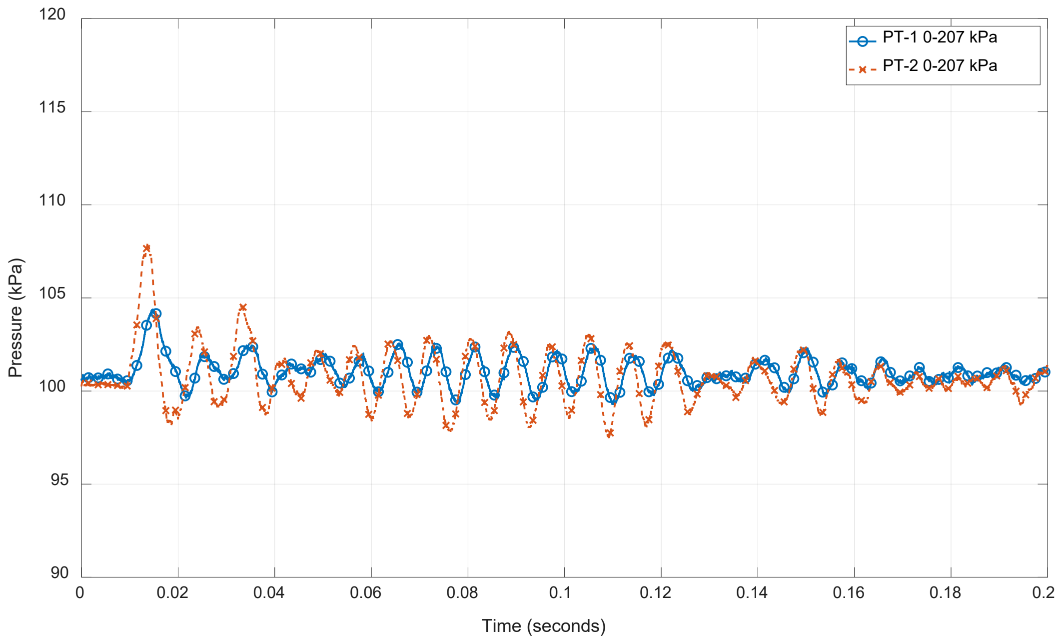

Fig. 33. Pressure measurements from Experiment 2-33A. Measurement uncertainty ± 3 percent.

3.1.2.3. Electrical Measurements

Experiment 2-33A used KEMA circuit S03 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230817-9004. Key experimental measurements are presented in Table 14. Plots of the electrical measurements are presented in Appendix B.

Table 14. Key measurements from Experiment 2-33A. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}	613		
Making current	kA_{peak}	-26.7	-26.1	31.2
Current, AC component, beginning	kA_{RMS}	11.7	13.7	11.4
Current, AC component, middle	kA_{RMS}	10.8	12.2	12.2
Current, AC component, end	kA_{RMS}	10.1	12.2	9.60
Current, AC component, average	kA_{RMS}	10.6	11.0	10.8
Current, AC component, three-phase average	kA_{RMS}	10.8		
Duration	s	0.504	0.504	0.504
Arc Energy	MJ	3.33		

3.2. Experiment 2-33B – 480 V, 15 kA, 8 s Duration, Copper Bus, Steel Enclosure

Experiment 2-33B was performed on August 17, 2023, at 11:45 AM eastern daylight time (EDT). The temperature was approximately 26 °C (78 °F), the relative humidity was approximately 79 percent, and the atmospheric pressure was approximately 100.6 kPa. The weather was cloudy with a wind of approximately 5 km/h (3 mi/h) out of the southeast.

This experiment used the same low-voltage "lineup" configuration used in Experiment 2-33A, consisting of Enclosures EV51 ("A"), EV52 ("B"), and EV53 ("C"). Openings in the metal enclosure caused by arcing during the 2-33A experiment were closed using a sheet metal plate secured by self-tapping metal screws. The arc wire was located at the upper vertical bus bars at the connection point to the breaker in the middle of Enclosure EV52 ("B"). These bus bars connect the breaker to the main bus. Scoping experiments performed in March 2023 indicated that this arc location was likely to be sustained for an extended duration. The arcing wire was installed between all three phases, and marked-up illustrations of the arc wire location is presented in Fig. 34.

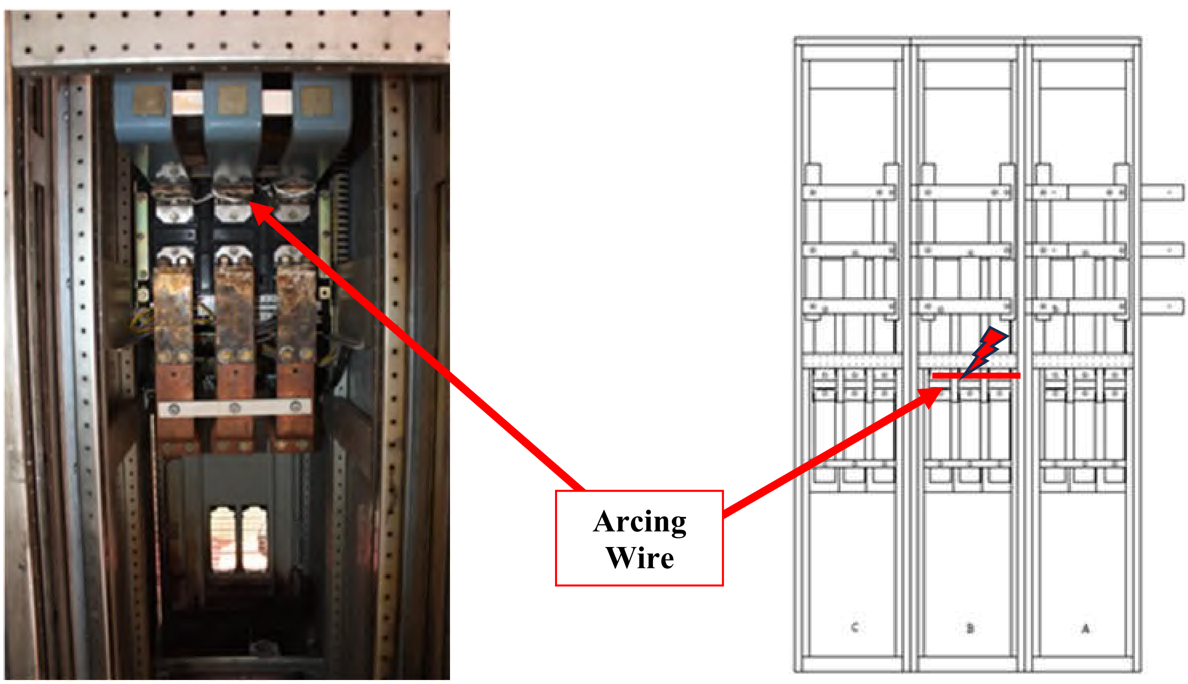

Fig. 34. Experiment 2-33B configuration. Left – photo of arcing wire (#10 AWG) installed, Right – drawing of internal bus work showing location of arc initiation.

3.2.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 15 and include an approximate time reference. Corresponding images are provided in Fig. 35, with thermography images presented in Fig. 36.

This was the second LV switchgear in this series of experiments. During the experiment, the arc was maintained for the expected duration of 8 s. However, there was a momentary arc extinguishment of approximately 500 ms in duration that occurred at approximately 5.11 s into the experiment. See Appendix B for the electrical measurements showing a loss of current on all three phases.

Following the arcing event, the enclosure experienced fire development. The thermal imaging cameras showed the heat progression throughout the compartment as the fire gained intensity. The breaker in compartment B appears to ignite immediately after the event, and then the fire progressed into the upper instrumentation cubicles and associated cable compartments. Significant smoke developed in the top cubicle of Enclosures B and C. The fire began to flashover outside of the compartment B at 14.45 minutes after the arc initiation and then the full fire development spread into Enclosure C. The fire progressed to full flame development when the relay equipment on the front face of Enclosures B and C melted away allowing air to enter the top cubicles. Nearly all combustible material in both the B and C cubicles was consumed. No visible cable damage was observed an any cable coupon on any instrument racks.

Table 15. Observations from Experiment 2-33B.

Time (ms)	Observation
0	Initial light observed
350	Smoke reaches front rack
1 851	Flames emanating from top of switchgear
3 319	Significant amount of arc ejecta expelled from front of switchgear
7 791	Side breach of enclosure
8 058	End of arc

Fig. 35. Sequence of Images from Experiment 2-33B (image time stamps are in seconds).

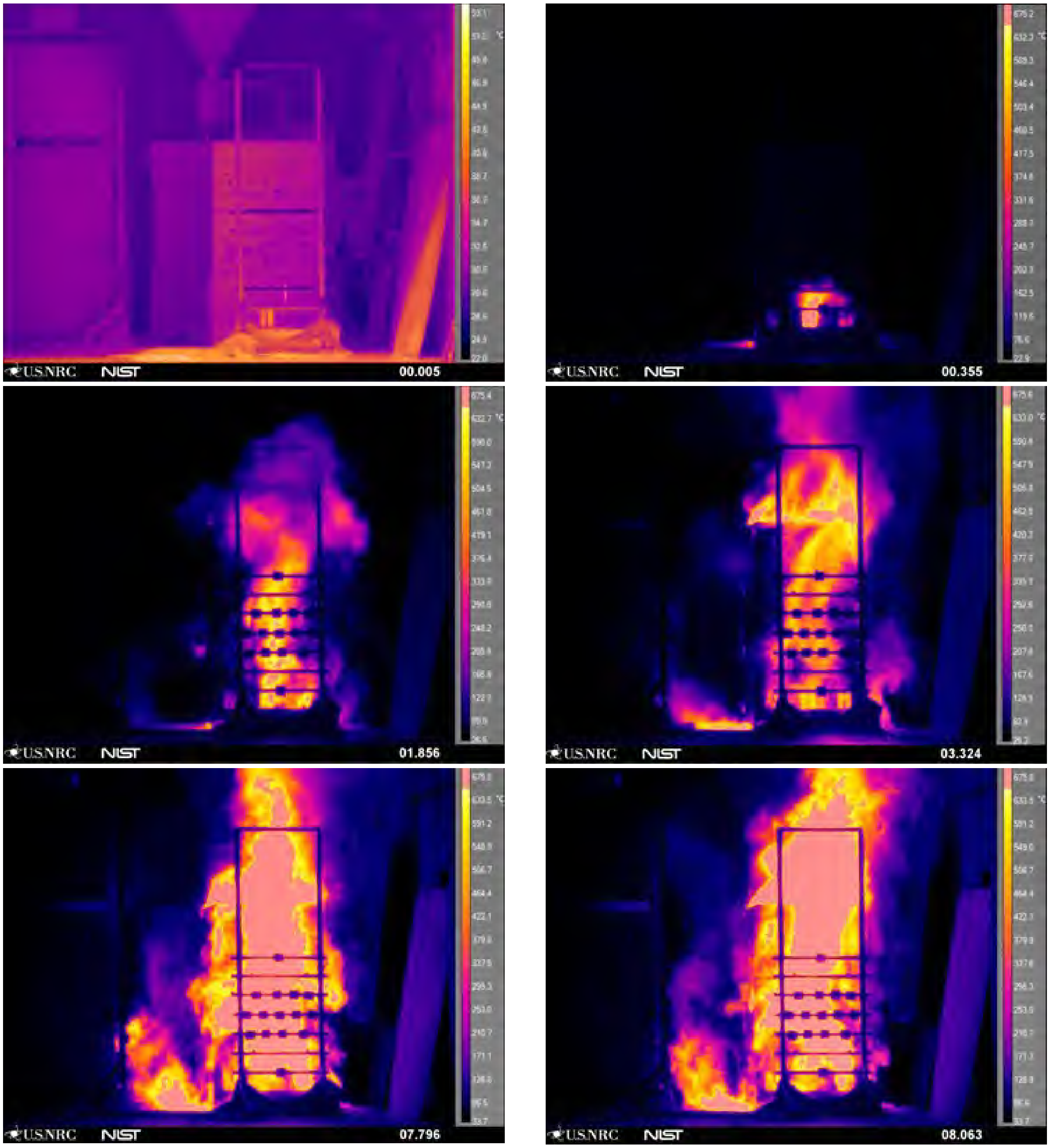

Fig. 36. Sequence of Thermal Images from Experiment 2-33B (image time stamp in seconds)

A photograph of the enclosures following the experiment is presented in Fig. 37. The enclosures did experience a breach on the exterior and internal panel of Enclosure 'C' (EV53). Internal panels also experienced damage and material loss. The internal breach mass loss was estimated at approximately 283.0 g and the exterior mass loss was estimated at approximately 61.8 g. Detailed photos are provided in Appendix D.

Fig. 37. Enclosures Post-Experiment 2-33B. Note the external breach on the middle side panel of Enclosure 'C'.

Images of the bus bars removed from the enclosure after the experiment are shown in Fig. 38. The total mass loss of the bus bars was approximately 4 612.0 g. Additional details are presented in Appendices C and D.

Fig. 38. Photos of Experiment 2-33B vertical supply bus bars post-experiment. Location with material loss (top of image) is where the bus connected to the breaker. Bar orientation as shown in photo is C-B-A.

3.2.2. Measurements

Measurements made during Experiment 2-33B are presented below. These measurements included:

- Thermal
    - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
    - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
    - Temperature – Fiber optic sensors inside of switchgear
- Pressure
    - Internal pressure
- Mass Loss
    - Pre- / Post-experimental measurements
- Electrical
    - Voltage profiles
    - Current profiles
    - Power and energy profiles

3.2.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-33B. These include PT measurements in Table 16, ASTM Slug Calorimeter measurements in Table 17, and T_{cap} slug measurements in Table 18. The maximum reading is identified with bold text. The maximum temperature exceeded the fiber optic sensors range. Table 19 presents the time for the fiber optic sensors to reach maximum range. Note that there was re-ignition/fire growth late in this experiment.

Table 16. Summary of plate thermometer measurements Experiment 2-33B.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
1	1	Top	**242**	39	**620**
1	3	Mid-Right	66	30	250
1	5	Mid-Center	94	**46**	350
1	7	Mid-Left	69	29	300
1	9	Bottom	119	32	270
2	10	Top	34	16	120
2	12	Mid-Right	26	15	110
2	14	Mid-Center	37	16	120
2	16	Mid-Left	26	14	100
2	18	Bottom	29	11	80
3	19	Top	26	8	190
3	21	Mid-Right	58	13	140
3	23	Mid-Center	34	14	130
3	25	Mid-Left	25	9	90
3	27	Bottom	115	34	250

Table 17. Summary of ASTM slug calorimeter measurements, Experiment 2-33B.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder Type
1	A	Top	318.3	15.9	AG
1	B	Bottom	**399.6**	15.8	Pb-Sn
2	C	Top	149.0	12.2	AG
2	D	Bottom	121.5	11.5	Pb-Sn
3	E	Top	133.0	24.06	AG
3	F	Bottom	161.9	16.5	Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 18. Summary of T_{cap} slug measurements, Experiment 2-33B.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	43.6	158.9	**1455.5**
1	4	Mid-Right	70.8	319.6	1107.6
1	6	Mid-Left	**73.6**	**343.8**	1226.2
1	8	Bottom	64.8	322.1	908.6
2	11	Top	20.2	108.6	362.5
2	13	Mid-Right	23.9	126.6	325.0
2	15	Mid-Left	22.5	118.5	310.4
2	17	Bottom	19.7	102.1	305.2
3	20	Top	17.3	71.9	695.6
3	22	Mid-Right	21.5	79.9	669.8
3	24	Mid-Left	22.3	88.7	517.0
3	26	Bottom	28.3	129.0	503.9

Table 19. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-33B.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)	Note
61	C	5	> 200.0	34	Exceed device range
62	B	5	> 200.0	12	Exceed device range
63	A	5	> 200.0	94	Exceed device range

3.2.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 39. After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear enclosure was approximately 4.0 kPa (0.6 psi) above ambient at its peak.

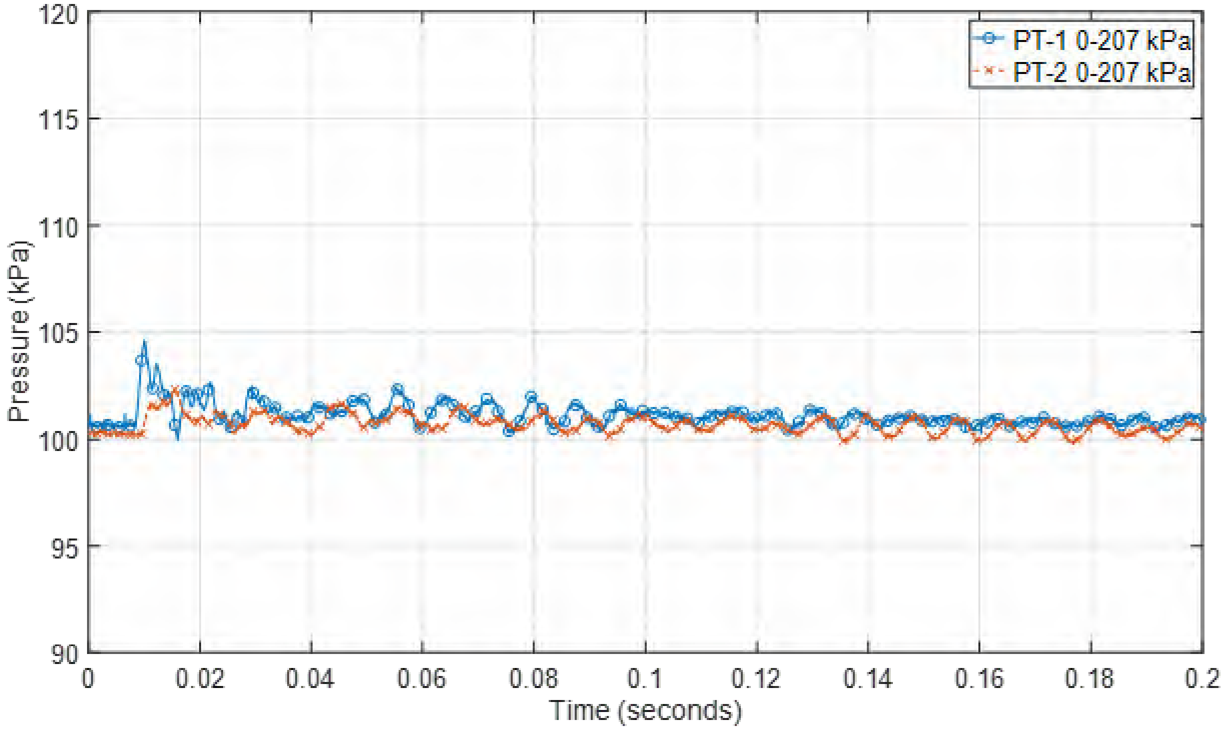

Fig. 39. Pressure measurements from Experiment 2-33B. Measurement uncertainty ± 3 percent.

3.2.2.3. Electrical Measurements

Experiment 2-33B used KEMA circuit S03 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230817-9005. Key experimental measurements are presented in Table 20. Plots of the electrical measurements are presented in Appendix B.

Table 20. Key measurements from Experiment 2-33B. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}	613		
Making current	kA_{peak}	16.7	-15.4	-18.0
Current, AC component, beginning	kA_{RMS}	10.8	10.4	12.0
Current, AC component, middle	kA_{RMS}	12.0	12.0	11.5
Current, AC component, end	kA_{RMS}	9.43	9.77	9.33
Current, AC component, average	kA_{RMS}	11.4	11.8	11.5
Current, AC component, three-phase average	kA_{RMS}	11.6		
Duration	s	8.00	8.00	8.00
Arc Energy	MJ	52.1		

3.3. Experiment 2-34 – 600 V, 8 kA, 17.5 s Duration, Copper Bus, Steel Enclosure

Experiment 2-34 was performed on August 18, 2023, at 8:50 AM eastern daylight time (EDT). The temperature was approximately 21 °C (69 °F), the relative humidity was approximately 84 percent, and the atmospheric pressure was approximately 100.0 kPa. The weather was fair with a wind of approximately 11 km/h (7 mi/h) out of the west.

Experiment 2-34 used a configuration similar to experiments 2-33A and 2-33B. However, instead of just three enclosures, an additional the unit lineup configuration was used with both lineup configurations placed back-to-back. In total six units were used. Enclosures EU51 ("D"), EU52 ("E") and EU53 ("F") were in one lineup configuration with the arc initiating in unit EU52. The additional three Enclosures EV51 ("A"), EV52 ("B"), and EV53 ("C"), were placed behind in the "back-to-back" configuration (Fig. 6). The arc wire was located at the upper vertical bus bars at the connection point to the breaker in the middle Enclosure EU52 ("E"). These bus bars connect the breaker to the main bus. The arcing wire was installed between all three phases and marked-up illustrations of the arc wire location is presented in Fig. 40.

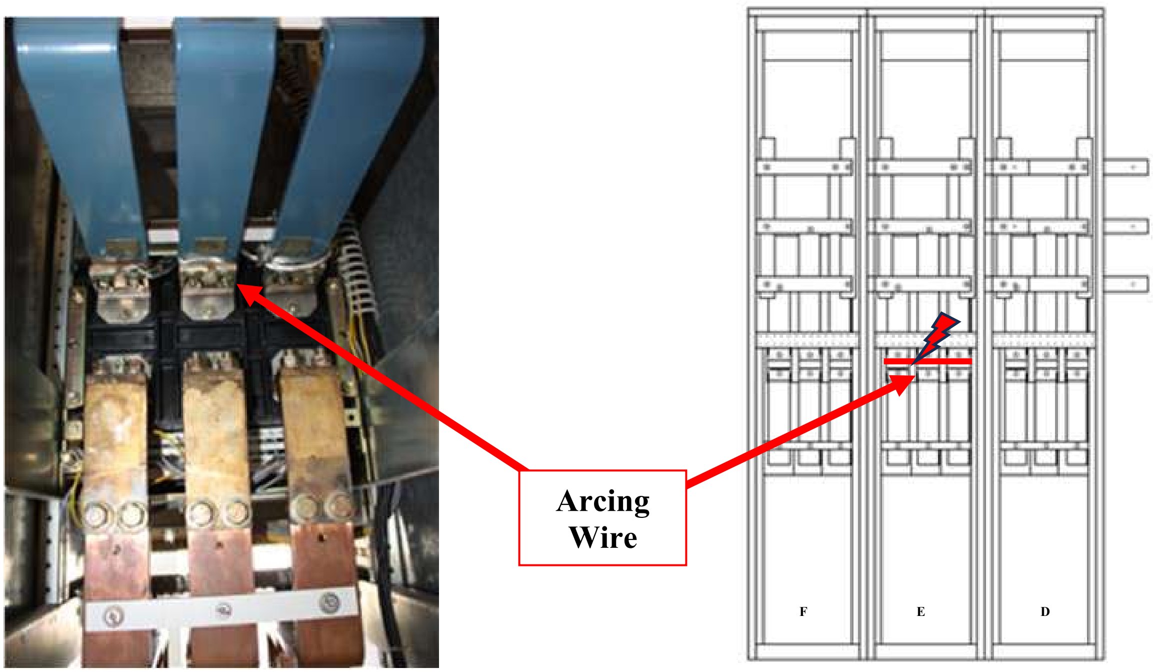

Fig. 40. Experiment 2-34 configuration. Left – photo of arcing wire (#10 AWG) installed, Right – drawing of internal bus work showing location of arc initiation.

3.3.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 21 and include an approximate time reference. Corresponding images are provided in Fig. 41, with thermography images presented in Fig. 42.

This was the last LV switchgear experiment and the last experiment of the experimental series. This "back-to-back" configuration was requested by members of the OECD/NEA HEAF 2 project. Following the experiment, the breaker cubicle door of Enclosure 'E' (EU52) was opened. There was minimal thermal damage to the front of the arc initiating switchgear. There were several enclosure breaches on Enclosure 'F', farthest from the incoming power supply. The breaches were at the location of the horizontal main bus. No new damage to the non-energized lineup of Enclosures (A-C) were noted. The arc sustained for approximately 4.44 s before self-terminating. Review of electrical data (see Appendix B) indicated that Phase A terminated earlier at approximately 2.9 s while the other two phases continued to arc until approximately 4.44 s. Note that the horizontal phase 'A' main bus was shorter than the other two phases and likely contributed to the loss of arcing on phase 'A'. There was no ensuing fire. No visible cable damage was observed an any cable coupon on any instrument racks.

Table 21. Observations from Experiment 2-34.

Time (ms)	Observation
0	Initial light observed
133	Center-Mid Door opens
800	Arc eject observed above enclosure
1 301	Fire exiting Center-Mid cubicle
2 469	Arc breach to side panel
4 454	Smoke begins to clear cell after end of arc

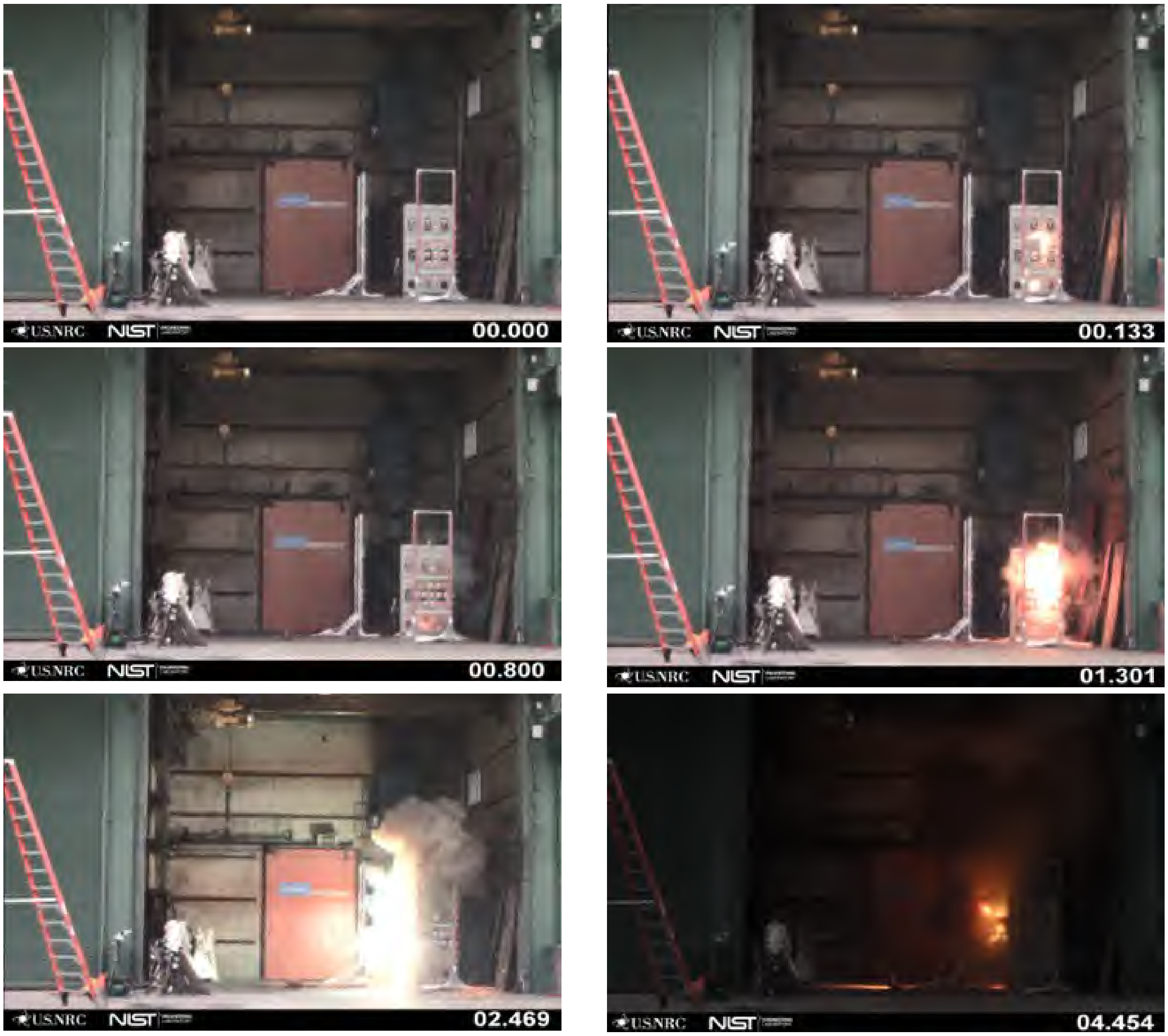

Fig. 41. Sequence of Images from Experiment 2-34 (image time stamps are in seconds).

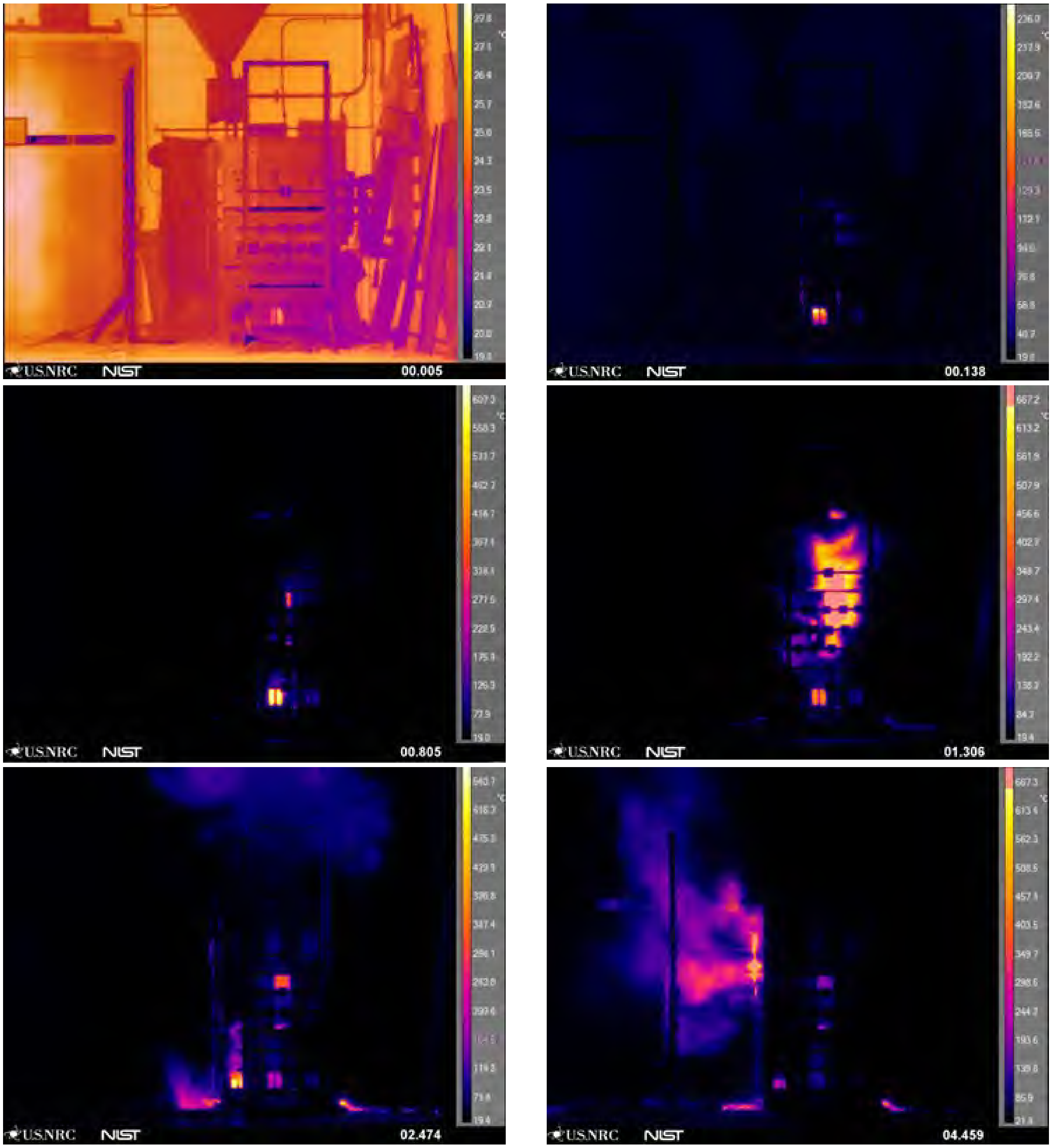

Fig. 42. Sequence of Thermal Images from Experiment 2-34 (image time stamp in seconds).

Photographs of the enclosures following the experiment are presented in Fig. 43. Enclosure ‘F’ did experience two breaches with a total estimated mass loss of approximately 314 g.

Fig. 43. Enclosures Post-Experiment 2-34. Left – enclosure breach on side of Enclosure ‘F’ (EU53), Right – front view of enclosures showing open door on breaker cubicle of Enclosure ‘E’ (EU52).

An image of the bus bars removed from the enclosures after the experiment are shown in Fig. 44. The total mass loss of the bus bars was approximately 176.0 g. Additional details are presented in Appendix C and D.

Fig. 44. Photo of Experiment 2-34 bus bars post-experiment (arc location shown right).

3.3.2. Measurements

Measurements made during Experiment 2-34 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.3.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-34. These include PT measurements in Table 22, ASTM Slug Calorimeter measurements in Table 23, and T_{cap} slug measurements in Table 24. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 89 °C. Table 25 presents the maximum temperatures and time for the fiber optic sensors.

Table 22. Summary of plate thermometer measurements Experiment 2-34.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) Greater of ± 15 %
1	1	Top	57	9	37
1	3	Mid-Right	**142**	12	47
1	5	Mid-Center	35	5	21
1	7	Mid-Left	21	4	13
1	9	Bottom	12	2	9
2	10	Top	42	12	59
2	12	Mid-Right	21	7	28
2	14	Mid-Center	62	13	51
2	16	Mid-Left	78	**20**	**100**

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 15 %
2	18	Bottom	33	5	22

Table 23. Summary of ASTM slug calorimeter measurements, Experiment 2-34.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder Type
1	A	Top	53.7	3.2	AG
1	B	Bottom	16.7	4.3	Pb-Sn
2	C	Top	47.0	25.6	AG
2	D	Bottom	**61.3**	13.4	Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 24. Summary of T_{cap} slug measurements, Experiment 2-34.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	19.2	34.1	38.7
1	4	Mid-Right	19.0	37.5	44.7
1	6	Mid-Left	9.9	19.6	23.3
1	8	Bottom	10.3	19.6	23.0
2	11	Top	17.3	19.8	95.2
2	13	Mid-Right	15.5	26.3	63.0
2	15	Mid-Left	**30.3**	**51.0**	**107.2**
2	17	Bottom	6.8	12.1	52.7

Table 25. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-34.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)
61	F	5	65.0	290
62	E	5	**89.0**	27
63	D	5	66.3	82
64	C	5	25.6	304
65	B	5	26.5	306
66	A	5	28.3	313

3.3.2.2. Pressure Measurements

The pressure profiles for the *first five seconds* are shown in Fig. 45. The pressure profile was different from prior experiments because there was only a minimal pressure spike after arc initiation. However, at approximately 1.5 s into the experiment there were higher pressure readings on both pressure transducers. Note that both pressure transducers were located on Enclosure ‘F’ (EU53). The maximum change in pressure in the switchgear enclosure was approximately 3.6 kPa (0.52 psi) above ambient at its peak.

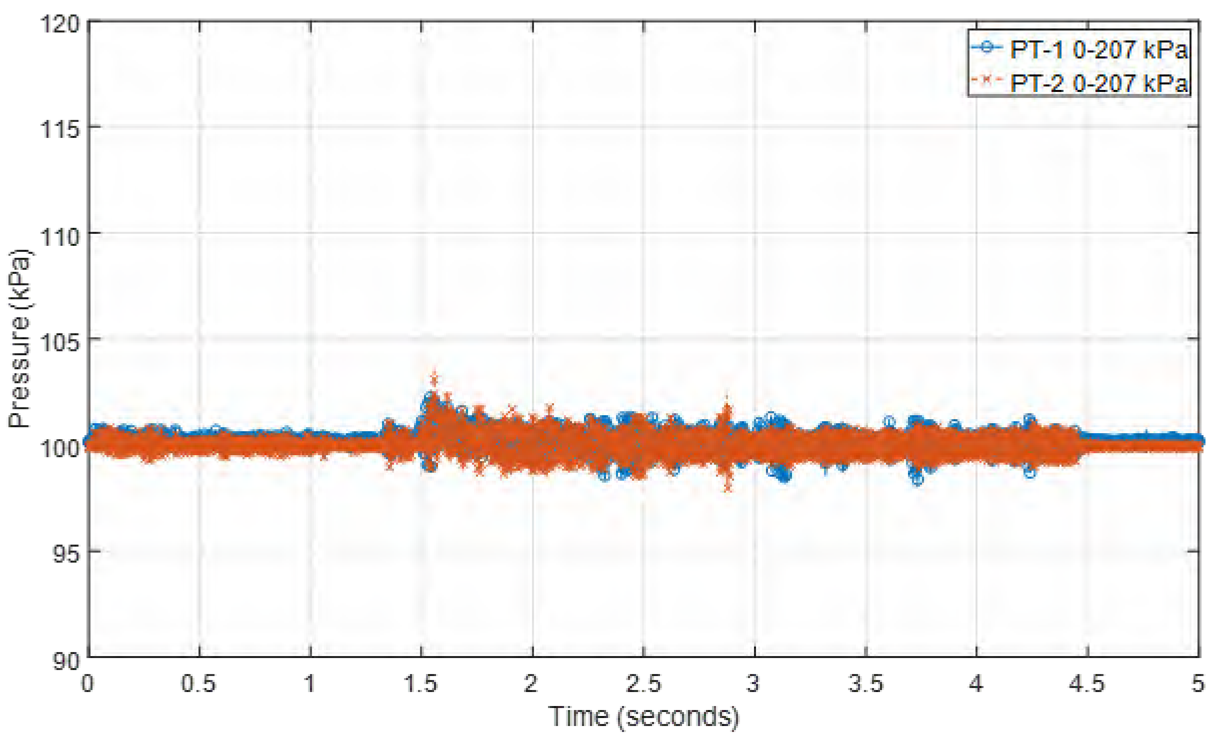

Fig. 45. Pressure measurements from Experiment 2-34. Measurement uncertainty ± 3 percent.

3.3.2.3. Electrical Measurements

Experiment 2-34 used KEMA circuit S04 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230818-9001. Key experimental measurements are presented in Table 26. Plots of the electrical measurements are presented in Appendix B.

Table 26. Key measurements from Experiment 2-34. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}		614	
Making current	kA_{peak}	15.4	16.9	-21.0
Current, AC component, beginning	kA_{RMS}	8.13	8.06	6.54
Current, AC component, middle	kA_{RMS}	6.50	6.14	6.20
Current, AC component, end	kA_{RMS}	6.59	5.25	5.21
Current, AC component, average	kA_{RMS}	6.80	6.85	5.59
Current, AC component, three-phase average	kA_{RMS}		6.41	
Duration	s	2.89	4.44	4.44
Arc Energy	MJ		13.0	

3.4. Experiment 2-35 – 6.9 KV, 25 kA, 4 s Duration, Copper Bus, Steel Enclosure

Experiment 2-35 was performed on August 9, 2023, at 12:20 PM eastern daylight time (EDT). The temperature was approximately 28 °C (82 °F), the relative humidity was approximately 48 percent, and atmospheric pressure was approximately 100.9 kPa. The weather was sunny with a wind of approximately 15 km/h (9 mi/h) out of the west north-west.

This experiment used two medium-voltage (MV) electrical enclosures. These were designated Enclosure "O" and "P". Both enclosures were of a vertical lift design (GE Magne-blast). Enclosure "O" contained copper bus, while Enclosure "P" contained aluminum bus. Available equipment limited the possibility of using all copper bussed equipment. Both units were electrically connected to the power supply via the main bus. The arc wire was located on the copper main bus in Enclosure "O". Insulation was not present at the arc initiation location. The arcing wire was installed between all three phases. A marked-up illustration and photo of the arc wire location is presented in Fig. 46.

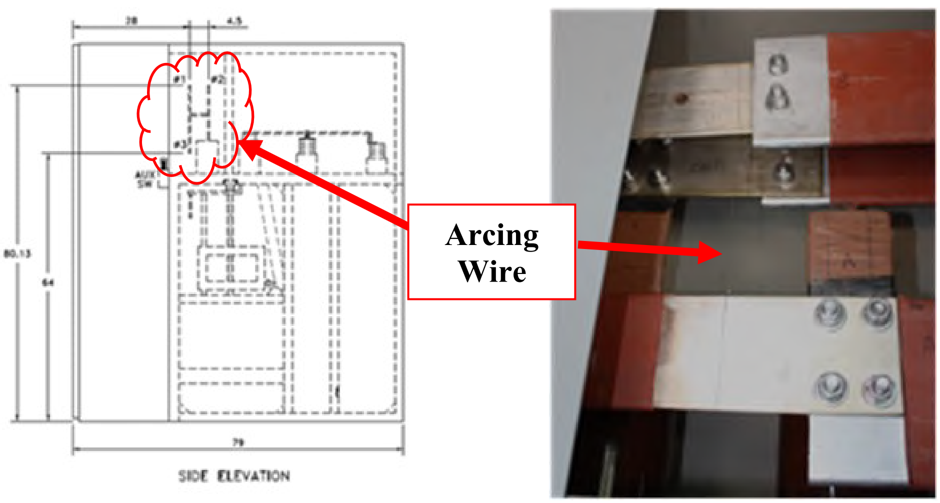

Fig. 46. Experiment 2-35 configuration. Left – drawing of internal bus work showing location of arc initiation in Enclosure "O", Right – photo of arcing wire (#24 AWG) installed.

3.4.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 27 and include an approximate time reference. Corresponding images are provided in Fig. 47, with thermography images presented in Fig. 48.

This was the first medium-voltage switchgear experiment of the series. The door of Enclosure "O" opened shortly after arc initiation, swung fully open, and then rebounded and swung to a near closed position. Due to this behavior, thermal exposure to the instrumentation Rack #1 immediately in front of Enclosure "O" was limited. Subsequently, it was apparent that the arc migrated into and sustained arcing in Enclosure "P". Heat damage and metal deformation was observed on the outside of Enclosure "P" in a geometry consistent with the main bus compartment cross-section. No arc induced thermal burn-through of the exterior enclosure was observed. The upper internal panel in Enclosure "P" did experience arc burn-through. The door on Enclosure "P" did not open during the experiment, but the two door mounted instruments (amp and voltage) located near the top of the door melted. The two vertical instrumentation racks (#1 and #2) appeared relatively clean. The horizontal rack above the Enclosure "O" showed some signs of thermal insult. No visible cable damage was observed an any cable coupon on any instrument racks. The arc lasted for the expected duration (4.12 s).

Table 27. Observations from Experiment 2-35.

Time (ms)	Observation
0	Initial light observed
166	Door begins to open
533	Arc ejecta exiting top of left enclosure
1 084	Arc migrates to right enclosure
3 003	Flaming from left enclosure and arcing in right enclosure
4 120	End of arc

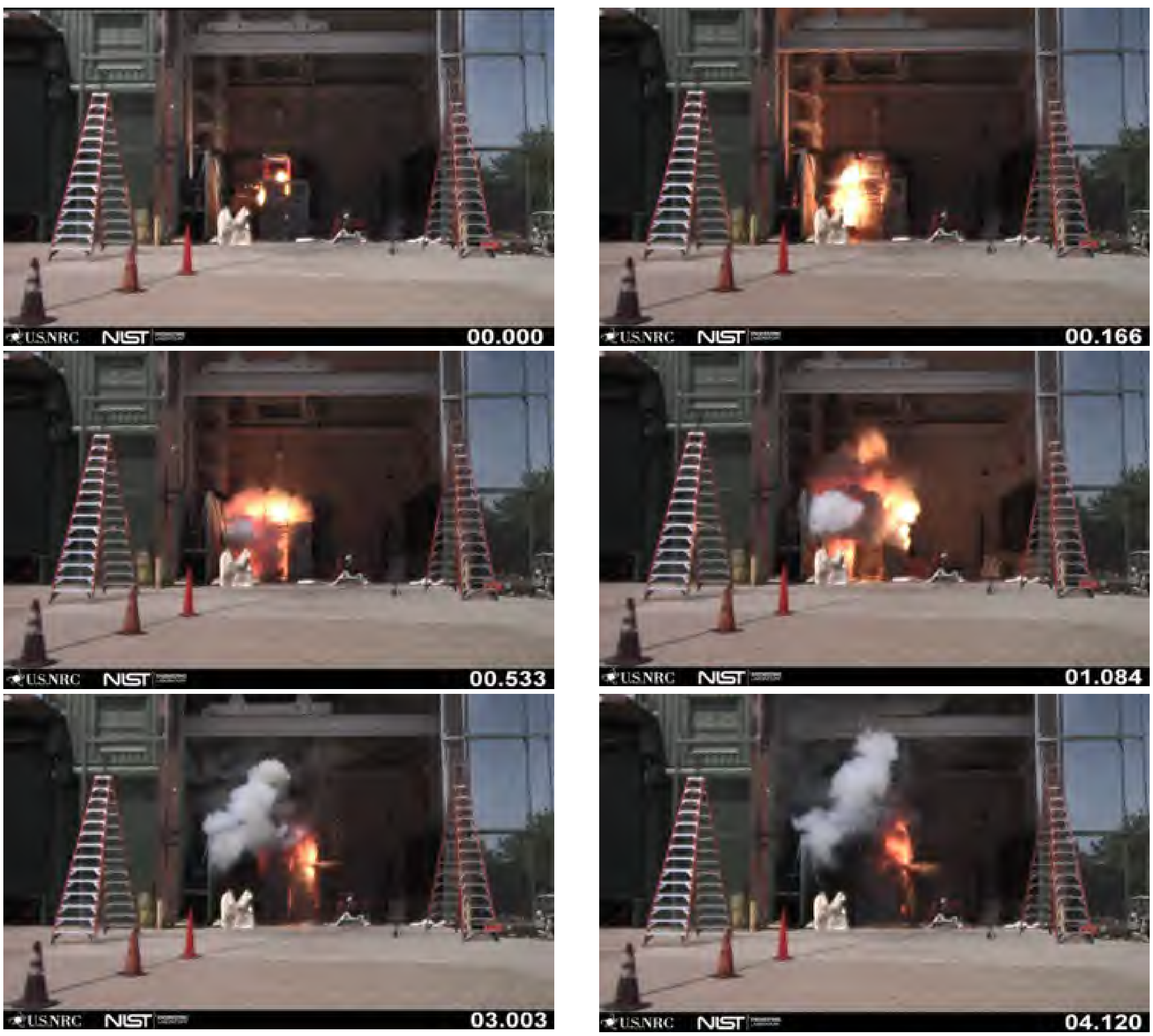

Fig. 47. Sequence of Images from Experiment 2-35 (image time stamps are in seconds).

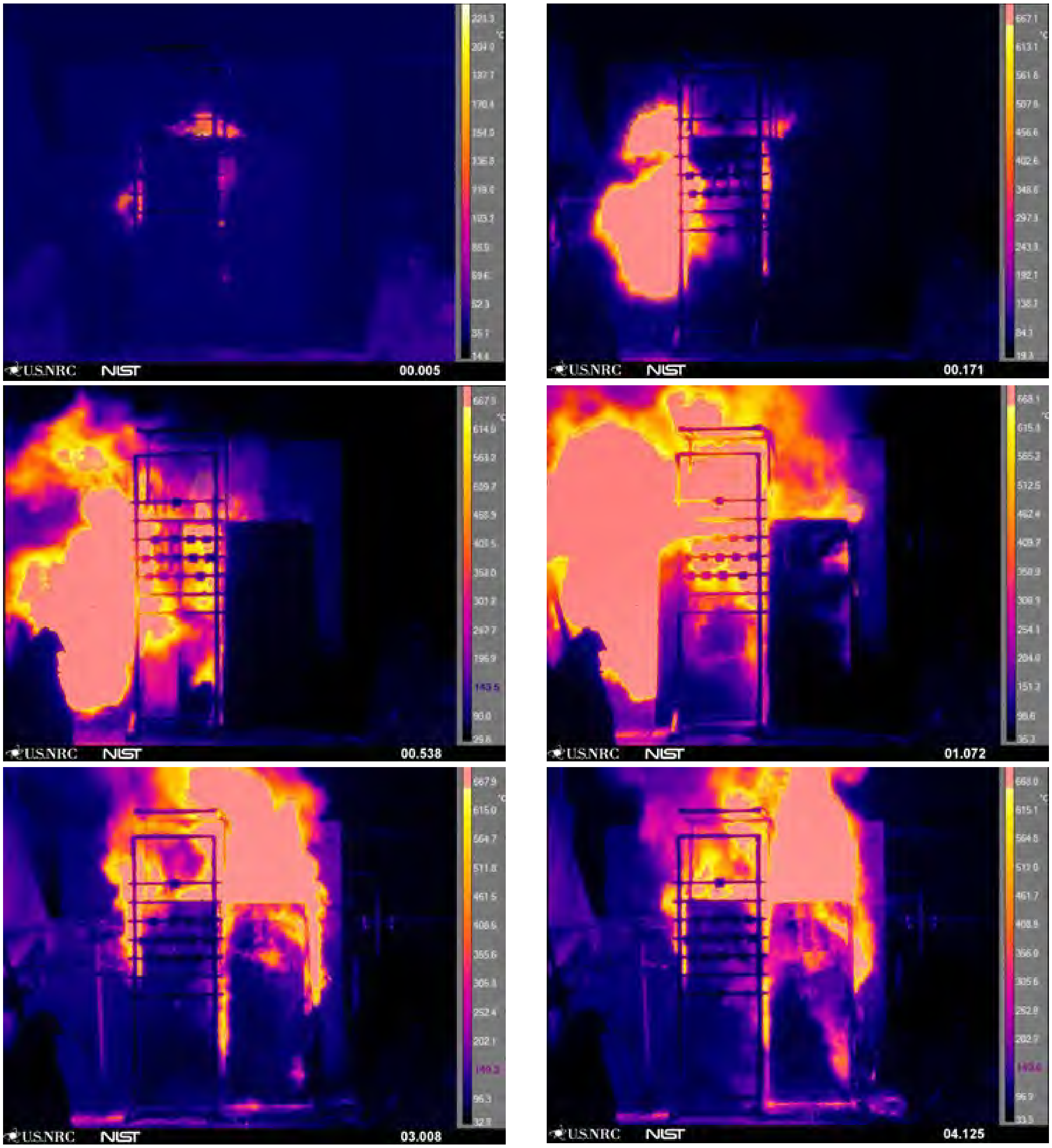

Fig. 48. Sequence of Thermal Images from Experiment 2-35 (image time stamp in seconds).

Photographs of Enclosure "O" and "P" following the experiment is presented in Fig. 49. Enclosure "P" experienced a breach on the inner left panel and openings were created in the upper portion of the enclosure. The total estimated mass loss was approximately 1 938.0 g. Significant heat damage also occurred on the side of Enclosure "P", but no external enclosure burn-through. Detailed photos presented in Appendix D.

Fig. 49. Enclosure Post-Experiment 2-35 (Left – front view with Rack #1 in front of Enclosure "O", Right – side of Enclosure "P").

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 50. The total mass loss of the copper bus bars located in Enclosure "O" was approximately 54.0 g and the total mass loss of the aluminum bus bar located in Enclosure "P" was approximately 2 559.5 g.

Fig. 50. Photo of Experiment 2-31 bus bars post-experiment (arc location shown right).

3.4.2. Measurements

Measurements made during Experiment 2-35 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.4.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-35. These include PT measurements in Table 28, ASTM Slug Calorimeter measurements in Table 29, and T_{cap} slug measurements in Table 30. The maximum temperature exceeded the fiber optic sensor range. Table 31 presents the fiber optic sensor data. Note that there was continuous fire growth during this experiment.

Table 28. Summary of plate thermometer measurements Experiment 2-35.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
1	1	Top	163	43	180
1	3	Mid-Right	79	37	140
1	5	Mid-Center	93	30	120
1	7	Mid-Left	184	49	180
1	9	Bottom	113	23	90
2	10	Top	54	21	90
2	12	Mid-Right	148	29	110
2	14	Mid-Center	71	15	54
2	16	Mid-Left	31	9	32
2	18	Bottom	43	9	33

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
3	19	Top	132	43	230
3	21	Mid-Right	**1 906**	**279**	**1 095**
3	23	Mid-Center	928	183	710
3	25	Mid-Left	348	115	440
3	27	Bottom	181	72	340

Table 29. Summary of ASTM slug calorimeter measurements, Experiment 2-35.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder Type
1	A	Top	150.6	13.4	AG
1	B	Bottom	131.7	12.9	Pb-Sn
2	C	Top	177.0	7.0	AG
2	D	Bottom	36.7	6.8	AG
3	E	Top	511.5	38.6	AG
3	F	Bottom	**531.9**	19.3	Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 30. Summary of T_{cap} slug measurements, Experiment 2-35.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	42.7	130.9	427.9
1	4	Mid-Right	34.1	108.5	481.8
1	6	Mid-Left	41.8	116.0	329.5
1	8	Bottom	37.3	108.0	383.5
2	11	Top	16.3	46.9	175.8
2	13	Mid-Right	21.5	61.3	163.6
2	15	Mid-Left	11.1	31.4	184.6
2	17	Bottom	27.1	63.2	167.7
3	20	Top	103.1	316.7	1 545.7
3	22	Mid-Right	**203.6**	**664.4**	**2 245.0**
3	24	Mid-Left	170.1	436.9	1521.8
3	26	Bottom	175.0	538.9	2 028.3

Table 31. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-35.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)	Notes
61	O	10	>200.0	6	Exceeded device range
62	P	10	172.2	196	

3.4.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 51. After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear enclosure was approximately 11.0 kPa (1.6 psi) above ambient at its peak. PT-1 was in Enclosure “O”, while PT-2 was in Enclosure “P.” Both pressure sensors were located in the breaker compartment approximately 1.2 m (3.8 ft) above the enclosure floor and 20 cm (8 in) from the front door surface. See Appendix A for more information on pressure sensor location.

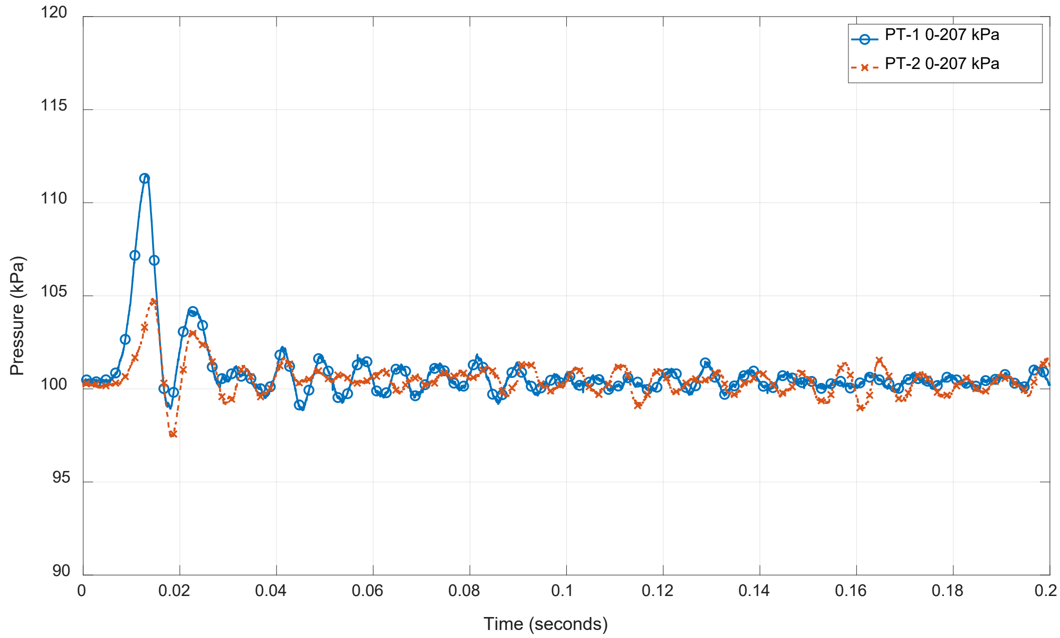

Fig. 51. Pressure measurements from Experiment 2-35. Measurement uncertainty ± 3 percent.

3.4.2.3. Electrical Measurements

Experiment 2-35 used KEMA circuit S02 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230809-9003. Key experimental measurements are presented in Table 32. Plots of the electrical measurements are presented in Appendix B.

Table 32. Key measurements from Experiment 2-35. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	48.2	55.4	-65.1
Current, AC component, beginning	kA_{RMS}	25.9	26.5	25.7
Current, AC component, middle	kA_{RMS}	24.2	24.9	24.3
Current, AC component, end	kA_{RMS}	23.5	23.3	23.3
Current, AC component, average	kA_{RMS}	24.6	24.9	24.4
Current, AC component, three-phase average	kA_{RMS}		24.6	
Duration	s	4.12	4.12	4.12
Arc Energy	MJ		83.1	

3.5. Experiment 2-36 – 6.9 KV, 32 kA, 4 s Duration, Copper Bus, Steel Enclosure

Experiment 2-36 was performed on August 11, 2023, at 10:50 AM eastern daylight time (EDT). The temperature was approximately 25 °C (77 °F), the relative humidity was approximately 66 percent, and the atmospheric pressure was approximately 100.2 kPa. The weather was fair with a wind of approximately 5 km/h (3 mi/h) out of the west.

This experiment used two medium-voltage (MV) electrical enclosures in series. Enclosure “H” was donated to the program as part of the contributions from one of the member countries and the other Enclosure “N” was procured. Both enclosures were connected to each other physically and electrically. Enclosure “H” was provided with partial copper bus work, the main bus bars were missing. Cylindrical copper bus was therefore procured and fit to Enclosure “H” and also extended into Enclosure “N” to allow an electrical connection to that enclosure. The arc was initiated in Enclosure “H” at the lowest point on the vertical runbacks to the breaker. The arcing wire was installed between all three phases, and marked-up illustrations of the arc wire location is presented in Fig. 52.

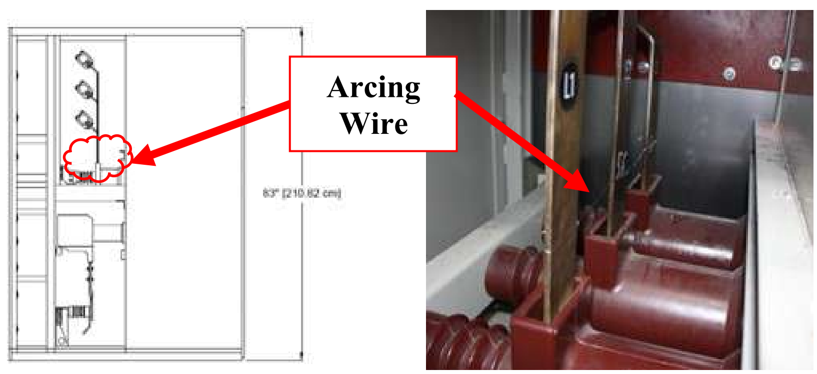

Fig. 52. Experiment 2-36 configuration. Left – drawing of internal bus work showing location of arc initiation inside Enclosure “H”, Right – photo of arcing wire (#24 AWG) installed.

3.5.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 33 and include an approximate time reference. Corresponding images are provided in Fig. 53, with thermography images presented in Fig. 54.

This was the third electrical switchgear enclosure experiment of the series. The arc was stabilized in the main bus section, and from post-experiment inspection, it appeared that the runbacks were completely vaporized on both the A and B phases, while the C phase runback was partially vaporized. Once the A and B phase runbacks were exhausted the arc appeared to have migrated to the main bus bars in Enclosure H. The arc lasted for the expected duration (4.1 s).

Table 33. Observations from Experiment 2-36.

Time (ms)	Observation
0	Initial light observed
133	Particle ejecta observed at top instrumentation rack
1 000	Plume reaches cell crane
2 118	Arcing starts in right enclosure; intermittent arcing subsequently occurs in both enclosures.
3 086	Enclosures fully involved
4 120	End of arc

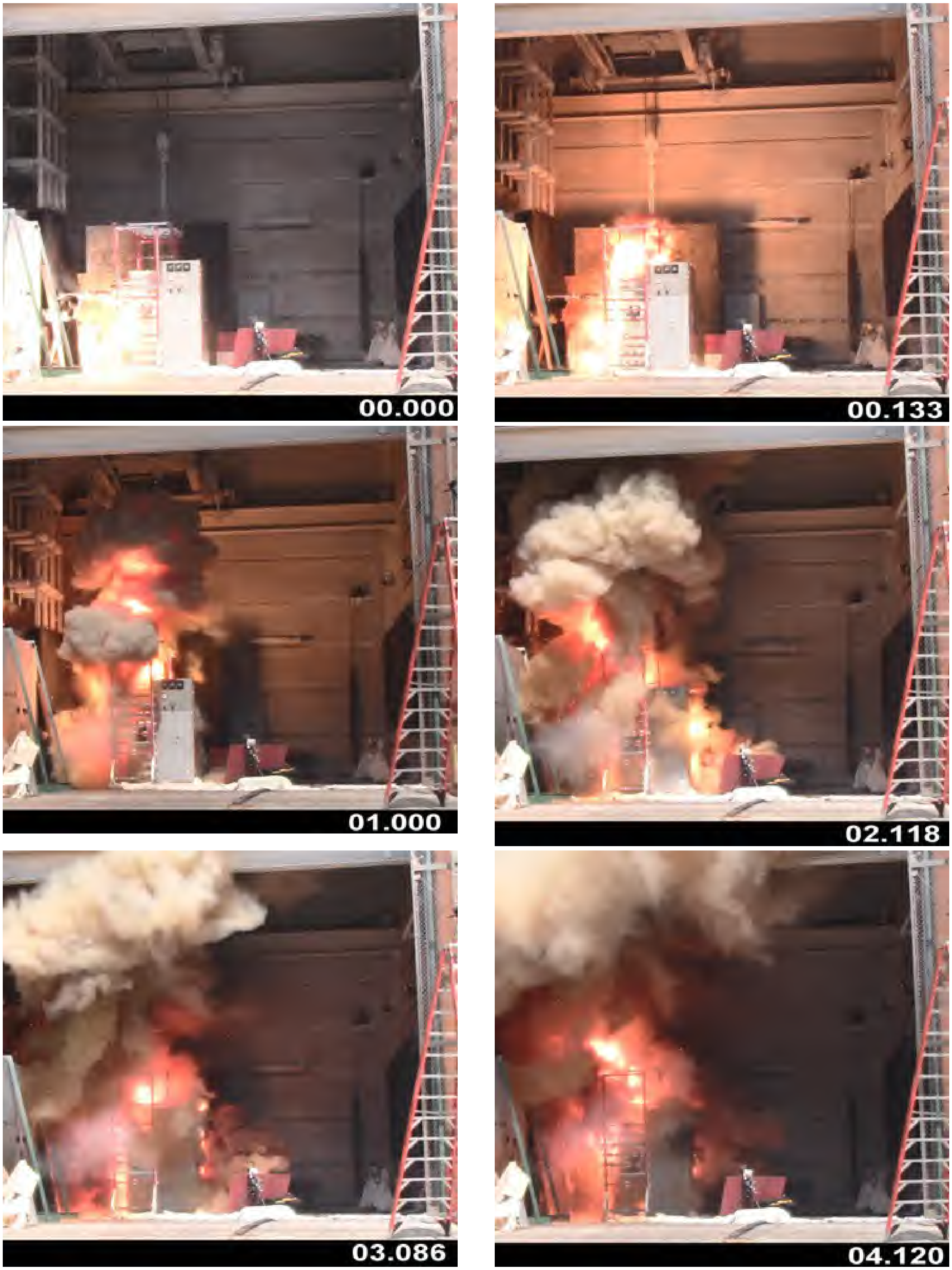

Fig. 53. Sequence of Images from Experiment 2-36 (image time stamps are in seconds).

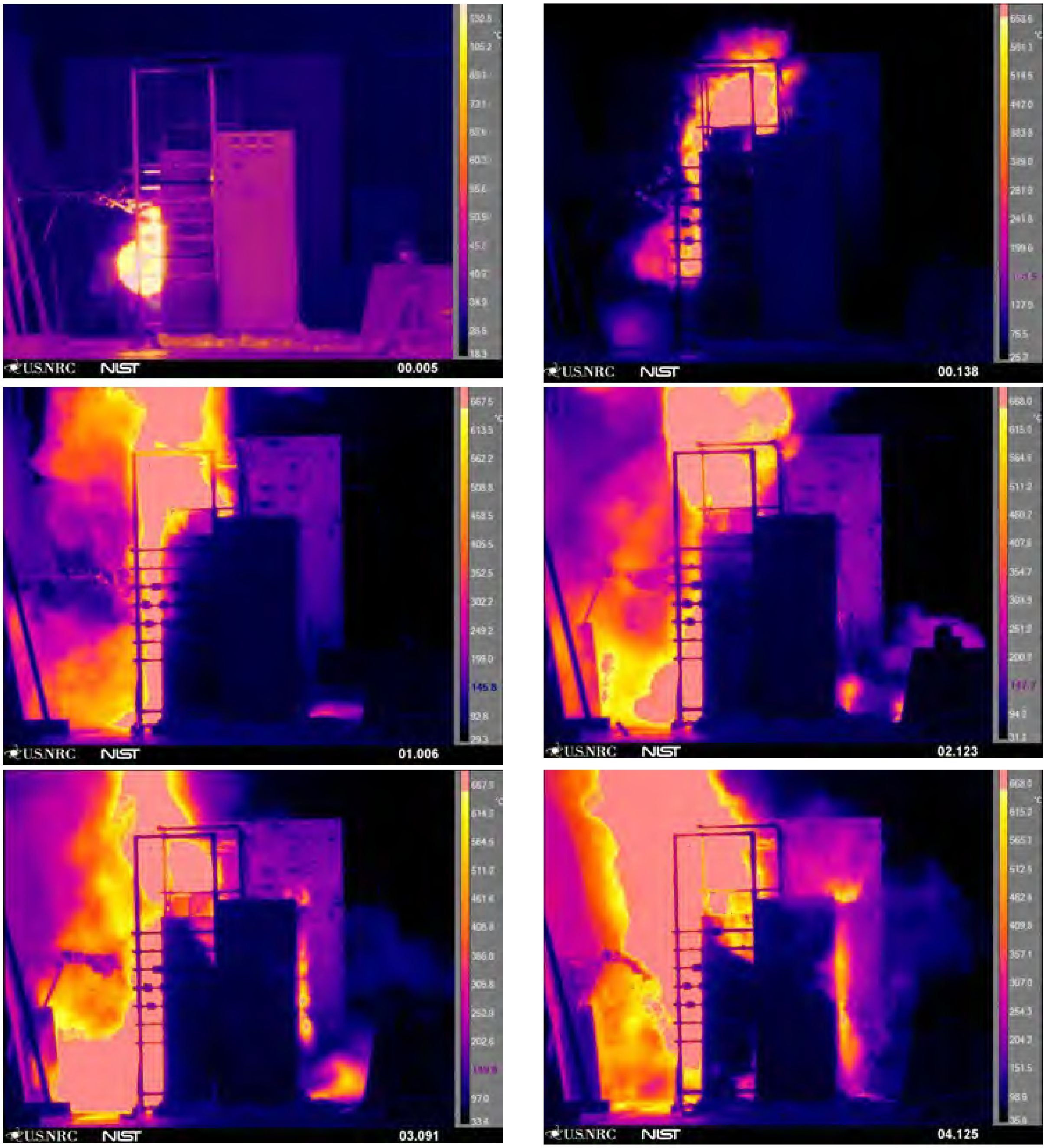

Fig. 54. Sequence of Thermal Images from Experiment 2-36 (image time stamp in seconds).

Photograph of the enclosure following the experiment is presented in Fig. 55. The enclosure experienced a breach at two locations. On the side, the phenolic panel was separated from the switchgear. Note that the panel movement was limited due to the incoming power supply bus configuration. On the top, two adjacent panels were deformed, but still connected to the top of the enclosure. There were numerous arc-induced-breaches to the internal structure of the enclosures. The total mass loss from the steel enclosures is approximately 5 821.5 g. Additional detailed information can be found in Appendices C and D.

Fig. 55. Enclosure Post-Experiment 2-36. Note, the phenolic panel was separated from the switchgear side, and two adjacent top panels were deformed but remained attached.

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 56. The total mass loss of the bus bars was 4 842 g.

Fig. 56. Photo of Experiment 2-36 bus bars. Top – pre-experiment, Bottom – post-experiment.

3.5.2. Measurements

Measurements made during Experiment 2-36 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.5.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-36. These include PT measurements in Table 34, ASTM Slug Calorimeter measurements in Table 35, and T_{cap} slug measurements in Table 36. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 70 °C. Table 37 presents the fiber optic sensor data. Note that there was fire growth late in the experiment.

Table 34. Summary of plate thermometer measurements, Experiment 2-36.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 15 %
1	1	Top	83	46	170
1	3	Mid-Right	29	16	59
1	5	Mid-Center	42	27	100
1	7	Mid-Left	358	61	230
1	9	Bottom	32	19	70
2	10	Top	162	93	350
2	12	Mid-Right	526	217	830
2	14	Mid-Center	309	85	320
2	16	Mid-Left	87	48	180
2	18	Bottom	133	68	270
3	19	Top	155	99	390
3	21	Mid-Right	347	145	570
3	23	Mid-Center	**1 405**	461	1 760
3	25	Mid-Left	1 082	**599**	**2 380**
3	27	Bottom	585	245	940

Table 35. Summary of ASTM slug calorimeter measurements, Experiment 2-36.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m²) Greater of ± 18 kJ/m² or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment	Solder Type
1	A	Top	117.3	5.2		AG
1	B	Bottom	131.7	6.5		AG
2	C	Top	575.1	3.8		AG
2	D	Bottom	- - -	- - -	Non-functional prior to experiment	AG
3	E	Top	850.8	6.9		AG
3	F	Bottom	**2 431.9**	5.2		Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 36. Summary of T_{cap} slug measurements, Experiment 2-36.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	36.2	144.6	184.8
1	4	Mid-Right	22.8	88.0	115.0
1	6	Mid-Left	33.6	123.8	185.9
1	8	Bottom	24.7	87.1	129.1
2	11	Top	96.2	332.1	582.5
2	13	Mid-Right	133.2	439.8	657.1
2	15	Mid-Left	50.7	168.4	495.1
2	17	Bottom	84.3	299.9	519.4
3	20	Top	259.9	932.1	1 925.0
3	22	Mid-Right	186.2	813.6	2 145.2
3	24	Mid-Left	**494.1**	**1 512.0**	**3 460.1**
3	26	Bottom	297.8	1 275.6	3 120.9

Table 37. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-36.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)
61	H	28	**69.6**	1 342
62	N	35	40.8	1 339

3.5.2.2. Pressure Measurements

The pressure profiles for the first five seconds are shown in Fig. 57. PT-1 was mounted to the top panel of Enclosure “H” which was displaced due to the enclosure overpressure. This caused some abnormal readings on the transducer and were not likely the true pressure measurements. Any use of the PT-1 data should be used with caution. Pressure measurements during the first 0.02 s may be accurate, however, because of the damage, the accuracy of the PT-1 measurement cannot be confirmed. Data for PT-1 is included for reference. PT-2 was mounted to the top of Enclosure “N.” After the initial pressure spike, the pressure for PT-2 continued to be variable until approximately 1.5 seconds. At this point higher pressure spikes were observed. The maximum change in pressure in Enclosure “N” for PT-2 was approximately 13.5 kPa (2.0 psi) above ambient at its peak.

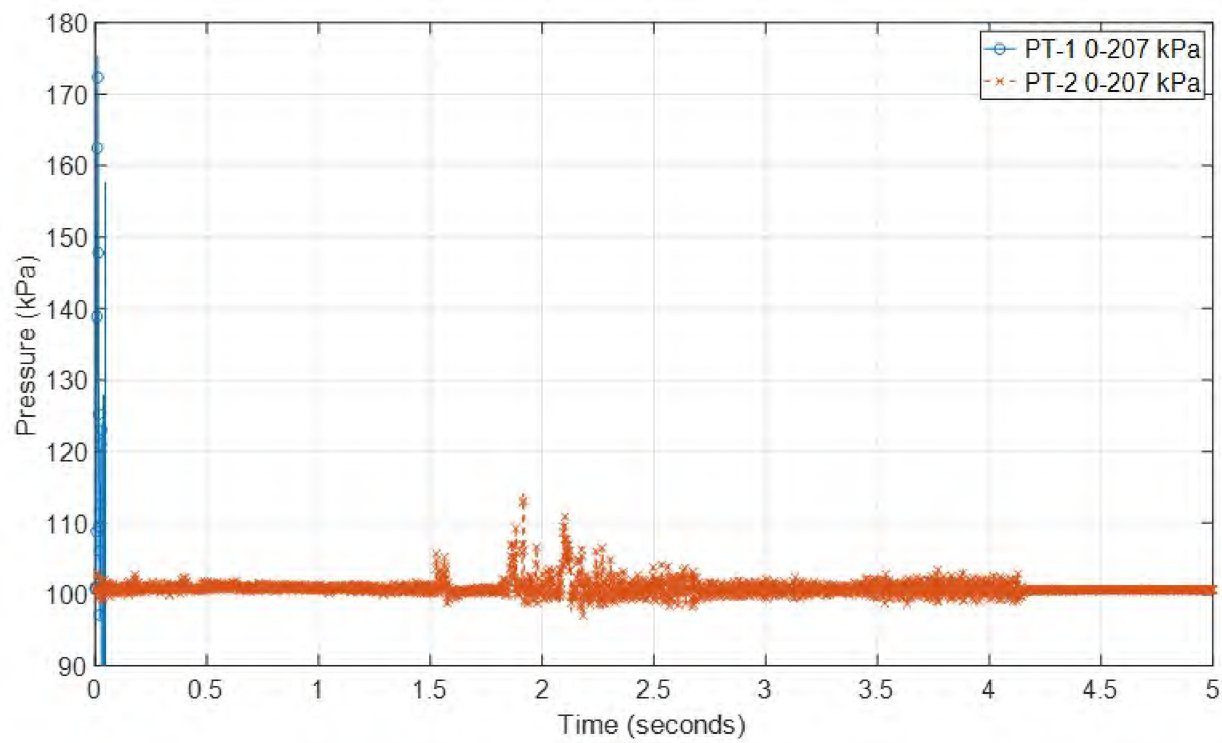

Fig. 57. Pressure measurements from Experiment 2-36. Measurement uncertainty ± 3 percent. Note that pressure probe “PT-1” and its cable were physically damaged during the experiment, and PT-1 data after approximately 0.023 s is not valid.

3.5.2.3. Electrical Measurements

Experiment 2-36 used KEMA circuit S02 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230811-9001. Key experimental measurements are presented in Table 38. Plots of the electrical measurements are presented in Appendix B.

Table 38. Key measurements from Experiment 2-36. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	49.6	52.4	-64.4
Current, AC component, beginning	kA_{RMS}	26.2	26.2	25.8
Current, AC component, middle	kA_{RMS}	23.9	24.4	23.4
Current, AC component, end	kA_{RMS}	22.9	22.9	23.1
Current, AC component, average	kA_{RMS}	24.5	24.6	24.1
Current, AC component, three-phase average	kA_{RMS}		24.4	
Duration	s	4.13	4.13	4.13
Arc Energy	MJ		74.9	

3.6. Experiment 2-37 – 6.9 KV, 25 kA, 4 s Duration, Copper Bus, Steel Enclosure

Experiment 2-37 was performed on August 10, 2023, at 11:15 AM eastern daylight time (EDT). The temperature was approximately 25 °C (77 °F), the relative humidity was approximately 76 percent, and the atmospheric pressure was approximately 100.7 kPa. The weather included rain showers with a wind of approximately 5 km/h (3 mi/h) out of the south.

This experiment used two medium-voltage (MV) electrical enclosures. Both enclosures were of a horizontal draw-out design (ITE Type HK). Both enclosures contained copper bus and were connected to the power supply via main bus extensions outside of Enclosure “J”. The arc wire was located on the breaker stab in Enclosure “J”. The arcing wire was installed between all three phases, and marked-up illustrations of the arc wire location is presented in Fig. 58. Fig. 59 shows the experimental setup. Three instrumentation racks were used and surrounded Enclosure “J”.

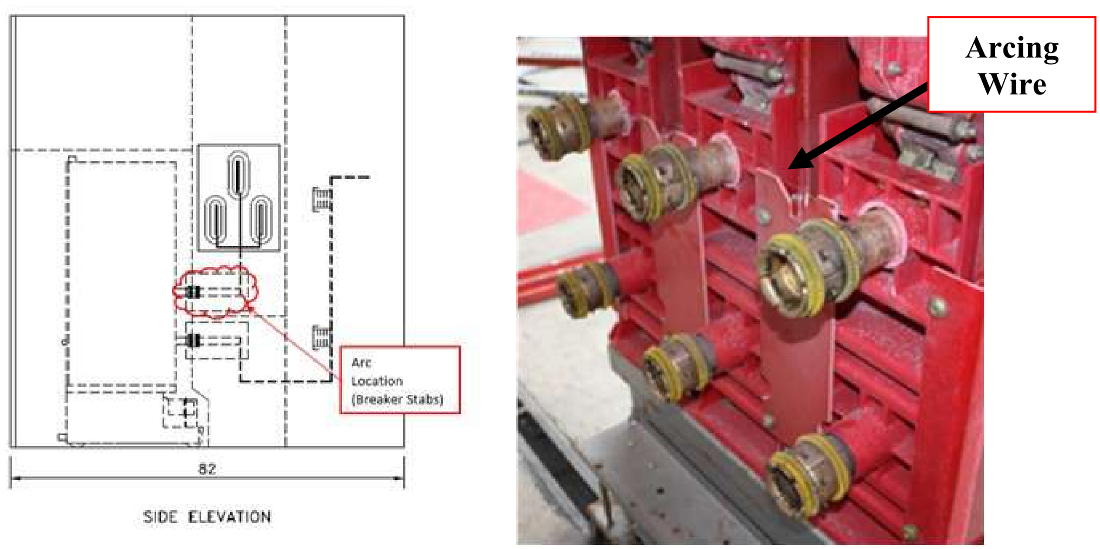

Fig. 58. Experiment 2-37 configuration. Left – drawing of internal bus work showing location of arc initiation inside Enclosure “J”, Right – photo of arcing wire (#24 AWG) installed.

Fig. 59. Pre-experimental setup for experiment 2-37. Left – Front of switchgear showing Enclosure "J" left where arc was initiated on breaker stabs and Enclosure "I" to the right, Right– rear angle view showing general experimental configuration with Enclosure "I" to the left.

3.6.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 39 and include an approximate time reference. Corresponding images are provided in Fig. 61, with thermography images presented in Fig. 62.

This was the second switchgear experiment and first with all copper bus. Approximately 33 ms after arc ignition the front door of the Enclosure "J" switchgear unit detached from the enclosure and subsequently struck the instrumentation rack located 94 cm (37 in) in front of the door (see Fig. 60). The velocity of the 31.5 kg (69 lb.) door was approximately 14 m/s (46 ft/s). The door strike on the instrument rack caused the instrumentation rack to skid away from its initial location and subsequently fall to the ground. The measurements from Rack #1 do not accurately reflect the exposure at the planned 0.9 m (3 ft) and are not reported. The nearest part of the instrument rack foot was located approximately 4.9 m (16 ft) from the enclosure front and the farthest point of the instrument rack was approximately 7.9 m (26 ft) from the enclosure face. No visible cable damage was observed on any cable coupon on the instrument racks. Fire suppression agent was applied. The arc lasted for the expected duration (4.11 s).

Fig. 60. Post-Experiment photo of Experiment 2-37 showing resting place of Enclosure “J” front door and breaker front cover.

Table 39. Observations from Experiment 2-37.

Time (ms)	Observation
0	Initial light observed
33	Door detached from frame of enclosure
83	Door impacts instrumentation rack
1 251	Door lands on ground and instrumentation rack continues to fall due to impact
3 420	Breach of right enclosure side
4 120	End of arc

Fig. 61. Sequence of Images from Experiment 2-37 (image time stamps are in seconds).

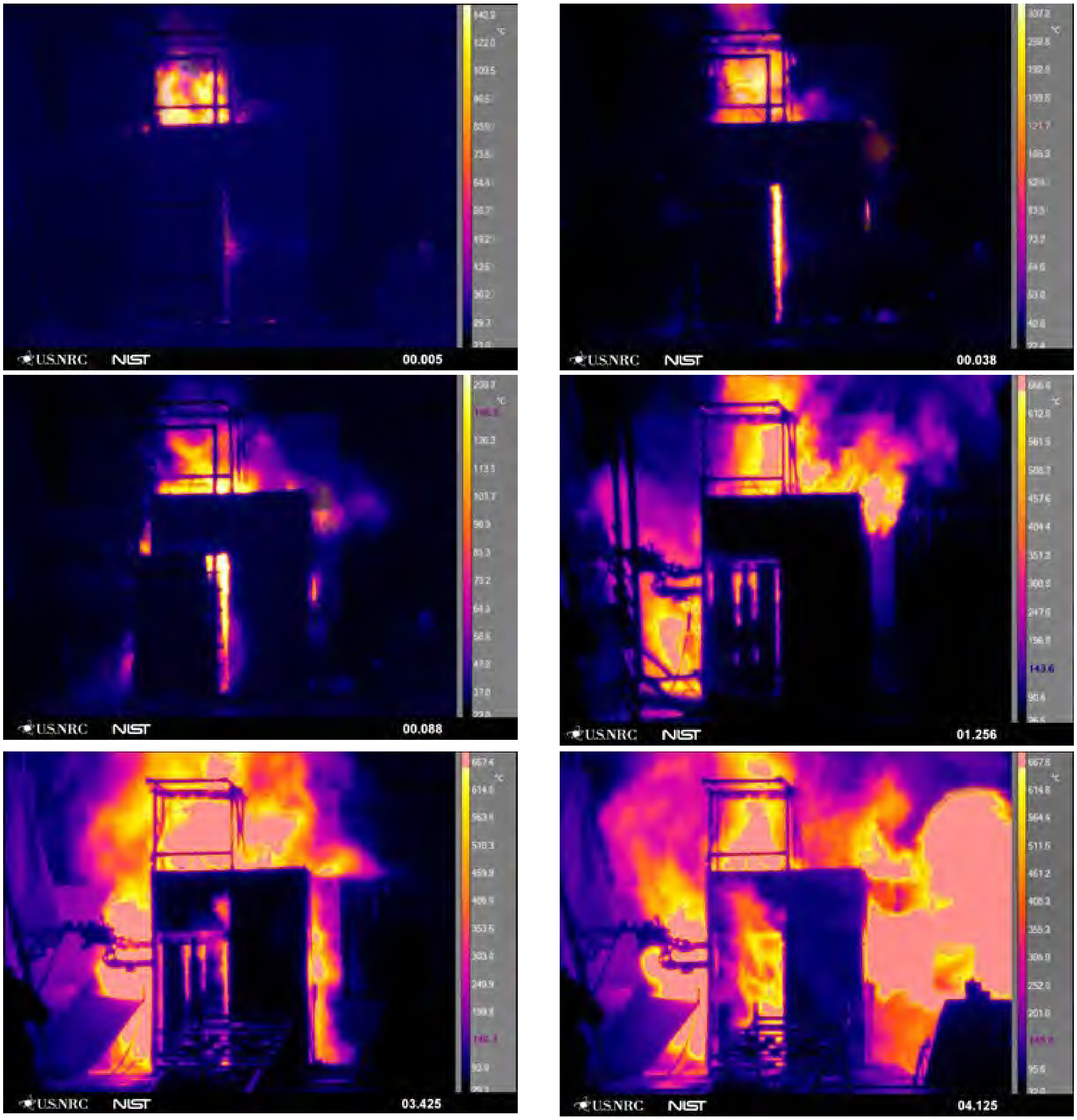

Fig. 62. Sequence of Thermal Images from Experiment 2-37 (image time stamp in seconds).

Photographs of the enclosures following the experiment is presented in Fig. 63. The enclosures did not experience a breach due to arc burn-through. However, three openings did occur: 1.) door on Enclosure “J” was blown off, 2.) side cover of Enclosure “I” near main bus compartment was blown off, and 3.) the two rear panels of Enclosure “J” bowed, and several fastener failures occurred causing a gap of no less than approximately 10 cm (4 in).

Fig. 63. Enclosure Post-Experiment 2-37. Door of Enclosure “J” was blown off, side panel of Enclosure “I” was blown off, and both rear panels were bowed.

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 64. The total mass loss of the bus bars was approximately 2 804.0g. Additional details are presented in Appendix C and D.

Fig. 64. Photo of Experiment 2-37 bus bars post-experiment.

3.6.2. Measurements

Measurements made during Experiment 2-37 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.6.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-37. These include PT measurements in Table 40, ASTM Slug Calorimeter measurements in Table 41 and T_{cap} slug measurements in Table 42. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 35 °C. Table 43 presents the maximum temperatures and time for the fiber optic sensors. Note there was continuous fire growth during this experiment.

Table 40. Summary of plate thermometer measurements, Experiment 2-37.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
1	1	Top	- - -	- - -	- - -
1	3	Mid-Right	- - -	- - -	- - -
1	5	Mid-Center	- - -	- - -	- - -
1	7	Mid-Left	- - -	- - -	- - -
1	9	Bottom	- - -	- - -	- - -
2	10	Top	178	77	300
2	12	Mid-Right	322	157	610
2	14	Mid-Center	322	121	460
2	16	Mid-Left	256	76	300

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
2	18	Bottom	**416**	**181**	**690**
3	19	Top	117	64	350
3	21	Mid-Right	69	34	150
3	23	Mid-Center	86	49	200
3	25	Mid-Left	98	31	150
3	27	Bottom	55	13	110

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned.

Table 41. Summary of ASTM slug calorimeter measurements, Experiment 2-37.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment	Solder Type
1	A	Top	- - -	- - -	Rack displaced	AG
1	B	Bottom	- - -	- - -	Rack displaced	Pb-Sn
2	C	Top	499.4	8.2		AG
2	D	Bottom	**510.8**	7.4		Pb-Sn
3	E	Top	342.8	1.8		AG
3	F	Bottom	179.5	9.8		AG

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned. AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 42. Summary of T_{cap} slug measurements, Experiment 2-37.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	- - -	- - -	- - -
1	4	Mid-Right	- - -	- - -	- - -
1	6	Mid-Left	- - -	- - -	- - -
1	8	Bottom	- - -	- - -	- - -
2	11	Top	161.6	364.4	716.8
2	13	Mid-Right	161.6	380.8	784.3
2	15	Mid-Left	119.1	289.3	715.1
2	17	Bottom	**226.0**	**542.9**	**866.8**
3	20	Top	75.0	171.4	786.0
3	22	Mid-Right	67.1	182.1	730.5
3	24	Mid-Left	69.5	168.3	728.0
3	26	Bottom	52.5	129.3	646.4

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned.

Table 43. Maximum temperatures from fiber optic sensors inside enclosure for experiment 2-37.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)
61	J	35	**34.9**	936
62	I	35	32.8	942

3.6.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 39. PT-1 was located in Enclosure "J" where the arc was initiated, while PT-2 was located in Enclosure "I". After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear enclosure was approximately 42.6 kPa (3.3 psi) above ambient at its peak.

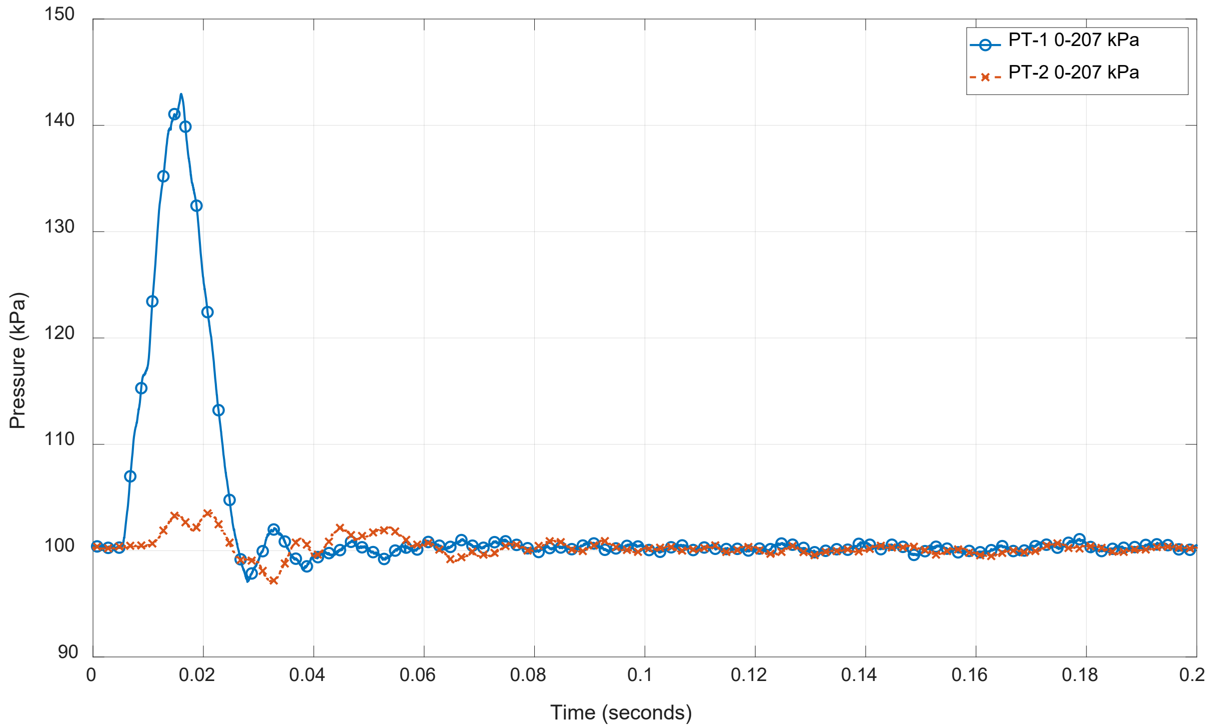

Fig. 65. Pressure measurements from Experiment 2-37. Measurement uncertainty ± 3 percent.

3.6.2.3. Electrical Measurements

Experiment 2-37 used KEMA circuit S02 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230810-9001. Key experimental measurements are presented in Table 44. Plots of the electrical measurements are presented in Appendix B.

Table 44. Key measurements from Experiment 2-37. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	42.9	50.6	-57.3
Current, AC component, beginning	kA_{RMS}	25.8	25.6	25.6
Current, AC component, middle	kA_{RMS}	23.7	24.1	23.7
Current, AC component, end	kA_{RMS}	22.7	22.3	22.4
Current, AC component, average	kA_{RMS}	24.0	24.4	24.0
Current, AC component, three-phase average	kA_{RMS}		24.1	
Duration	s	4.11	4.11	4.11
Arc Energy	MJ		93.3	

3.7. Experiment 2-38 – 6.9 KV, 25 kA, 4 s Duration, Copper Bus, Steel Enclosure

Experiment 2-38 was performed on August 14, 2023, at 1:45 PM eastern daylight time (EDT). The temperature was approximately 29 °C (85 °F), the relative humidity was approximately 62 percent, and the atmospheric pressure was approximately 100.7 kPa. The weather was fair with a variable wind of approximately 11 km/h (7 mi/h).

This experiment used four medium-voltage (MV) electrical enclosures. All enclosures were of a horizontal draw-out design (ITE Type HK). One switchgear lineup was energized and consisted of Enclosure “K” with copper bus and a second enclosure, Enclosure “L” containing aluminum bus. The arc wire was installed on the main bus between all three phases on the copper section of the energized bus inside Enclosure “K”. A marked-up illustration of the arc wire location is presented in Fig. 66. A second switchgear lineup was located approximately 1.0 m (3.3 ft) in front of the energized switchgear lineup. This second switchgear lineup consisted of Enclosures “I” and “M” and was not connected to a power source. Enclosure “I” was previously used in experiment 2-37. This configuration was referred to as “cross-aisle” (see Fig. 5).

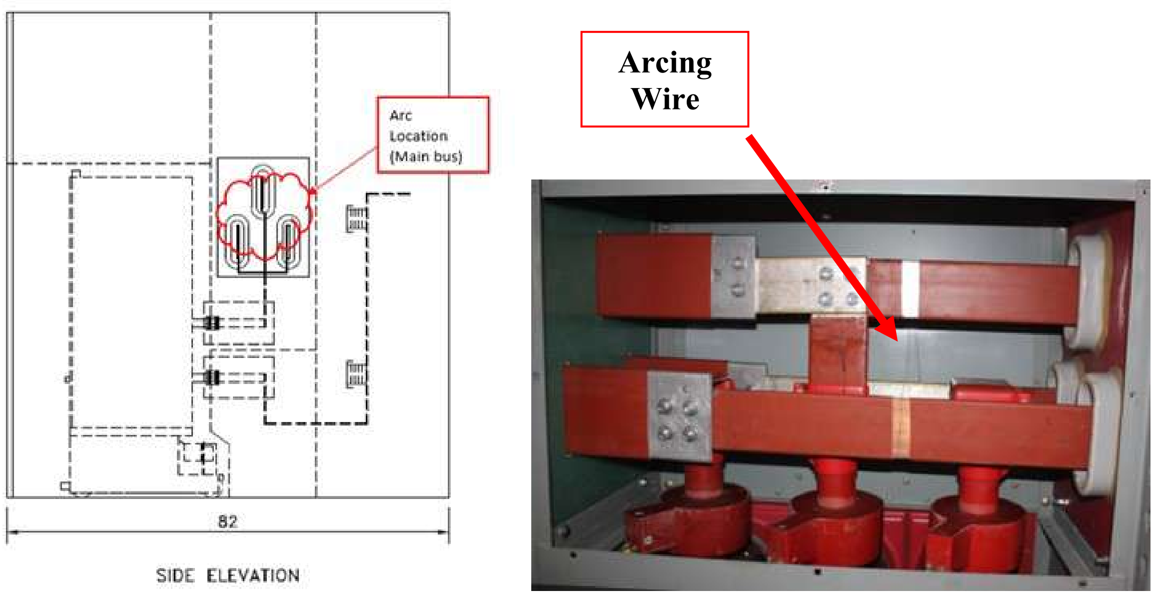

Fig. 66. Experiment 2-38 configuration. Left – drawing of internal bus work showing location of arc initiation for Enclosure “K”, Right – photo of arcing wire (#24 AWG) installed in Enclosure “K”.

3.7.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 45 and include an approximate time reference. Corresponding images are provided in Fig. 67, with thermography images presented in Fig. 68.

Table 45. Observations from Experiment 2-38.

Time (ms)	Observation
0	Initial light observed
100	Particle ejecta observed at top and rear instrumentation racks
1 251	Arcing observed in adjacent enclosure
2 017	Arcing continues in adjacent enclosure
2 969	Arc jet transitions to bottom of enclosure
4 120	End of arc

Fig. 67. Sequence of Images from Experiment 2-38 (image time stamps are in seconds).

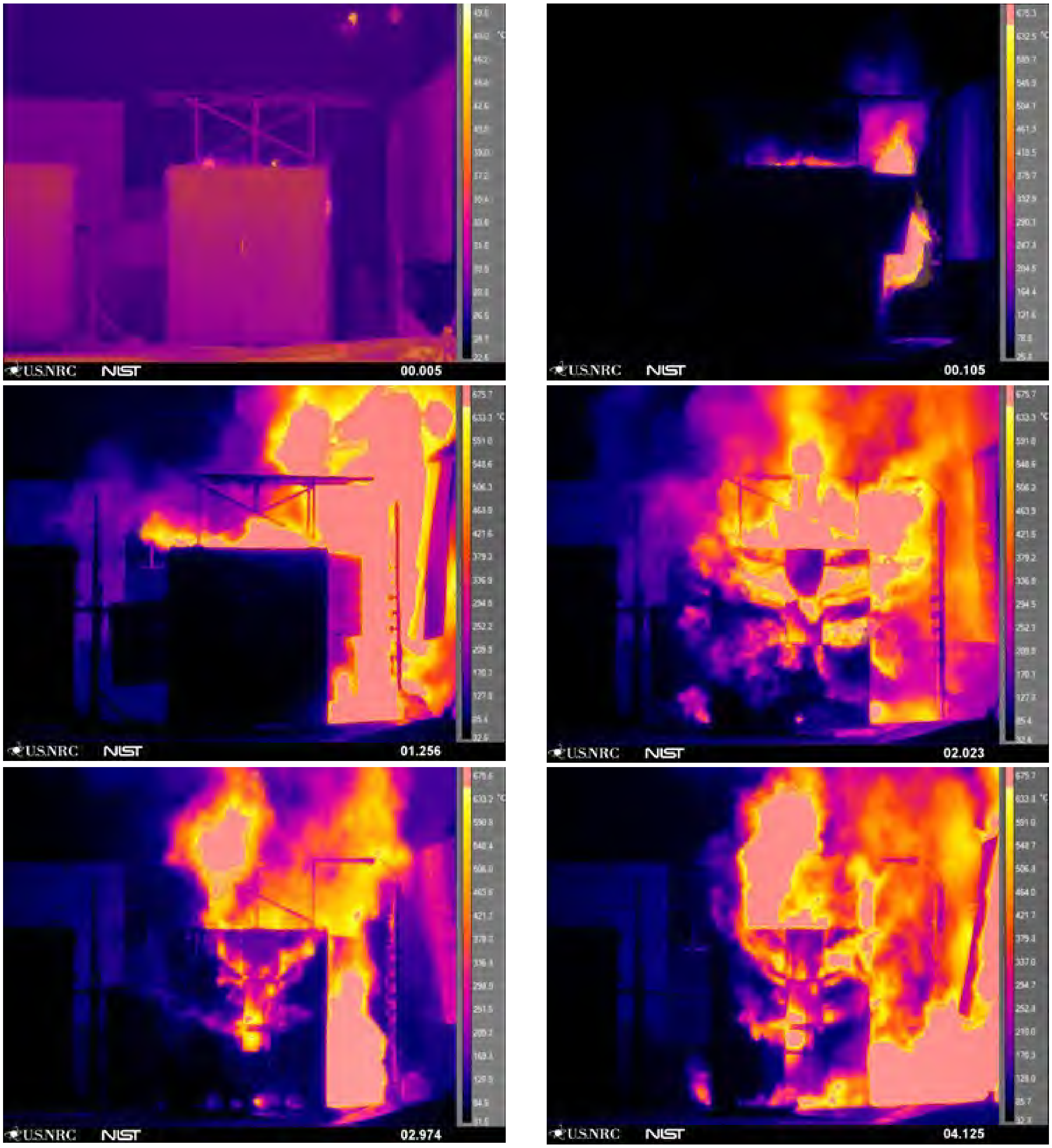

Fig. 68. Sequence of Thermal Images from Experiment 2-38 (image time stamp in seconds).

A photograph of the enclosures following the experiment is presented in Fig. 69. The enclosure did not experience a breach through external panels due to thermal damage, but did experience internal breaches between compartments. The internal breach area was minimal, and the total mass loss was approximately 81.7 g. During the experiment two rear panel covers became unsecured on one side. Internal panels enclosing main bus compartment were found laying on the ground outside of the enclosure. One panel was laying next to the enclosure (at rear), while the second panel was approximately 3 m (10 ft) from the rear corner of the enclosure. Each internal panel of enclosure "K" weighted approximately 8 kg (17.5 lbs).

Fig. 69. Enclosure Post-Experiment 2-38. Enclosure "K" is in the foreground attached to the laboratories power supply, Enclosure "I" is across the aisle from "K".

An image of the bus bars removed from the enclosure after the experiment is shown in Fig. 70. The total mass loss of the bus bars was approximately 1 797.5 g. Additional details are presented in Appendices C and D.

Fig. 70. Photo of Experiment 2-38 bus bars post-experiment (initial arc location shown by arrow).

3.7.2. Measurements

Measurements made during Experiment 2-38 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.7.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-38. These include PT measurements in Table 46, ASTM Slug Calorimeter measurements in Table 47, and T_{cap} slug measurements in Table 48. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 43 °C. Table 49 presents the maximum temperatures and time for the fiber optic sensors. Note that there was fire growth during this experiment.

Table 46. Summary of plate thermometer measurements, Experiment 2-38.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
1	1	Top	228	89	330
1	3	Mid-Right	**844**	**175**	**660**
1	5	Mid-Center	204	63	230
1	7	Mid-Left	114	51	190
1	9	Bottom	177	65	250
2	10	Top	12	4	18
2	12	Mid-Right	6	2	6
2	14	Mid-Center	12	2	7
2	16	Mid-Left	14	4	13

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 15 %
2	18	Bottom	4	1	5
3	19	Top	232	88	330
3	21	Mid-Right	535	150	560
3	23	Mid-Center	135	54	210
3	25	Mid-Left	136	43	160
3	27	Bottom	77	31	120

Table 47. Summary of ASTM slug calorimeter measurements, Experiment 2-38.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m²) Greater of ± 18 kJ/m² or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder Type
1	A	Top	**468.4**	4.1	AG
1	B	Bottom	234.1	6.8	Pb-Sn
2	C	Top	15.0	354.2	AG
2	D	Bottom	9.2	5.0	Pb-Sn
3	E	Top	312.5	9.9	AG
3	F	Bottom	197.8	11.9	Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 48. Summary of T_{cap} slug measurements, Experiment 2-38.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	56.5	191.1	558.5
1	4	Mid-Right	132.9	**432.5**	674.0
1	6	Mid-Left	51.0	188.3	571.0
1	8	Bottom	81.1	263.6	571.4
2	11	Top	4.0	10.0	27.0
2	13	Mid-Right	2.3	6.0	27.4
2	15	Mid-Left	3.3	8.8	24.3
2	17	Bottom	1.6	5.5	24.1
3	20	Top	83.8	242.2	648.7
3	22	Mid-Right	**137.0**	335.2	**744.7**
3	24	Mid-Left	69.2	213.4	609.0
3	26	Bottom	63.5	192.4	636.5

Table 49. Maximum temperatures from fiber optic sensors inside enclosure for Experiment 2-38.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)	Notes
61	K	36	35.0	660	End of experiment
62	L	35	**42.9**	660	End of experiment
63	M	36	33.0	660	End of experiment
64	I	35	30.5	660	End of experiment

3.7.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 71. After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear Enclosure “K” was approximately 27 kPa (3.9 psi) above ambient at its peak, while Enclosure “L” was approximately 9 kPa (1.3 psi) above ambient at its peak.

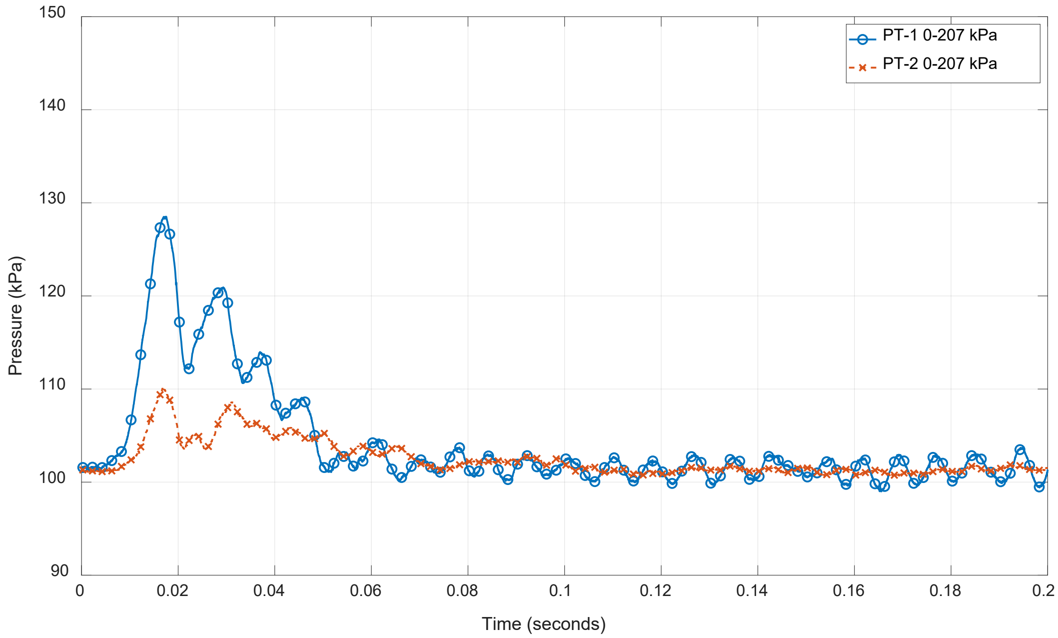

Fig. 71. Pressure measurements from Experiment 2-38. Measurement uncertainty ± 3 percent.

3.7.2.3. Electrical Measurements

Experiment 2-38 used KEMA circuit S02 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230814-9002. Key experimental measurements are presented in Table 50. Plots of the electrical measurements are presented in Appendix B.

Table 50. Key measurements from Experiment 2-38. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.99	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.90	
Making current	kA_{peak}	54.7	51.6	-61.2
Current, AC component, beginning	kA_{RMS}	25.8	26.1	25.6
Current, AC component, middle	kA_{RMS}	23.9	24.1	23.5
Current, AC component, end	kA_{RMS}	22.4	22.9	22.7
Current, AC component, average	kA_{RMS}	24.3	24.4	23.9
Current, AC component, three-phase average	kA_{RMS}		24.2	
Duration	s	4.12	4.12	4.12
Arc Energy	MJ		93.6	

3.8. Experiment 2-39 – 6.9 KV, 25 kA, 4 s Duration, Copper Bus, Steel Enclosure

Experiment 2-39 was performed on August 15, 2023, at 12:40 PM eastern daylight time (EDT). The temperature was approximately 29 °C (84 °F), the relative humidity was approximately 64 percent, and the atmospheric pressure was approximately 100.8 kPa. The weather was mostly cloudy with a wind of approximately 11 km/h (7 mi/h) out of the west.

This experiment used four medium-voltage (MV) electrical enclosures. All enclosures were of a horizontal draw-out design (ITE Type HK). One switchgear lineup was energized and consisted of enclosures “M” and “I” containing aluminum bus. The arc wire was installed on the breaker stabs between all three phases in Enclosure “M”. A marked-up illustration of the arc wire location is presented in Fig. 72. A second switchgear lineup was located behind the energized switchgear lineup with no space between the rear of the enclosures of both lineups. This second switchgear lineup consisted of Enclosures “K” and “L” and was not connected to a power source. Enclosures “K” and “L” were previously used in experiment 2-38. This configuration was referred to as “back-to-back” (see Fig. 6).

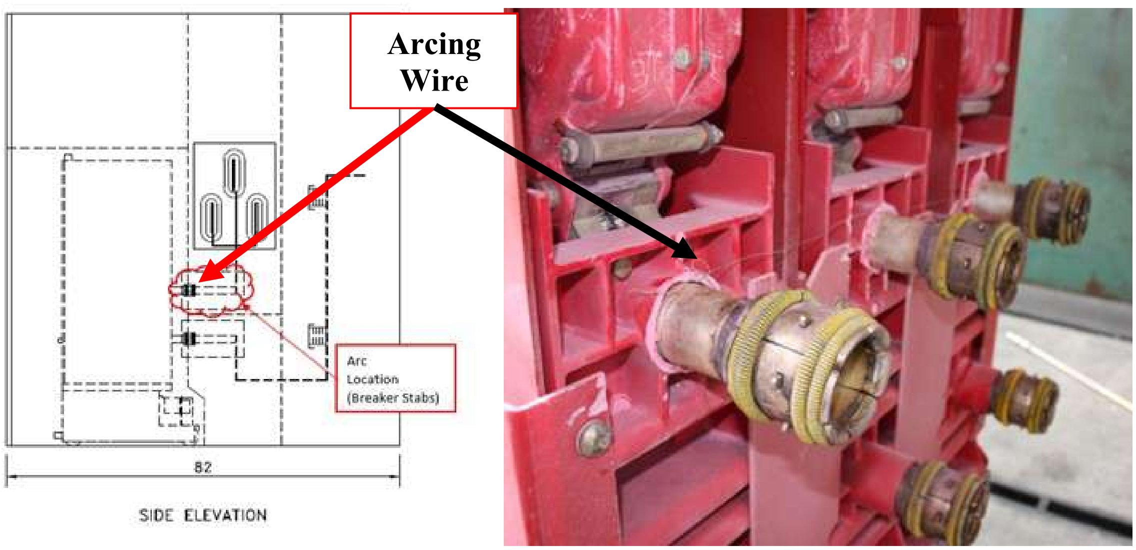

Fig. 72. Experiment 2-39 configuration. Left – drawing of internal bus work showing location of arc initiation in Enclosure “M”, Right – photo of arcing wire (#24 AWG) installed.

3.8.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 51 and include an approximate time reference. Corresponding images are provided in Fig. 73, with thermography images presented in Fig. 74.

This was the second horizontal draw-out type four-unit experiment. This configuration was similar to Experiment 2-37 and performed to understand the consistency of the front door failure observed in the earlier experiment. In Experiment 2-39 instrument Rack #1 was re-positioned to reduce the likelihood of the front door impacting the rack and to observe the distance the door would travel unimpeded by the instrumentation rack. Similar to Experiment 2-37, the door

Time (ms)	Observation
0	Initial light observed
33	Door detaches from frame
100	Door impact instrumentation rack
1 701	Door lands on ground
2 535	Enclosure “I” arcing and flaming
4 120	End of arc

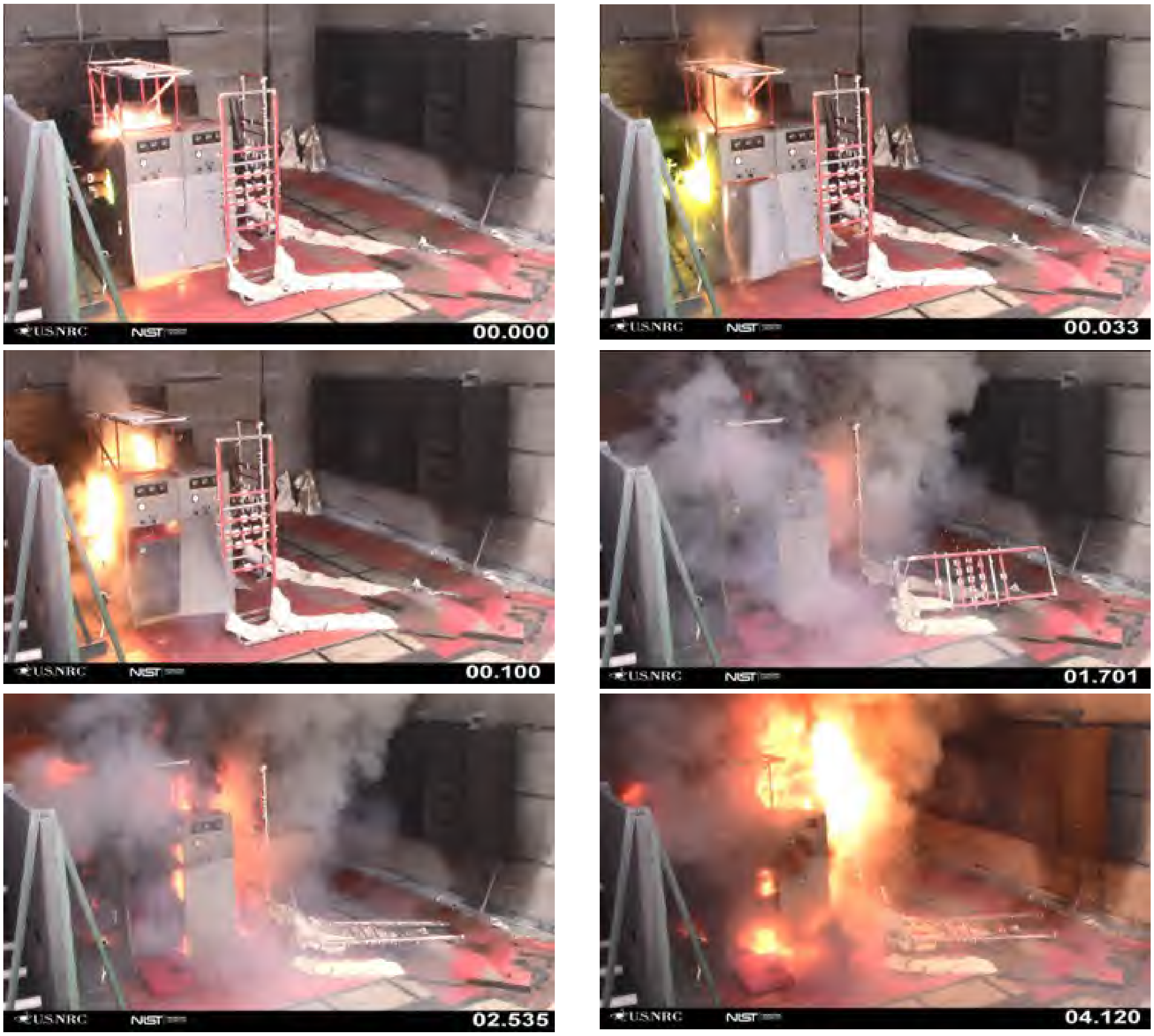

Fig. 73. Sequence of Images from Experiment 2-39 (image time stamps are in seconds).

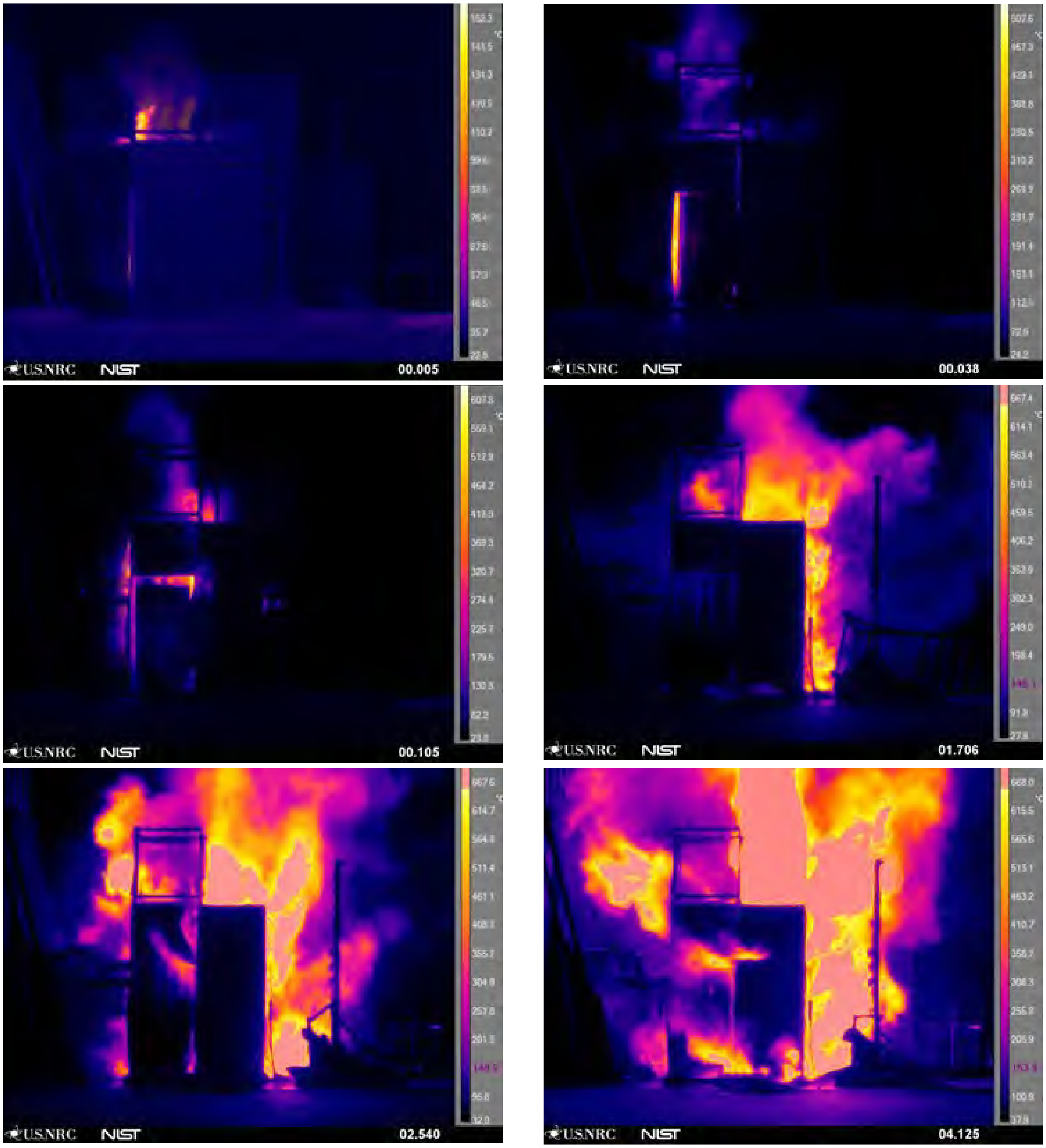

Fig. 74. Sequence of Thermal Images from Experiment 2-39 (image time stamp in seconds).

A photograph of the area surrounding the enclosures following the experiment is presented in Fig. 75.

Fig. 75. Enclosure Post-Experiment 2-39. The front door is approximately 4.9 m (16 ft) from Enclosure “M”. Instrument Rack #1 is laying on ground due to impact from Enclosure “M” front door during experiment.

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 76. The total mass loss of the bus bars was approximately 114.5 g. Additional details are presented in Appendices C and D.

Fig. 76. Photo of Experiment 2-39 bus bars post-experiment.

3.8.2. Measurements

Measurements made during Experiment 2-39 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeters, Plate Thermometers, Tcap Slug Calorimeters
  - Temperature – Fiber optic sensors inside of switchgear
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.8.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-39. These include PT measurements in Table 52, ASTM Slug Calorimeter measurements in Table 53, and T_{cap} slug measurements in Table 54. The maximum reading is identified with bold text. The maximum temperature of the fiber optic sensors located in the switchgear was approximately 56 °C. Table 55 presents the maximum temperatures and time for the fiber optic sensors. Note that there was continuous fire growth during this experiment.

Table 52. Summary of plate thermometer measurements, Experiment 2-39.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 15 %
1	1	Top	- - -	- - -	- - -
1	3	Mid-Right	- - -	- - -	- - -
1	5	Mid-Center	- - -	- - -	- - -
1	7	Mid-Left	- - -	- - -	- - -
1	9	Bottom	- - -	- - -	- - -
2	10	Top	142	**57**	290
2	12	Mid-Right	156	49	320
2	14	Mid-Center	78	33	330
2	16	Mid-Left	59	27	280

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
2	18	Bottom	69	31	**400**
3	19	Top	38	8	160
3	21	Mid-Right	33	9	110
3	23	Mid-Center	69	13	180
3	25	Mid-Left	**180**	41	320
3	27	Bottom	68	23	120

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned.

Table 53. Summary of ASTM slug calorimeter measurements, Experiment 2-39.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment	Solder Type
1	A	Top	- - -	- - -	Rack displaced	AG
1	B	Bottom	- - -	- - -	Rack displaced	Pb-Sn
2	C	Top	- - -	- - -	Non-functional prior to experiment	AG
2	D	Bottom	- - -	- - -	Non-functional prior to experiment	Pb-Sn
3	E	Top	51.2	18.8		AG
3	F	Bottom	**106.0**	15.4		Pb-Sn

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned. Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 54. Summary of T_{cap} slug measurements, Experiment 2-39.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	- - -	- - -	- - -
1	4	Mid-Right	- - -	- - -	- - -
1	6	Mid-Left	- - -	- - -	- - -
1	8	Bottom	- - -	- - -	- - -
2	11	Top	43.3	109.9	2 101.9
2	13	Mid-Right	**51.6**	116.3	2 216.3
2	15	Mid-Left	34.6	83.1	2 122.0
2	17	Bottom	48.0	**117.5**	**2 294.9**
3	20	Top	24.0	51.4	1 048.7
3	22	Mid-Right	15.4	38.7	782.3
3	24	Mid-Left	42.0	91.2	1 266.7
3	26	Bottom	19.4	56.9	916.5

Note: Rack #1 was displaced during the experiment and was not exposed to the thermal insult as planned.

Table 55. Maximum temperatures from fiber optic sensors inside enclosure for Experiment 2-39.

Sensor No.	Switchgear Unit ID	Approx. distance from top of enclosure (cm)	Max. Temp. (°C) ± 1.0 °C	Approx. Time of Max. Temp. (s)	Notes
61	M	36	36.7	835	End of experiment
62	I	35	**55.6**	835	End of experiment
63	K	36	30.5	835	End of experiment
64	L	35	29.9	835	End of experiment

3.8.2.2. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 77. After the initial pressure spike, the pressure rapidly decayed to a relative steady state. The maximum change in pressure in the switchgear Enclosure "M" was approximately 41.6 kPa (6.0 psi) above ambient at its peak, while Enclosure "I" was approximately 3.9 kPa (0.6 psi) above ambient at its peak.

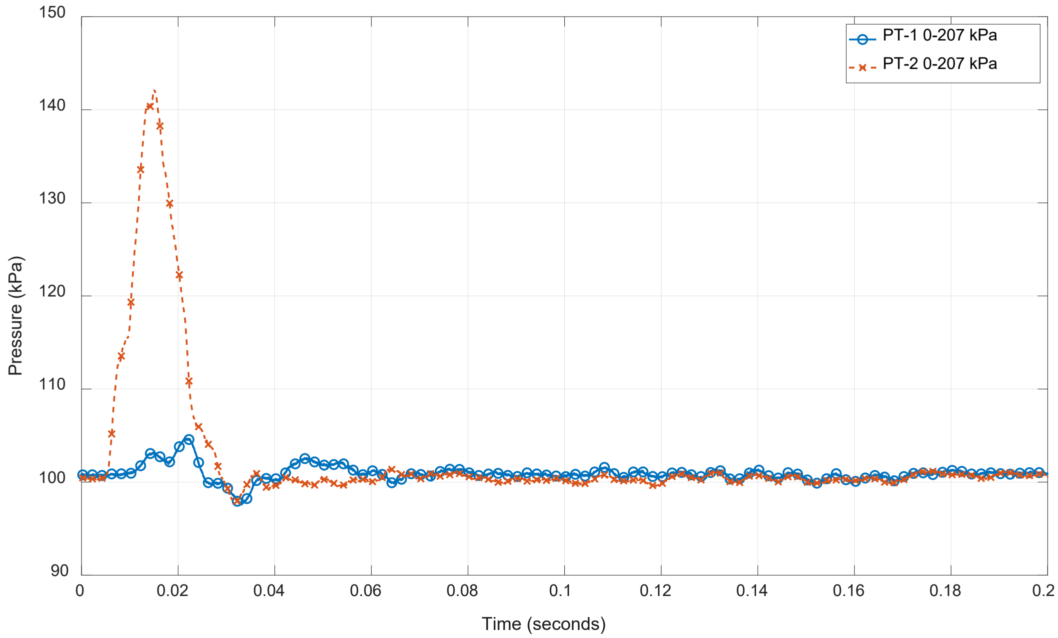

Fig. 77. Pressure measurements from Experiment 2-39. PT-1 Enclosure "I", PT-2 Enclosure "M". Measurement uncertainty ± 3 percent.

3.8.2.3. Electrical Measurements

Experiment 2-39 used KEMA circuit S02 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230815-9002. Key experimental measurements are presented in Table 56. Plots of the electrical measurements are presented in Appendix B.

Table 56. Key measurements from Experiment 2-39. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	43.6	50.7	-58.1
Current, AC component, beginning	kA_{RMS}	26.0	25.7	25.8
Current, AC component, middle	kA_{RMS}	23.7	24.1	23.9
Current, AC component, end	kA_{RMS}	20.8	23.0	23.1
Current, AC component, average	kA_{RMS}	24.1	24.5	24.3
Current, AC component, three-phase average	kA_{RMS}		24.3	
Duration	s	4.12	4.12	4.12
Arc Energy	MJ		104	

3.9. Experiment 2-40 – 4.16 KV, 30 kA, 4 s Duration, Copper Bus, Aluminum Enclosure

Experiment 2-40 was performed on August 7, 2023, at 2:50 PM eastern daylight time (EDT). The temperature was approximately 28 °C (82 °F), the relative humidity was approximately 71 percent, and the atmospheric pressure was approximately 100.8 kPa. The weather was cloudy with a wind of approximately 13 km/h (8 mi/h) out of the south southeast.

This experiment used two straight medium-voltage (MV) bus duct sections. The bus duct was constructed of aluminum and the bus bars were copper. Only one section contained bus bars. The experiment device was elevated approximately 173 cm (68 in) above ground measured to the center of the duct. This elevation allowed for instruments placed below the duct and observations of any effluent below the duct. The arcing wire was located at the end of the bus bars, approximately 135 cm (53 in) from the bus duct flange nearest the incoming power supply. The arcing wire was installed by the KEMA technician prior to the experiment. The arcing wire was installed between all three phases, and a marked-up photo of the arc wire location is presented in Fig. 78. The end of the bus duct nearest the incoming power supply was closed with 1.3 cm (0.5 in) GPO3 insulator board. The end of the bus duct section farthest from the incoming power supply was not closed.

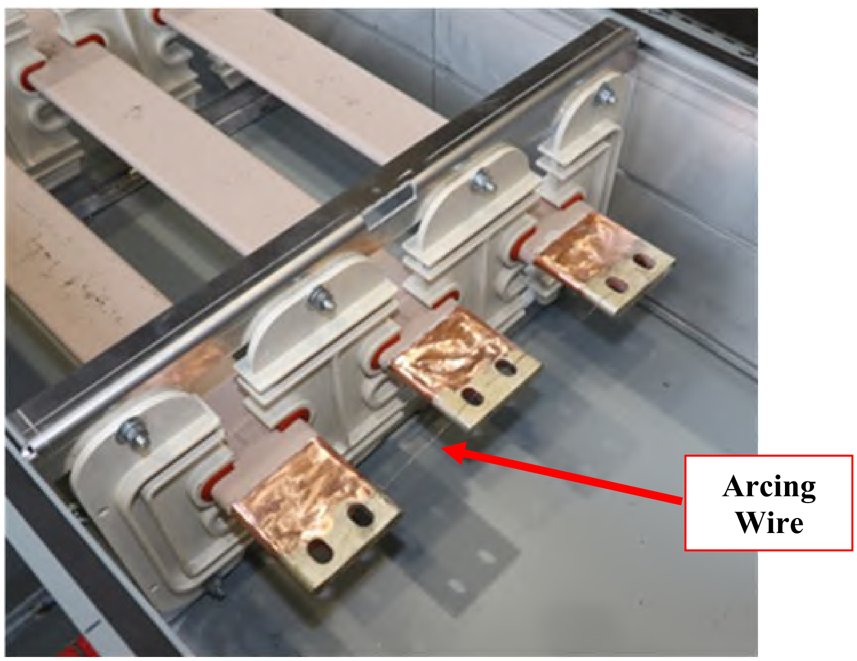

Fig. 78. Arcing wire (#24 AWG) location at the end of the bus bars for Experiment 2-40.

3.9.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 57 and include an approximate time reference. Corresponding images are provided in Fig. 79, with thermography images presented in Fig. 80.

This was the first experiment in this series of experiments. The arc successfully stabilized at the end of the bus bars and lasted for the expected duration (4.13 s). Fire suppression was not required. Aluminum slag was found throughout the test cell and courtyard with the majority of the slag found below the bus duct. Bus duct bottom and internal support pieces were found on the top of instrument Rack #5, which may have affected the readings of that rack. One vertical GPO-3 thermocouple protective cover ("U" channel) was found lying on the ground after the experiment. It is believed that the channel was inadequately secured prior to the experiment and the HEAF effluent caused the securement to fail.

Table 57. Observations from Experiment 2-40.

Time (ms)	Observation
0	Initial light observed
266	Particle ejecta reaches right instrumentation rack
800	Particle ejecta reaches wall right
1 651	Large smoke plume / fire ball exiting cell
3 003	Mid-experiment exposure
4 120	End of arc

Fig. 79. Sequence of Images from Experiment 2-40 (image time stamps are in seconds).

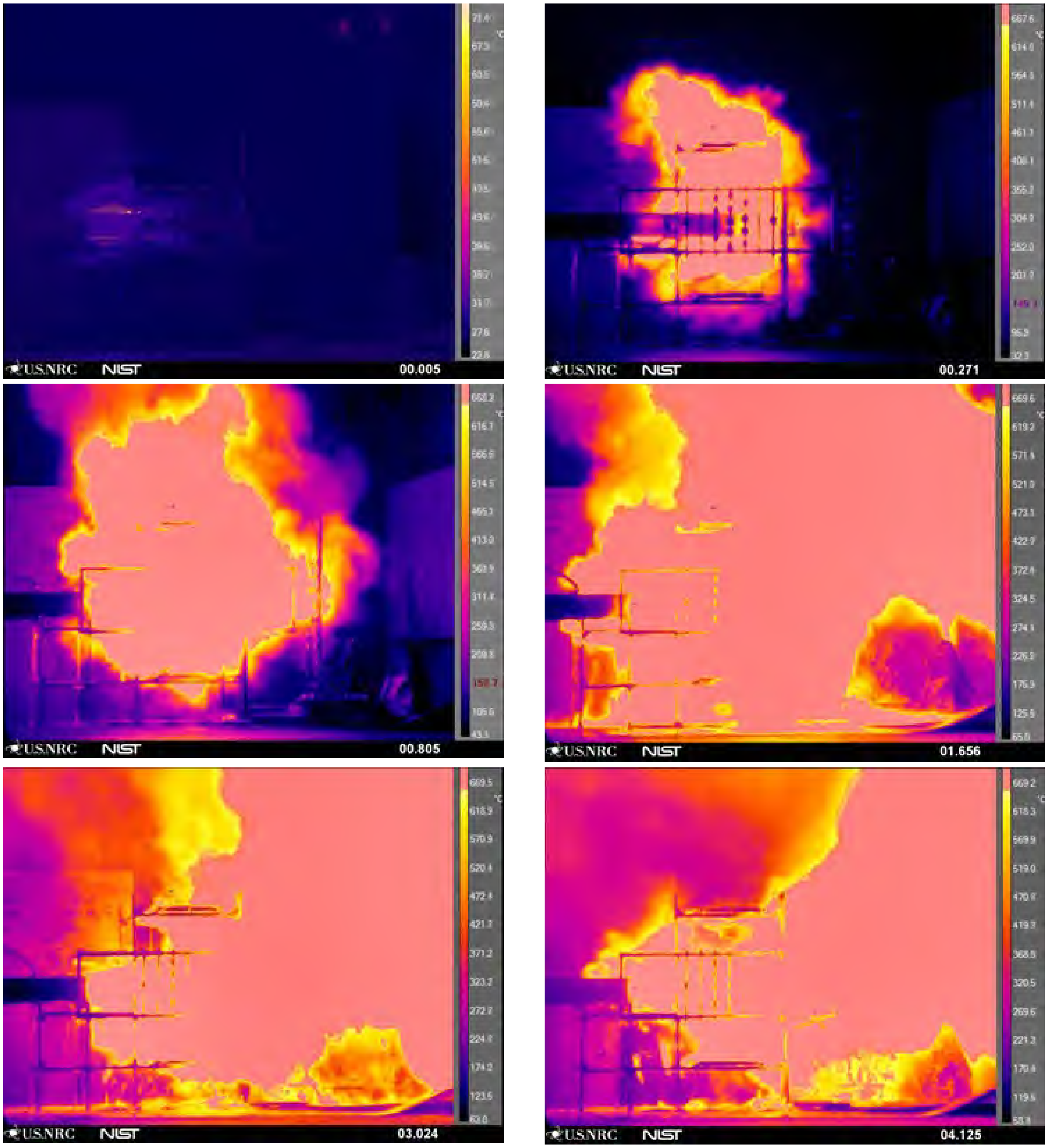

Fig. 80. Sequence of Thermal Images from Experiment 2-40 (image time stamp in seconds).

A photograph of the bus duct enclosure following the experiment is presented in Fig. 81. The enclosure was completely severed as shown below. The top cover was largely intact due to the overpressure and a large section of the bottom cover was found lying on instrumentation Rack #5.

Fig. 81. Enclosure Post-Experiment 2-40.

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 82. The total mass loss of the bus bars was approximately 5 125.0 g. The mass loss from the aluminum enclosure was estimated at approximately 16 088 g. Additional details are presented in Appendix C and D.

Fig. 82. Photo of Experiment 2-40 bus bars post-experiment (arc location at arrow).

3.9.2. Measurements

Measurements made during Experiment 2-40 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeter, Plate Thermometers, Tcap Slug Calorimeters
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.9.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-40. These include PT measurements in Table 58, ASTM Slug Calorimeter measurements in Table 59, and T_{cap} slug measurements in Table 60. The maximum reading is identified with bold text.

Table 58. Summary of plate thermometer measurements, Experiment 2-40.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
1	1	Top	1 953	799	3 110
1	3	Mid-Right	2 659	881	3 400
1	5	Mid-Center	2 304	892	3 430
1	7	Mid-Left	901	531	2 180
1	9	Bottom	1 878	909	3 500
2	10	Top	908	511	1 960
2	12	Mid-Right	1 309	773	3 020
2	14	Mid-Center	1 244	586	2 330
2	16	Mid-Left	2 526	948	3 620
2	18	Bottom	815	313	1 190
3	19	Top	949	577	2 290
3	21	Mid-Right	2 038	782	3 050
3	23	Mid-Center	2 121	1 090	4 050
3	25	Mid-Left	1 609	786	3 070
3	27	Bottom	2 316	**1 275**	**4 580**

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) Greater of ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) Greater of ±1 kW/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 15 %
4	28	Top	1693	793	3090
4	30	Mid-Right	692	481	1940
4	32	Mid-Center	846	419	1610
4	34	Mid-Left	1806	736	2890
4	36	Bottom	**2715**	706	2780
5	37	Front	2268	1006	- - - ‡
5	39	Center-Right	1782	858	- - - ‡
5	41	Center-Mid	242	136	670
5	43	Center-Left	501	234	1140
5	45	Back	1596	714	2810

Note: ‡ indicates post arc damage to instrument

Table 59. Summary of ASTM slug calorimeter measurements, Experiment 2-40.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Solder type
1	A	Top	2684	7.1	AG
1	B	Bottom	3618	5.3	Pb-Sn
2	C	Top	2616	5.3	AG
2	D	Bottom	1694	5.3	Pb-Sn
3	E	Top	3514	6.3	AG
3	F	Bottom	4341	5.4	AG
4	G	Top	2177	5.1	AG
4	H	Bottom	**8166**	3.6	AG
5	I	Top	1025	62.1	AG
5	J	Bottom	1034	27.4	AG

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 60. Summary of T_{cap} slug measurements, Experiment 2-40.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	838.2	2945.7	3473.7
1	4	Mid-Right	- - - ‡	- - - ‡	- - - ‡
1	6	Mid-Left	749.1	2506.0	4032.0
1	8	Bottom	- - - ‡	- - - ‡	- - - ‡
2	11	Top	767.9	2306.3	2881.8
2	13	Mid-Right	610.2	1877.5	2762.8
2	15	Mid-Left	619.5	1893.5	2990.7
2	17	Bottom	493.7	1516.7	2130.6
3	20	Top	1070.6	3599.5	4934.9
3	22	Mid-Right	1280.8	4029.2	5058.0
3	24	Mid-Left	**1340.5**	**4453.3**	5381.0
3	26	Bottom	1308.3	4283.6	6024.0
4	29	Front	589.6	2045.7	2582.7
4	31	Center-Right	- - - ‡	- - - ‡	- - - ‡
4	33	Center-Left	534.4	1659.1	2301.2
4	35	Back	- - - ‡	- - - ‡	- - - ‡
5	38	Front	316.7	908.6	2223.1
5	40	Center-Right	134.0	315.2	3410.9
5	42	Center-Left	426.2	1082.0	**7049.0**
5	44	Back	211.8	643.4	1365.6

Note: ‡ denotes a non-physical temperature peak during arc.

3.9.2.2. Pressure Measurements

No pressure measurements were made during this experiment.

3.9.2.3. Electrical Measurements

Experiment 2-40 used KEMA circuit S01 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230807-9003. Key experimental measurements are presented in Table 61. Plots of the electrical measurements are presented in Appendix B.

Table 61. Key measurements from Experiment 2-40. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	2.42	2.42	2.42
Applied voltage, phase-to-phase	kV_{RMS}		4.19	
Making current	kA_{peak}	54.1	64.0	-71.1
Current, AC component, beginning	kA_{RMS}	33.4	32.5	32.1
Current, AC component, middle	kA_{RMS}	28.8	29.8	27.6
Current, AC component, end	kA_{RMS}	26.6	29.0	26.5
Current, AC component, average	kA_{RMS}	29.5	30.3	28.3
Current, AC component, three-phase average	kA_{RMS}		29.4	
Duration	s	4.12	4.12	4.12
Arc Energy	MJ		110.6 ‡	

‡ The KEMA Report didn't provide an arc energy statistic. Arc Energy was calculated for this experiment using a MATLAB script.

3.10. Experiment 2-41 – 4.16 KV, 30 kA, 4 s Duration, Aluminum Bus, Aluminum Enclosure

Experiment 2-41 was performed on August 8, 2023, at 11:45 AM eastern daylight time (EDT). The temperature was approximately 24 °C (75 °F), the relative humidity was approximately 63 percent, and the atmospheric pressure was approximately 100.5 kPa. The weather was cloudy with a wind of approximately 16 km/h (10 mi/h) out of the west.

This experiment used two straight medium-voltage (MV) bus duct sections. The bus duct and bus bars were constructed of aluminum. Only one bus duct section contained bus bars. The experiment device was elevated approximately 173 cm (68 in) above ground measured to the center of the duct. This elevation allowed for instruments below the duct and observations of any effluent below the duct. The arcing wire was located at the end of the bus bars, approximately 135 cm (53 in) from the bus duct flange nearest the incoming power supply. The arcing wire was installed by the KEMA technician prior to the experiment. The arcing wire installed between all three phases is presented in Fig. 83. The end of the bus duct nearest the incoming power supply was closed with 1.3 cm (0.5 in) GPO3 insulator board. The end of the bus duct section farthest from the incoming power supply was not closed.

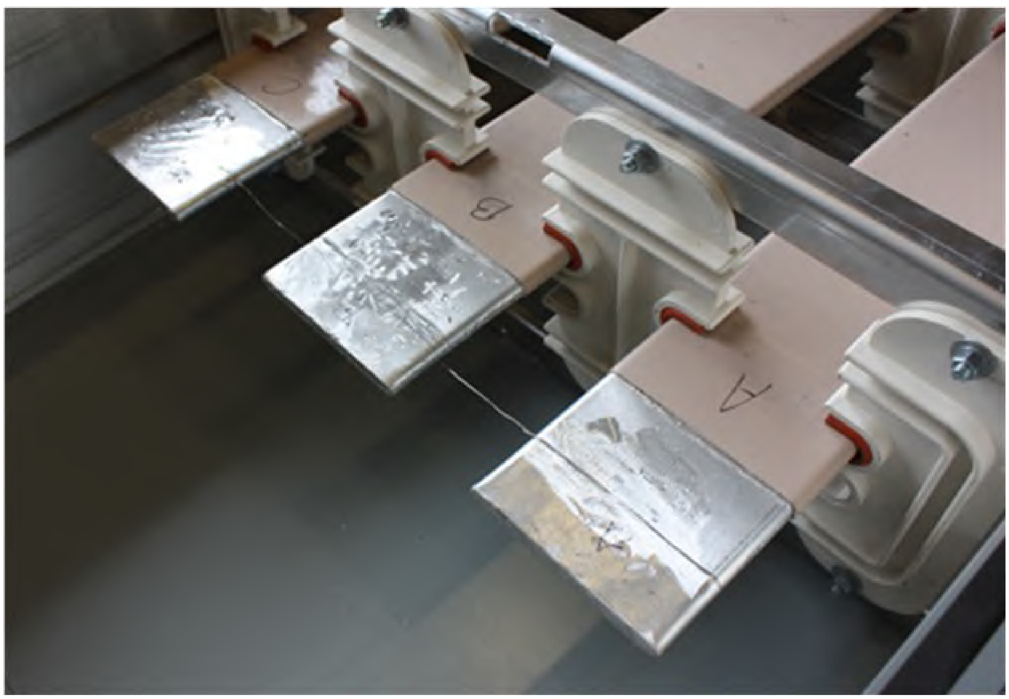

Fig. 83. Arcing wire (#24 AWG) location Experiment 2-41.

3.10.1. Observations

Observations documented below are based on review of video and thermal imaging recorded during the experiment. The observations are provided in Table 62 and include an approximate time reference. Corresponding images are provided in Fig. 84, with thermography images presented in Fig. 85.

This was the second and final bus duct experiment. The experiment assembly was acquired new. The assembly had the same voltage and continuous current carrying rating as other duct used in this series. Aluminum slag was found throughout the test cell and courtyard with the majority of slag found below the duct. No visible cable damage was observed an any cable coupon on the instrument racks. The arc lasted for the expected duration (4.14 s).

Table 62. Observations from Experiment 2-41.

Time (ms)	Observation
0	Initial light observed
266	Particle ejecta observed at instrumentation rack
550	Particle ejecta reaches right wall
1 251	Smoke reaches overhead crane
4 137	End of arc
14 147	Smoke begins to clear cell 10 s after end of arc

Fig. 84. Sequence of Images from Experiment 2-41 (image time stamps are in seconds).

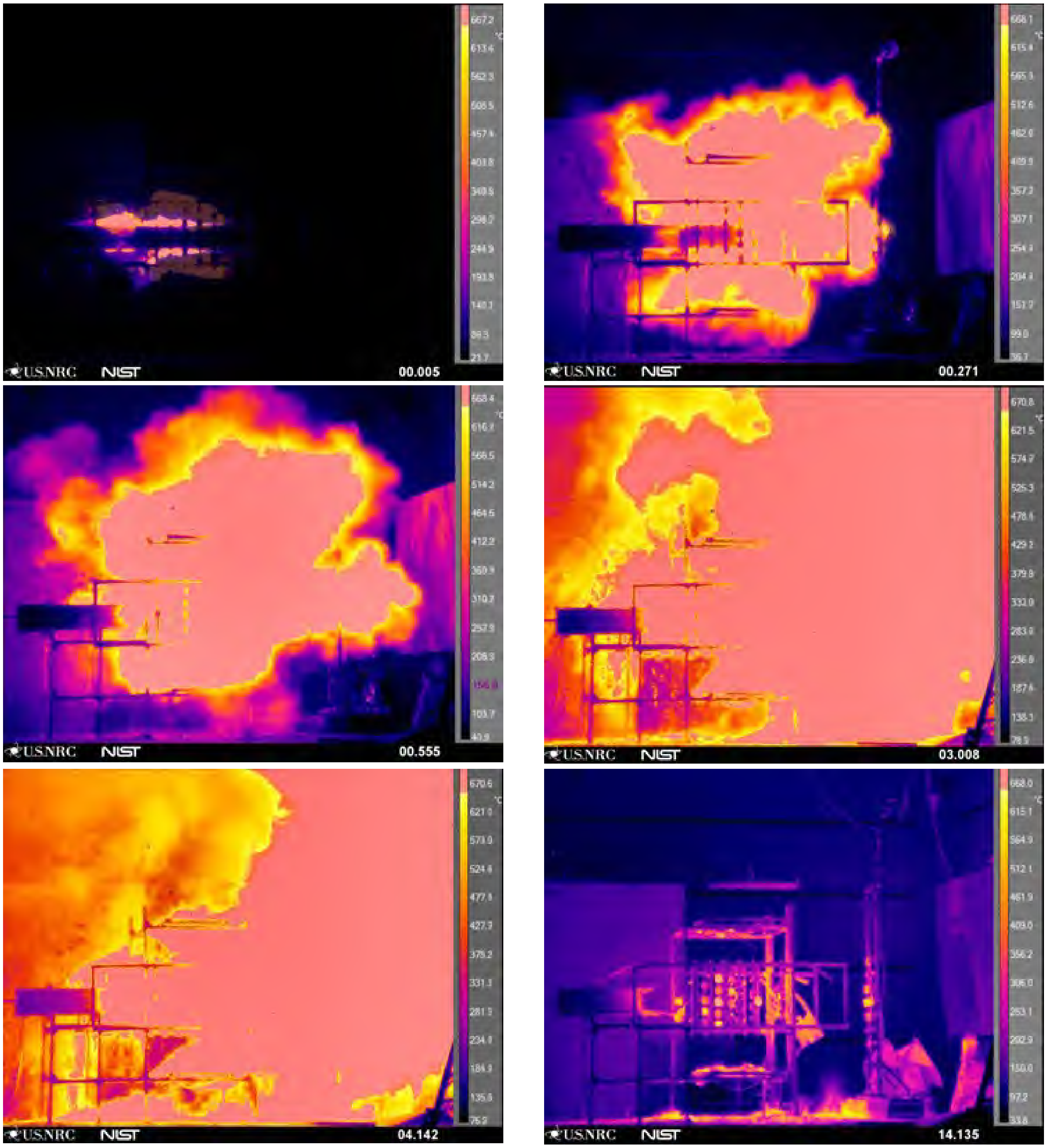

Fig. 85. Sequence of Thermal Images from Experiment 2-41 (image time stamp in seconds).

A photograph of the bus duct enclosure following the experiment is presented in Fig. 86. The enclosure was completely severed. Most of the duct in the straight section was missing post-experiment.

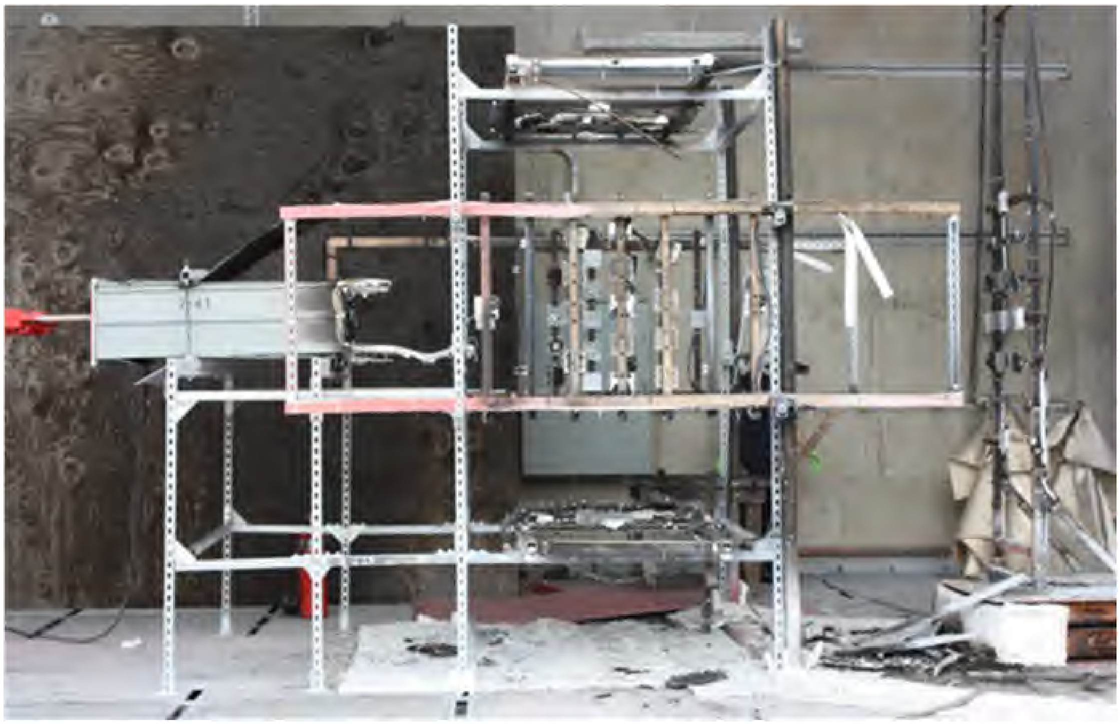

Fig. 86. Enclosure Post-Experiment 2-41.

An image of the bus bars removed from the enclosure after the experiment are shown in Fig. 87. The total mass loss of the bus bars was approximately 3 489.5 g. The mass loss from the aluminum enclosure was estimated at approximately 23 849 g. Additional details are presented in Appendices C and D.

Fig. 87. Photo of Experiment 2-41 bus bars post-experiment (arc location at arrow).

3.10.2. Measurements

Measurements made during Experiment 2-40 are presented below. These measurements included:

- Thermal
  - Heat flux – Plate Thermometers, Tcap Slug Calorimeters
  - Incident Energy – ASTM Slug Calorimeter, Plate Thermometers, Tcap Slug Calorimeters
- Pressure
  - Internal pressure
- Mass Loss
  - Pre- / Post-experimental measurements
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.10.2.1. Thermal Measurements

Thermal measurements from the active instruments are reported below for Experiment 2-41. These include PT measurements in Table 63, ASTM Slug Calorimeter measurements in Table 64, and T_{cap} slug measurements in Table 65. The maximum reading is identified with bold text.

Table 63. Summary of plate thermometer measurements, Experiment 2-41.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 15 %	Note
1	1	Top	1 308	1 054	3 960	
1	3	Mid-Right	1 802	1 407	4 910	
1	5	Mid-Center	2 086	1 510	5 170	
1	7	Mid-Left	1 372	1 064	3 980	
1	9	Bottom	1 972	1 327	4 710	
2	10	Top	1 082	765	3 000	
2	12	Mid-Right	2 994	939	3 600	
2	14	Mid-Center	2 448	1 105	4 100	
2	16	Mid-Left	1 686	847	3 300	
2	18	Bottom	1 676	496	1 900	
3	19	Top	1 185	994	3 770	
3	21	Mid-Right	678	318	2 050	

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) Greater of ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) Greater of ±1 kW/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 15 %	Note
3	23	Mid-Center	2 277	**1 635**	**5 440**	
3	25	Mid-Left	2 248	1 561	5 290	
3	27	Bottom	2 405	1 616	5 400	Cor.
4	28	Top	2 490	--	--	Over
4	30	Mid-Right	1 756	837	3 250	
4	32	Mid-Center	2 929	895	3 450	
4	34	Mid-Left	--	--	--	FDE
4	36	Bottom	3 276	1 562	5 340	
5	37	Front	1 448	954	3 650	
5	39	Center-Right	2 472	1 229	4 460	
5	41	Center-Mid	301	111	1 270	
5	43	Center-Left	436	248	2 100	
5	45	Back	**4 055**	1 201	5 430	

Notes:
Cor. indicates reported measurement was hand corrected based on data review.
Over indicates the device “over-ranged”
FDE indicates device failed during arc

Table 64. Summary of ASTM slug calorimeter measurements, Experiment 2-41.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m²) Greater of ± 18 kJ/m² or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment	Solder Type
1	A	Top	3	4.0		AG
1	B	Bottom	652	86.7		AG
2	C	Top	3 549	4.5		AG
2	D	Bottom	2 607	6.4		AG
3	E	Top	4 567	5.5		AG
3	F	Bottom	**5 642**	4.3		AG
4	G	Top	2 879	5.2		AG
4	H	Bottom	- - -	- - -	Exceeded Device Range	Pb-Sn
5	I	Top	1 412	99.6		Pb-Sn
5	J	Bottom	1 940	50.1		Pb-Sn

Note: AG is a tin/silver solder and Pb-Sn is a tin-lead solder.

Table 65. Summary of T_{cap} slug measurements, Experiment 2-41.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) Greater of ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) Greater of ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	1482.7	4986.7	7273.6
1	4	Mid-Right	- - - ‡	- - - ‡	- - - ‡
1	6	Mid-Left	1249.3	4119.7	6562.4
1	8	Bottom	4722.9	9317.9	--
2	11	Top	1012.0	3314.4	5246.8
2	13	Mid-Right	1141.3	3707.1	5595.6
2	15	Mid-Left	3779.6	9852.9	- - - ‡
2	17	Bottom	754.8	2680.3	3994.2
3	20	Top	- - - ‡	- - - ‡	- - - ‡
3	22	Mid-Right	1739.9	5877.3	7500.9
3	24	Mid-Left	1920.2	7215.3	8709.2
3	26	Bottom	2006.3	7083.6	8579.8
4	29	Front	717.4	1279.8	3404.5
4	31	Center-Right	1173.8	2698.5	4452.7
4	33	Center-Left	1490.7	5884.1	8012.8
4	35	Back	1167.3	2758.9	4221.6
5	38	Front	180.1	633.3	3585.4
5	40	Center-Right	546.8	1309.3	4159.1
5	42	Center-Left	299.6	859.0	4796.3
5	44	Back	227.7	721.9	4353.7

Note: ‡ indicate device failure during arc.

3.10.2.2. Pressure Measurements

No pressure measurements were made during this experiment.

3.10.2.3. Electrical Measurements

Experiment 2-41 used KEMA circuit S01 and is reported in Appendix F. Full-level circuit checks (calibration experiments) were performed prior to the experiment to verify the experimental parameters were acceptable. The KEMA report (Appendix F) identifies this experiment as 230808-9001. Key experimental measurements are presented in Table 66. Plots of the electrical measurements are presented in Appendix B.

Table 66. Key measurements from Experiment 2-41. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	2.42	2.42	2.42
Applied voltage, phase-to-phase	kV_{RMS}	4.19		
Making current	kA_{peak}	53.8	66.8	-72.0
Current, AC component, beginning	kA_{RMS}	31.8	33.0	31.1
Current, AC component, middle	kA_{RMS}	28.3	30.6	27.1
Current, AC component, end	kA_{RMS}	26.9	28.4	25.6
Current, AC component, average	kA_{RMS}	29.3	30.7	28.0
Current, AC component, three-phase average	kA_{RMS}	29.3		
Duration	s	4.14	4.14	4.14
Arc Energy	MJ	157		

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Appendix A. Engineering Drawings

This appendix provides detailed drawings and information on the experiment facility, experiment object, and instrumentation.

A.1. Experimental Facility

Drawings of the experimental facility are presented in Fig. 88 through Fig. 93.

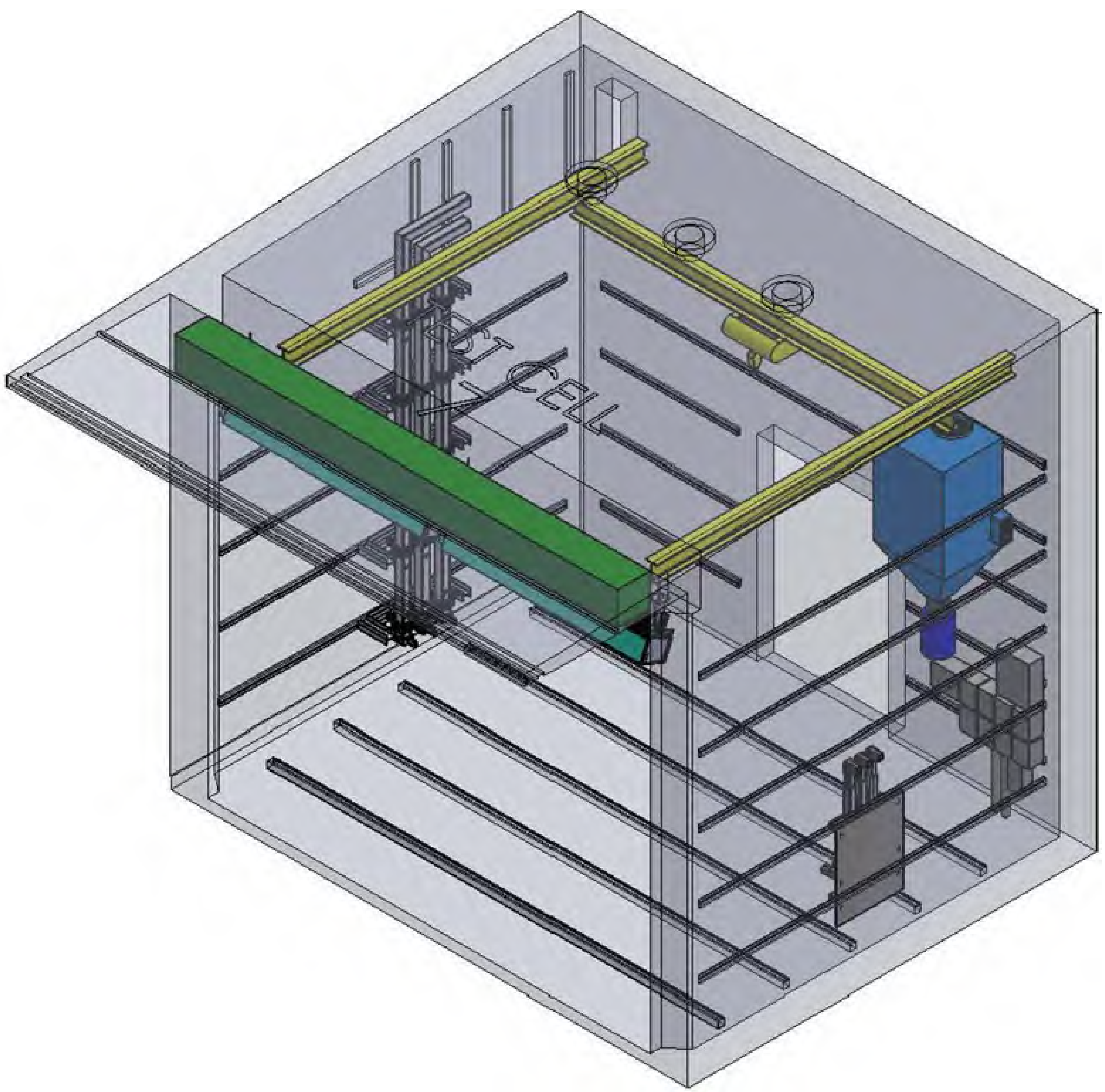

Fig. 88. Isometric drawing of test cell #7.

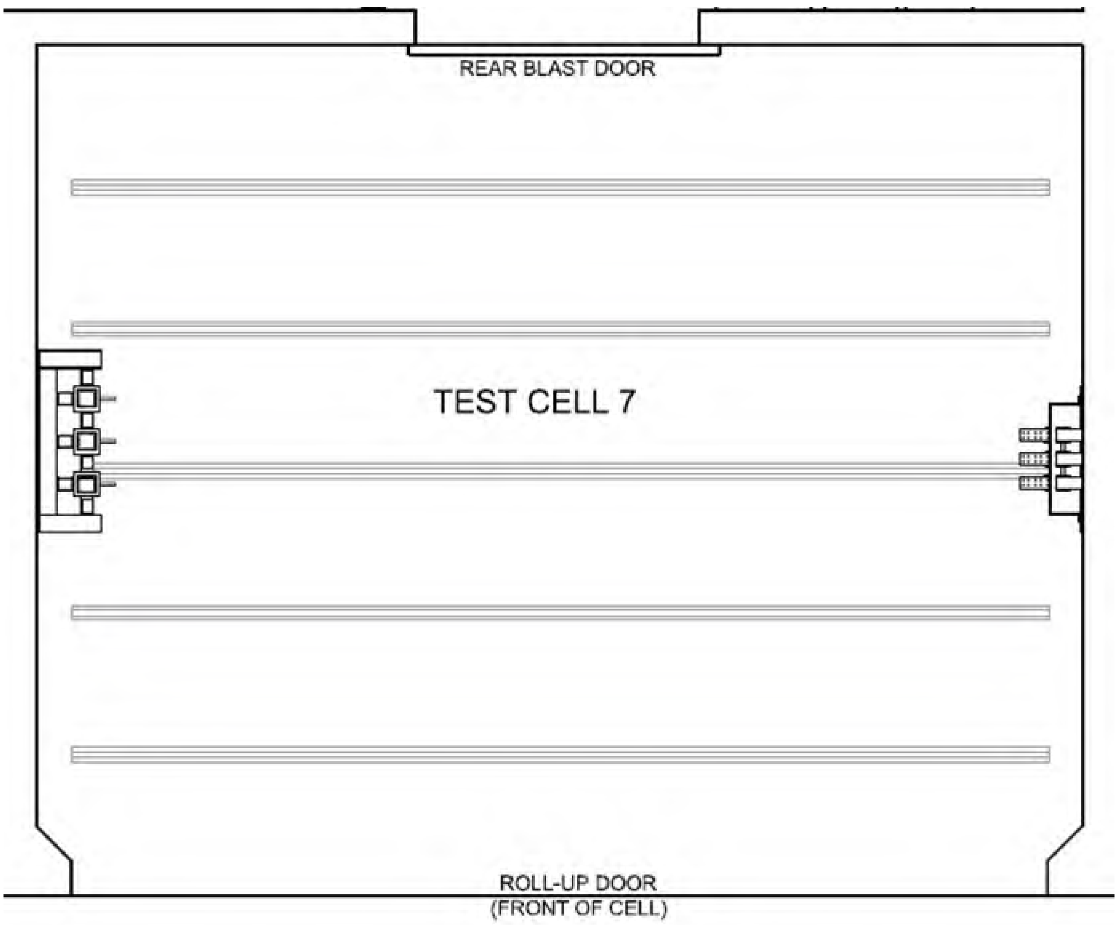

Fig. 89. Plan view of test cell #7. Low-voltage power connections located on right side of drawing. Cell #7 is approximately 8.9 m (29 ft) wide by 7.3 m (24 ft) deep.

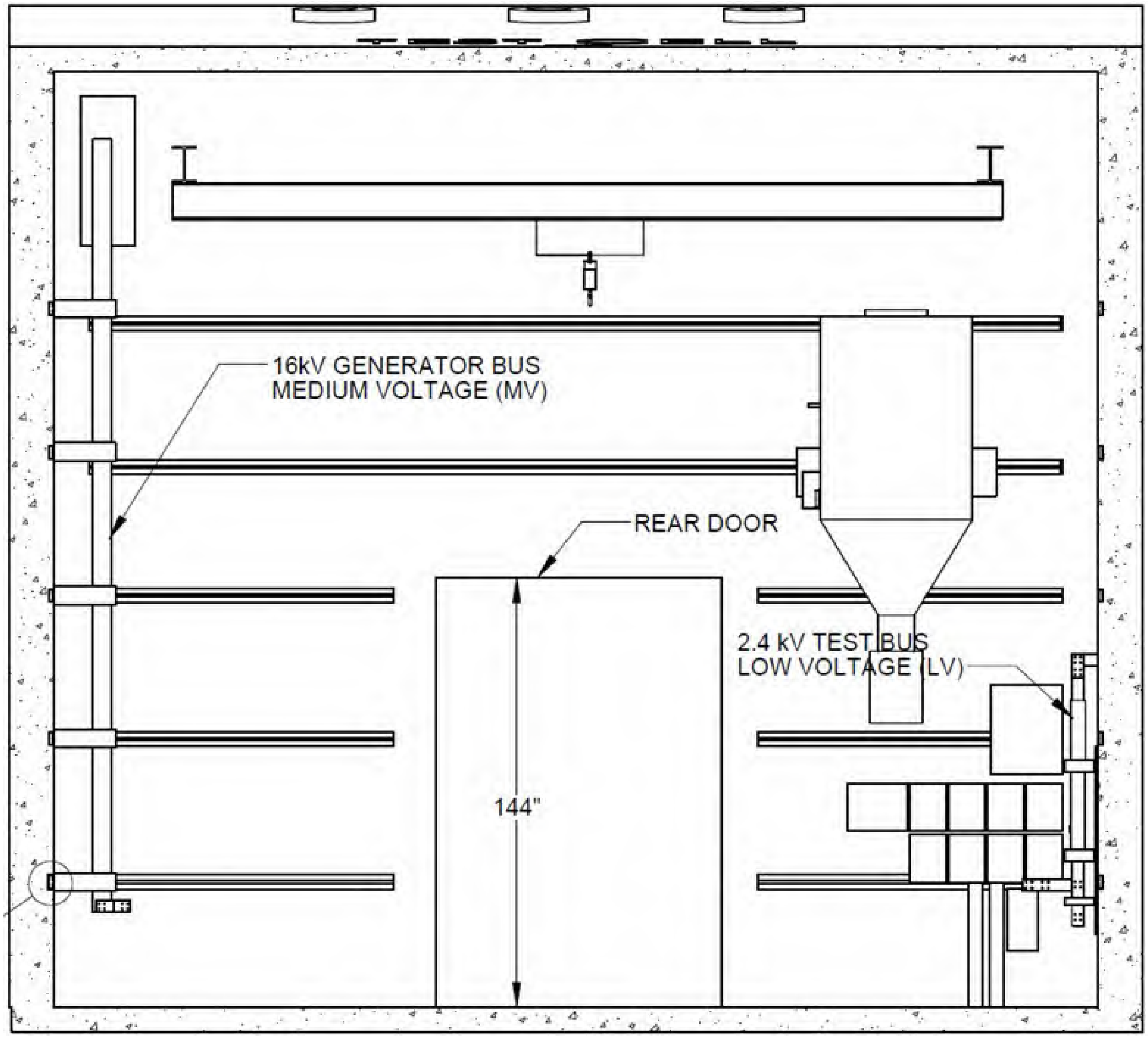

Fig. 90. Elevation view of Test Cell #7. Low-voltage power connections located on right side of drawing. Cell #7 is approximately 8.8 m (29 ft) wide by 7.9 m (26 ft) high.

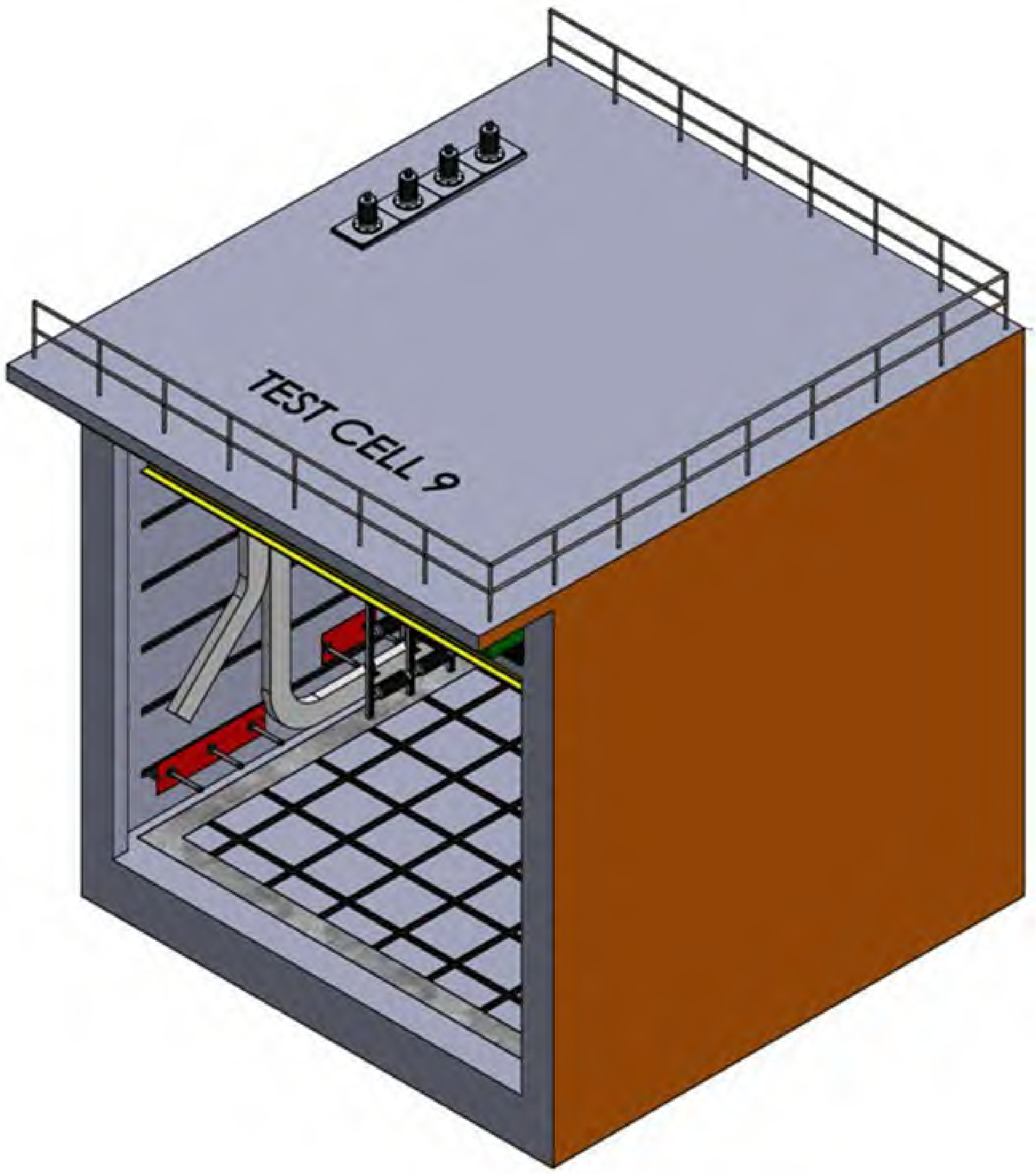

Fig. 91. Isometric drawing of test cell #9.

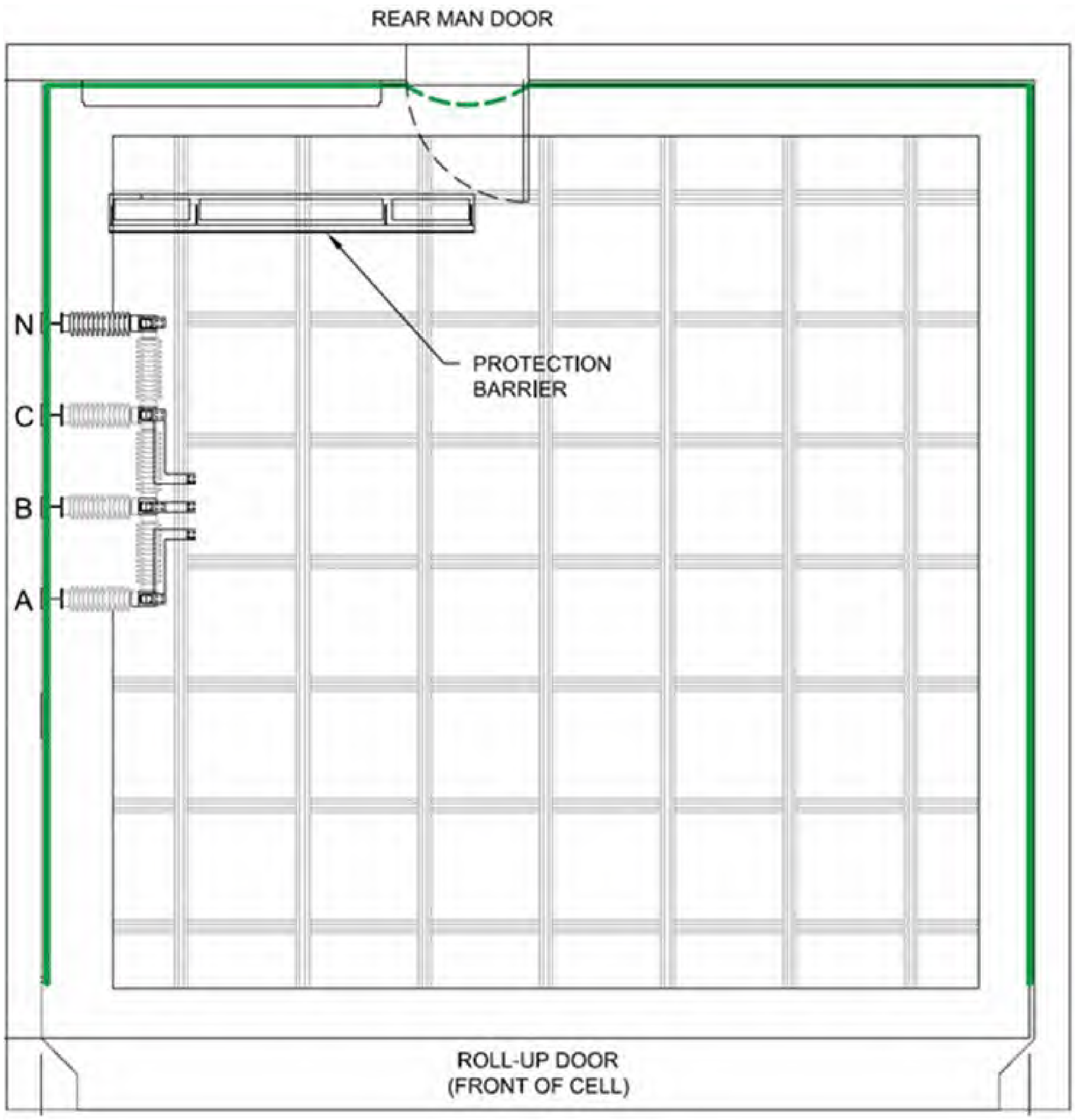

Fig. 92. Plan view of test cell #9. Medium-voltage power connections located on left side of drawing. Cell #9 is approximately 9.9 m (32.5 ft) wide by 9.6 m (31.5 ft) deep.

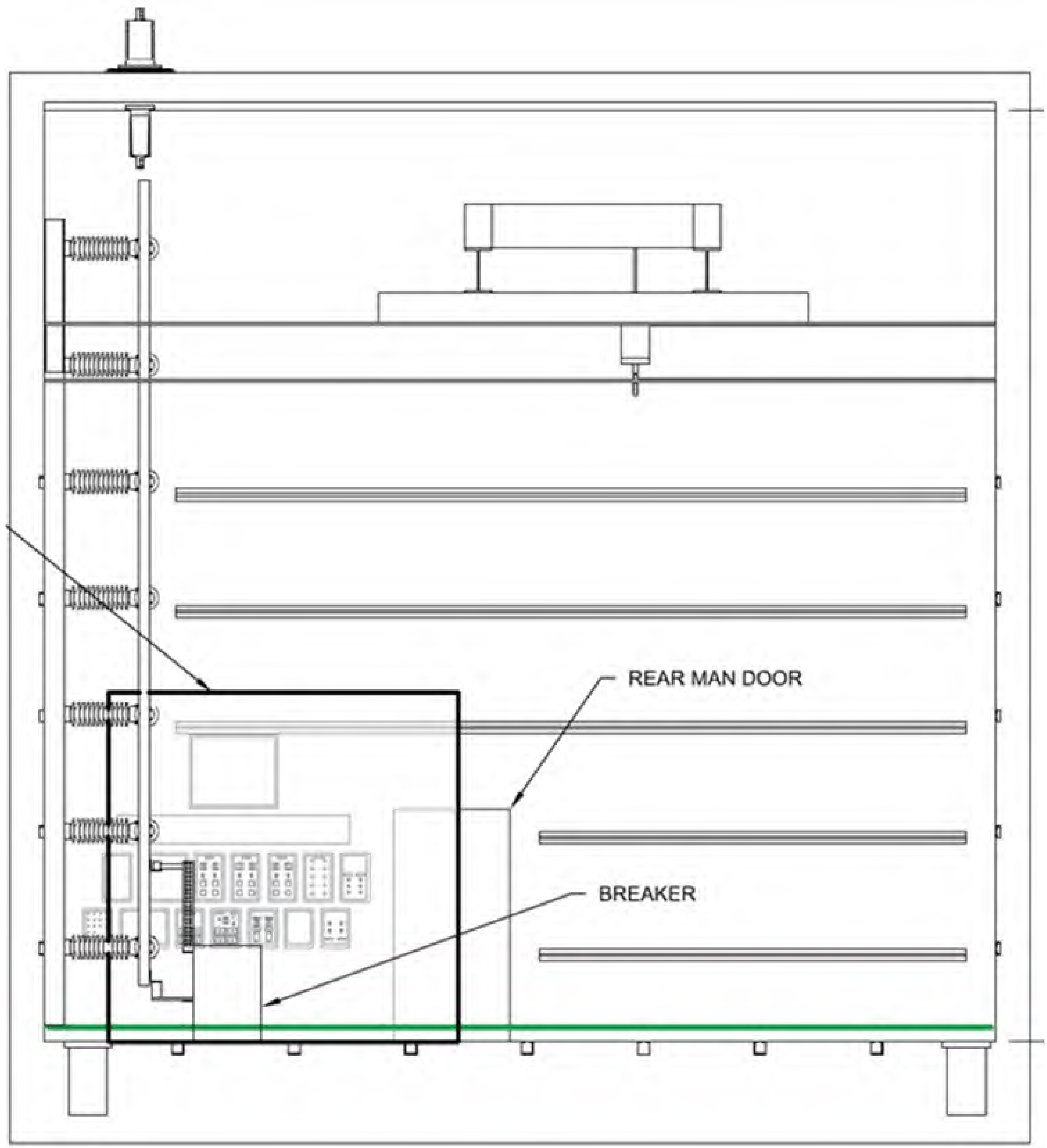

Fig. 93. Elevation view of test cell #9. Medium-voltage power connections located on left side of drawing. Breaker shown in drawing is part of KEMA protection system and was not used during this experimental series. Cell #9 is approximately 9.9 m (32.5 ft) wide by 9.8 m (32 ft) high.

A.2. Experiment Device

Low-voltage switchgear were provided by an OECD/NEA HEAF 2 member country. Dimensional drawings of these donated units are presented in Fig. 94 and Fig. 95.

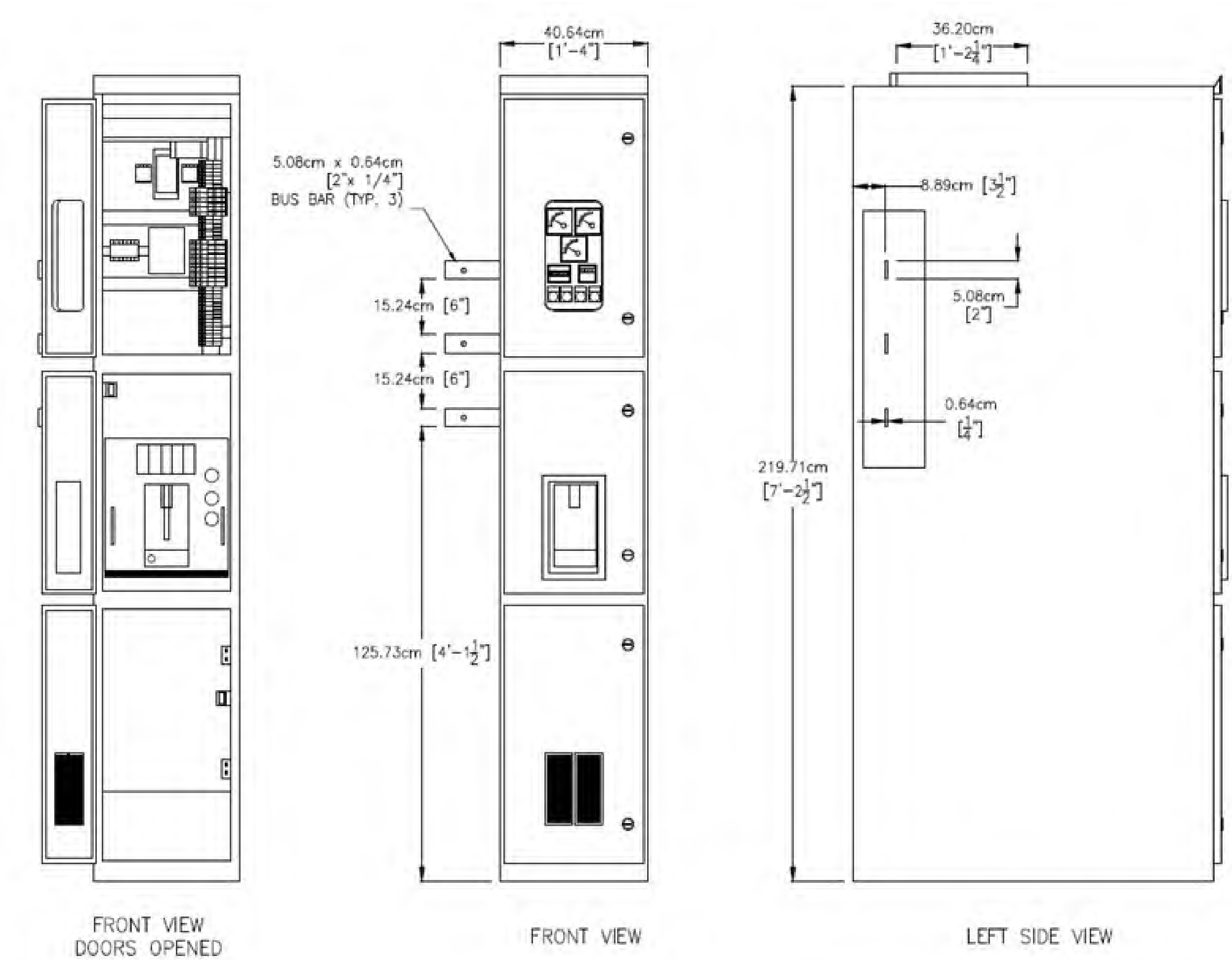

Fig. 94. Low-voltage switchgear provided by OECD/NEA HEAF 2 member country.

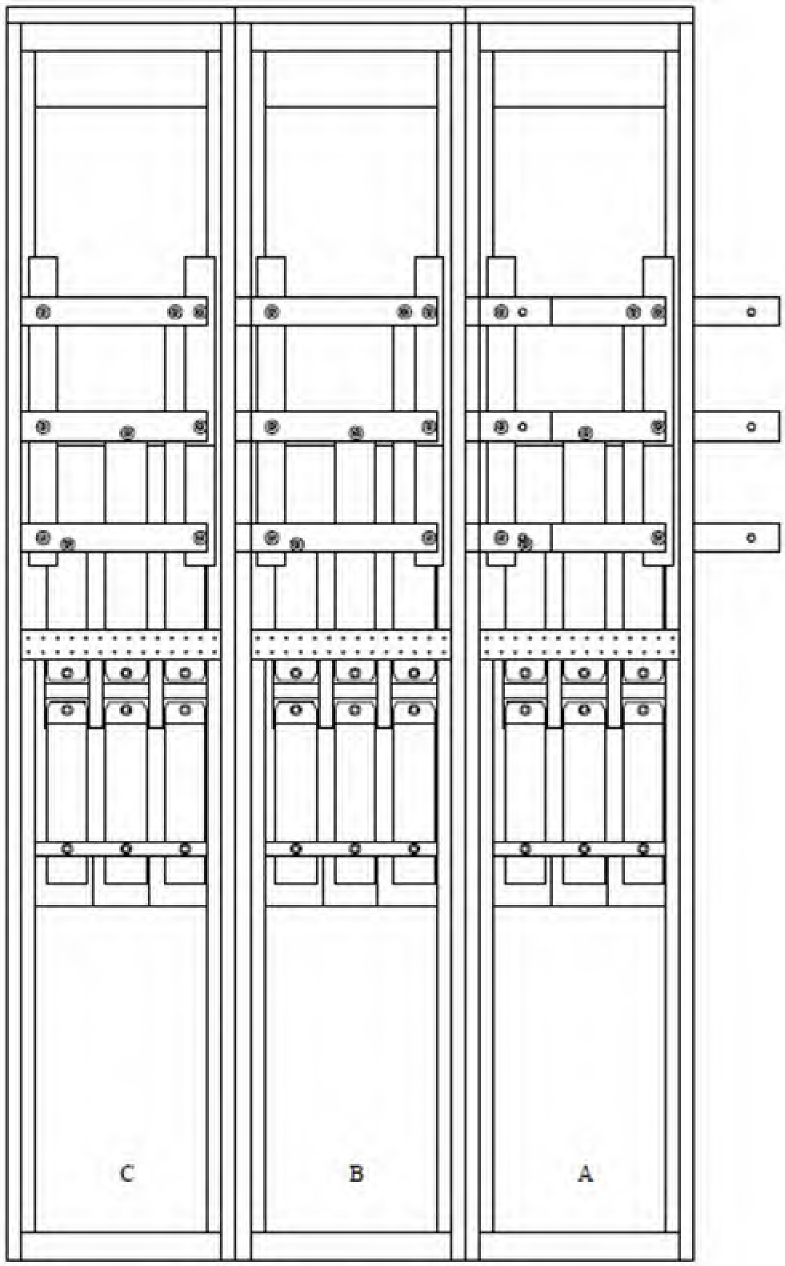

Fig. 95. Low-voltage switchgear shown in 3-unit lineup configuration viewed from rear, showing bus configuration.

Three types of medium-voltage switchgear were used in this experimental series. Dimensional drawings of the ITE-HK draw-out style switchgear are presented in Fig. 96, Fig. 97, Fig. 98, and Fig. 99.

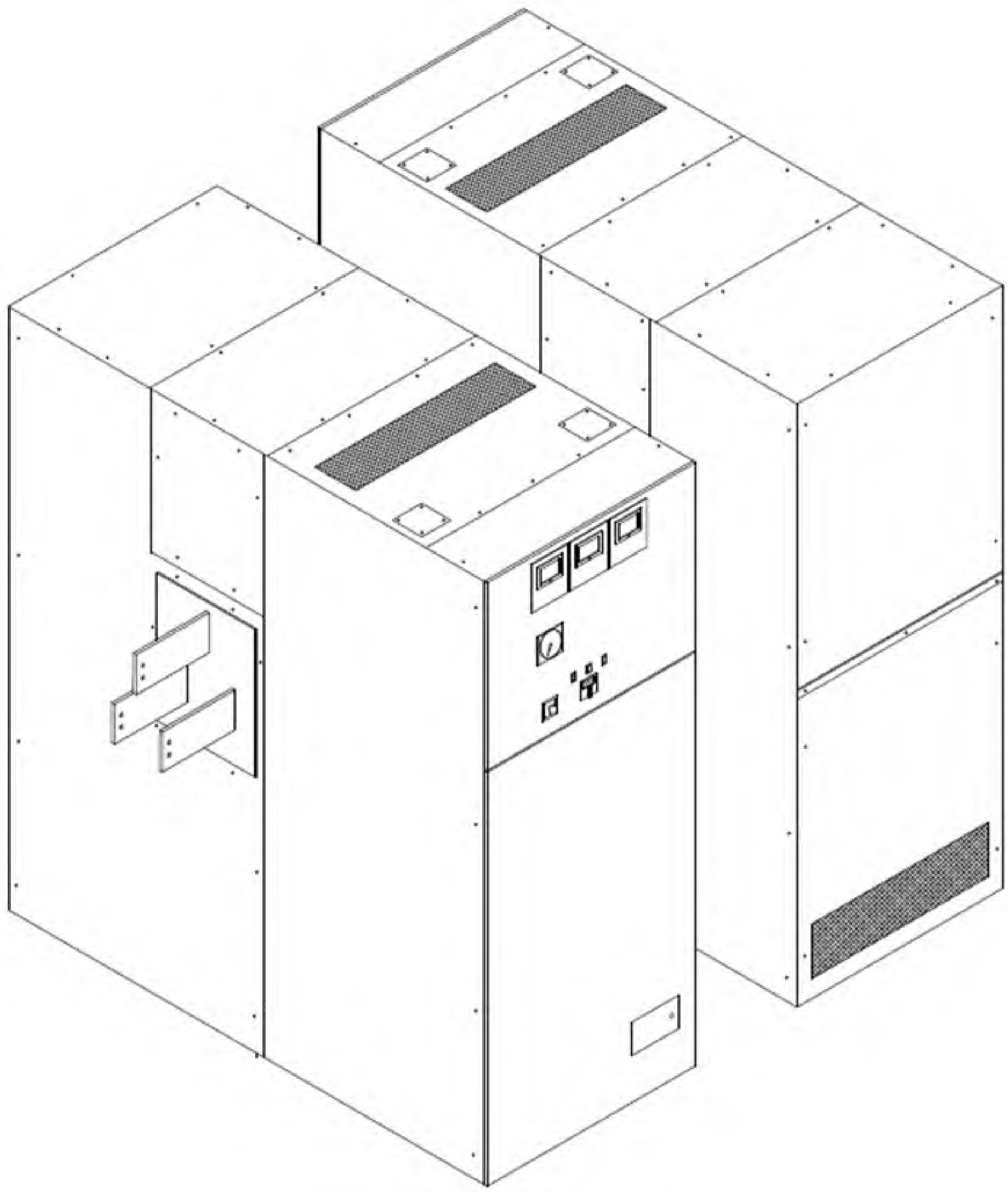

Fig. 96. Medium-voltage draw-out type switchgear (ITE Type HK).

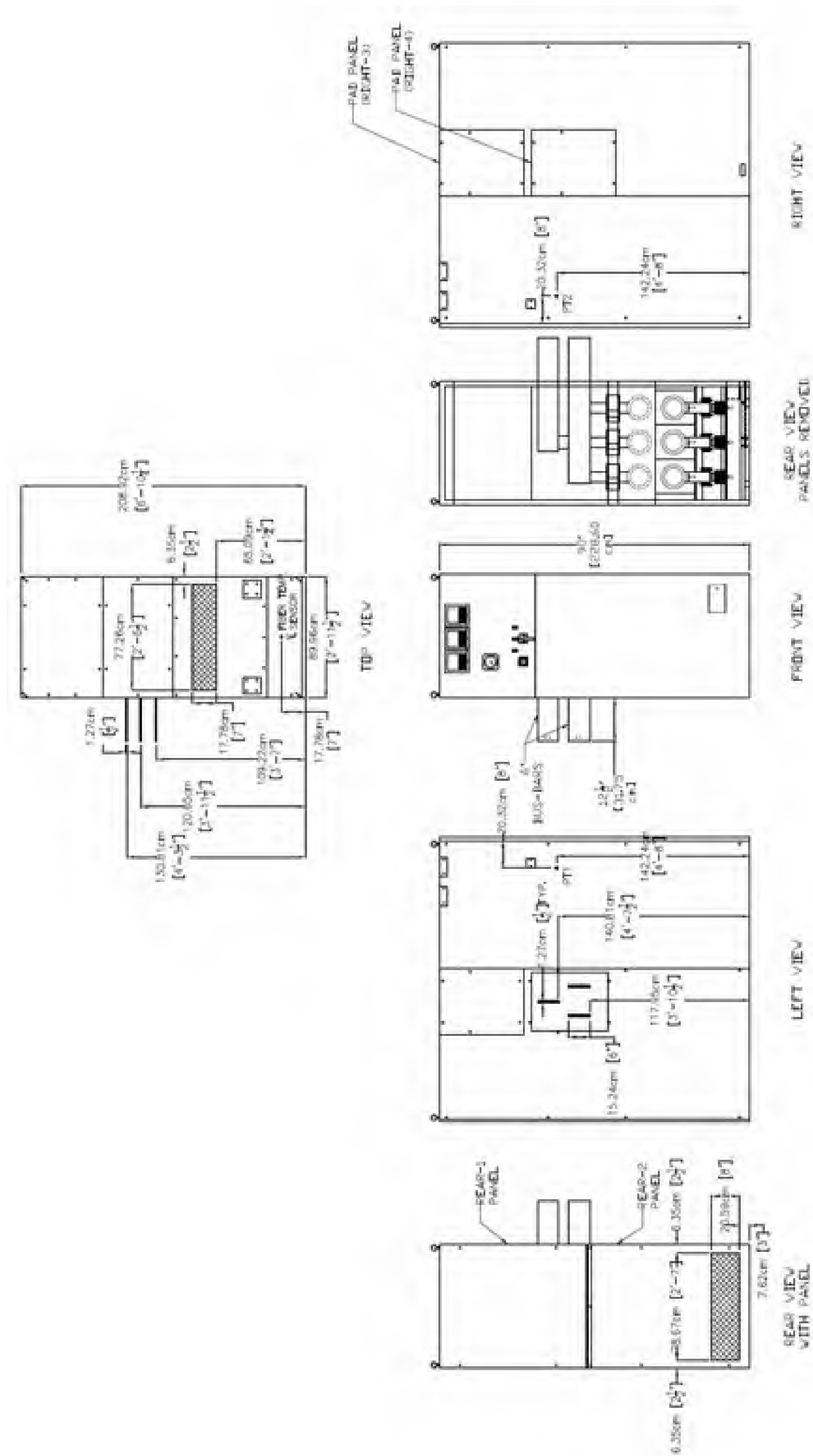

Fig. 97. Medium-voltage draw-out type switchgear dimensional drawing (ITE Type HK).

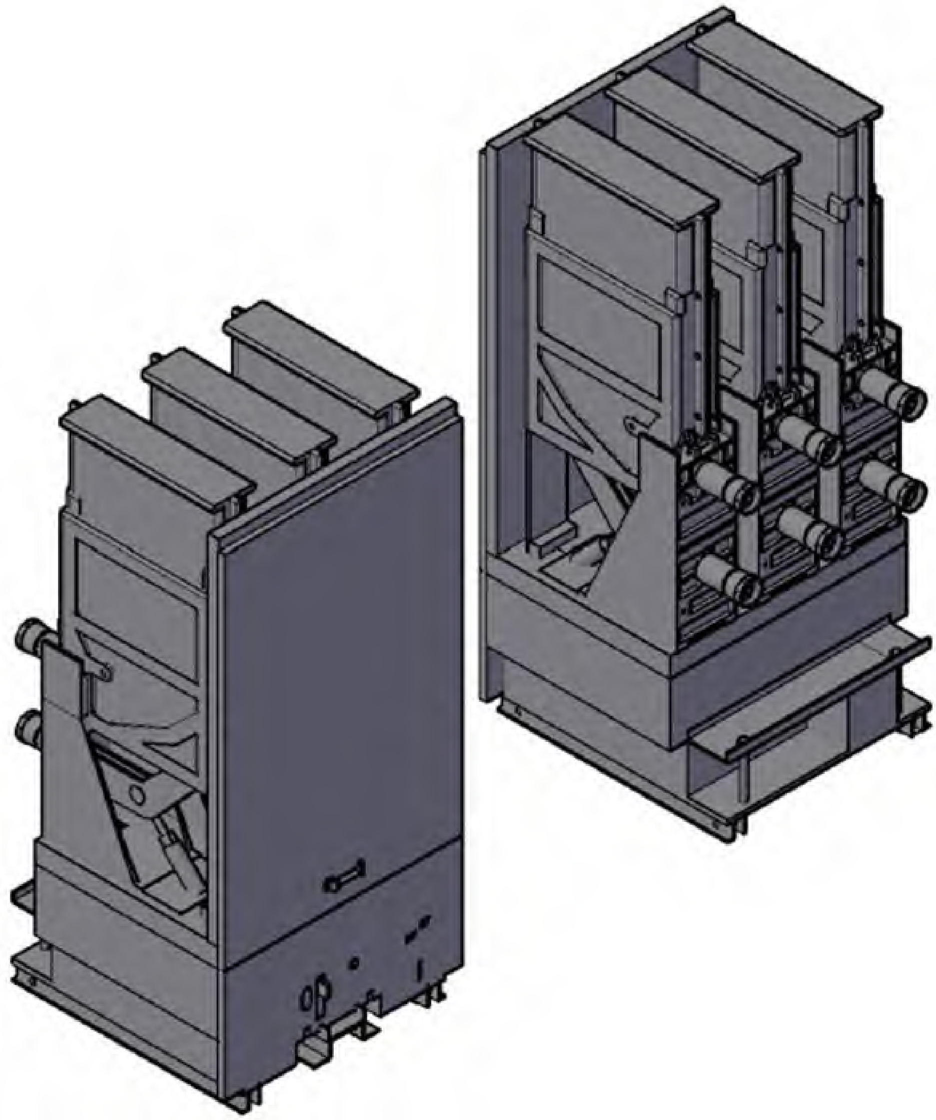

Fig. 98. Isometric drawing of medium-voltage horizontal draw-out style breaker (I-T-E Power Circuit Breakers Type 7.5 HK 500 circuit breaker).

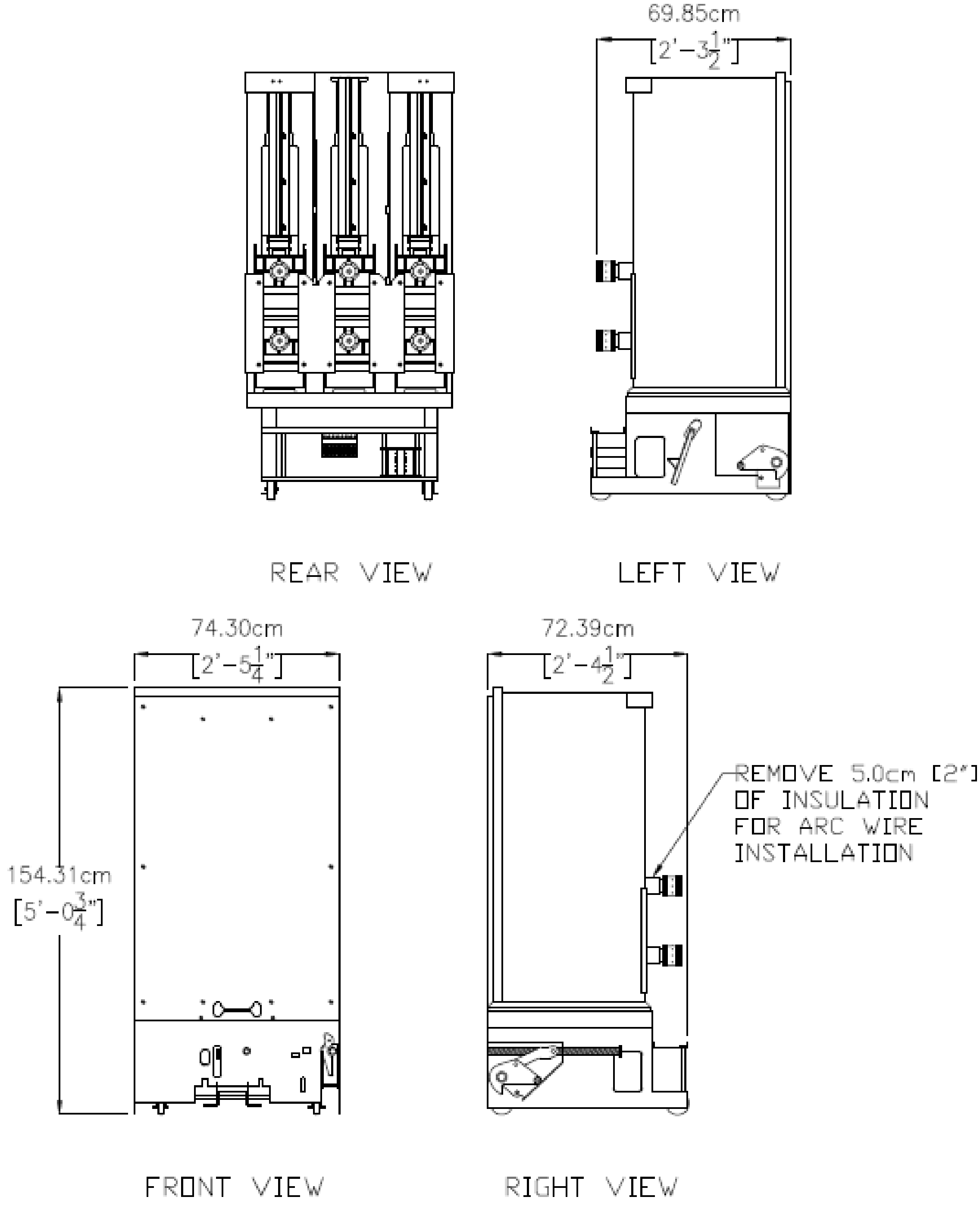

Fig. 99. Dimensional drawing of medium-voltage horizontal draw-out style breaker (I-T-E Power Circuit Breakers Type 7.5 HK 500 circuit breaker).

Drawings of the medium-voltage vertical lift style breakers manufactured by General Electric Type M-36 are presented in Fig. 100, Fig. 101, and Fig. 102.

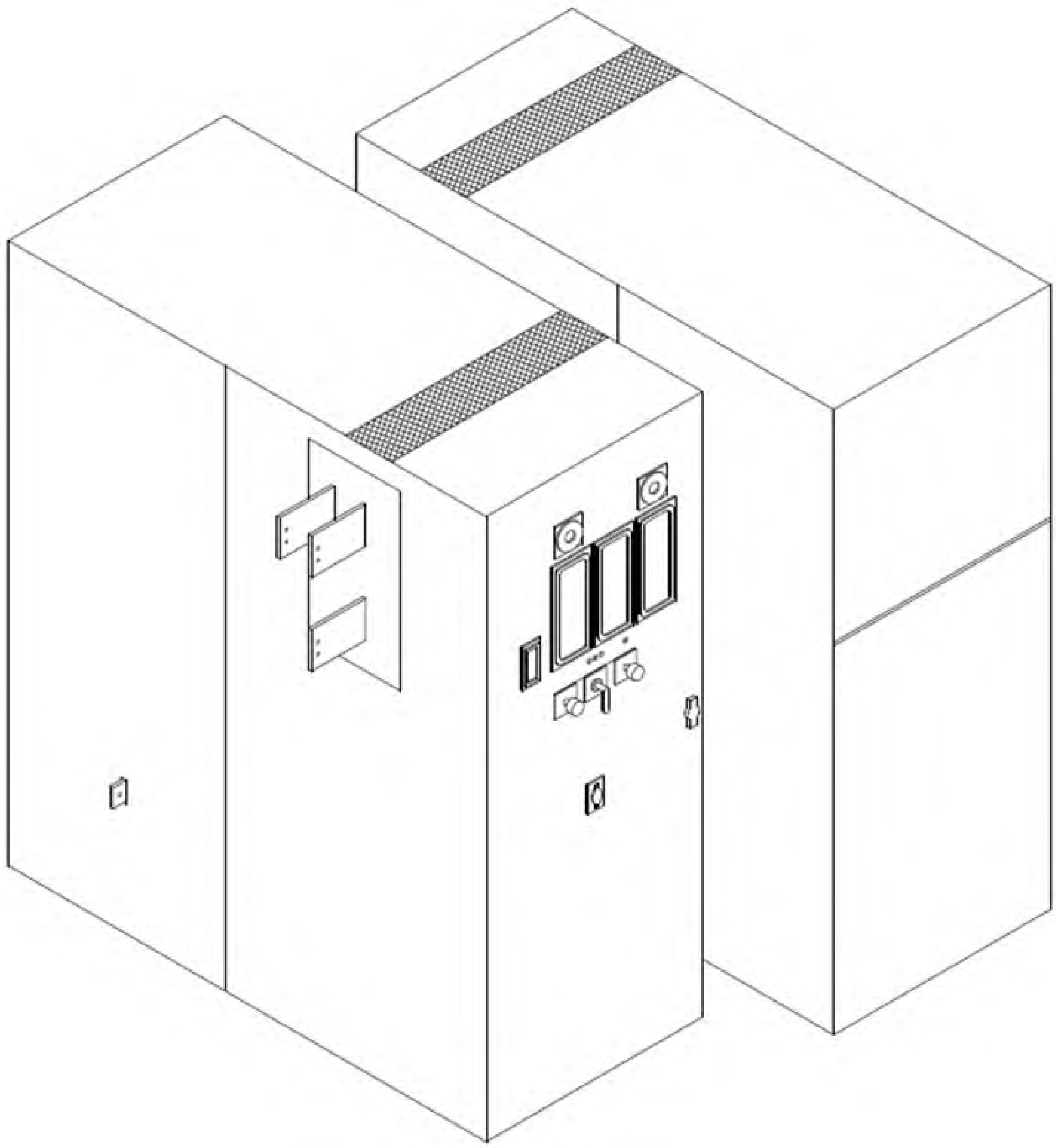

Fig. 100. Isometric drawing of medium-voltage vertical lift switchgear (General Electric Type M-36).

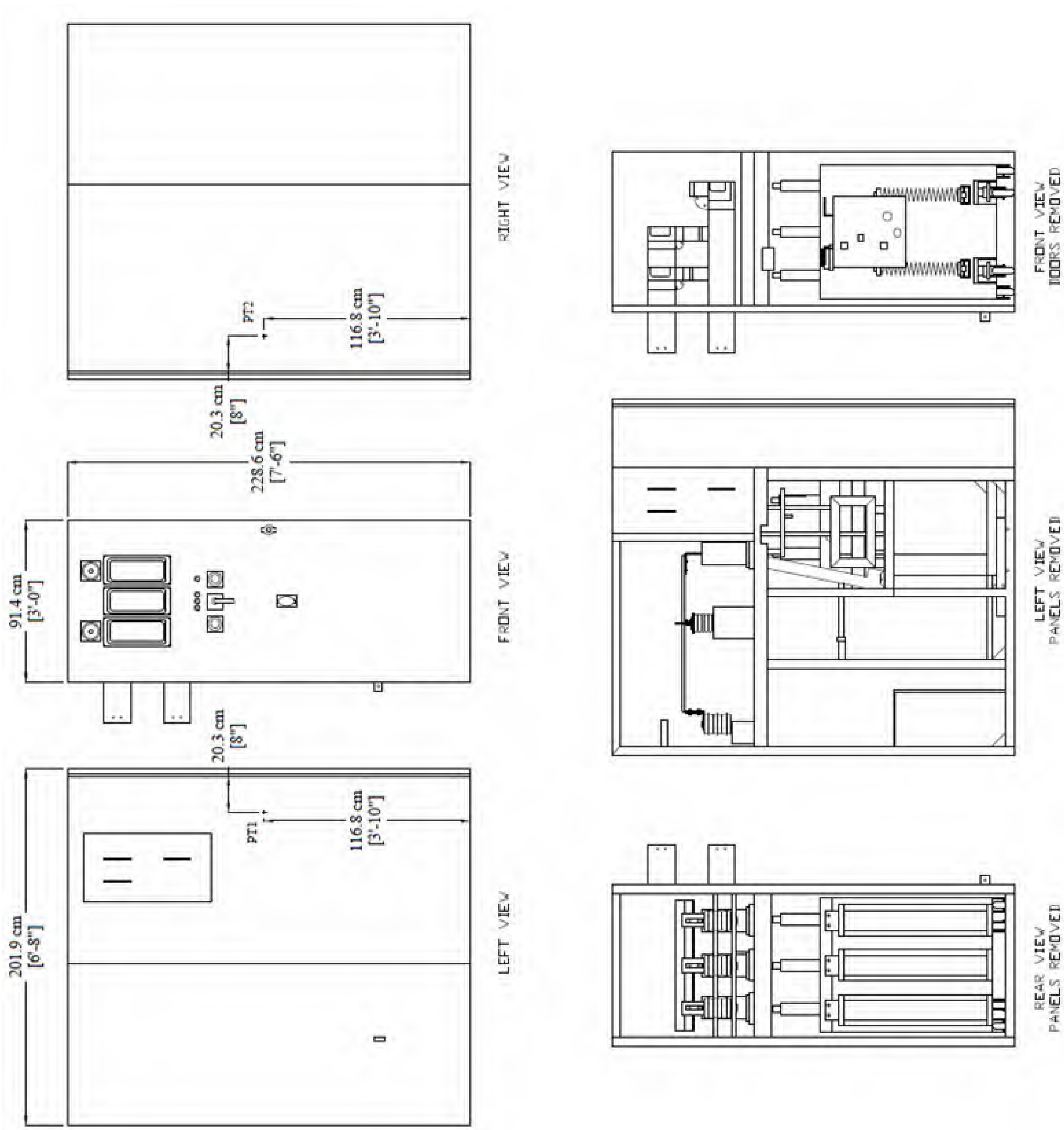

Fig. 101. Dimensional drawing of medium-voltage vertical lift switchgear (General Electric Type M-36).

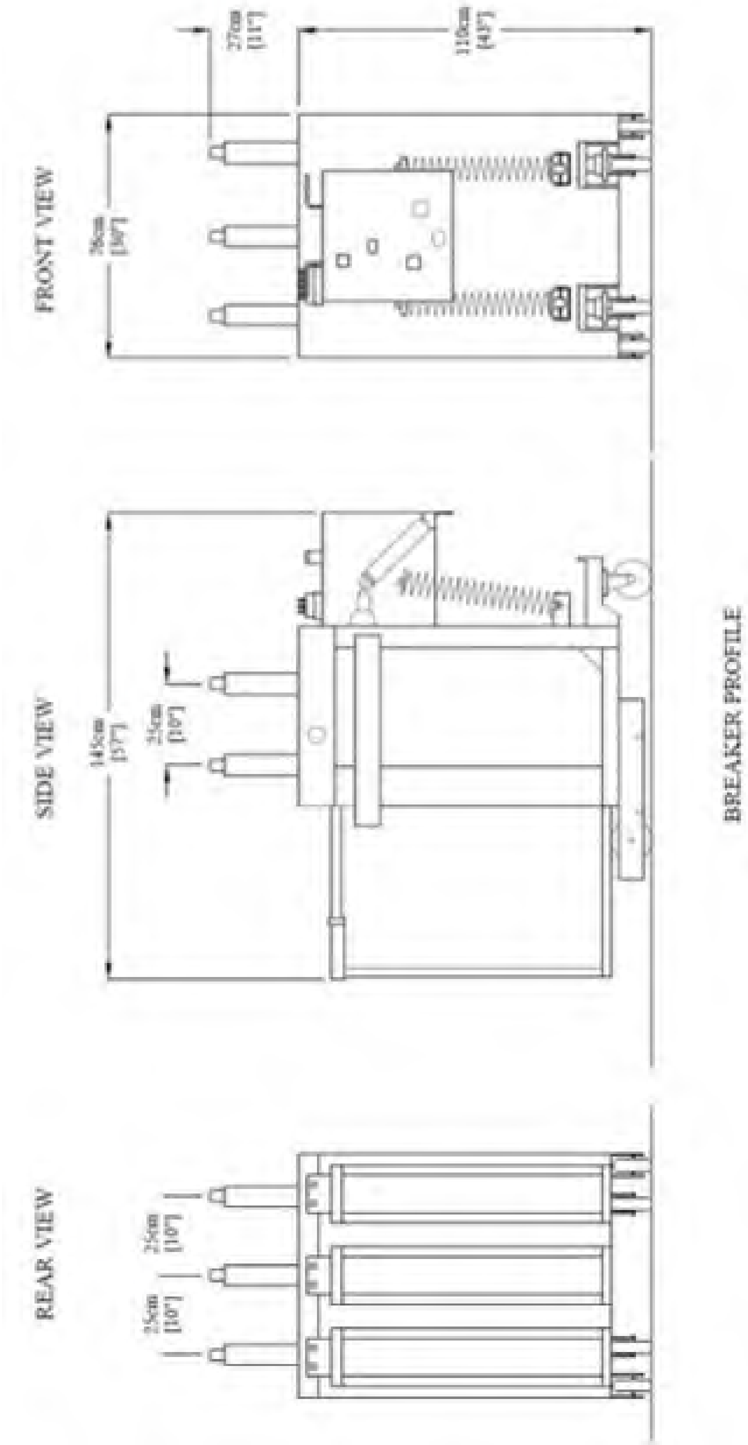

Fig. 102. Drawing of medium-voltage vertical lift breaker (GE Magne-blast Type AM-7.2-500 circuit breaker).

Drawings of medium-voltage SF6 switchgear donated by OECD/NEA HEAF 2 member countries are presented in Fig. 103 and Fig. 104.

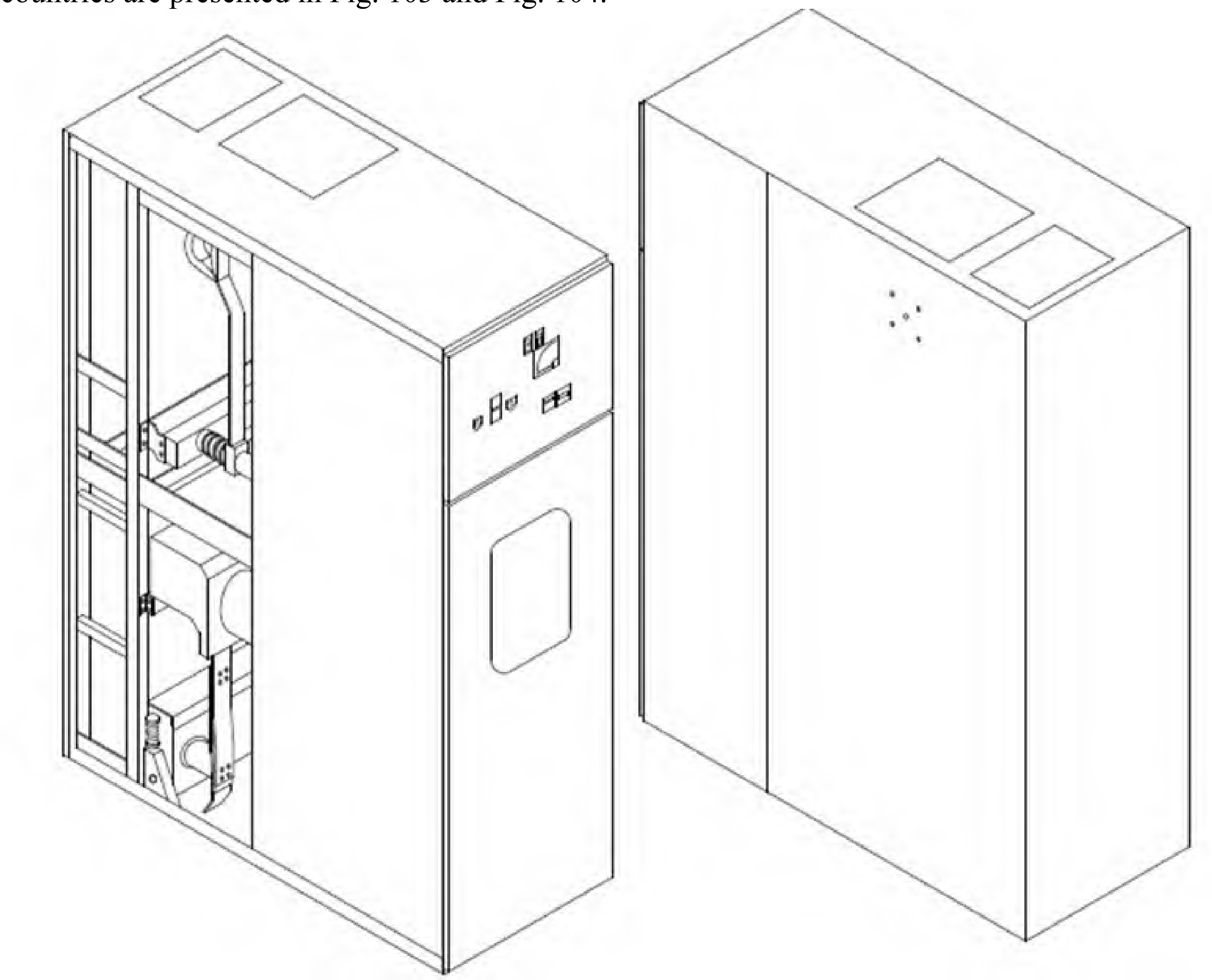

Fig. 103. Isometric drawing of medium-voltage SF6 switchgear donated by OECD/NEA HEAF 2 member country.

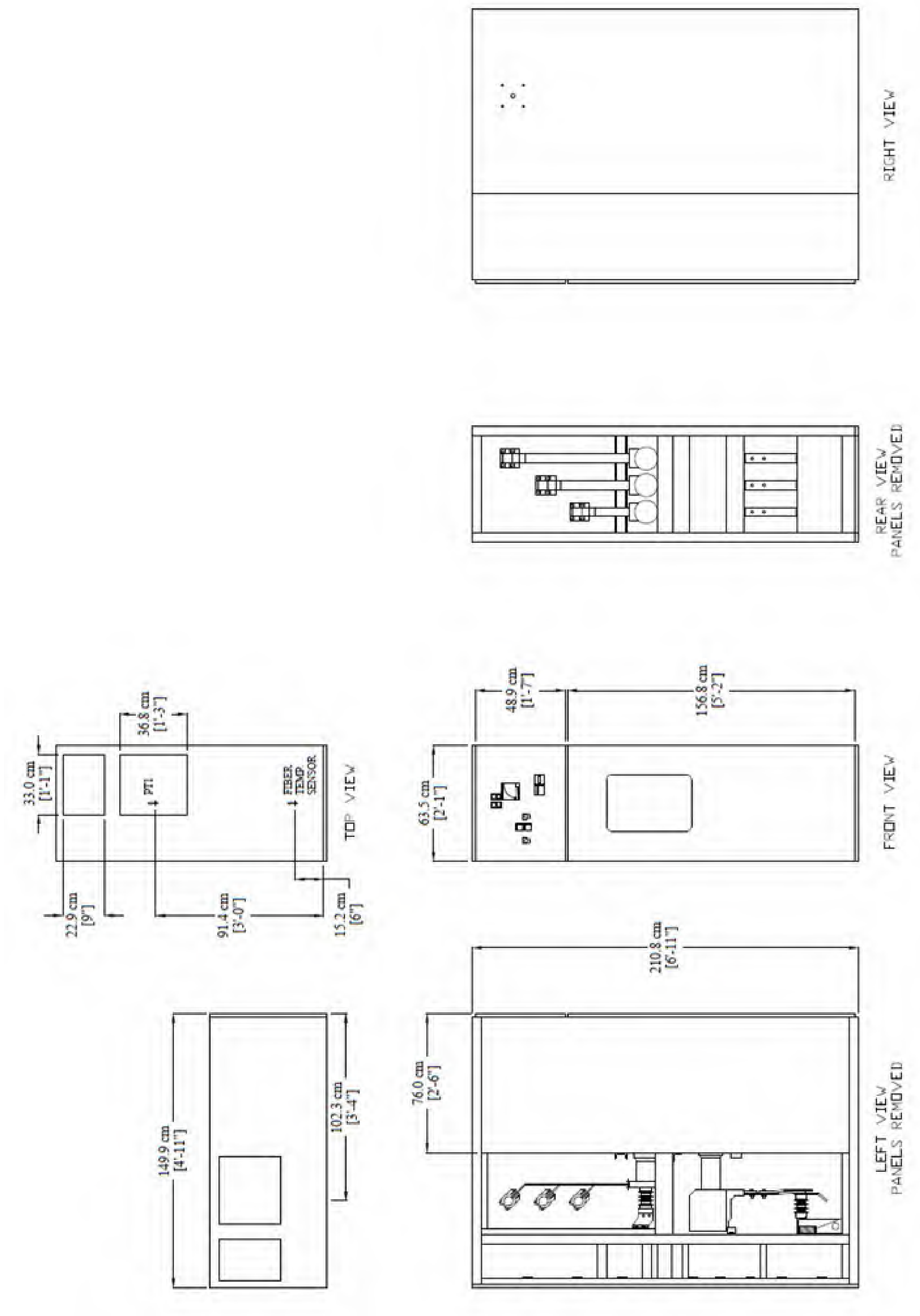

Fig. 104. Dimensional drawing of medium-voltage SF6 switchgear donated by OECD/NEA HEAF 2 member country.

Drawings for the medium-voltage non-segregated bus duct are shown in Fig. 105 through Fig. 108.

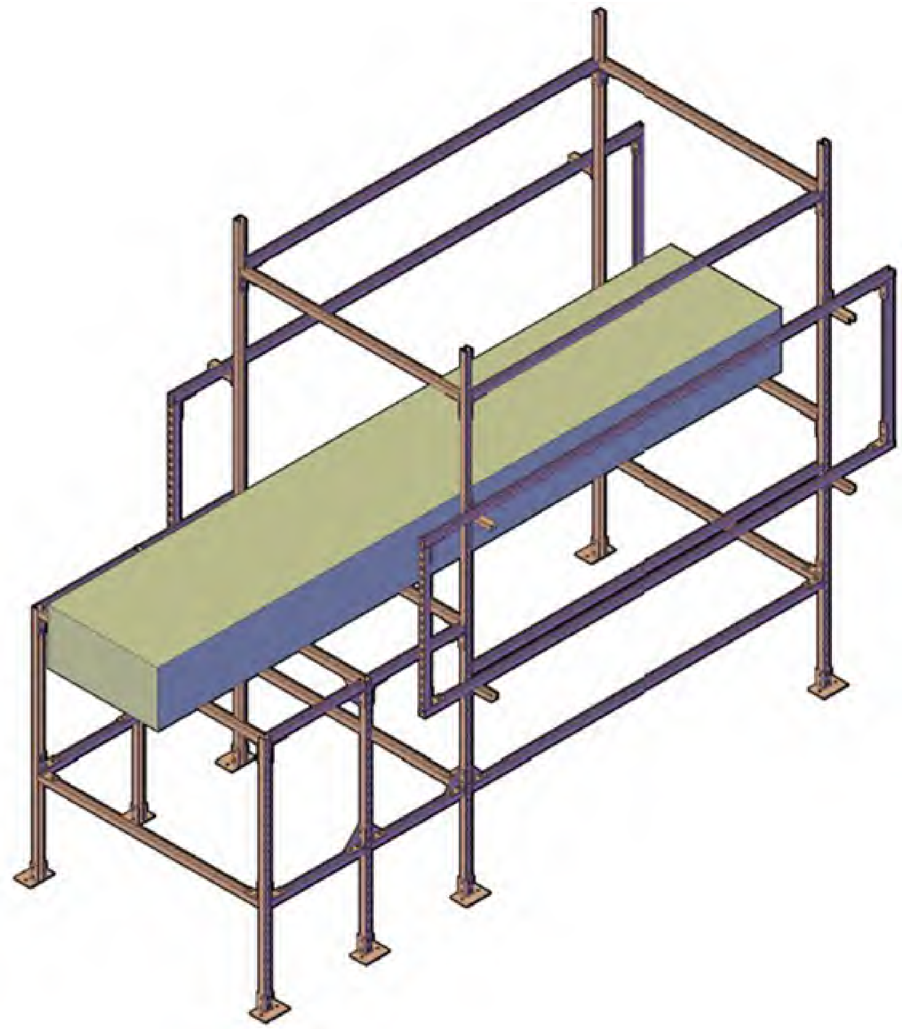

Fig. 105. Isometric drawing of general bus duct experiment configuration.

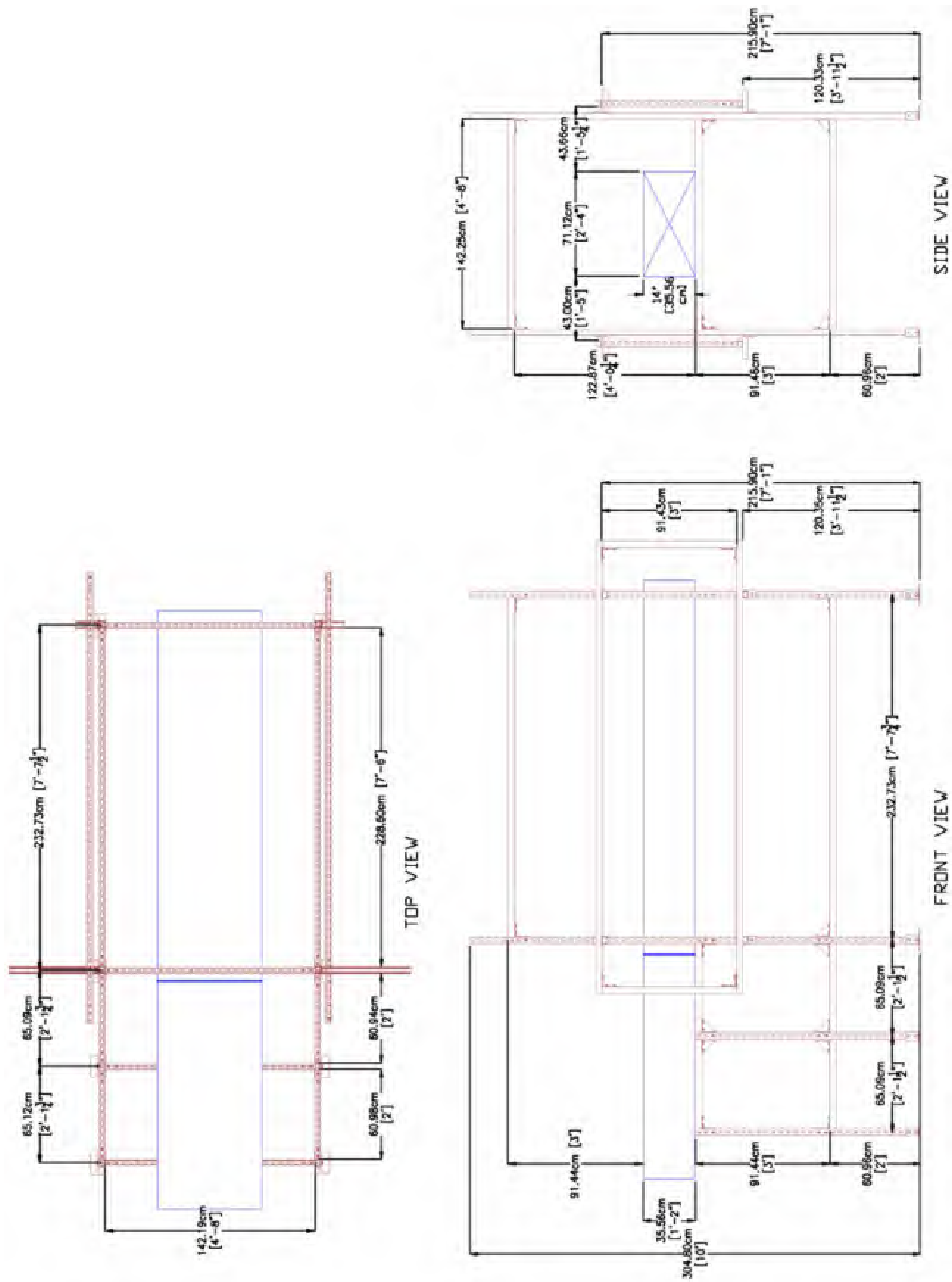

Fig. 106. Dimensional drawing of bus duct support structure.

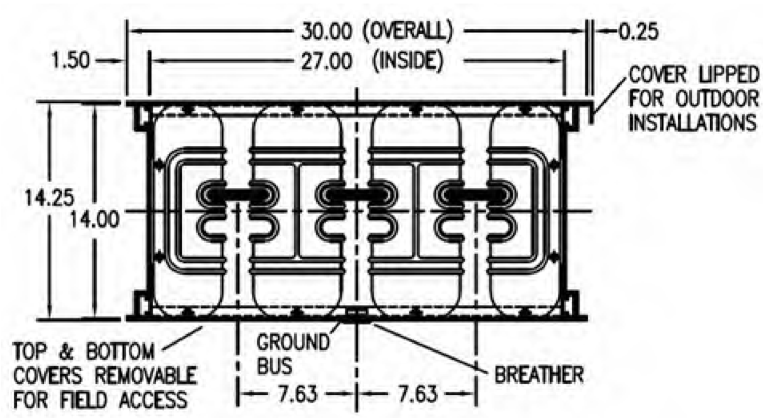

Fig. 107. Cross-section of Experiment 2-40 bus duct (Note measurements in inches approximated from manufacturer).

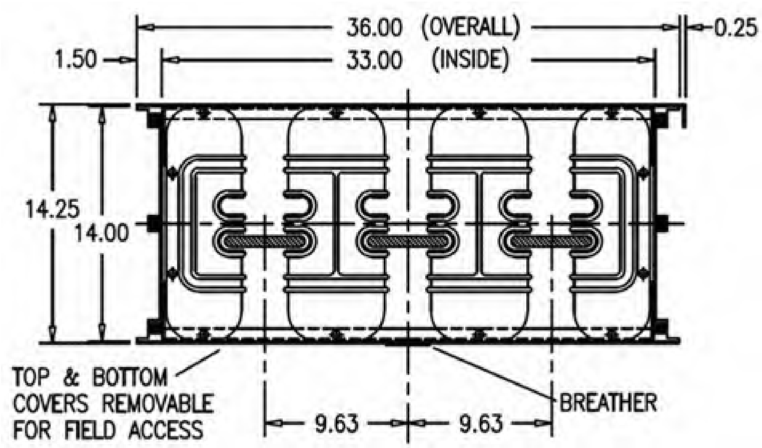

Fig. 108. Cross-section of Experiment 2-41 bus duct (Note measurements in inches approximated from manufacturer).

A.3. Support Drawings

Drawings of the ASTM slug calorimeter are presented in Fig. 109 and Fig. 110.

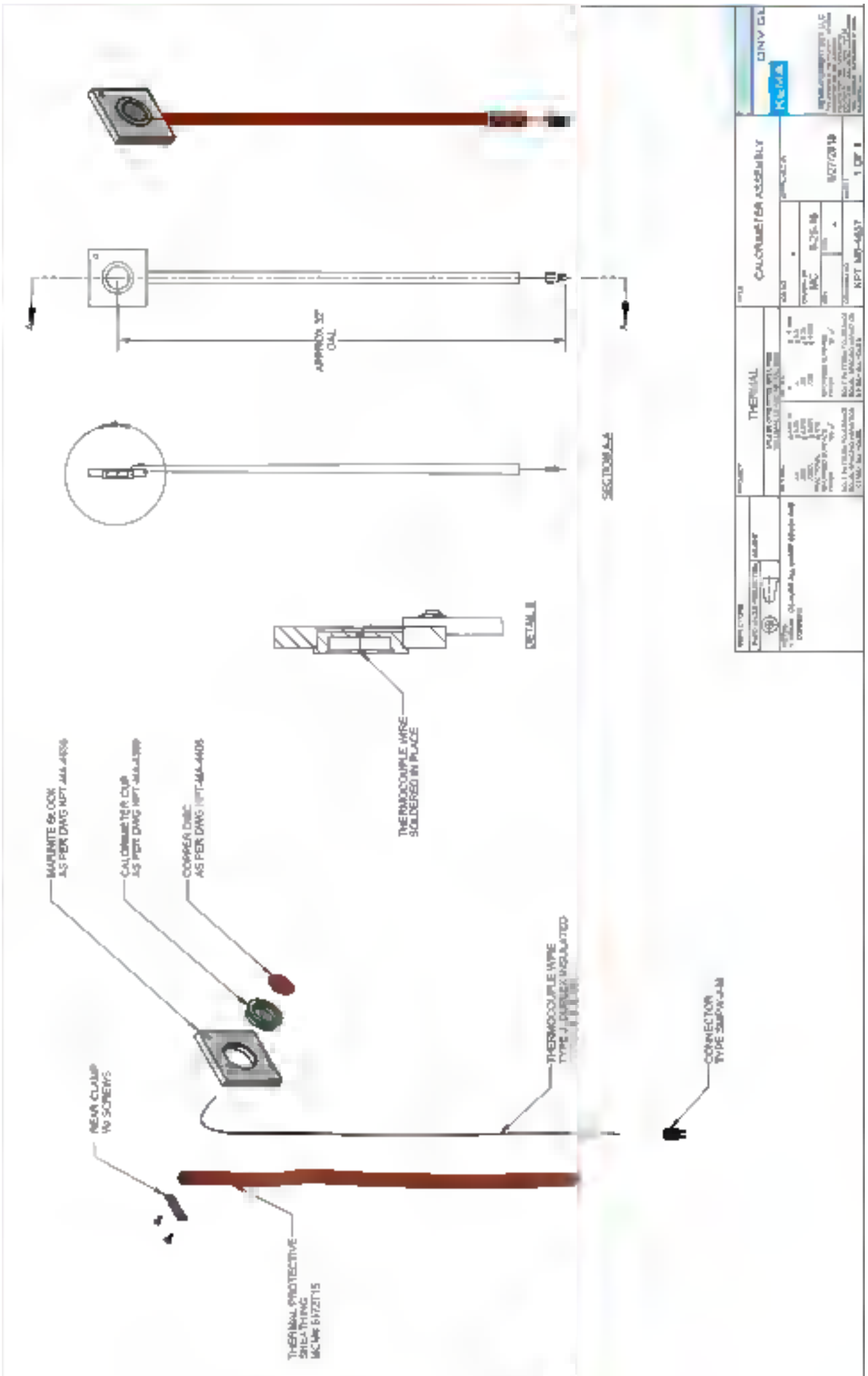

Fig. 109. Drawing KPT-MB-4657, ASTM Calorimeter Assembly.

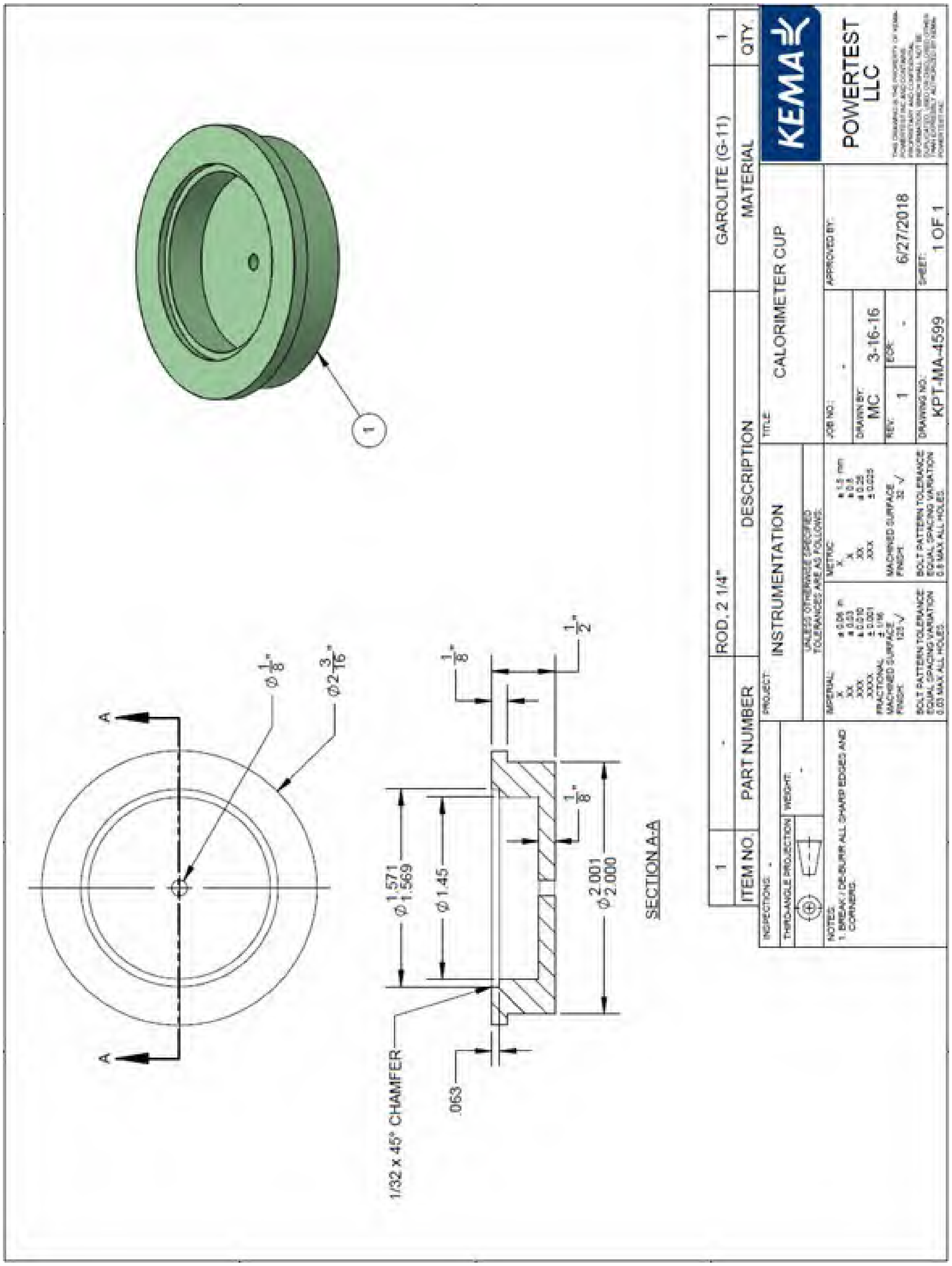

Fig. 110. Drawing KPT-MA-4599, ASTM Calorimeter Cup.

A.4. Instrumentation Racks

A.4.1. Medium-Voltage Switchgear Instrument Rack Drawings

Instrumentation rack drawings for switchgear experiments 2-35, 2-36, 2-37, 2-38, and 2-39 are shown below in Fig. 111 to Fig. 121.

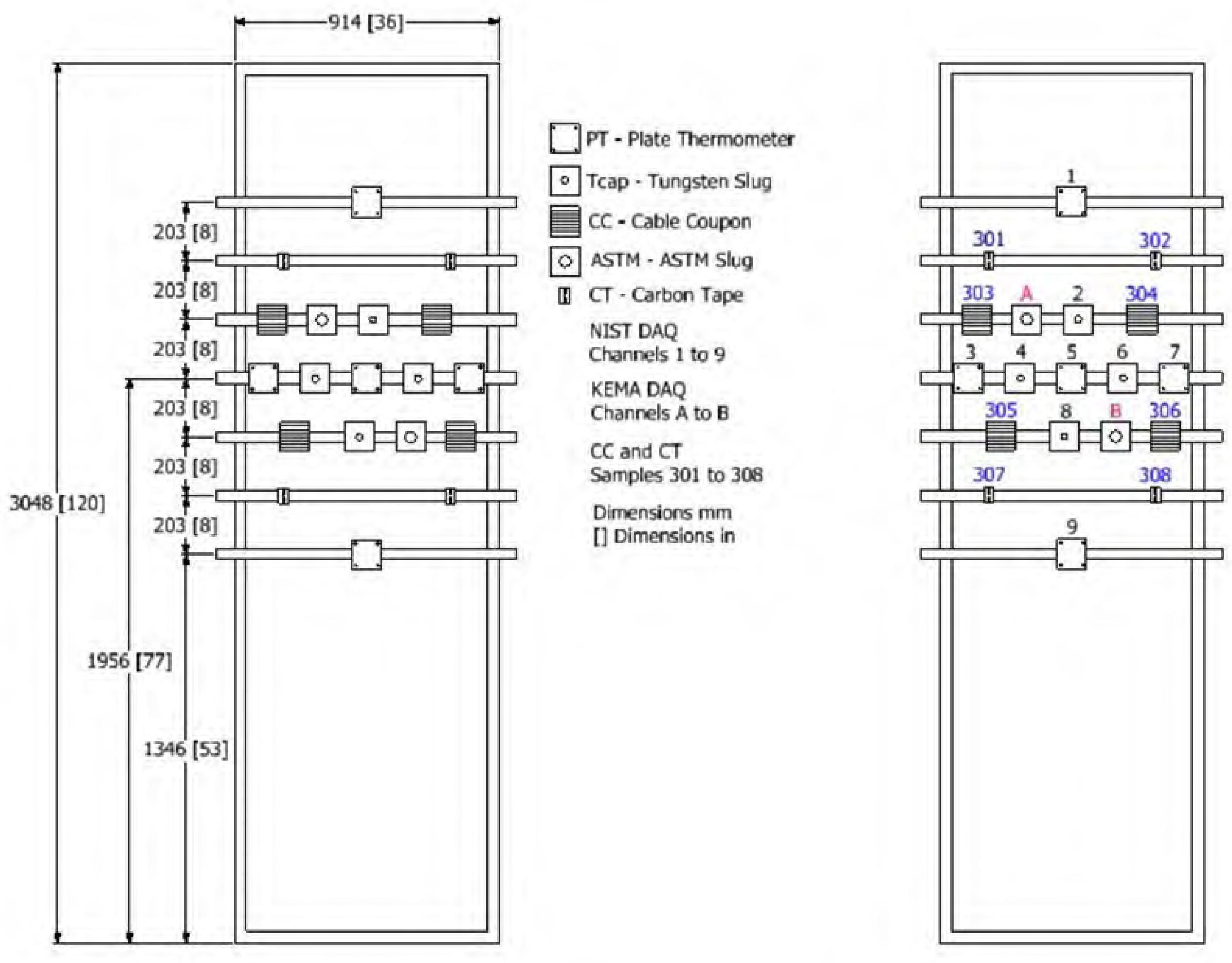

Fig. 111. Experiment 2-35 illustration of Vertical Instrumentation Rack #1 with data acquisition channels. Dimensions in mm ± 5 mm.

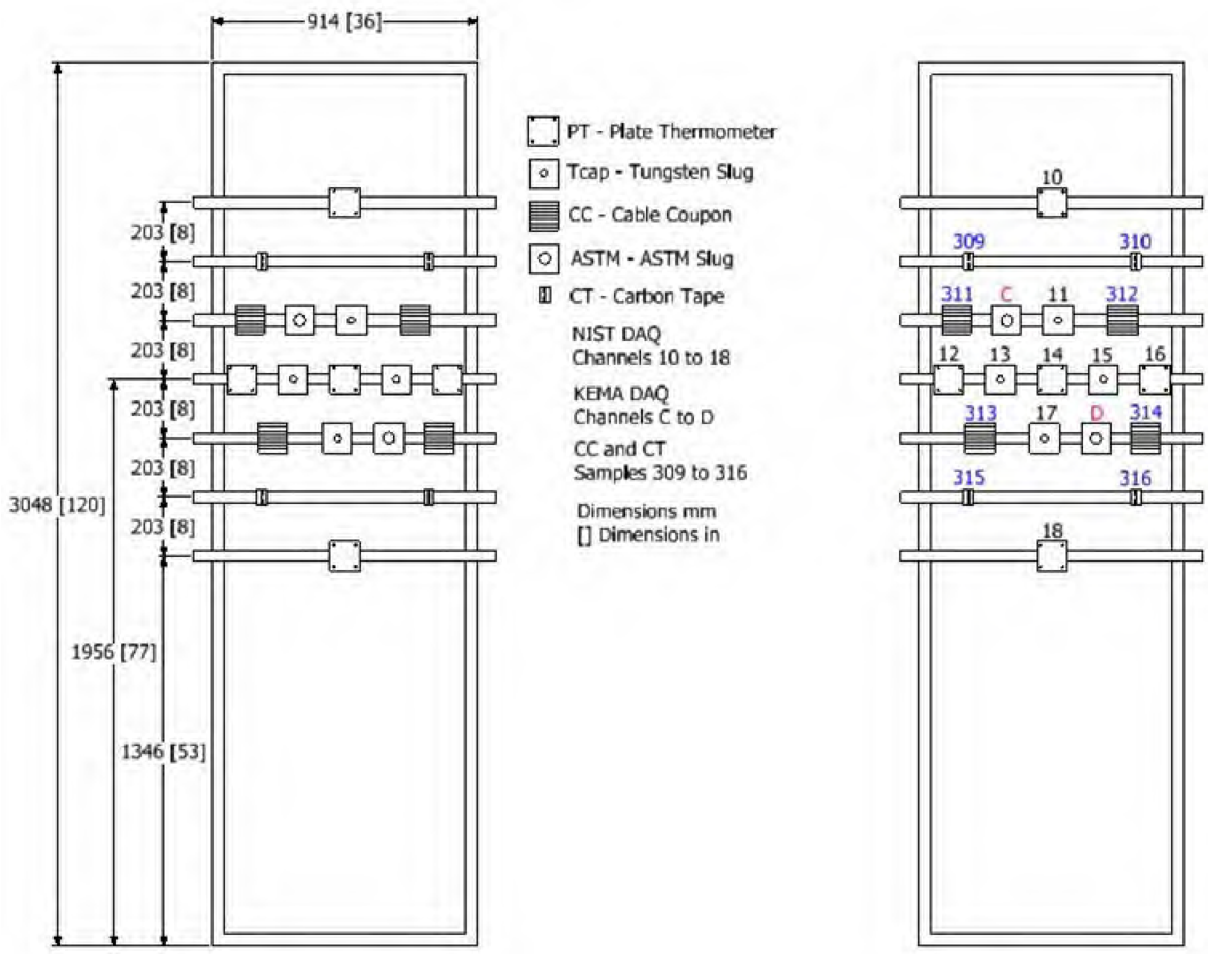

Fig. 112. Experiment 2-35 illustration of Vertical Instrumentation Rack #2 with data acquisition channels. Dimensions in mm ± 5 mm.

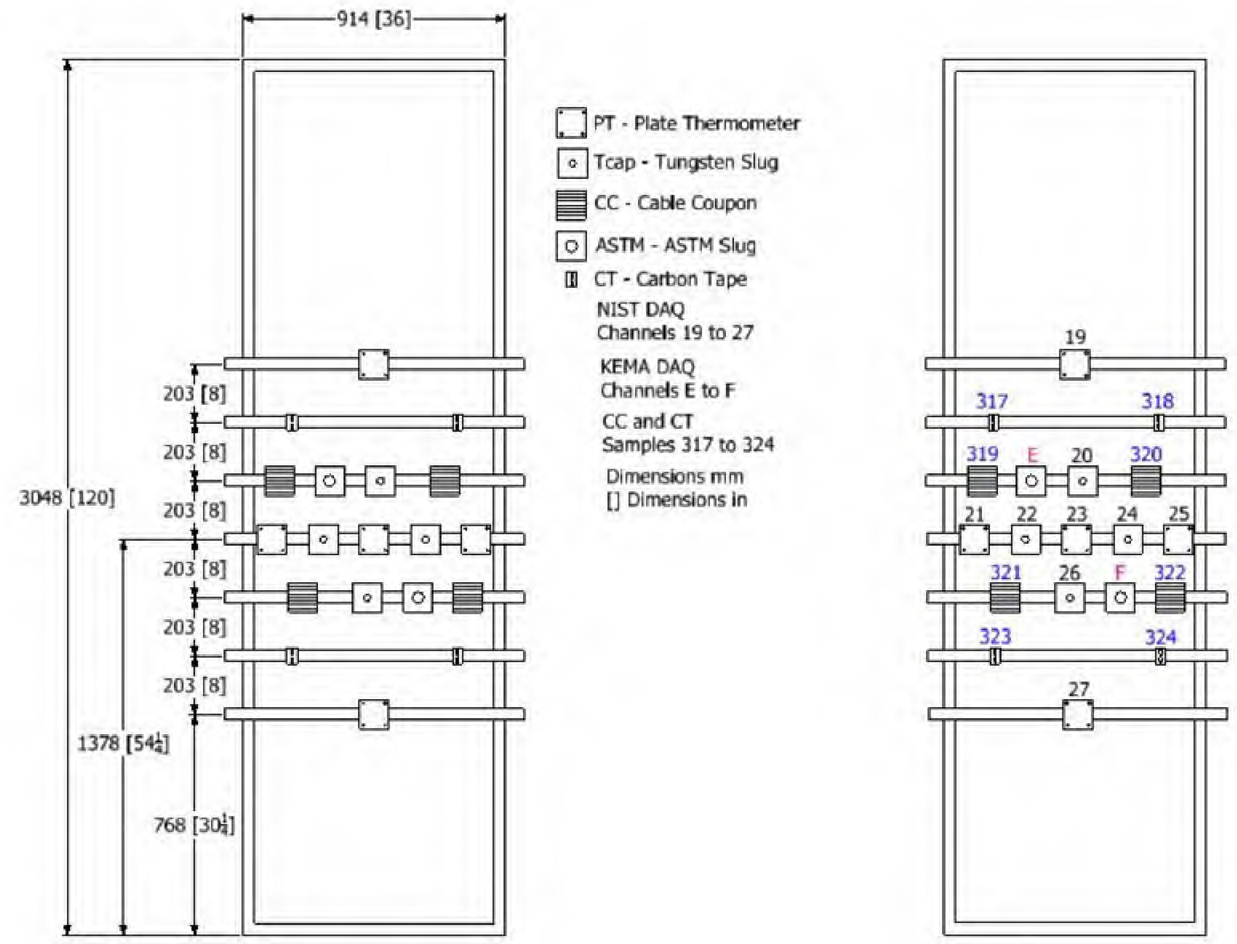

Fig. 113. Experiment 2-35 and 2-36 illustration of Horizontal Instrumentation Rack #3 with data acquisition channels.
Dimensions in mm ± 5 mm.

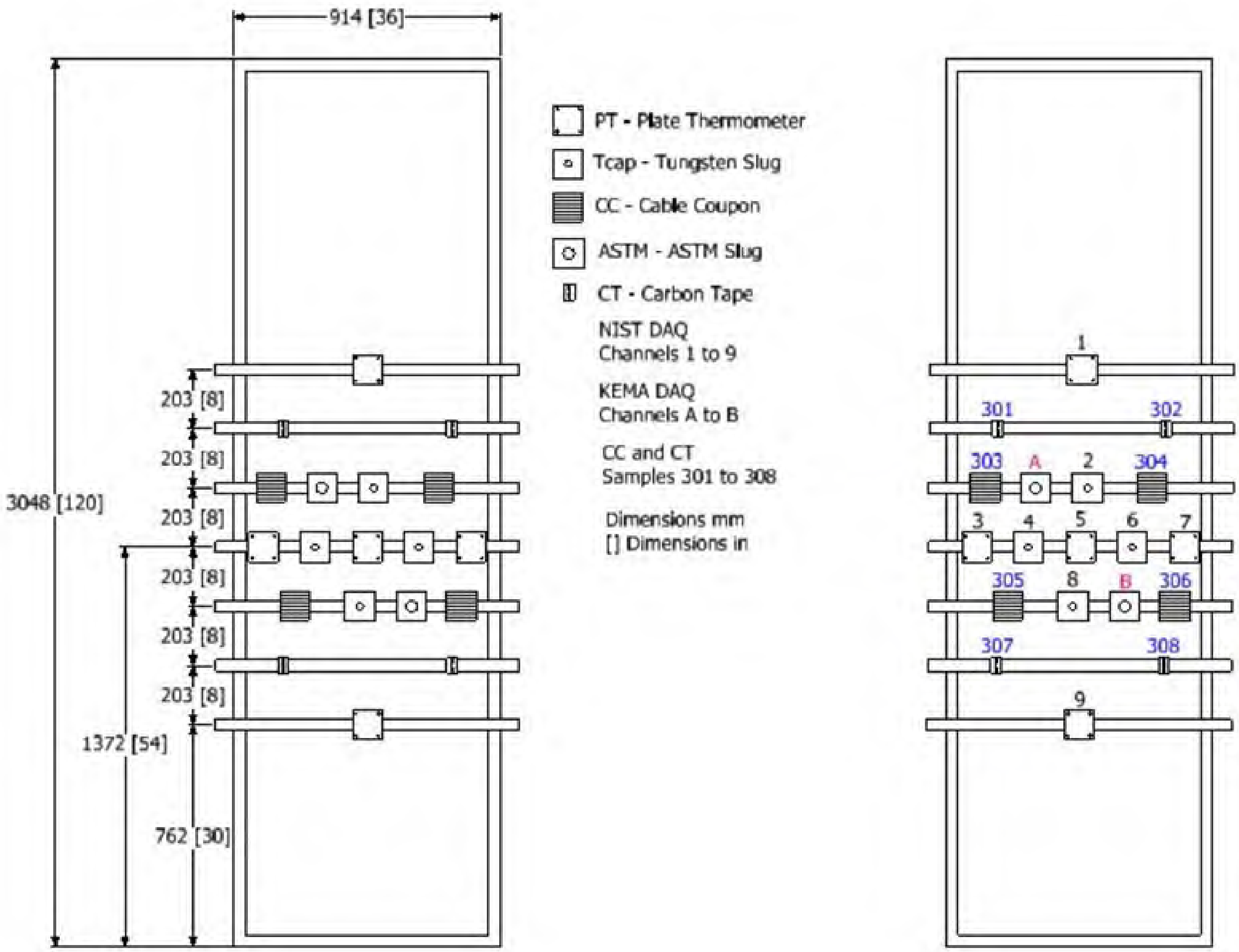

Fig. 114. Experiment 2-36 illustration of Vertical Instrumentation Rack #1 with data acquisition channels. Dimensions in mm ± 5 mm.

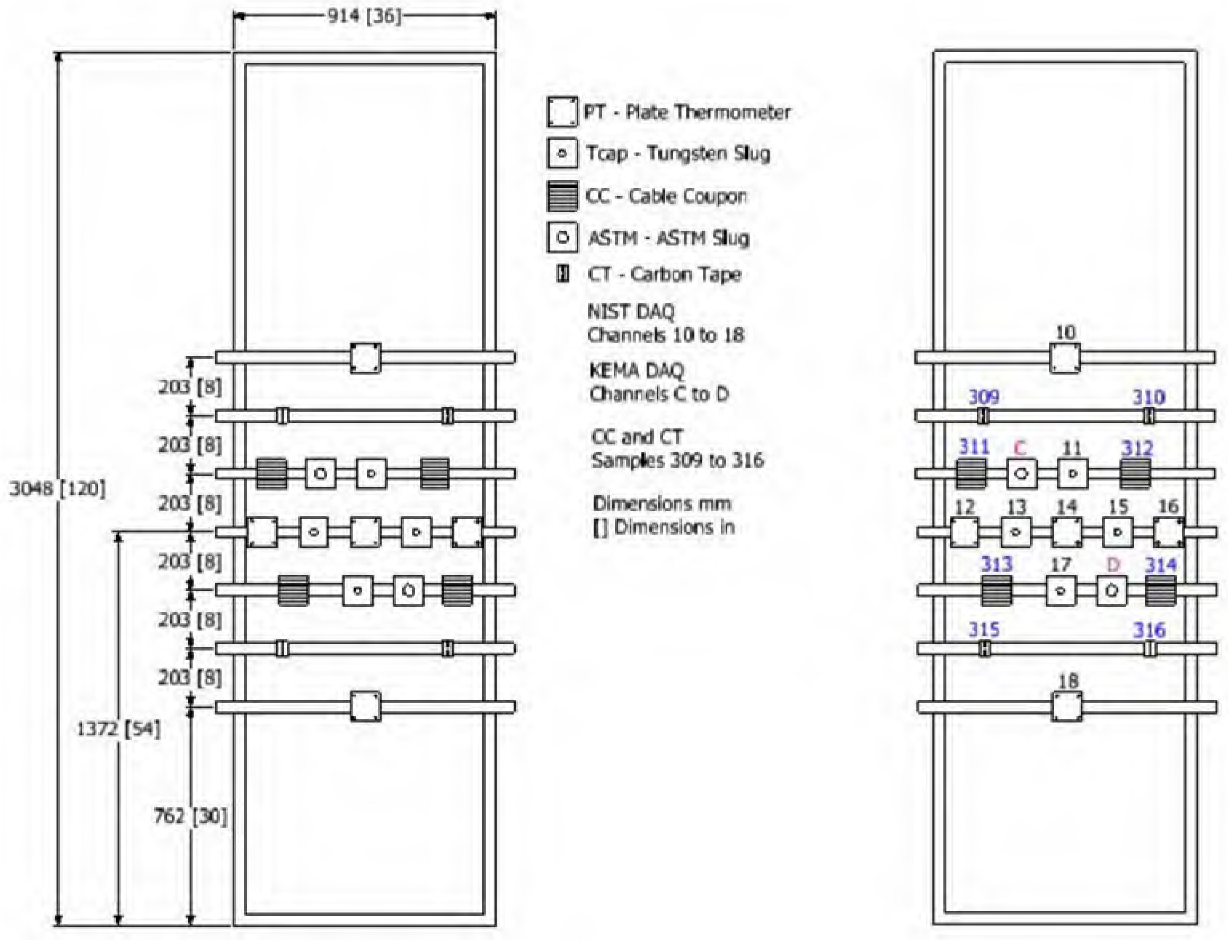

Fig. 115. Experiment 2-36 illustration of Vertical Instrumentation Rack #2 with data acquisition channels. Dimensions in mm ± 5 mm.

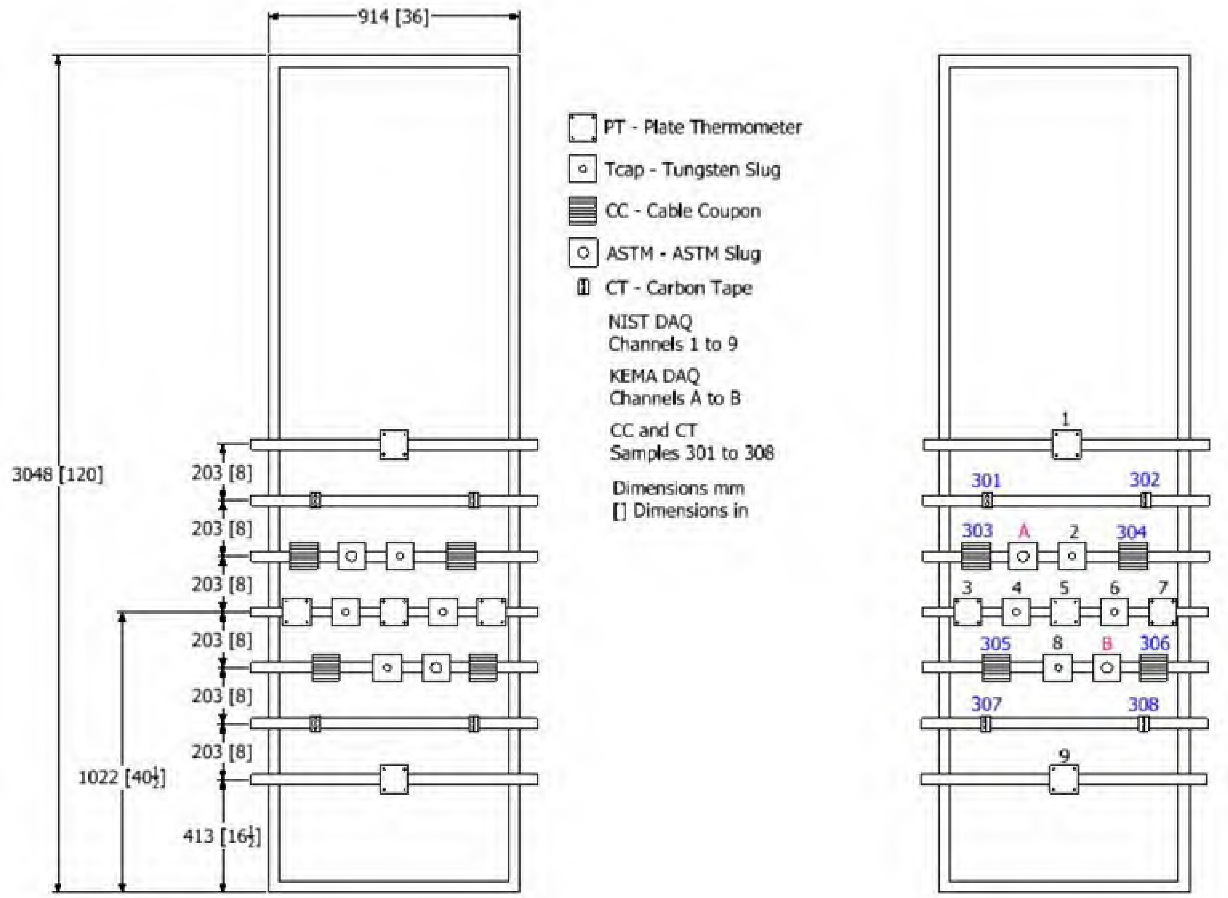

Fig. 116. Experiment 2-37 illustration of Vertical Instrumentation Rack #1 with data acquisition channels. Dimensions in mm ± 5 mm.

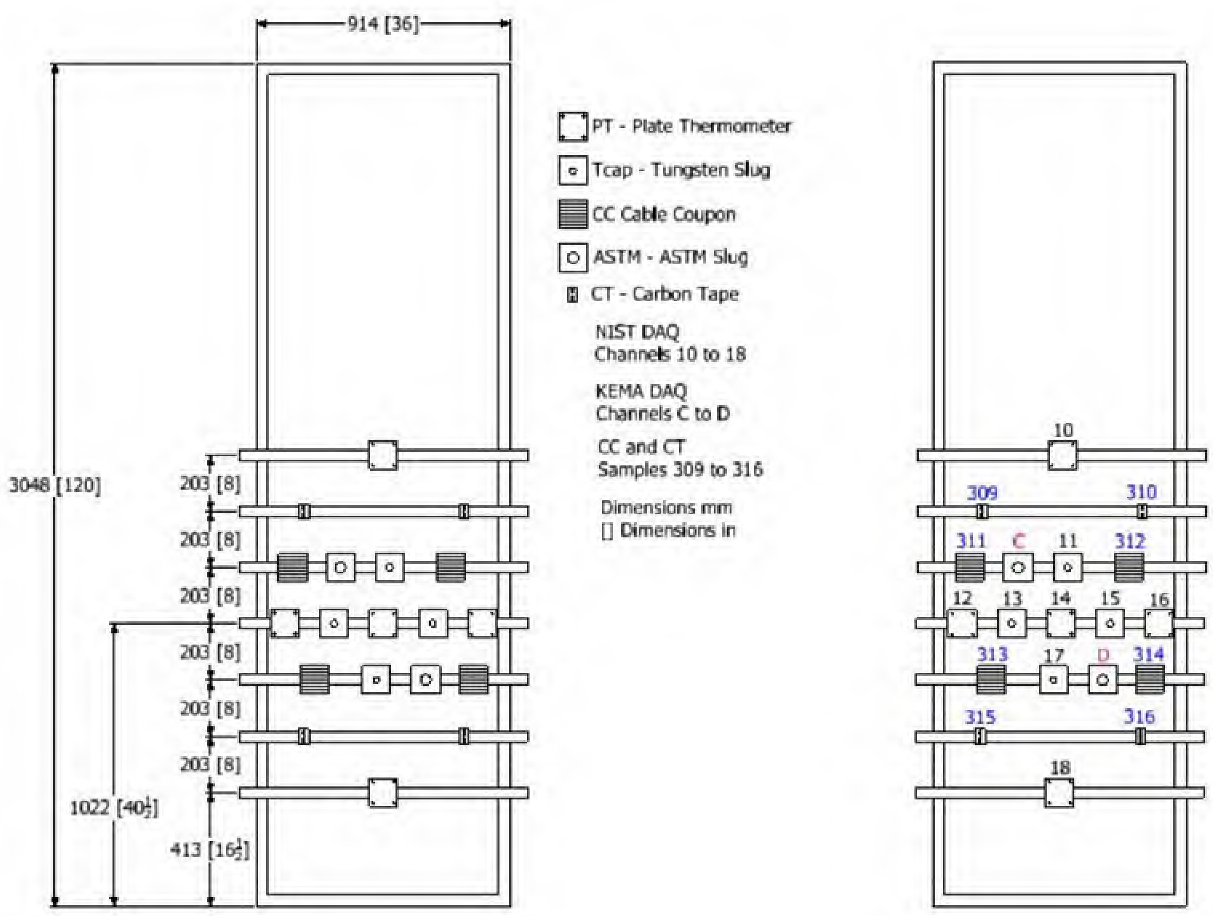

Fig. 117. Experiment 2-37 illustration of Vertical Instrumentation Rack #2 with data acquisition channels. Dimensions in mm ± 5 mm.

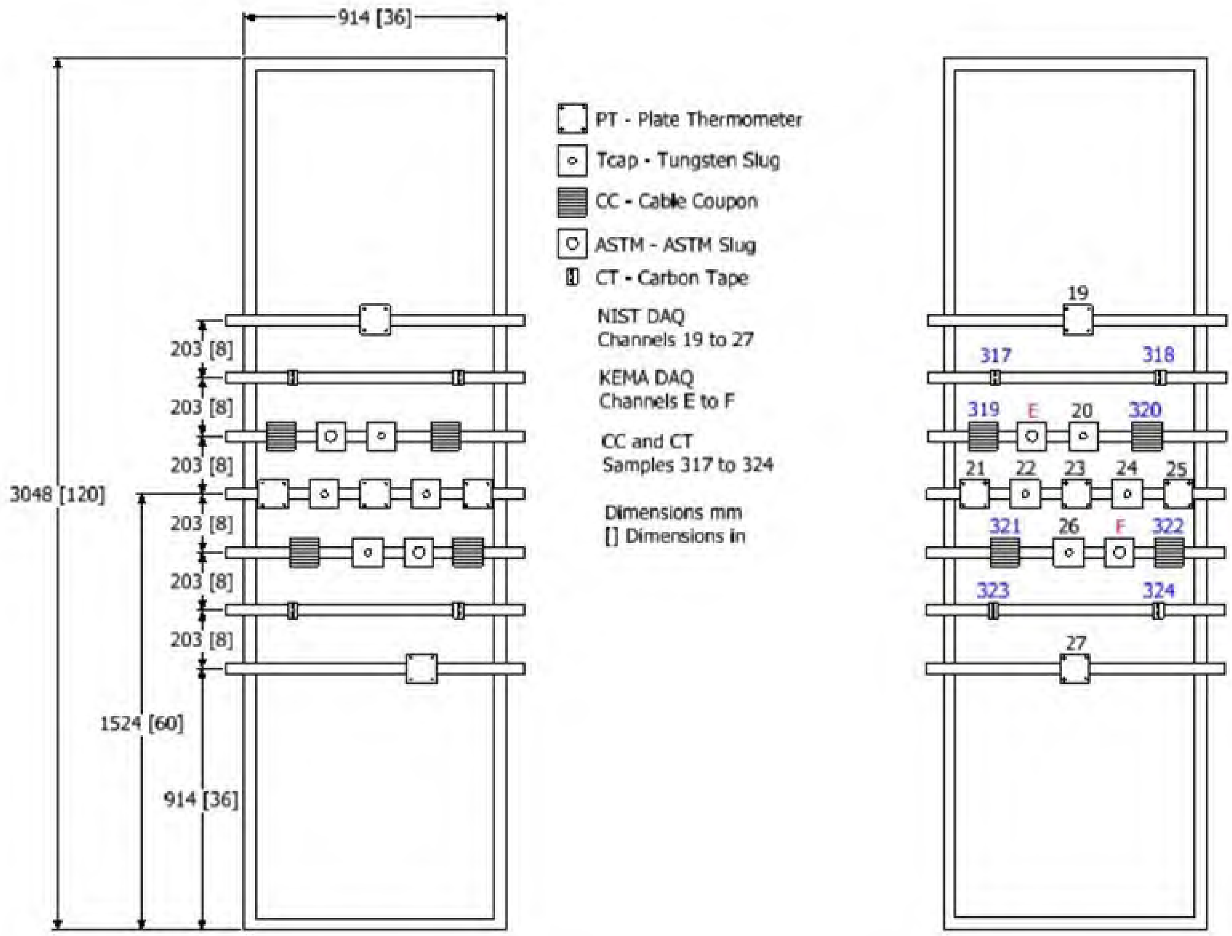

Fig. 118. Experiment 2-37 illustration of Horizontal Instrumentation Rack #3 with data acquisition channels. Dimensions in mm ± 5 mm.

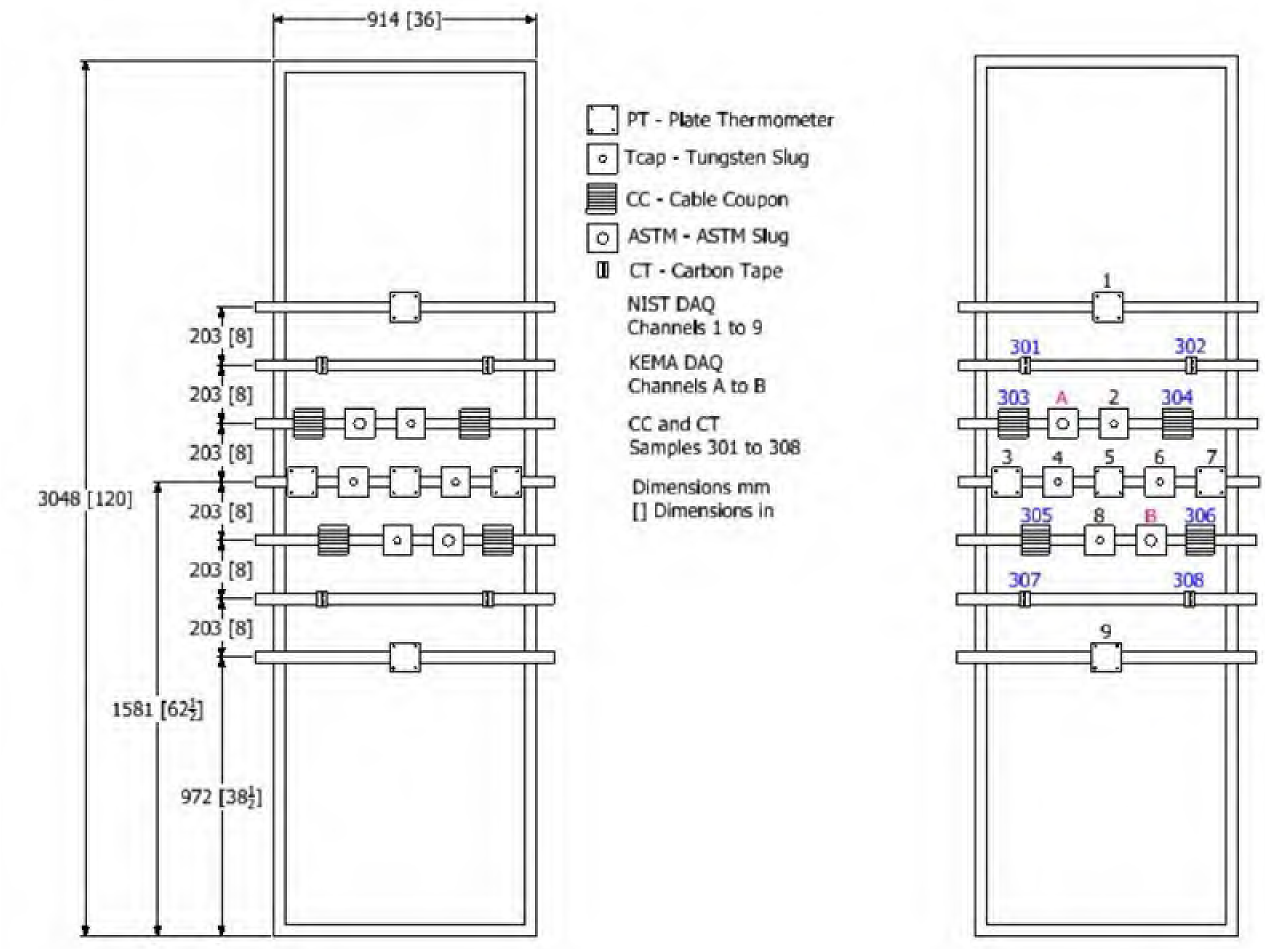

Fig. 119. Experiment 2-38 and 2-39 illustration of Vertical Instrumentation Rack #1 with data acquisition channels. Dimensions in mm ± 5 mm.

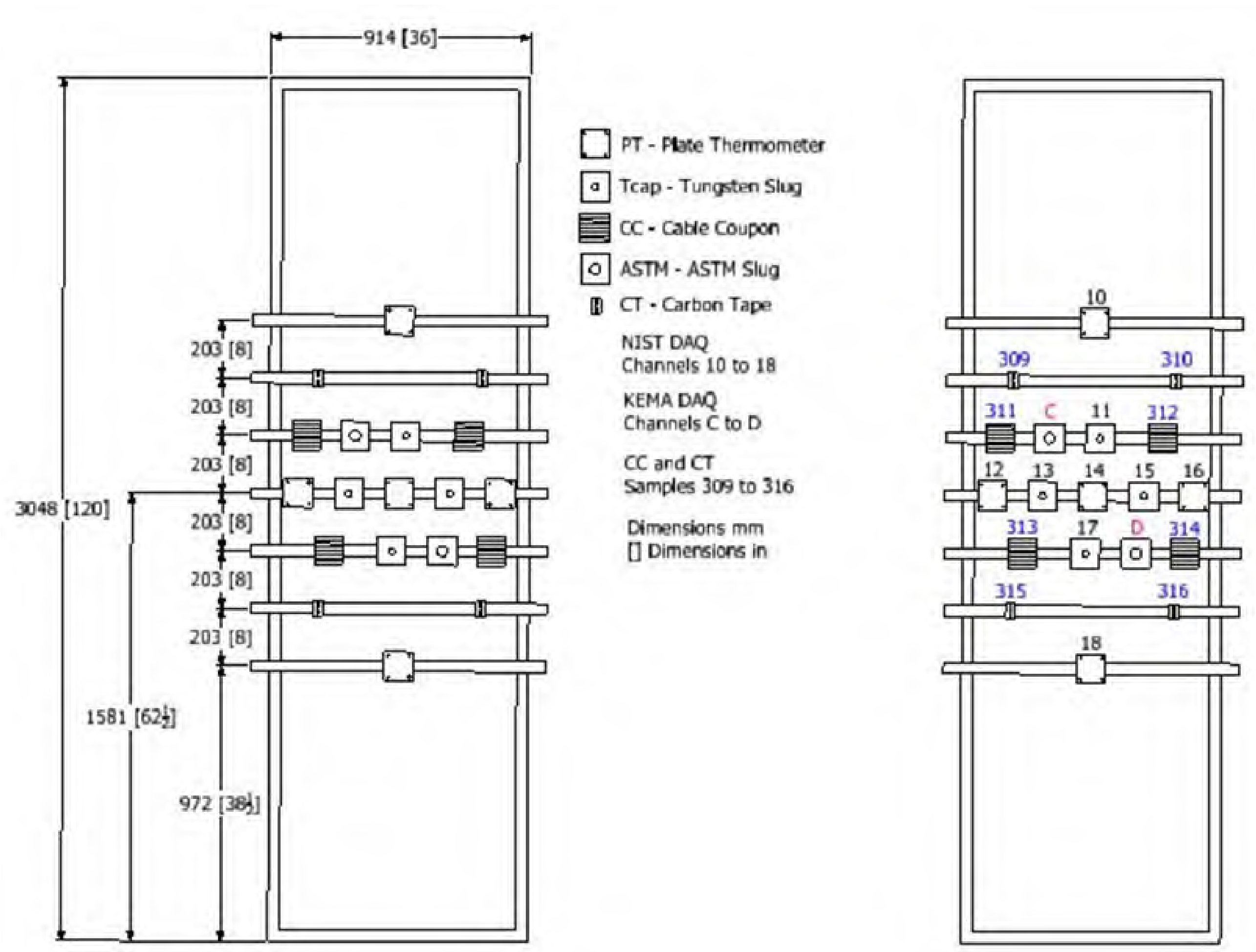

Fig. 120. Experiment 2-38 and 2-39 illustration of Vertical Instrumentation Rack #2 with data acquisition channels. Dimensions in mm ± 5 mm.

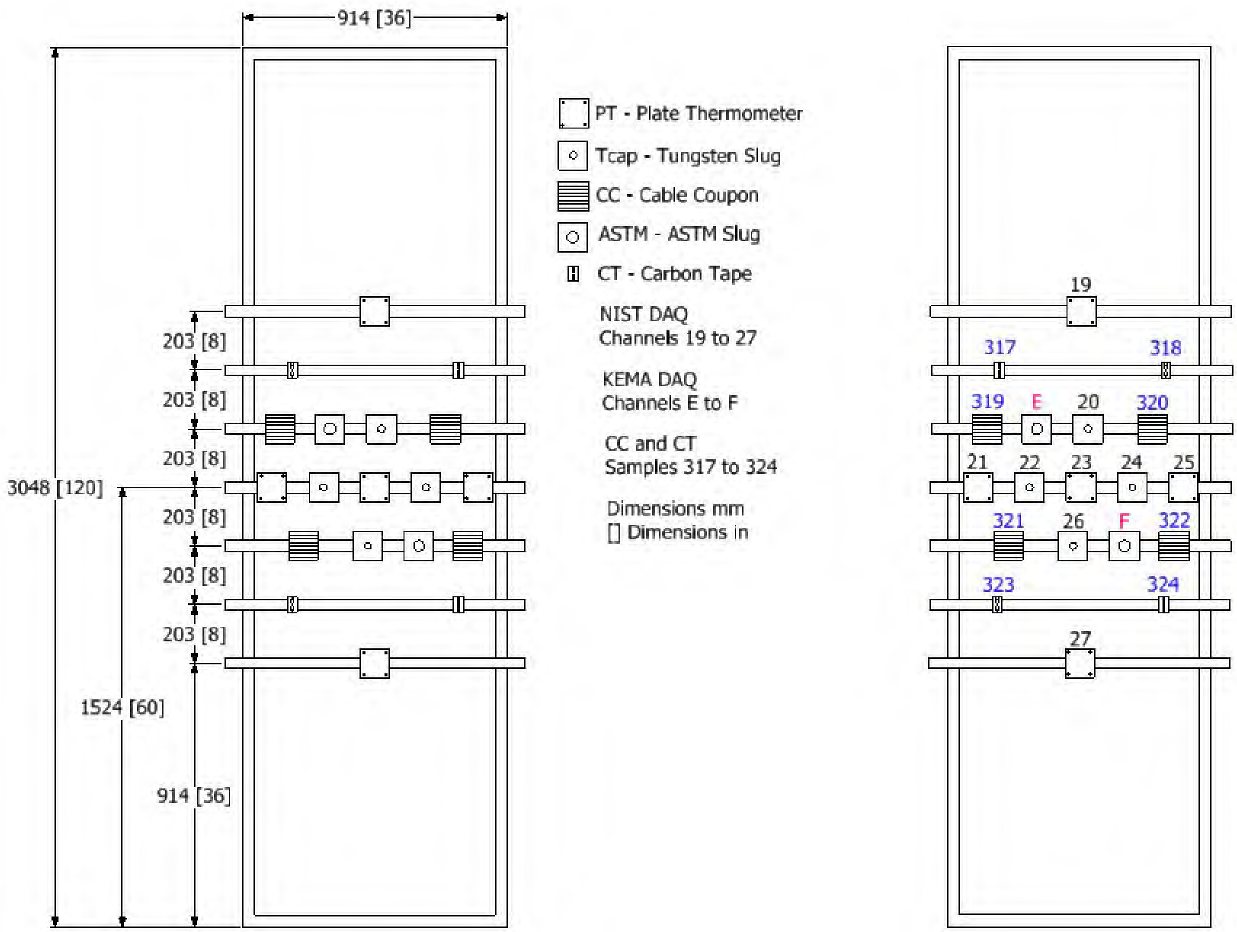

Fig. 121. Experiment 2-38 and 2-39 illustration of Horizontal Instrumentation Rack #3 with data acquisition channels. Dimensions in mm ± 5 mm.

A.4.2. Medium-Voltage Bus Duct Instrument Rack Drawings

Instrumentation rack drawings for bus duct experiments are shown below in Fig. 122 to Fig. 126.

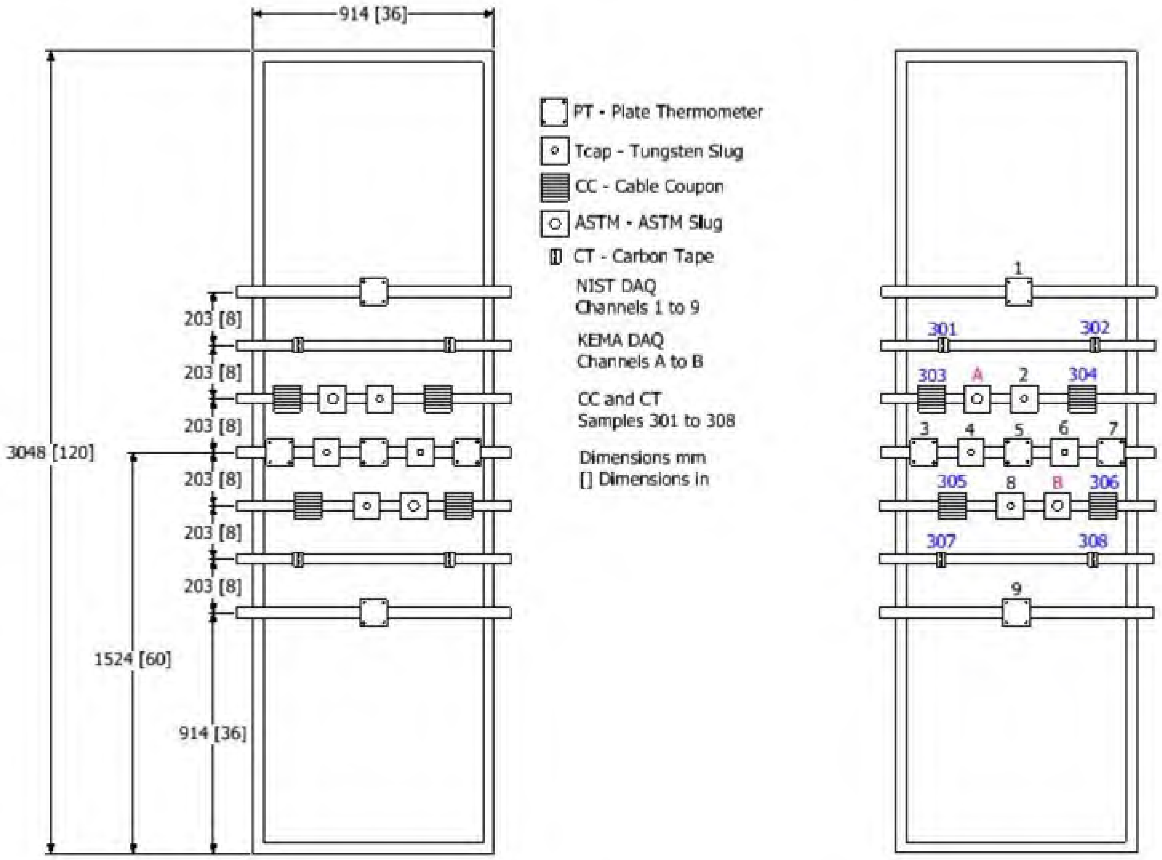

Fig. 122. Illustration of Horizontal Instrumentation Rack #1 used in experiments 2-40 & 2-41, with data acquisition channels. Dimensions in mm ± 5 mm.

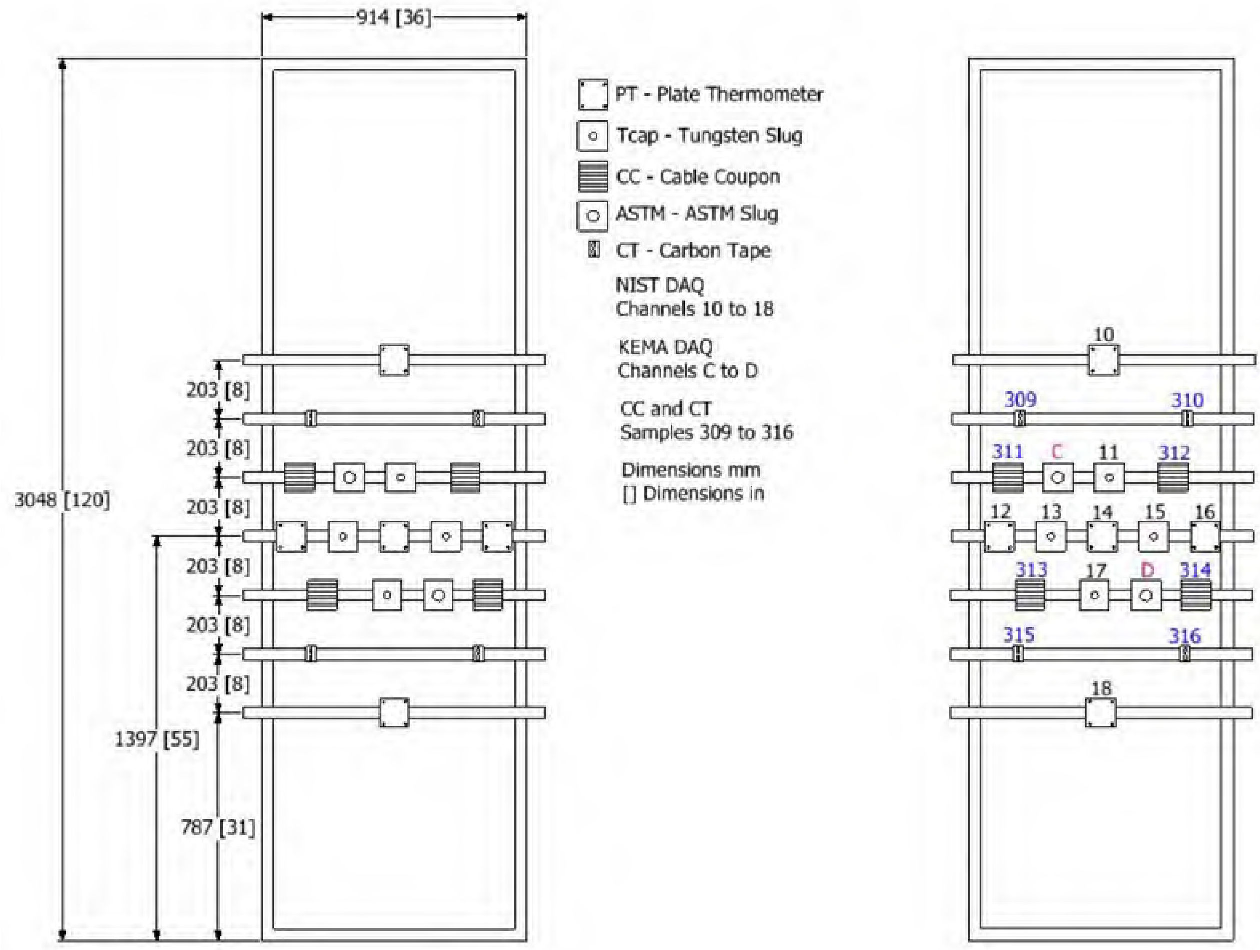

Fig. 123. Illustration of Vertical Instrumentation Rack #2 used in experiments 2-40 & 2-41, with data acquisition channels. Dimensions in mm ± 5 mm.

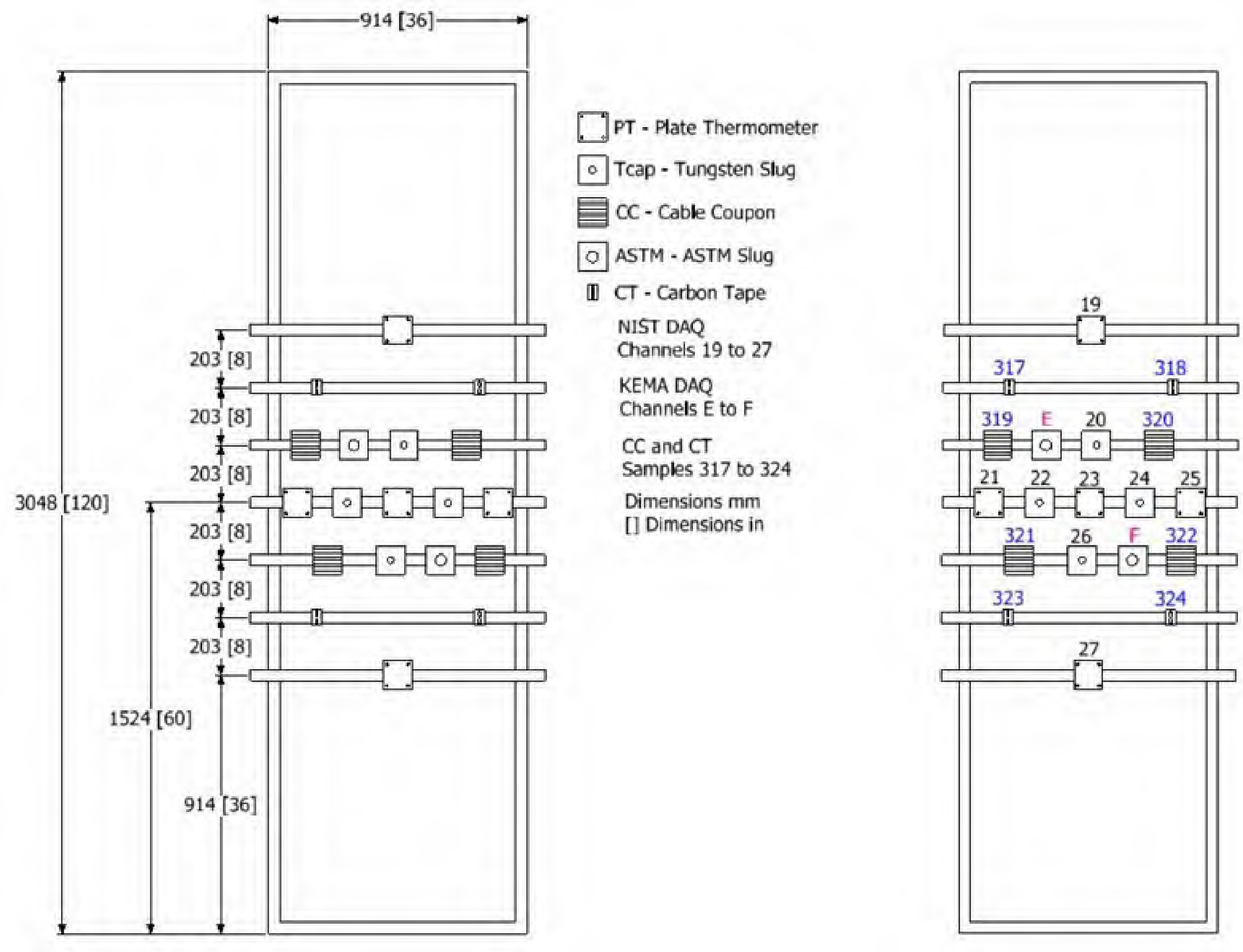

Fig. 124. Illustration of Horizontal Instrumentation Rack #3 used in experiments 2-40 & 2-41, with data acquisition channels. Dimensions in mm ± 5 mm.

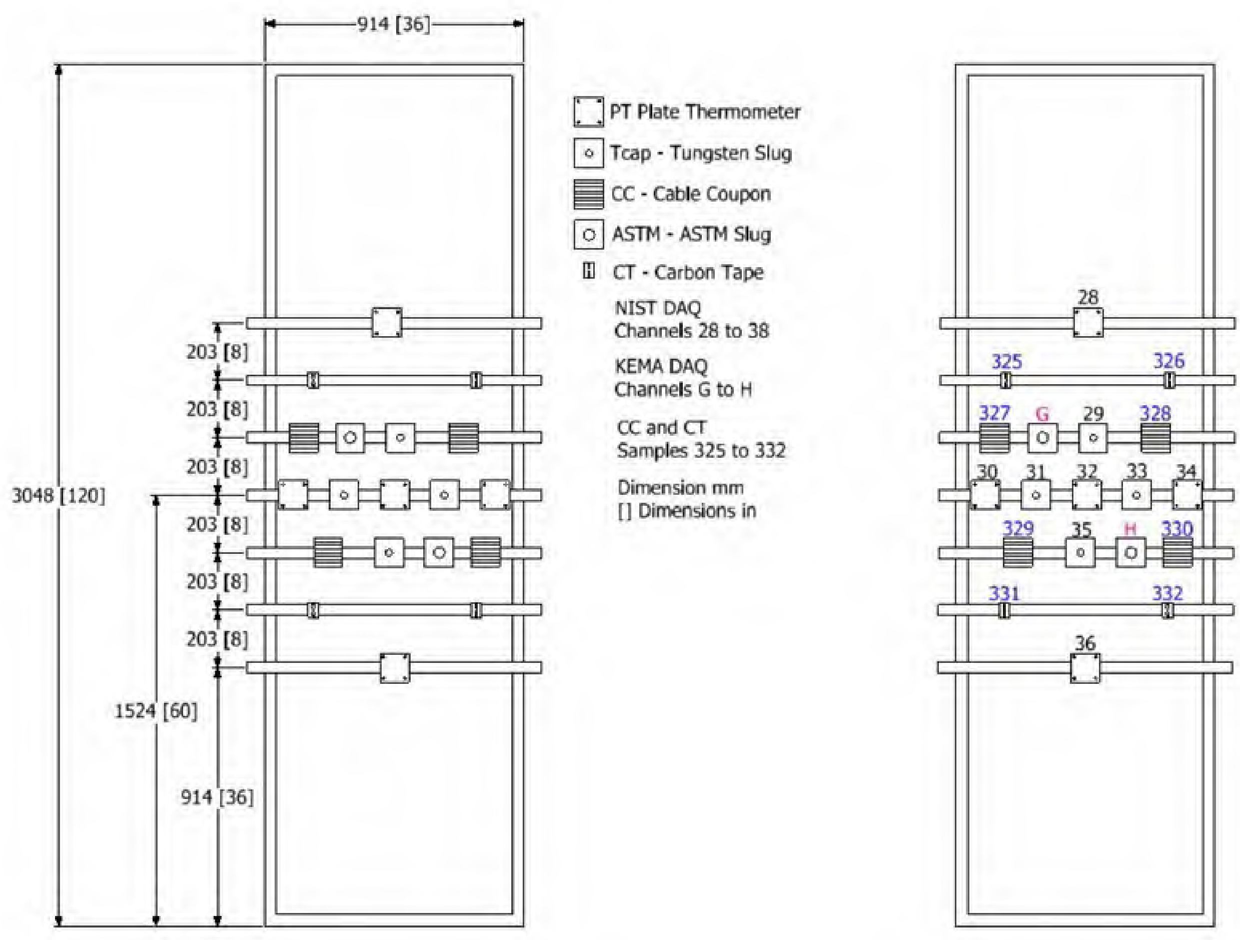

Fig. 125. Illustration of Horizontal Instrumentation Rack #4 used in experiments 2-40 & 2-41, with data acquisition channels. Dimensions in mm ± 5 mm.

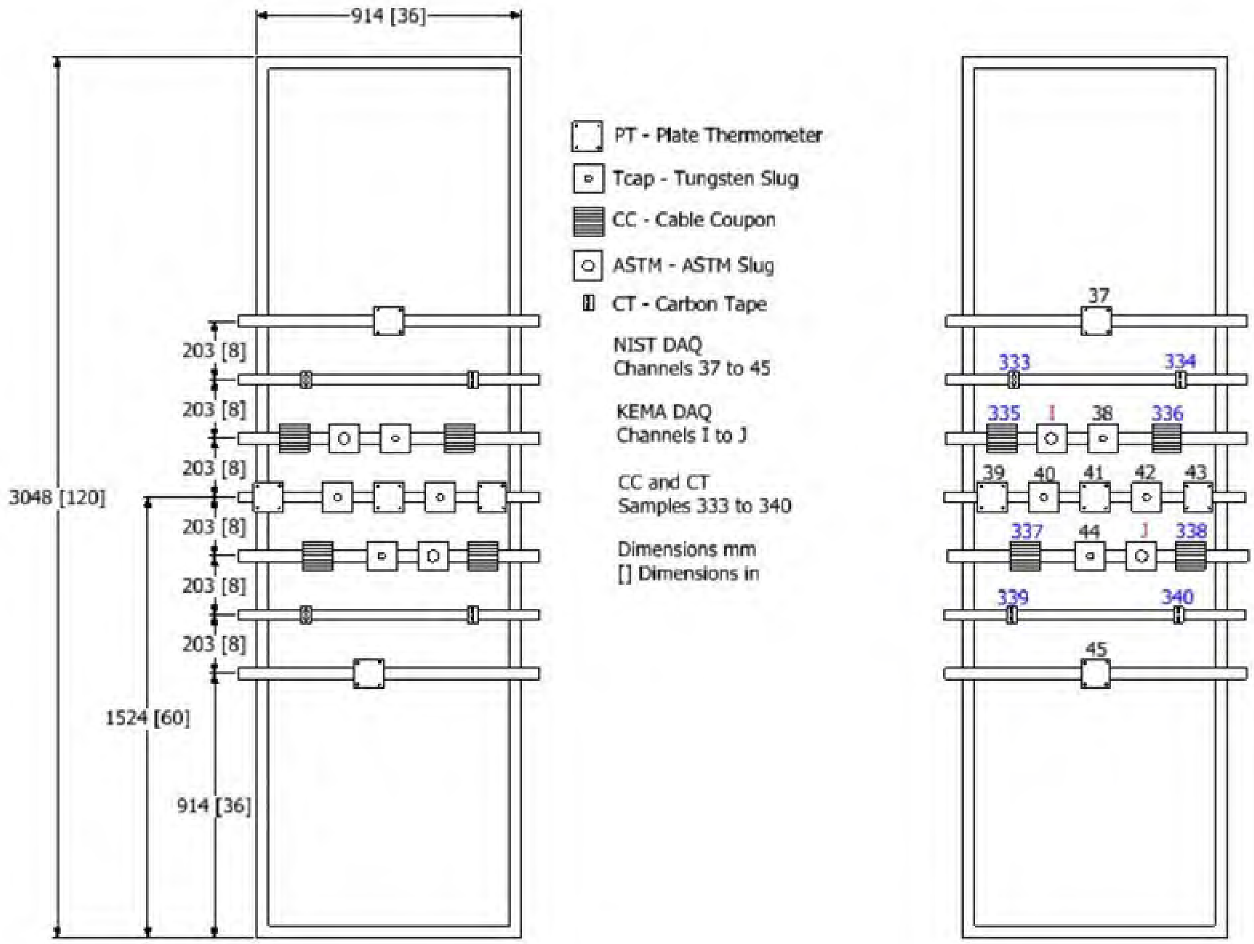

Fig. 126. Illustration of horizontal Instrumentation Rack #5 used in experiments 2-40 & 2-41, with data acquisition channels. Dimensions in mm ± 5 mm.

A.4.3. Low-Voltage Bus Duct Instrument Rack Drawings

Instrumentation rack drawings for low-voltage switchgear experiments are shown below in Fig. 127 to Fig. 129.

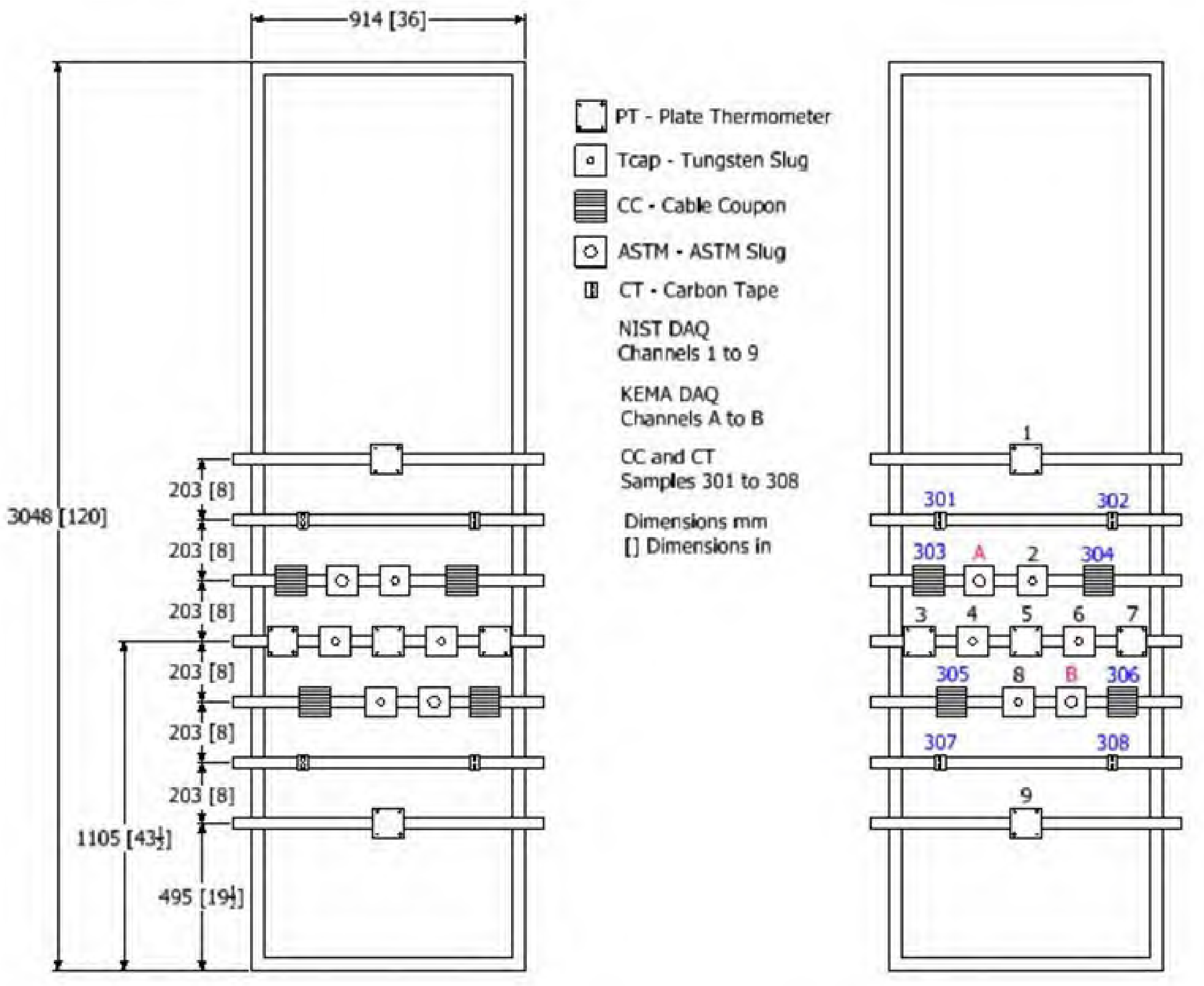

Fig. 127. Illustration of Vertical Instrumentation Rack #1 used in experiments 2-33A, 2-33B, and 2-34. Dimensions in mm ± 5 mm.

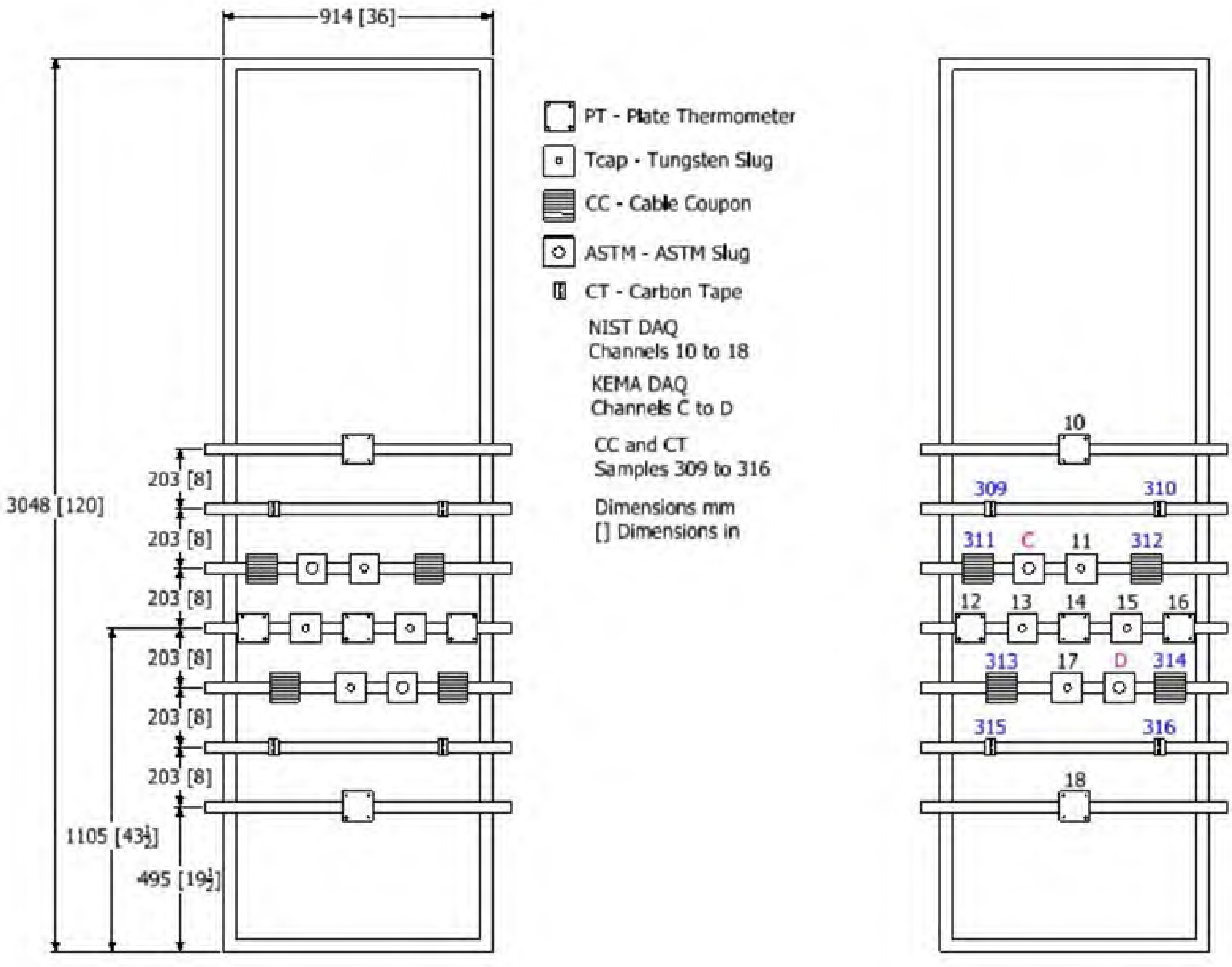

Fig. 128. Illustration of Vertical Instrumentation Rack #2 used in experiments 2-33A, 2-33B, and 2-34. Dimensions in mm ± 5 mm.

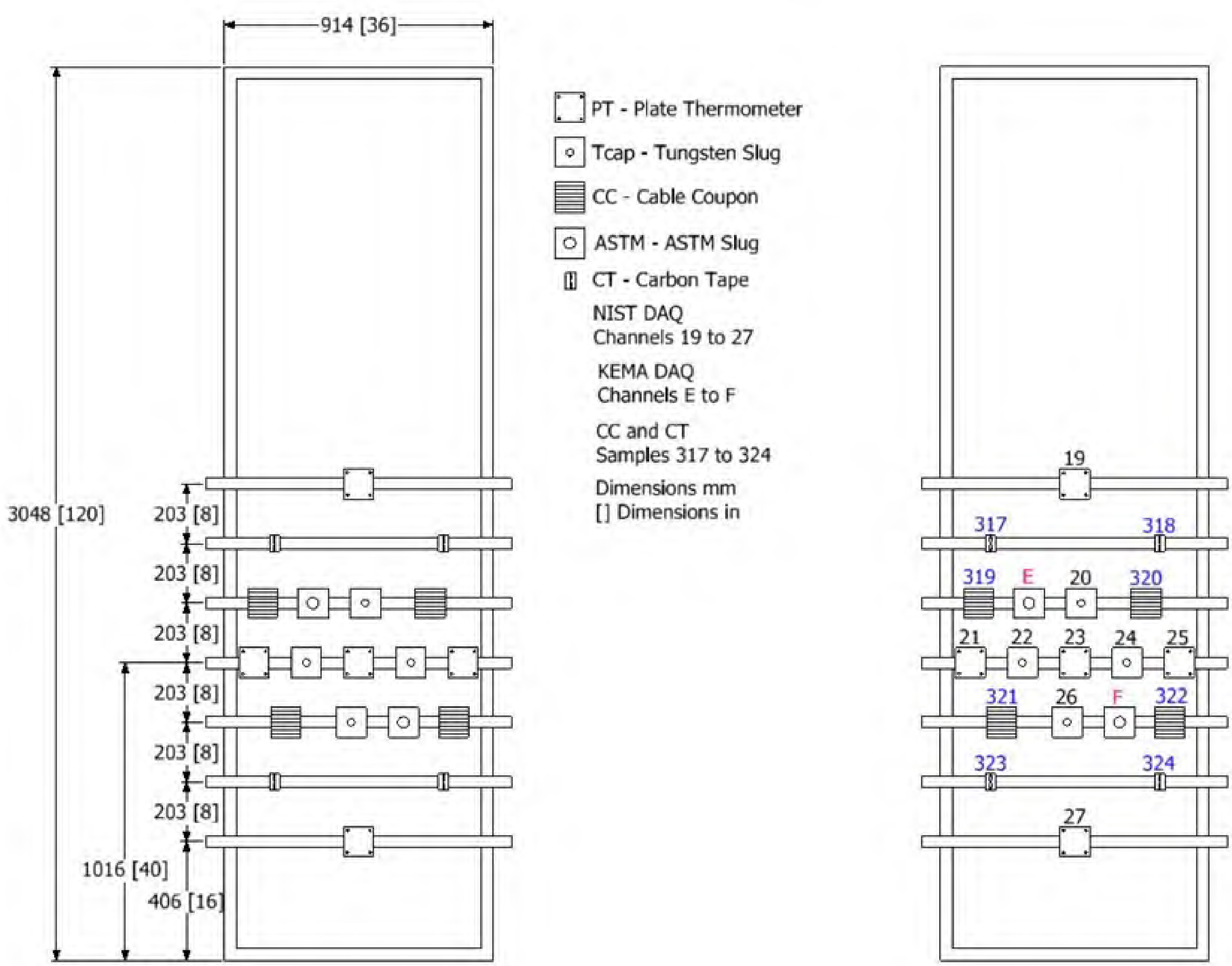

Fig. 129. Illustration of Vertical Instrumentation Rack #3 used in experiments 2-33A and 2-33B. Dimensions in mm ± 5 mm.

Appendix B. Electrical Measurements

This appendix presents plots of the electrical measurements made during each experiment. The raw data files were converted to Matlab™ files using the KEMA labs' proprietary software. Once in Matlab,™ the data was processed and plotted.

B.1. Experiment 2-33A (LV Switchgear, Copper Bus, Steel Enclosure, 600 V, 15 kA, 8 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 130. The transient region for current phases is presented in Fig. 131. Energy and power profiles are presented in Fig. 132.

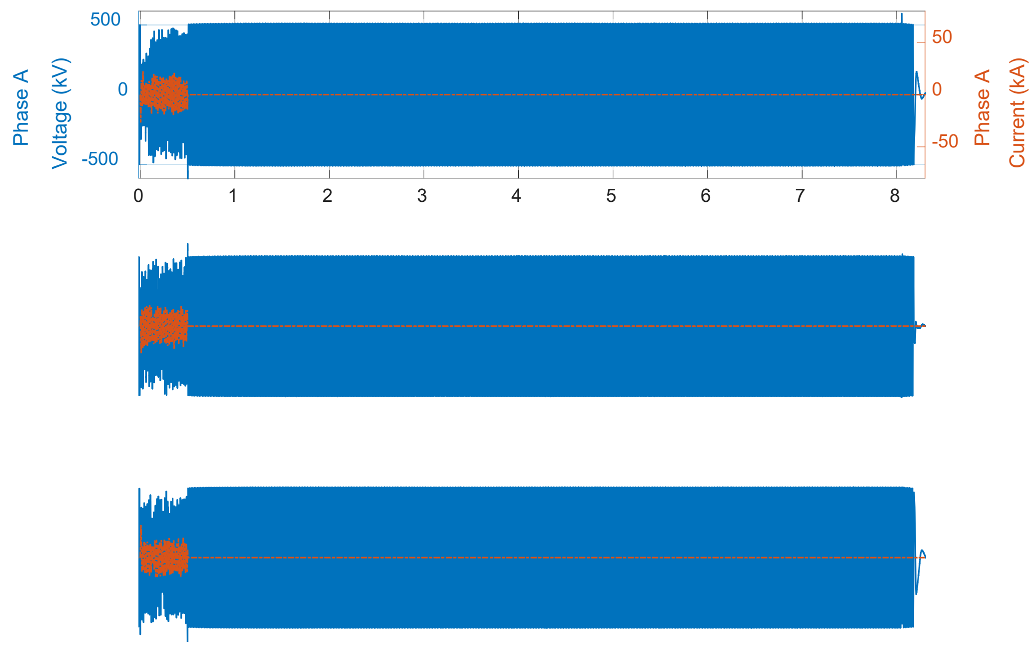

Fig. 130. Voltage and Current Profile during Experiment 2-33A. Measurement uncertainty ± 3 percent.

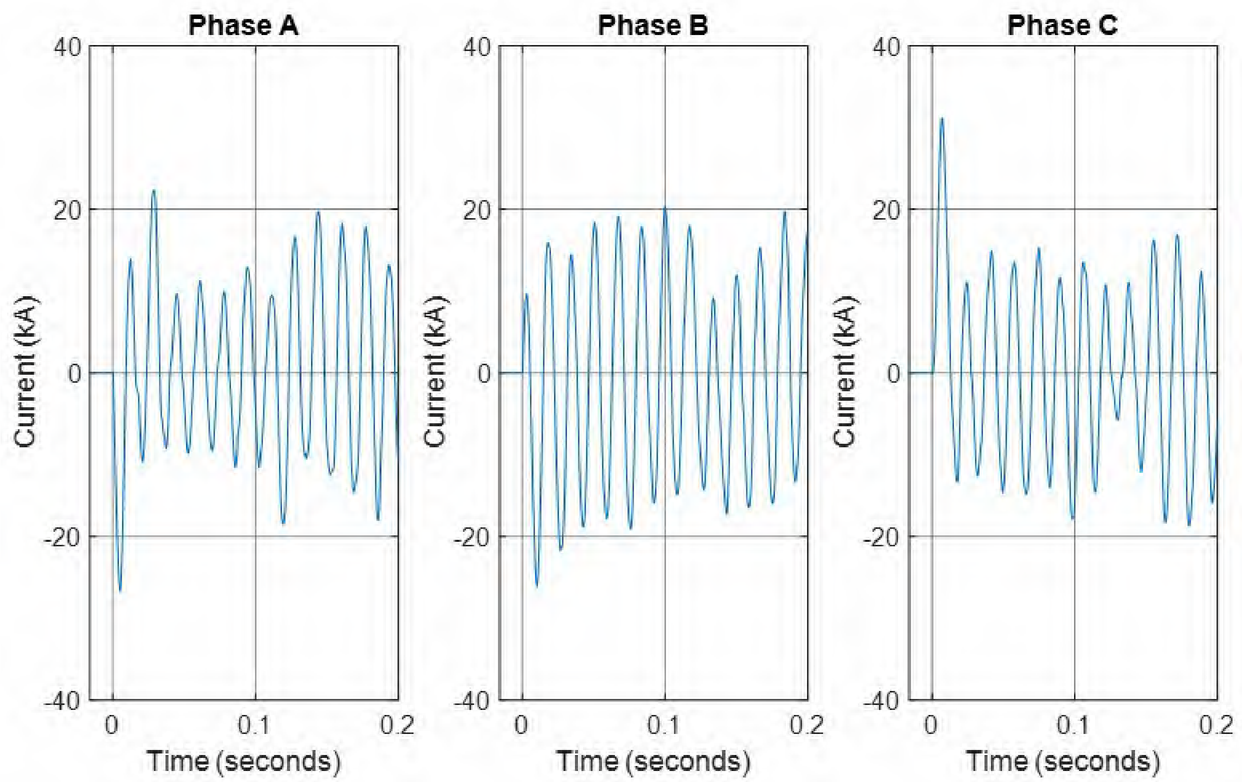

Fig. 131. Transient current profiles for Experiment 2-33A. Measurement uncertainty ± 3 percent.

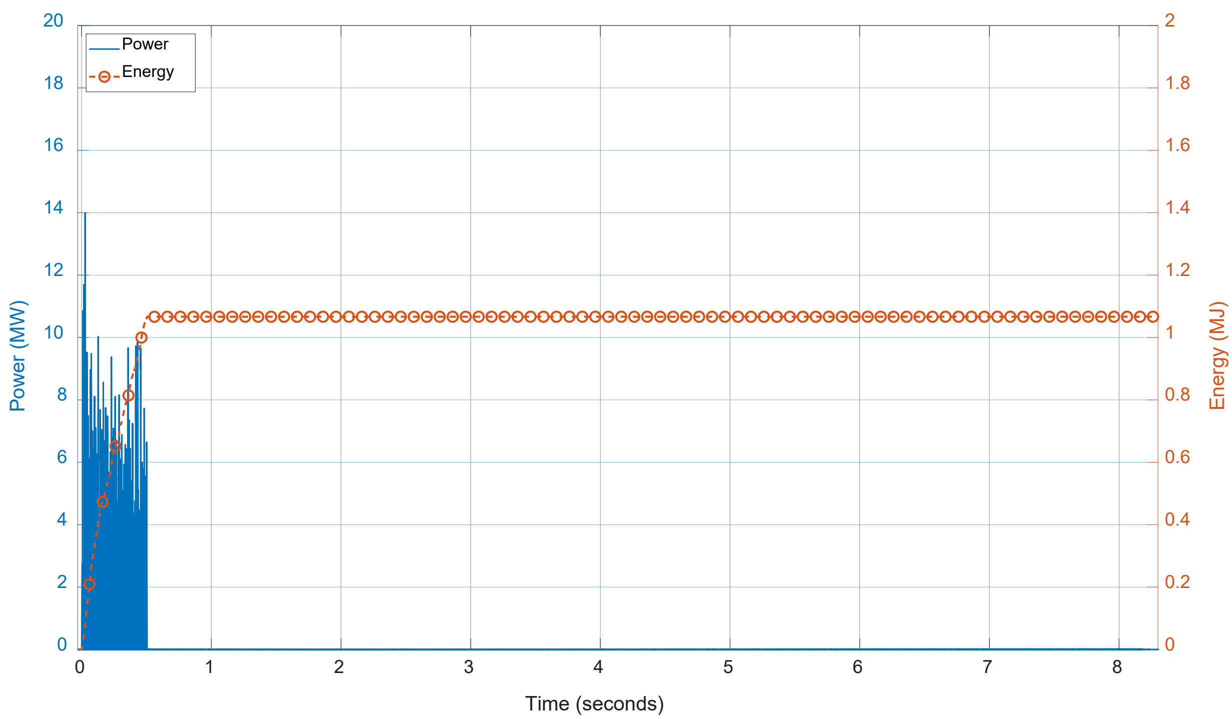

Fig. 132. Power and Energy for Experiment 2-33A. Measurement uncertainty ± 3 percent.

B.2. Experiment 2-33B (LV Switchgear, Copper Bus, Steel Enclosure, 600 V, 15 kA, 8 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 133. The transient region for current phases is presented in Fig. 134. Energy and power profiles are presented in Fig. 135.

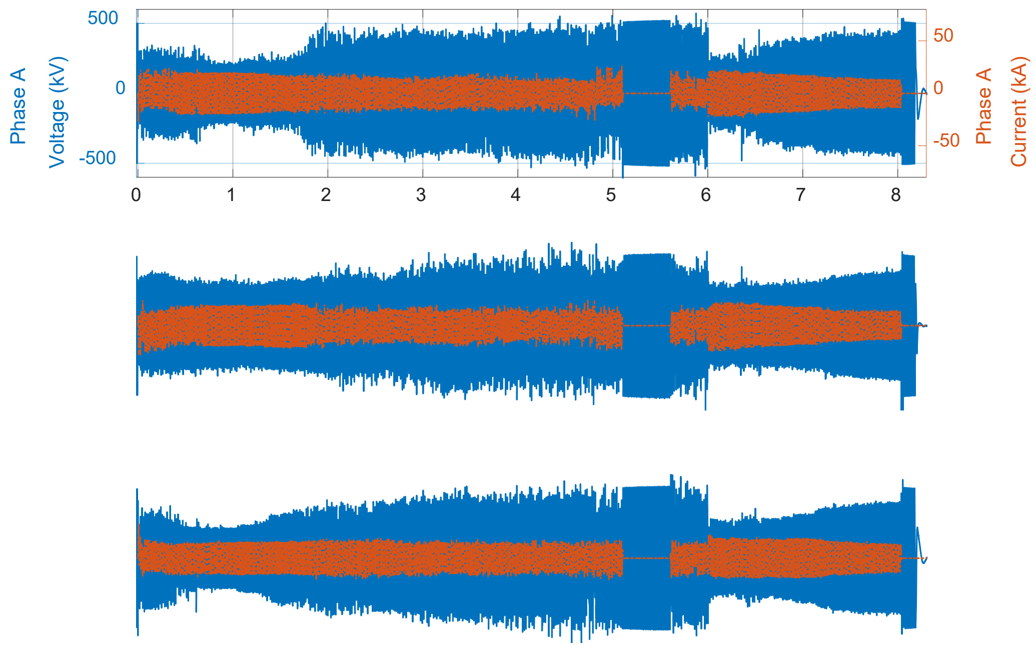

Fig. 133. Voltage and Current Profile during Experiment 2-33B. Measurement uncertainty ± 3 percent.

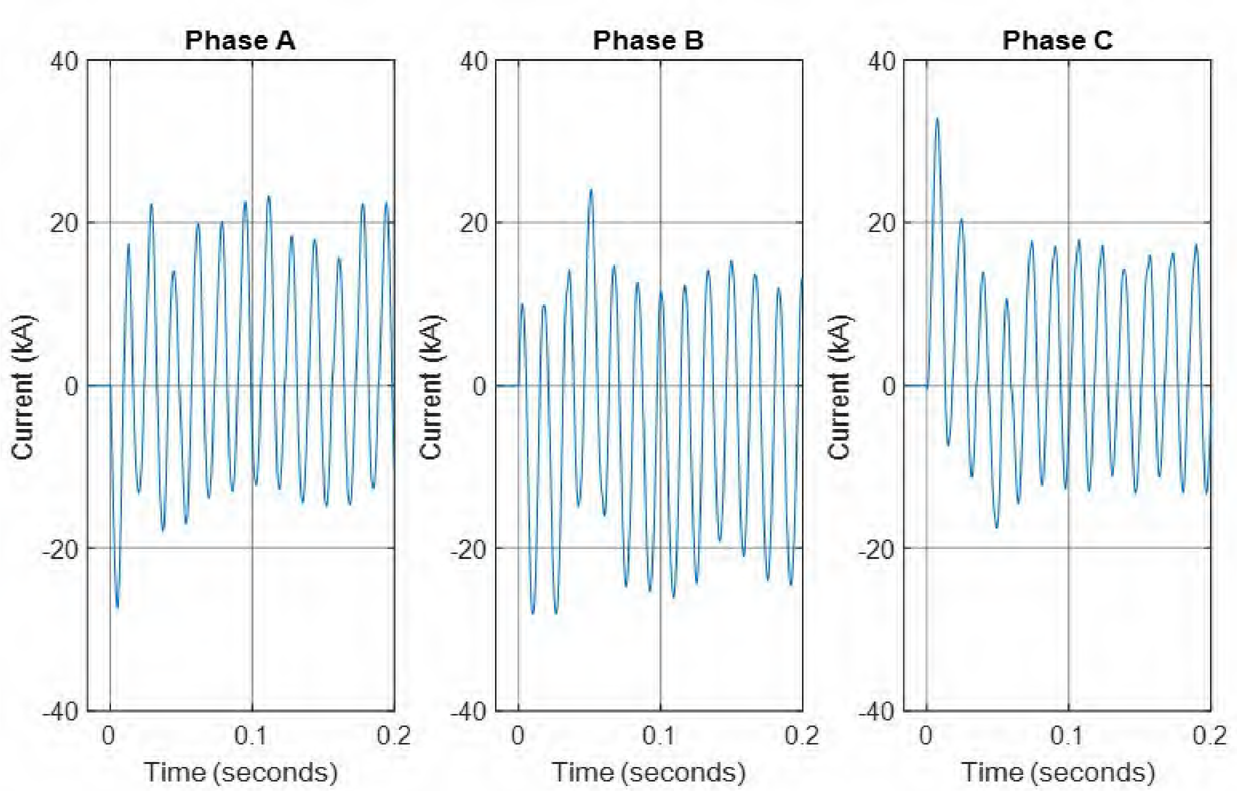

Fig. 134. Transient current profiles for Experiment 2-33B. Measurement uncertainty ± 3 percent.

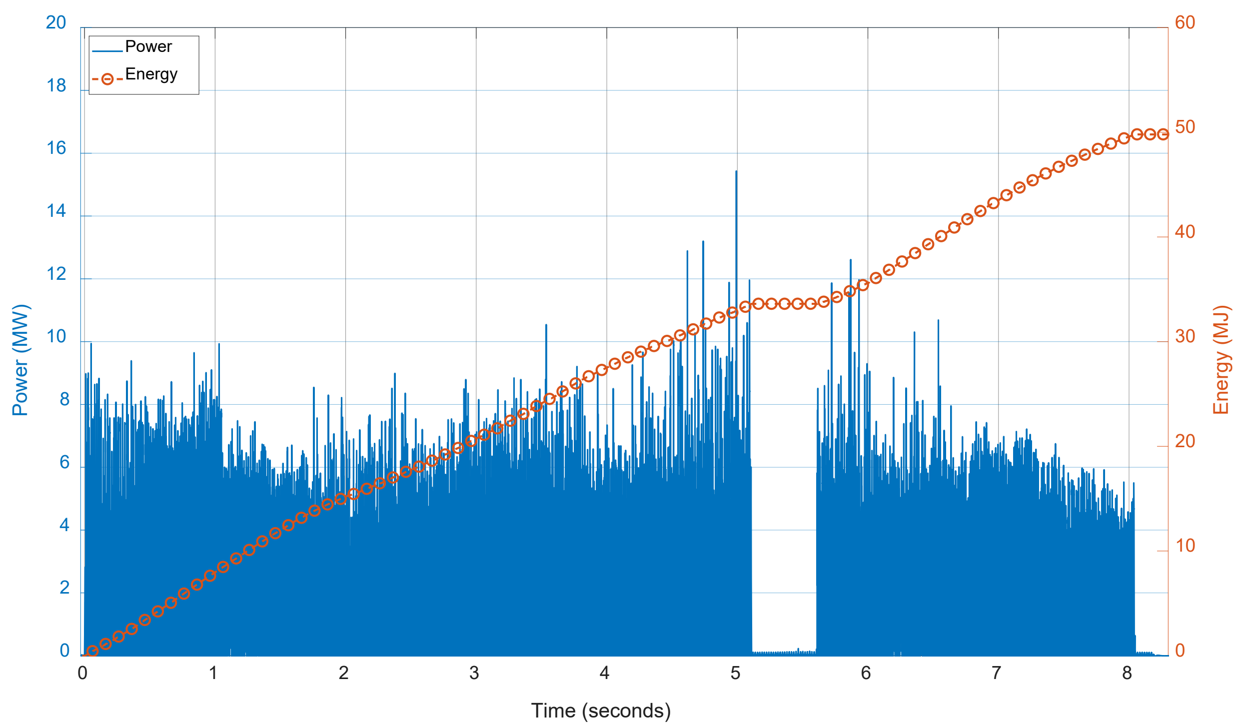

Fig. 135. Power and Energy for Experiment 2-33B. Measurement uncertainty ± 3 percent.

B.3. Experiment 2-34 (LV Bus Duct, Copper Bus, Steel Enclosure, 600 V, 8 kA, 17.5 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 136. The transient region for current phases is presented in Fig. 137. Energy and power profiles are presented in Fig. 138.

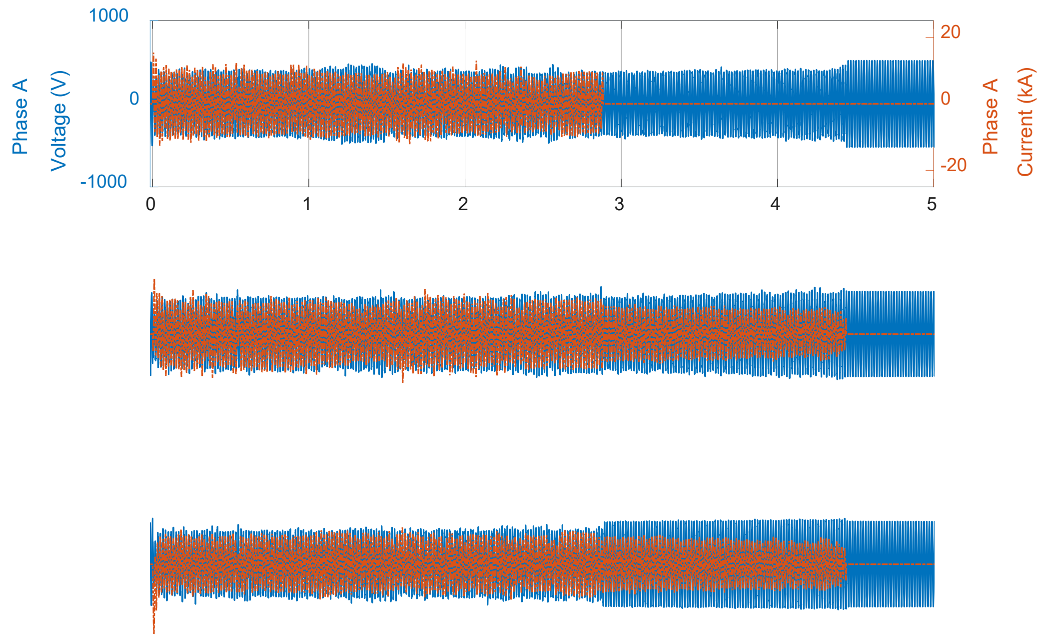

Fig. 136. Voltage and Current Profile during Experiment 2-34. Measurement uncertainty ± 3 percent.

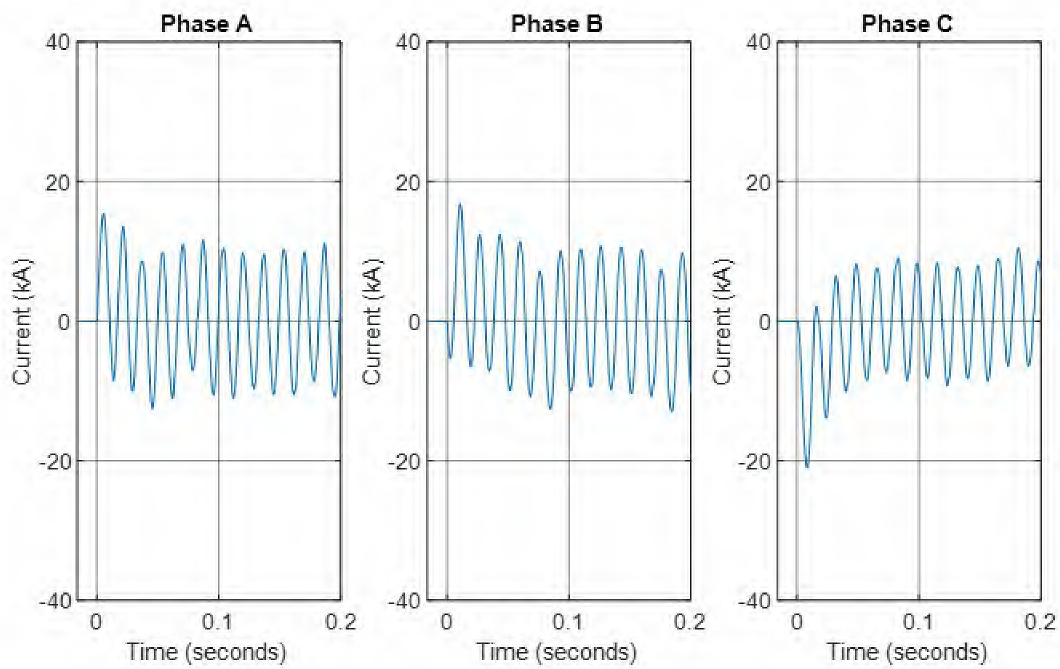

Fig. 137. Transient current profiles for Experiment 2-34. Measurement uncertainty ± 3 percent.

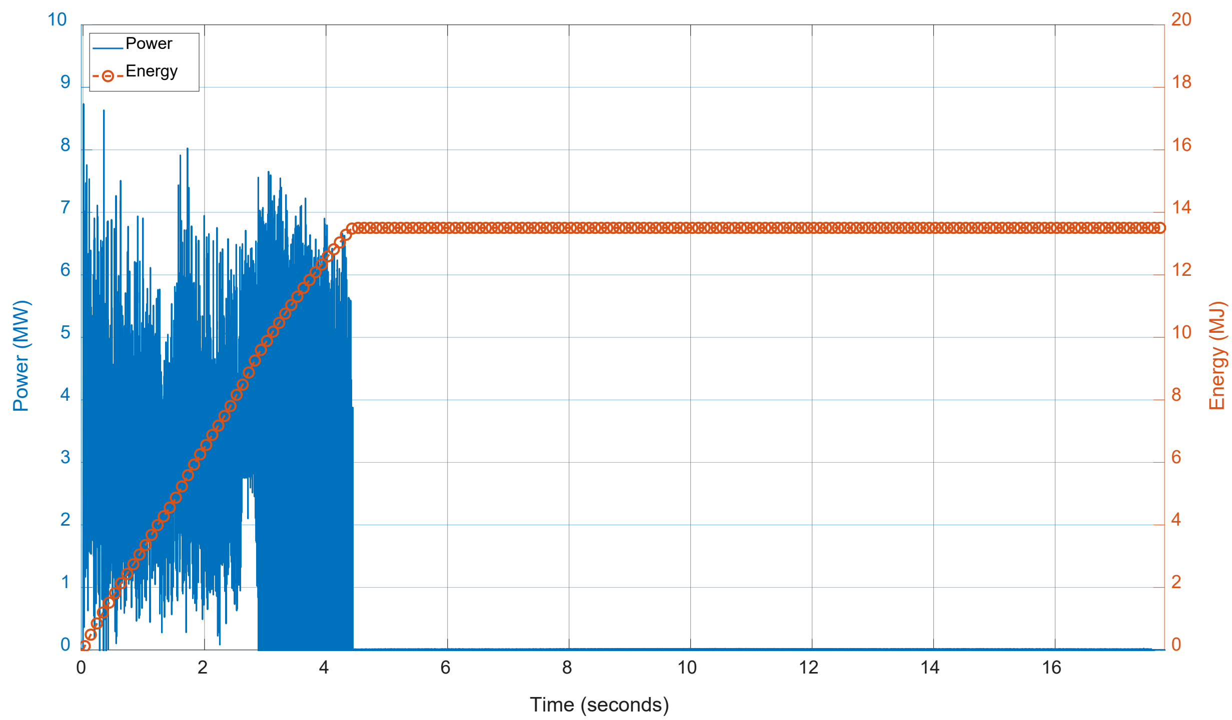

Fig. 138. Power and Energy for Experiment 2-34. Measurement uncertainty ± 3 percent.

B.4. Experiment 2-35 (MV Vertical Lift Switchgear, Copper Bus, Steel Enclosure, 6.9 kV, 25 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 139. The transient region for current phases is presented in Fig. 140. Energy and power profiles are presented in Fig. 141.

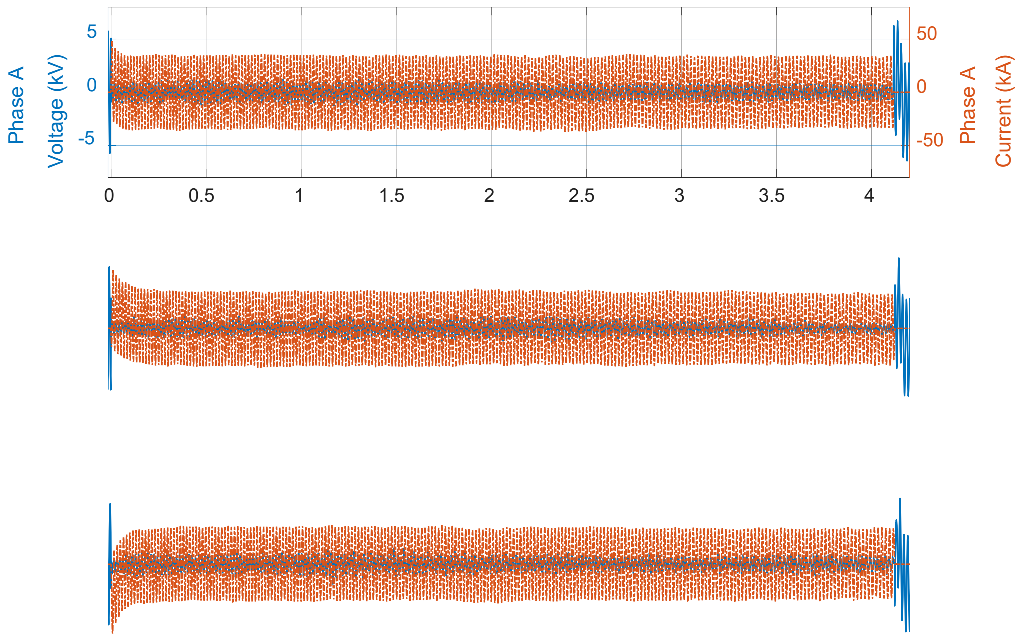

Fig. 139. Voltage and Current Profile during Experiment 2-35. Measurement uncertainty ± 3 percent.

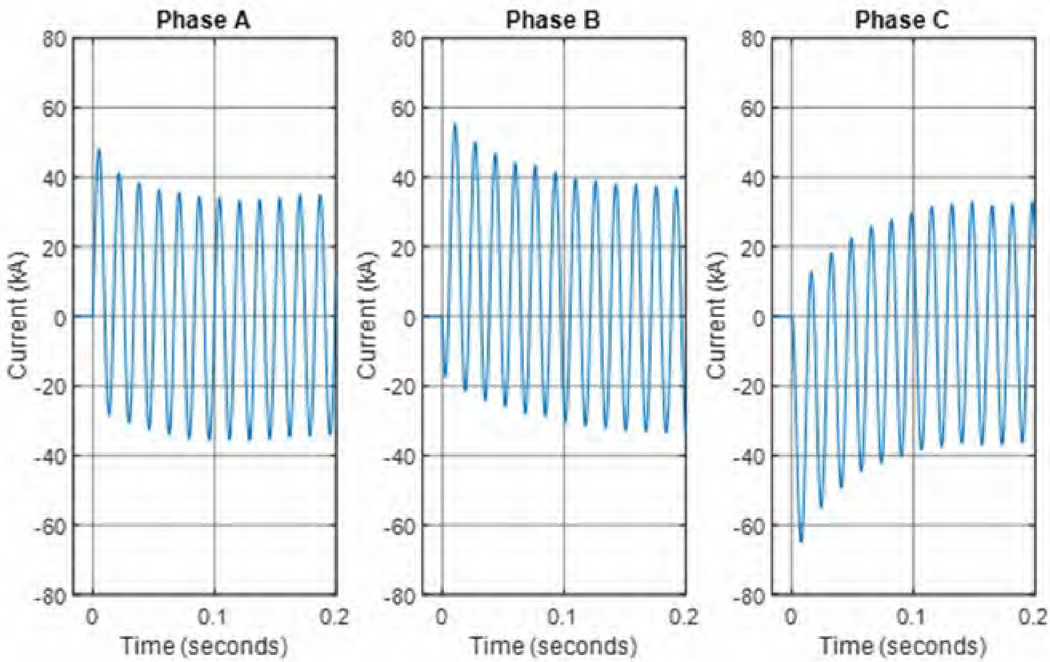

Fig. 140. Transient current profiles for Experiment 2-35. Measurement uncertainty ± 3 percent.

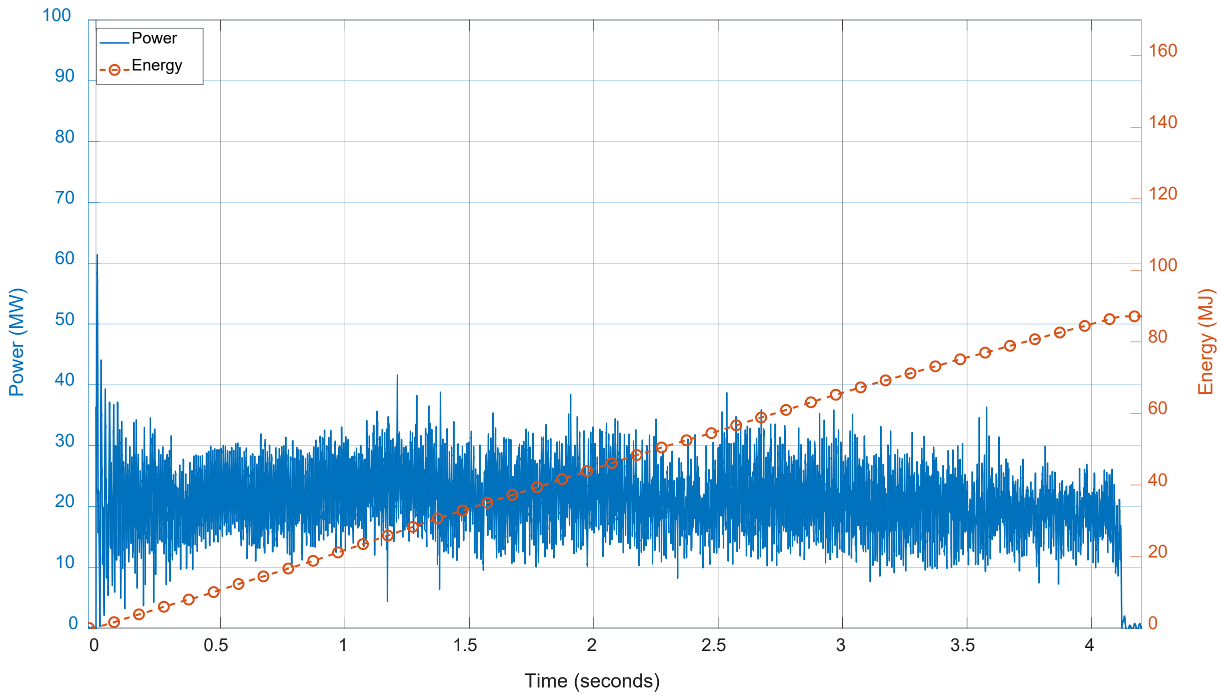

Fig. 141. Power and Energy for Experiment 2-35. Measurement uncertainty ± 3 percent.

B.5. Experiment 2-36 (MV Switchgear, Copper Bus, Steel Enclosure, 6.9 kV, 25 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 142. The transient region for current phases is presented in Fig. 143. Energy and power profiles are presented in Fig. 144.

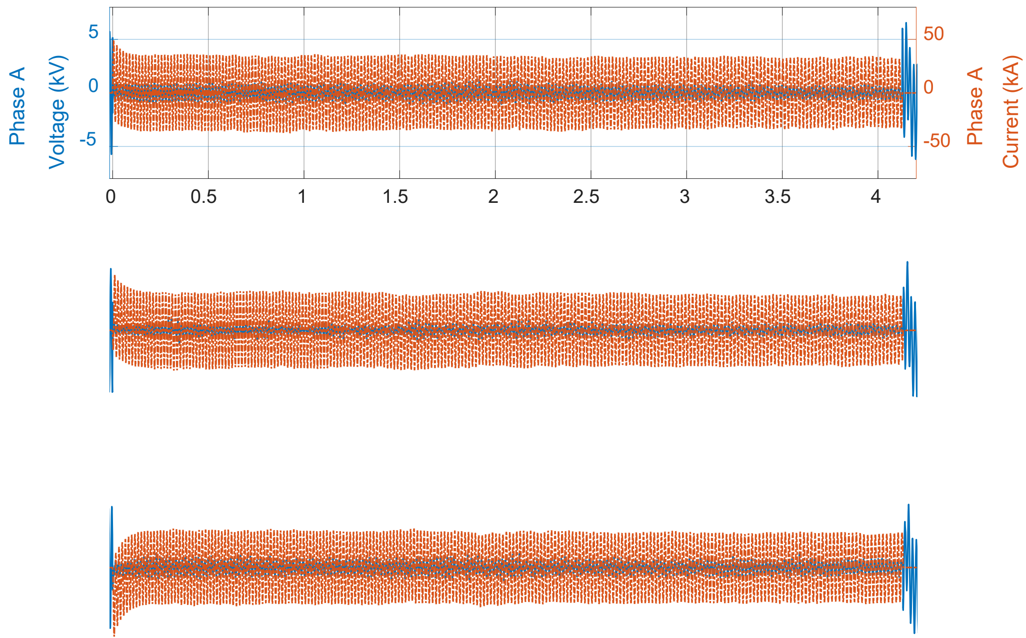

Fig. 142. Voltage and Current Profile during Experiment 2-36. Measurement uncertainty ± 3 percent.

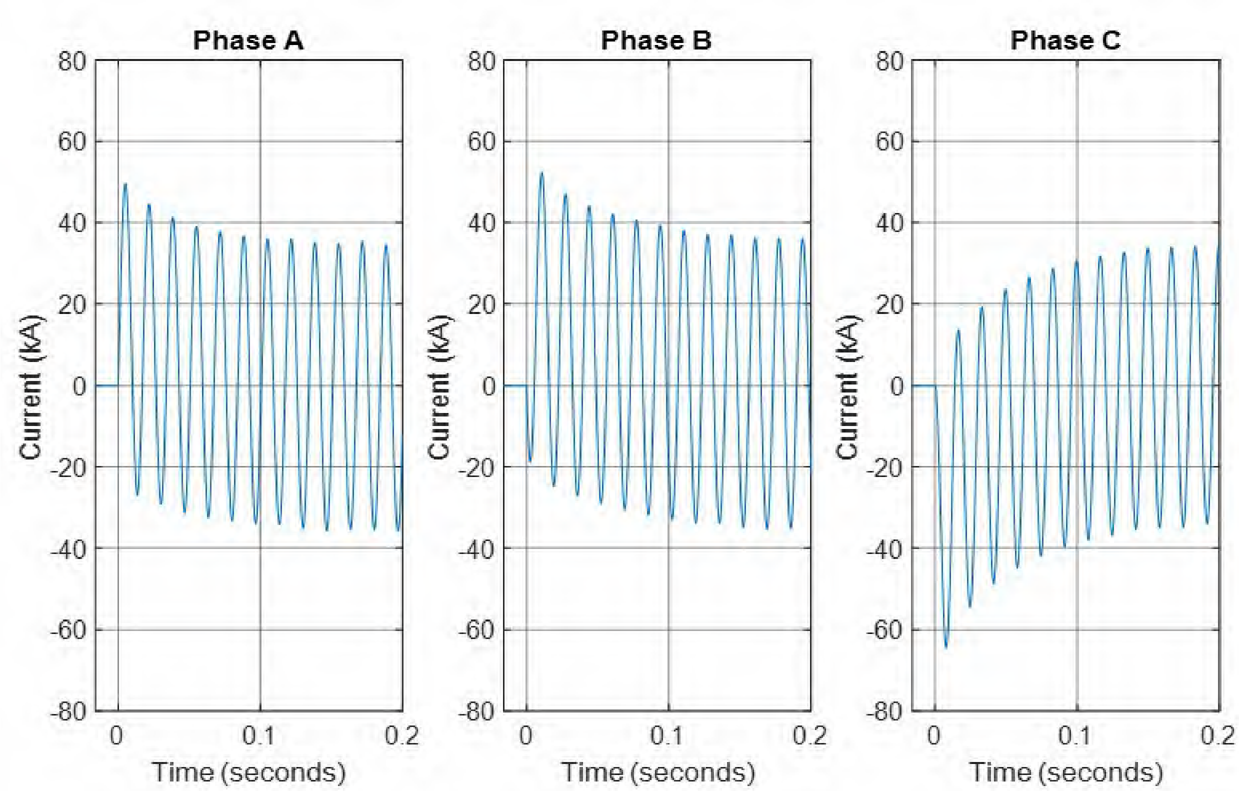

Fig. 143. Transient current profiles for Experiment 2-36. Measurement uncertainty ± 3 percent.

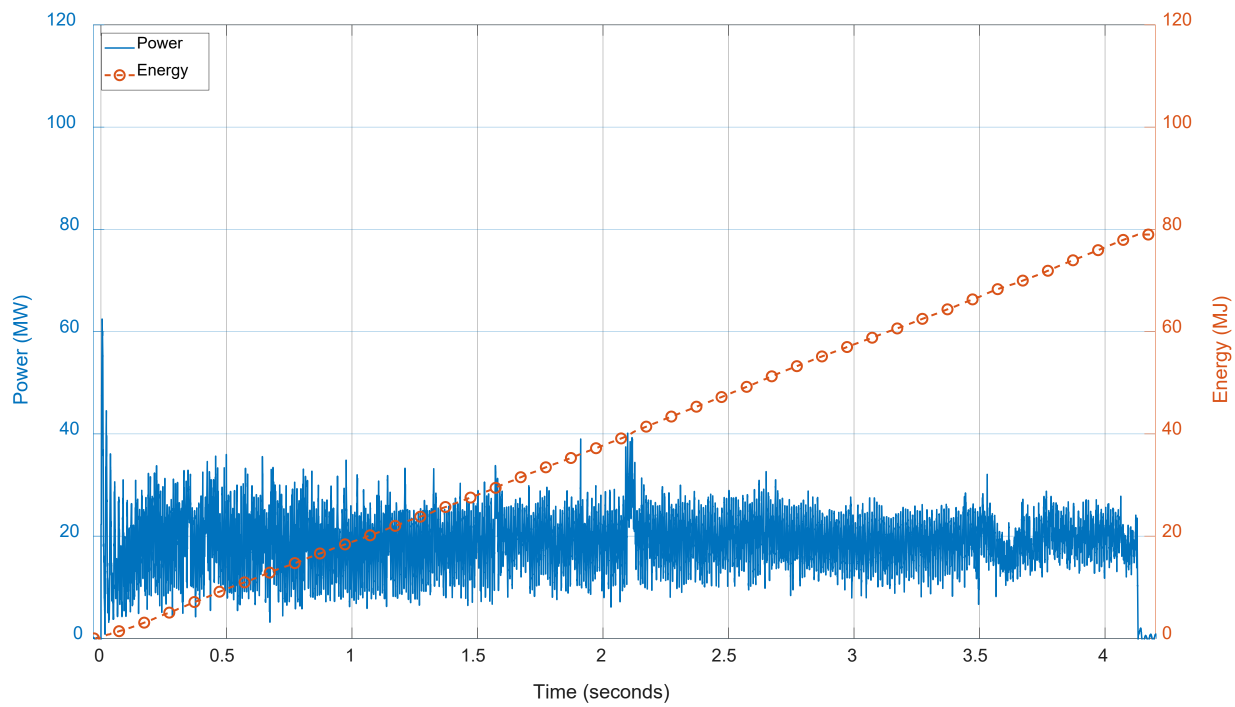

Fig. 144. Power and Energy for Experiment 2-36. Measurement uncertainty ± 3 percent.

B.6. Experiment 2-37 (MV Switchgear Horizontal Draw-out, Copper Bus, Steel Enclosure, 6.9 kV, 25 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 145. The transient region for current phases is presented in Fig. 146. Energy and power profiles are presented in Fig. 147.

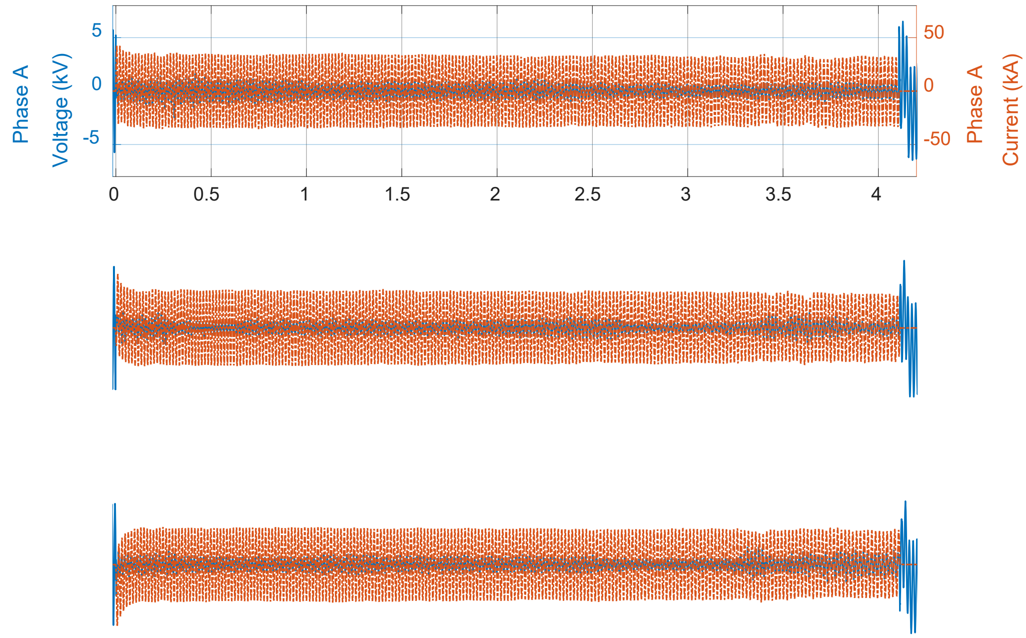

Fig. 145. Voltage and Current Profile during Experiment 2-37. Measurement uncertainty ± 3 percent.

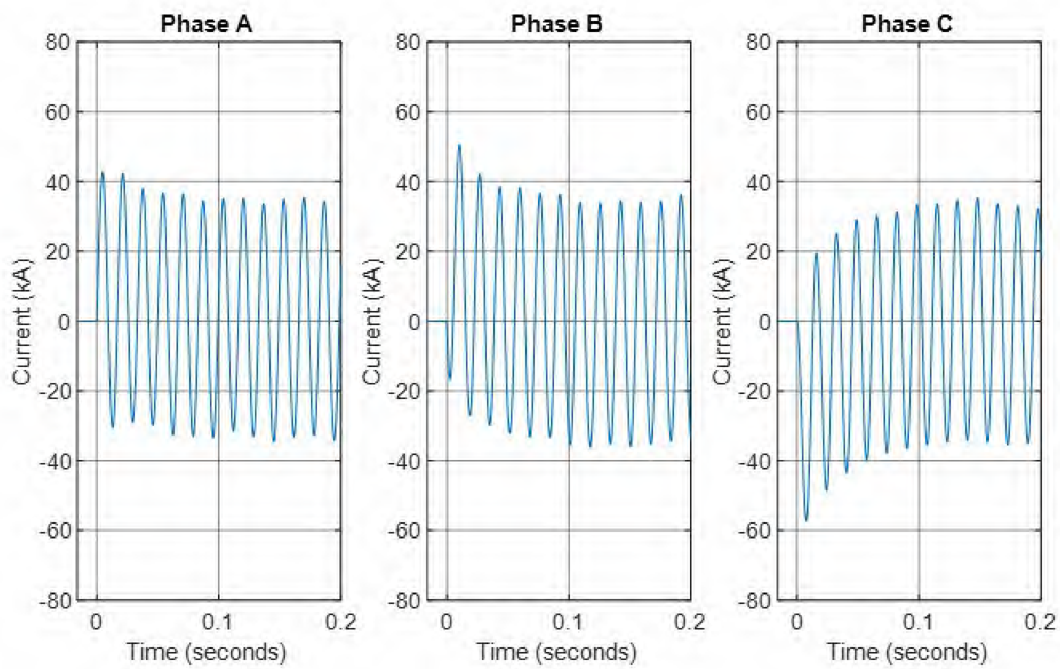

Fig. 146. Transient current profiles for Experiment 2-37. Measurement uncertainty ± 3 percent.

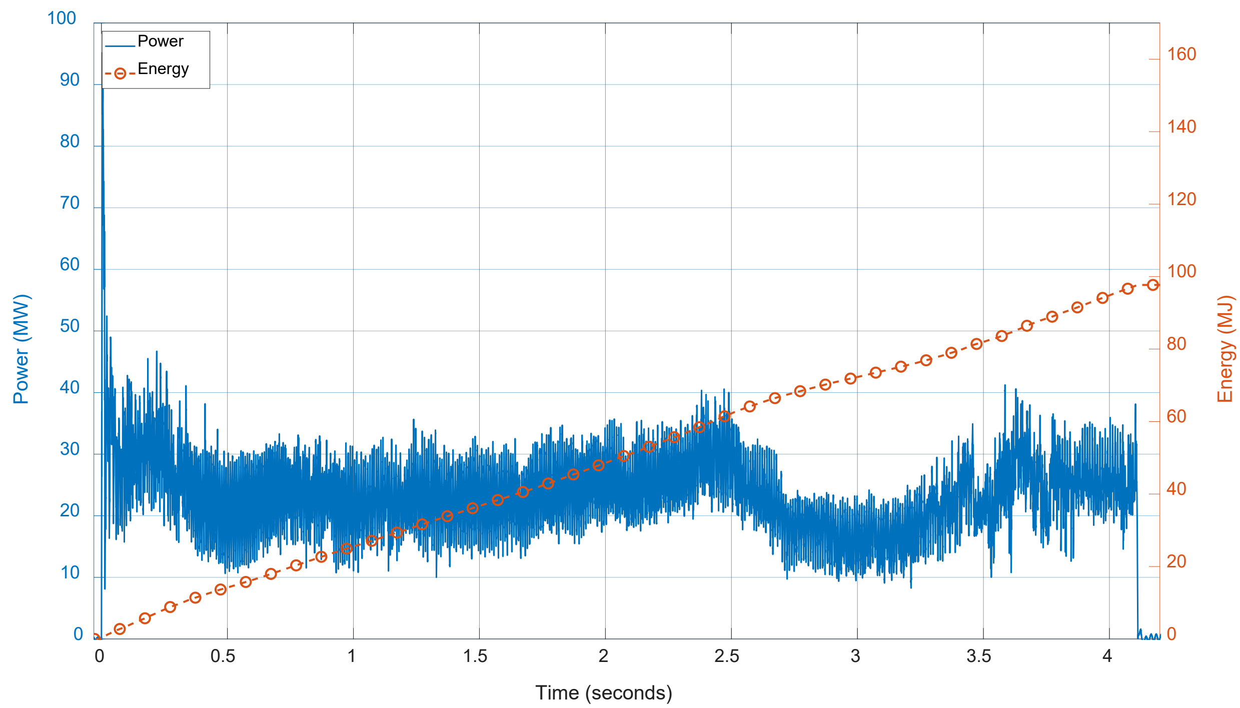

Fig. 147. Power and Energy for Experiment 2-37. Measurement uncertainty ± 3 percent.

B.7. Experiment 2-38 (MV Switchgear Cross-Aisle Configuration, Copper Bus, Steel Enclosure, 6.9 kV, 25 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 148. The transient region for current phases is presented in Fig. 149. Energy and power profiles are presented in Fig. 150.

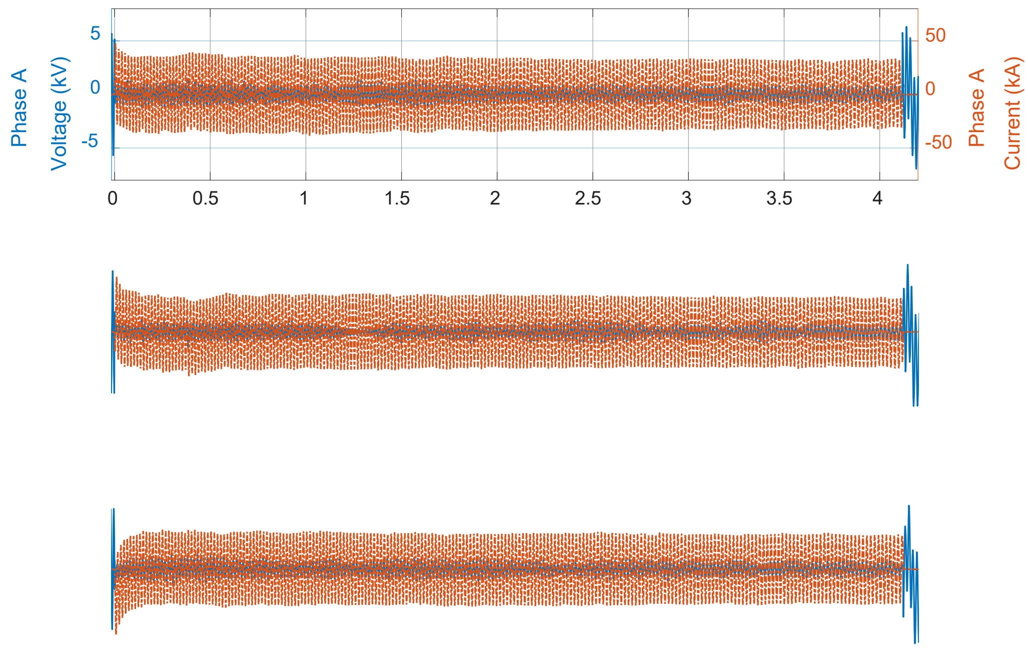

Fig. 148. Voltage and Current Profile during Experiment 2-38. Measurement uncertainty ±3 percent.

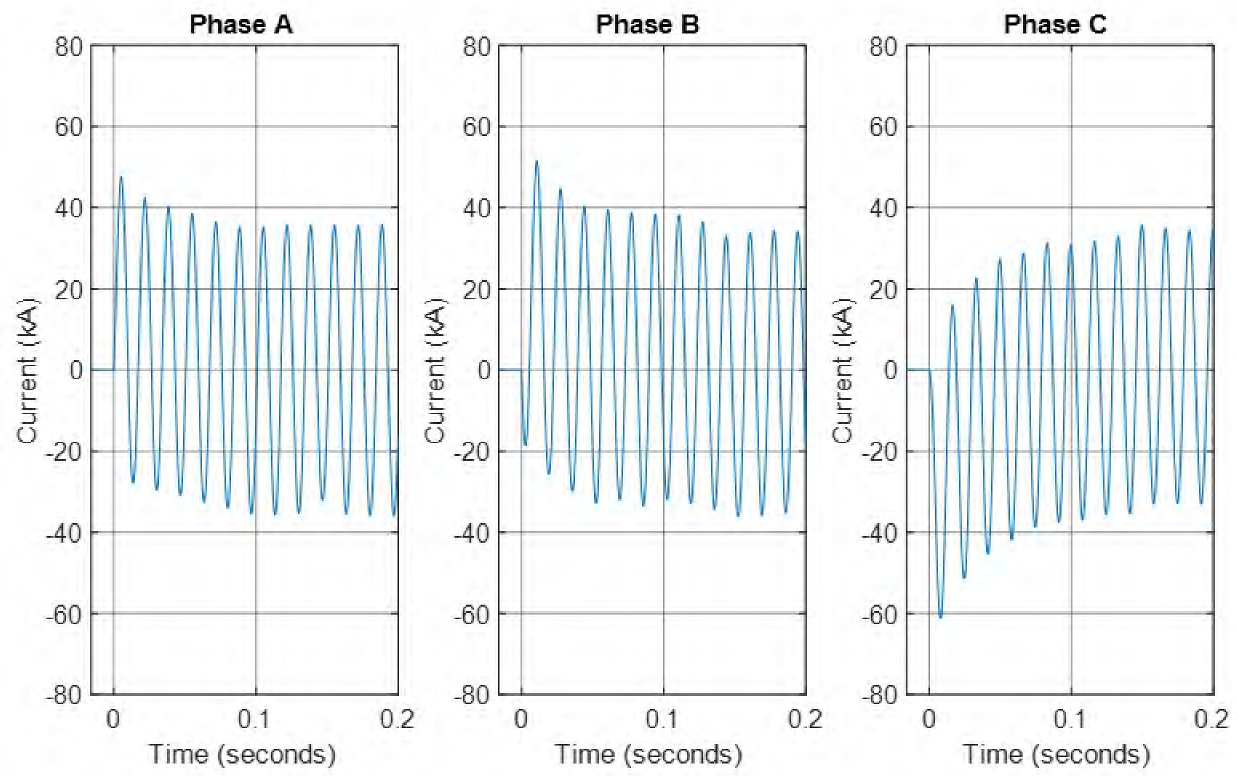

Fig. 149. Transient current profiles for Experiment 2-38. Measurement uncertainty ± 3 percent.

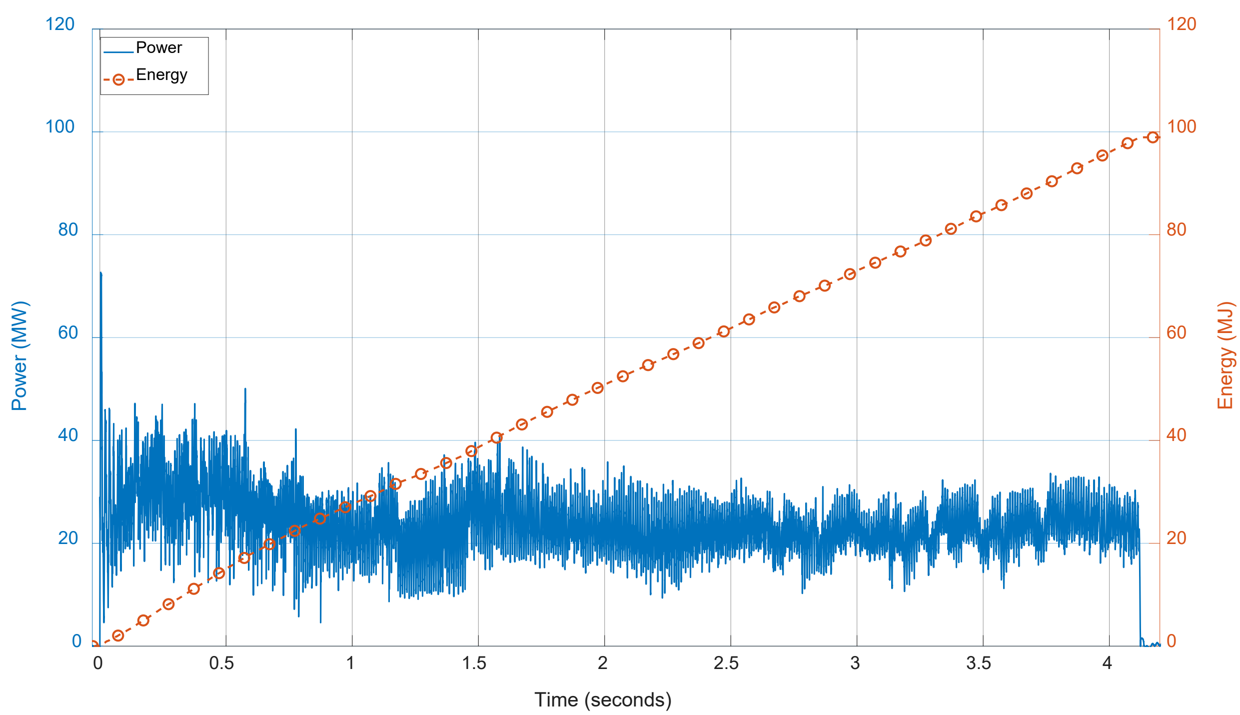

Fig. 150. Power and Energy for Experiment 2-38. Measurement uncertainty ± 3 percent.

B.8. Experiment 2-39 (MV Switchgear "Back-to-Back" Configuration, Copper Bus, Steel Enclosure, 6.9 kV, 25 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 151. The transient region for current phases is presented in Fig. 152. Energy and power profiles are presented in Fig. 153.

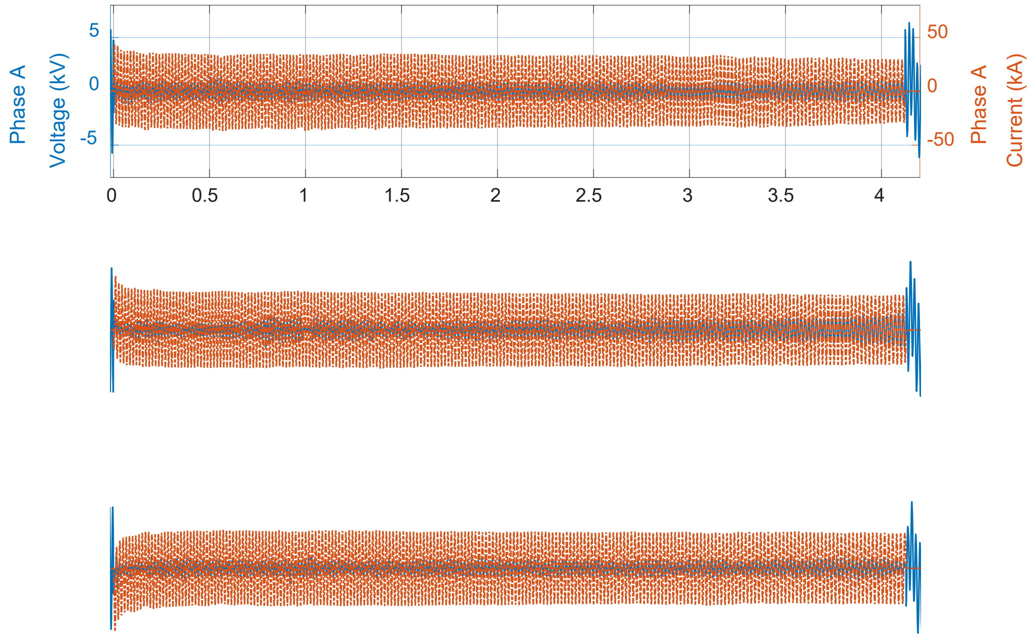

Fig. 151. Voltage and Current Profile during Experiment 2-39. Measurement uncertainty ± 3 percent.

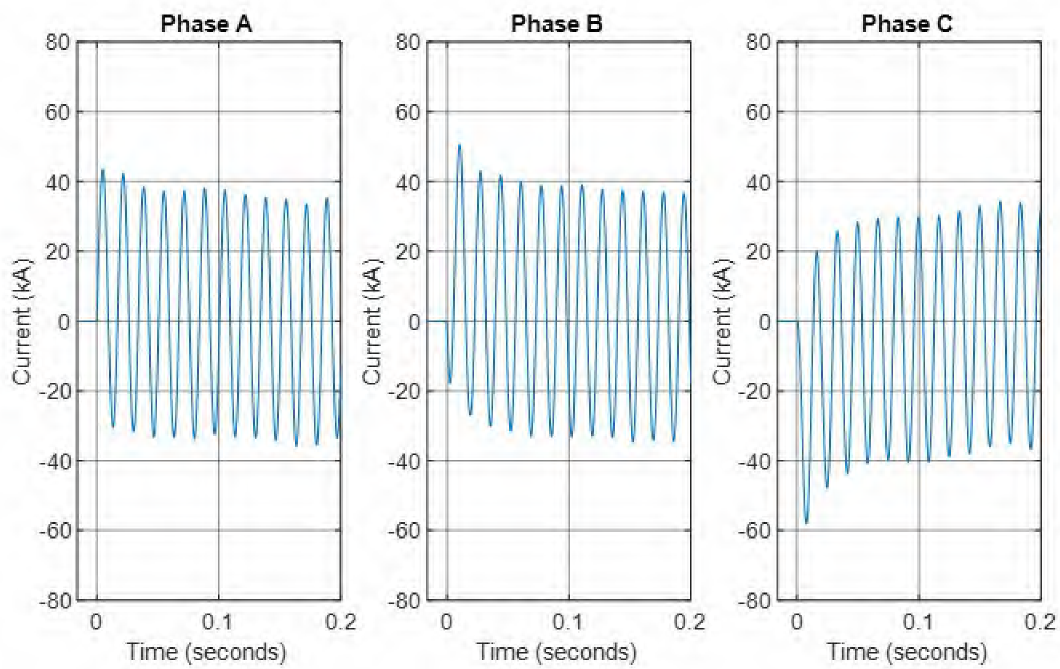

Fig. 152. Transient current profiles for Experiment 2-39. Measurement uncertainty ± 3 percent.

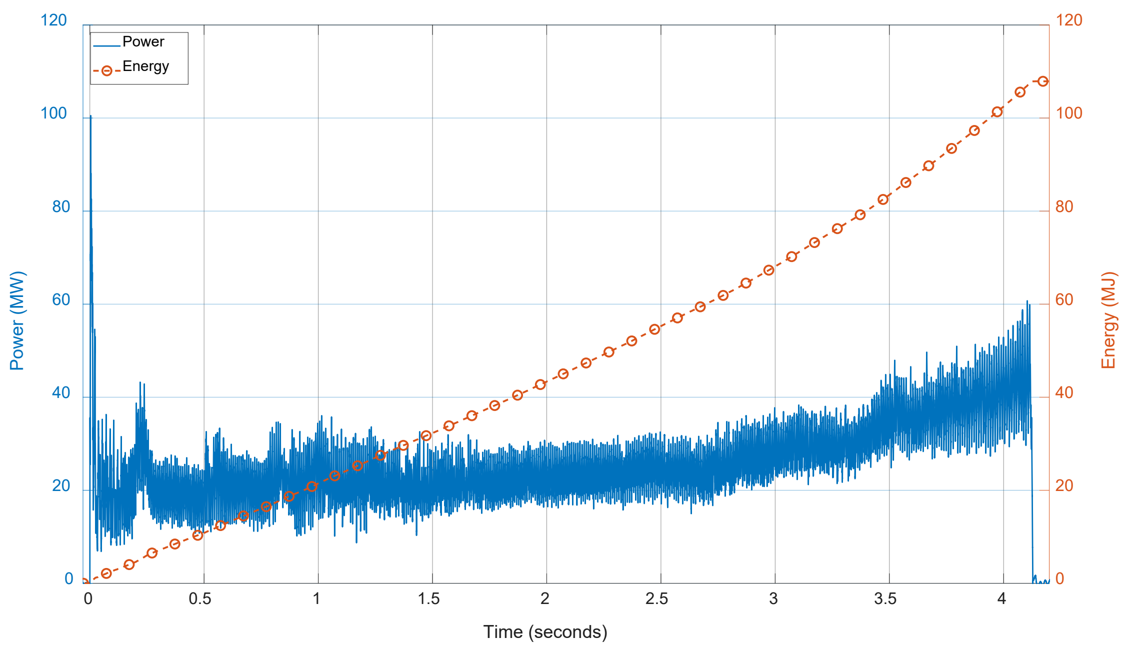

Fig. 153. Power and Energy for Experiment 2-39. Measurement uncertainty ± 3 percent.

B.9. Experiment 2-40 (MV Bus Duct, Copper Bus, Aluminum Enclosure, 4.16 kV, 30 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 154. The transient region for current phases is presented in Fig. 155. Energy and power profiles are presented in Fig. 156.

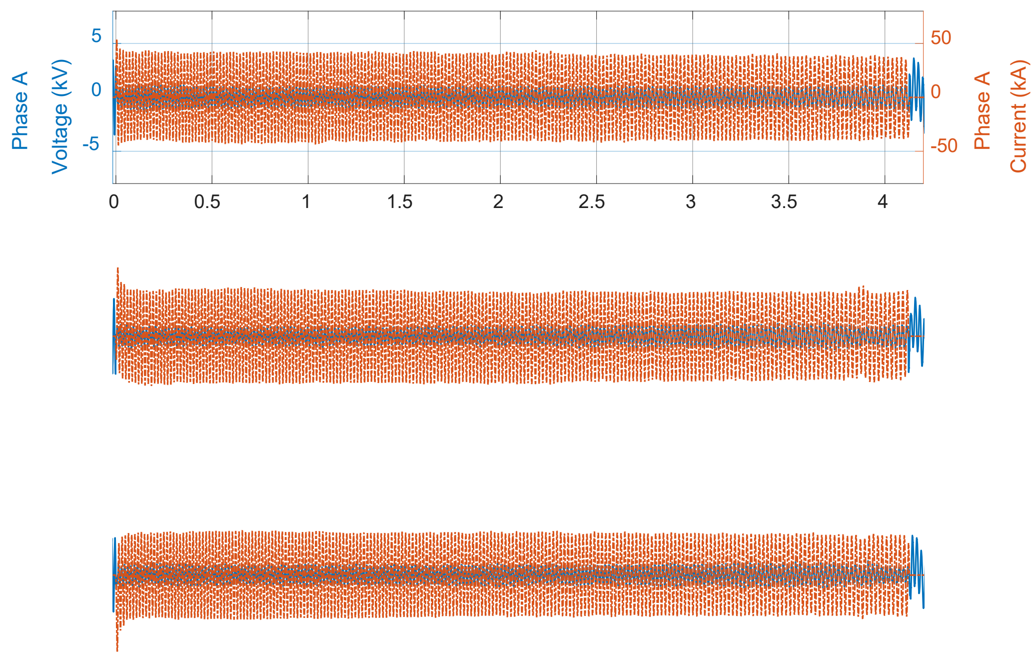

Fig. 154. Voltage and Current Profile during Experiment 2-40. Measurement uncertainty ± 3 percent.

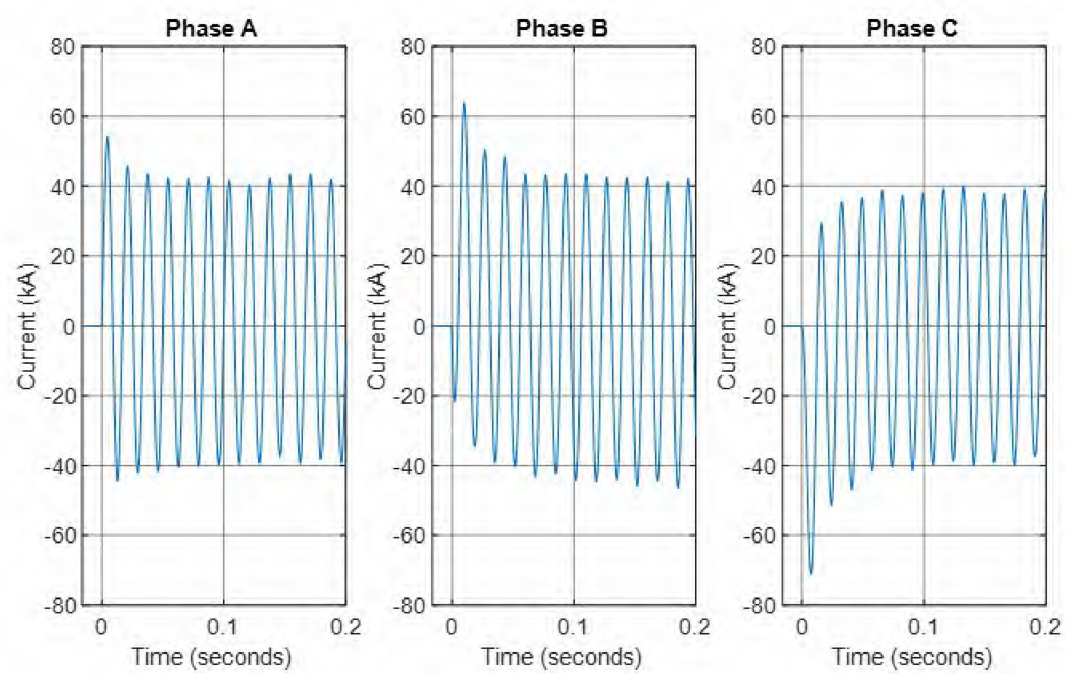

Fig. 155. Transient current profiles for Experiment 2-40. Measurement uncertainty ± 3 percent.

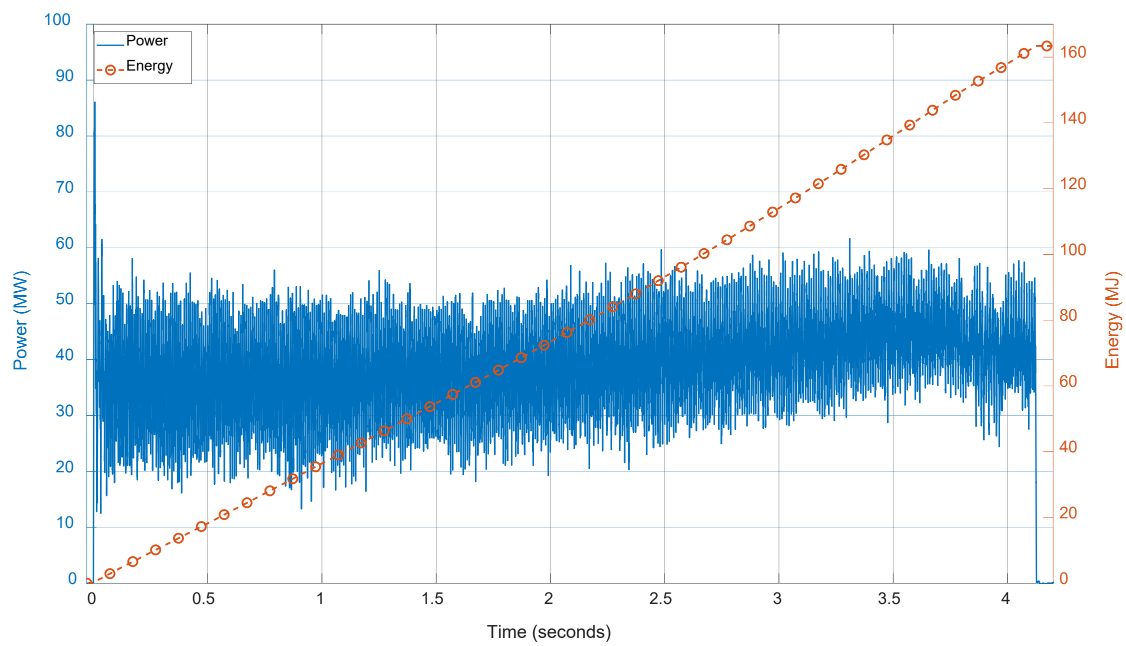

Fig. 156. Power and Energy for Experiment 2-40. Measurement uncertainty ± 3 percent.

B.10. Experiment 2-41 (MV Bus Duct, Aluminum Bus, Aluminum Enclosure, 4.16 kV, 30 kA, 4 s)

The voltage and current profile for the entire duration of the experiment is shown in Fig. 157. The transient region for current phases is presented in Fig. 158. Energy and power profiles are presented in Fig. 159.

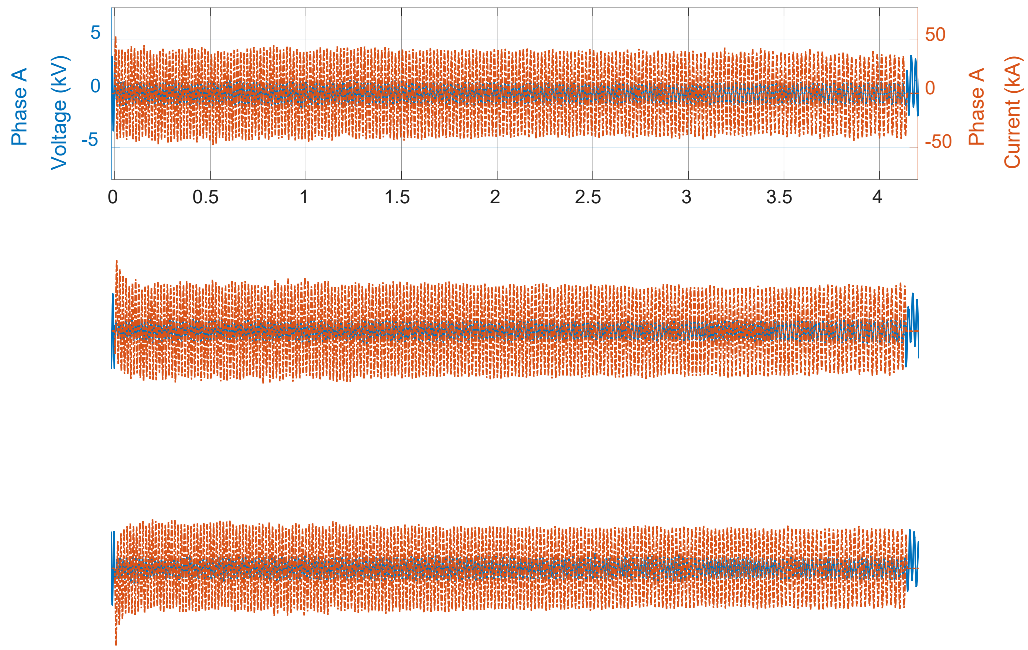

Fig. 157. Voltage and Current Profile during Experiment 2-41. Measurement uncertainty ± 3 percent.

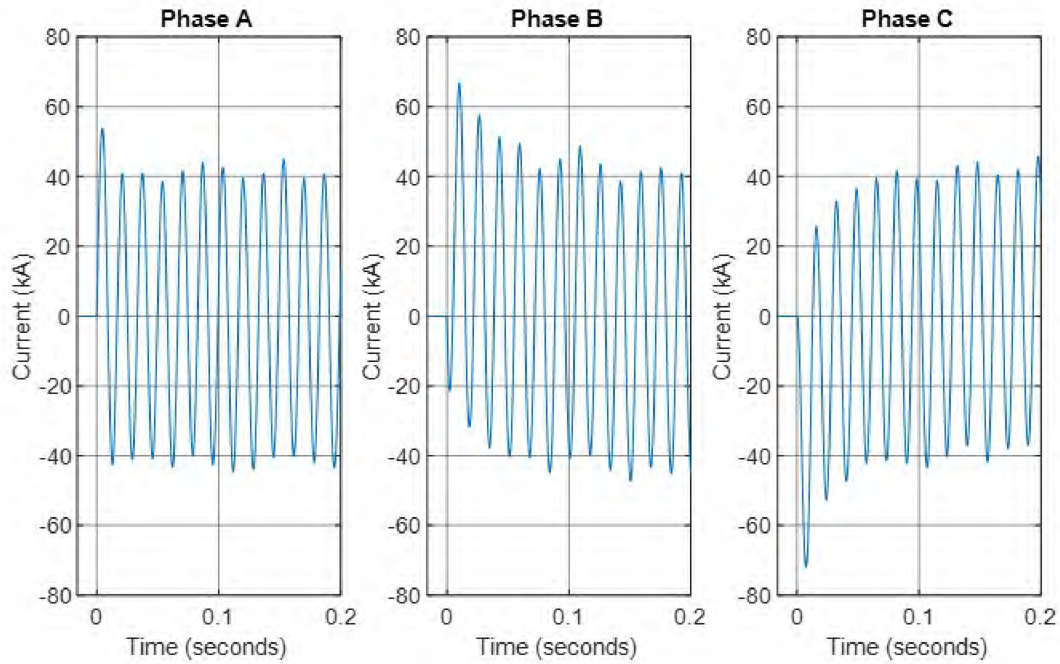

Fig. 158. Transient current profiles for Experiment 2-41. Measurement uncertainty ± 3 percent.

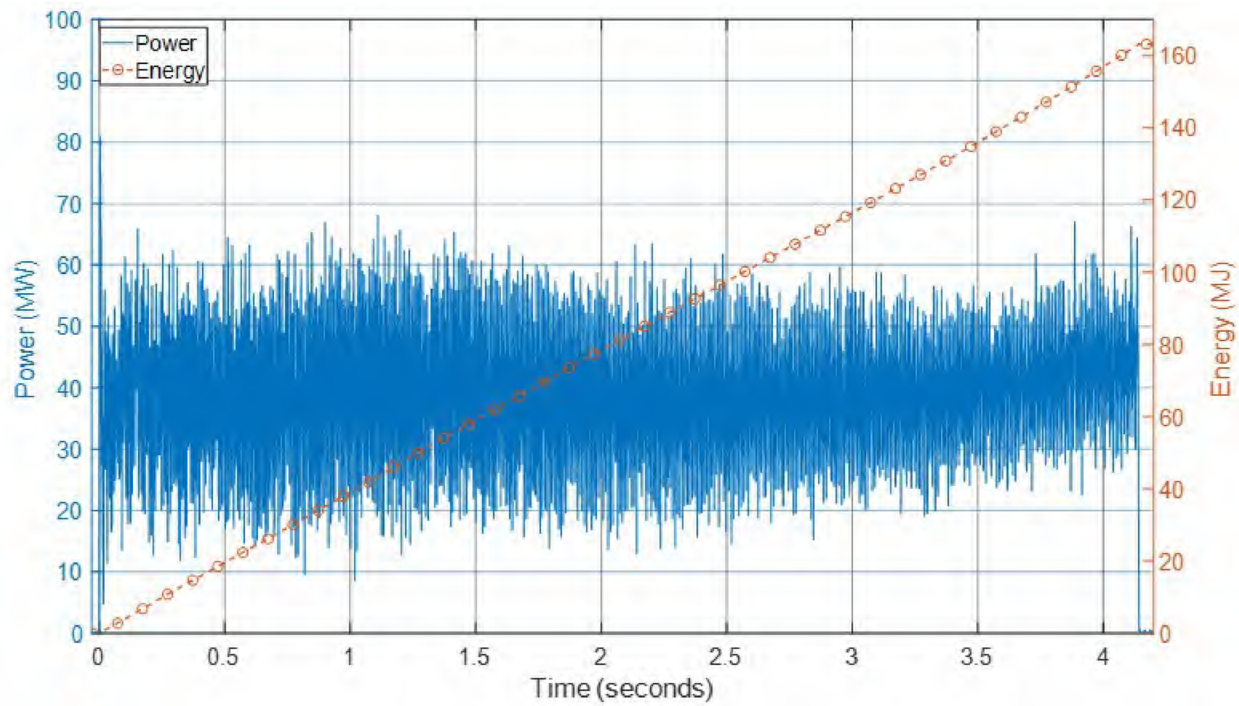

Fig. 159. Power and Energy for Experiment 2-41. Measurement uncertainty ± 3 percent.

Appendix C. Weights and Measurements

This appendix provides mass and dimension measurements of experiment object components.

C.1. Switchgear Electrical Enclosure and Conductors

Prior to performing high energy arcing fault experiments on the experiment devices, the electrical contractor removed the metal cladding, and with the support from NIST staff, each removed panel was weighed using calibrated mass balances. The mass loss measurements for the metal cladding after the experiments are presented below for each experiment device.

C.1.1. Switchgear Enclosure Weights

C.2. Non-Segregated Bus Duct Enclosure and Conductors

The bus duct enclosure panels, support members, and electrical conductors were measured and weighed. The initial and final measurements for the metal cladding are presented below for each experiment device.

C.2.2. Experiments 2-33A & 2-33B

The main bus bars were weighed prior to experiment 2-33A and after experiment 2-33B. There was no observable mass difference. For the other bus bars, the components were weighed separately for each vertical section of switchgear used.

C.2.2.1. Enclosure EV51

Enclosure EV51 (Enclosure "A") showed no observable mass loss and as such was not dismantled for weight measurements.

Table 67. Experiment Device Mass Measurements from Enclosure EV51 – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	8 589.5	N/A	-
Bus Phase B	8 585.0	N/A	-
Bus Phase C	8 594.0	N/A	-
		Total Mass Loss	0.0

C.2.2.2. Enclosure EV52

Enclosure EV52 (Enclosure "B") showed significant mass loss on the lower bars, which were severed from the arc damage and laying on the floor of the enclosure post-experiment. Mass loss measurements are shown in Table 68.

Table 68. Experiment Device Mass Measurements from Enclosure EV52 – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Upper	5 171.0	4 782.5	388.5
Bus Phase B – Upper	4 081.5	3 542.5	539.0
Bus Phase C – Upper	3 016.0	2 756.0	260.0
Bus Phase A – Lower	4 970.0	3767.5	1 202.5
Bus Phase B – Lower	4 954.0	3 907.0	1 047.0
Bus Phase C – Lower	4 961.5	3 906.5	1 055.0
		Total Mass Loss	4 492.0

C.2.2.3. Enclosure EV53

Enclosure EV53 (Enclosure "C") showed minimal mass loss on the lower conductors. Mass loss results are presented in Table 69.

Table 69. Experiment Device Mass Measurements from Enclosure EV53 – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Lower	4 813.0	4 766.0	47.0
Bus Phase B – Lower	4 812.0	4 780.5	31.5
Bus Phase C – Lower	4 812.0	4 770.5	41.5
		Total Mass Loss	120.0

C.2.3. Experiment 2-34

The main bus bars were weighed prior to and after Experiment 2-34. The results are presented in Table 70. For the other bus bars, the components were weighed only for section EU53 (Enclosure "F") which had observable mass loss. The other two enclosures did not show conductor mass loss and as such were not dismantled.

Table 70. Mass Measurements from horizontal bus bar conductors used as main bus in Experiment 2-34.

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	7101.5	7088.5	13.0
Bus Phase B	8391.5	8297.5	94.0
Bus Phase C	8386.0	8317.0	69.0
		Total Mass Loss	176.0

C.2.3.4. Enclosure EU51

Table 71. Experiment Device Mass Measurements from Enclosure EU51 (“D”) – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	8 506.0	N/A	-
Bus Phase B	8 506.5	N/A	-
Bus Phase C	8 506.0	N/A	-
		Total Mass Loss	0

C.2.3.5. Enclosure EU52

Table 72. Experiment Device Mass Measurements from Enclosure EU52 (“E”) – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Upper	5 236.5	N/A	-
Bus Phase B – Upper	4 125.0	N/A	-
Bus Phase C – Upper	3 052.5	N/A	-
Bus Phase A – Lower	5 042.0	N/A	-
Bus Phase B – Lower	5 039.5	N/A	-
Bus Phase C – Upper	5 040.5	N/A	-
		Total Mass Loss	0

C.2.3.6. Enclosure EU53

Table 73. Experiment Device Mass Measurements from Enclosure EU53 (“F”) – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	4 814.5	4 811.0	3.5
Bus Phase B	4 812.5	4 801.5	11.0
Bus Phase C	4 812.5	4 806.0	6.5
		Total Mass Loss	21.0

C.2.4. Enclosures "O" & "P" Experiment 2-35

Table 74. Experiment Device Mass Measurements from Enclosure "O" – Copper Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 38 3/8" x 4" x ¼"	5 934.5	5 897.5	- 37.0
Bus Phase B – Feeder 21 ½" x 4" x ¼"	3230.0	3222.5	- 7.5
Bus Phase B – Splice 20" x 4" x ¼"	2783.5	2787.0	3.5
Bus Phase C – Feeder 31 ½" x 4" x ¼"	4802.0	4787.5	-14.5
Bus Phase C – Splice 10 1/8" x 4" x ¼"	1377.5	1379.0	1.5
		Total Mass Loss	- 54.0

Table 75. Experiment Device Mass Measurements from Enclosure "P" – Aluminum Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A 38 ¾" x 6" x ½"	5 625.0	4 548.5	- 1 076.5
Bus Phase B 21 ½" x 6" x ½"	3 054.0	2 491.0	- 563.0
Bus Phase C 31 ½" x 6" x ½"	4 537.0	3 617.0	- 920.0
		Total Mass Loss	-2 559.5

C.2.5. Enclosure "H" Experiment 2-36

Table 76. Experiment Device Mass Measurements from Enclosure H – Copper Electrical Conductors 4.45 cm (1.75 in) round bar [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 122 cm (48 in)	16 944.0	13 227.0 + 2 468.5	1 248.5
Bus Phase B – Feeder 152 cm (60 in)	21 155.0	13 178.0 + 6 619.5	1 357.5
Bus Phase C – Feeder 182 cm (71.75 in)	25 293.0	13 821.0 + 10 552.0	920.0
		Total Mass Loss	3 526.0

Due to the construction of the switchgear, the vertical bus connecting the breaker to the main bus was not removed for weight measurements. Approximate measurements of the bus were as follows:

Phase A : 72 cm (28.5 in) x 5 cm (2 in) x 0.47 cm (0.1875 in)

Phase B : 53 cm (21 in) x 5 cm (2 in) x 0.47 cm (0.1875 in)

Phase C : 33 cm (13 in) x 5 cm (2 in) x 0.47 cm (0.1875 in)

C.2.6. Enclosures "J" and "I" Experiment 2-37

Table 77. Experiment Device Mass Measurements from Enclosure "J" – Copper Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 22" x 4" x ¼"	3 315.5	3 308.0	7.5
Bus Phase A – Splice 21" x 4" x ¼"	2 936.5	2 909.0	27.5
Bus Phase B – Feeder 32" x 4" x ¼"	4 868.0	4 808.0	60.0
Bus Phase B – Splice 10" x 4" x ¼"	1 343.5	1 328.5	15.0
Bus Phase C – Feeder 42" x 4" x ¼"	6 442.0	6 237.5	204.5
		Total Mass Loss	314.5

Table 78. Experiment Device Mass Measurements from Enclosure “I” – Copper Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 22 1/16” x 4” x ½”	3316.5	2214.0	1102.5
Bus Phase B – Feeder 32” x 6” x ½”	4891.0	3991.5	899.5
Bus Phase C – Feeder 40 1/8” x 6” x ½”	6080.5	5593.0	487.5
		Total Mass Loss	2489.5

C.2.7. Enclosure “K” Experiment 2-38

Table 79. Experiment Device Mass Measurements from Enclosure “K” – Copper Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 22” x 4” x ¼”	3317.0	3313.5	3.5
Bus Phase A – Splice 21 1/8” x 4” x ¼”	2883.5	2886.5	(3.0)
Bus Phase B – Feeder 32” x 4” x ¼”	4875.5	4847.0	28.5
Bus Phase B – Splice 11” x 4” x ¼”	1504.5	1441.0	63.5
Bus Phase C – Feeder 40 7/8” x 4” x ¼”	6219.5	6181.0	38.5
		Total Mass Loss	131.0

Table 80. Experiment Device Mass Measurements from Enclosure "L" – Aluminum Electrical Conductors
[made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 22" x 6" x ½"	3 128.0	2 678.5	449.5
Bus Phase B – Feeder 32" x 6" x ½"	4 651.0	4 162.5	488.5
Bus Phase C – Feeder 40 1/8" x 6" x ½"	5 820.5	5 092.0	728.5
		Total Mass Loss	1 666.5

C.2.8. Enclosure "M" Experiment 2-39

Table 81. Experiment Device Mass Measurements from Enclosure "M" – Aluminum Electrical Conductors
[made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A – Feeder 22" x 6" x ½"	3 140.0	3 140.0	-
Bus Phase B – Feeder 32" x 6" x ½"	4 645.5	4 645.5	-
Bus Phase B – Splice 12 5/8" x 4" x ¼" Copper	1 869.5	1 869.5	-
Bus Phase C – Feeder 42" x 6" x ½"	6 167.0	6 167.0	-
		Total Mass Loss	0

Table 82. Experiment Device Mass Measurements from Enclosure “I” – Aluminum Electrical Conductors
[made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A 40” x 6” x ½”	6 542.5	6 512.5	30.0
Bus Phase B 38 3/4” x 6” x ½”	6 369.0	6 353.0	16.0
Bus Phase C 40 5/8” x 6” x ½”	5 387.5	5 319.0	68.5
		Total Mass Loss	114.5

C.2.9. Experiment 2-40 NSBD Copper Bus, Aluminum Enclosure, 4s

The mass measurements from the electrical duct enclosure metal cladding are presented in Table 83. Mass lass was estimated using graphical analysis as discussed previously. The duct bottoms and tops were 0.29 cm (0.115 in) thick while the sides were 0.36 cm (0.14 in) thick. Assuming the aluminum density was 2.9 g/cm^3 then the breach mass loss can be estimated with reasonable accuracy. The analysis for this enclosure indicated a total of 16 088 g mass loss from the duct enclosure. The masses recorded from the electrical conductors are presented in Table 84. Soot and other loose byproducts were removed from the electrical conductors prior to measurement.

Table 83. Experiment Device Mass Measurements from Experiment 2-40 – Duct Enclosure Metal-Cladding

Description	Pre-Experiment Scale 2 (g)	∆ mass (g)
Top	9 978.0	- 1 497.0
Left Side (front)	9 767.5	- 6 349.0
Right Side (rear)	9 782.0	- 7 043.0
Bottom	9 990.0	- 1 199.0
	Total Mass Loss	- 16 088.0

Table 84. Experiment Device Mass Measurements from Experiment 2-40 – Electrical Conductors
[made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-Experiment w/insulation (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	25 916.5	24 278.5	- 1 638.0
Bus Phase B	25 816.5	23 937.0	- 1 879.5
Bus Phase C	25 839.0	24 231.5	- 1 607.5
		Total Mass Loss	- 5 125.0

C.2.10. Experiment 2-41 NSBD Aluminum Bus, Aluminum Enclosure, 4s

The mass measurements from the electrical duct enclosure metal cladding are presented in Table 85. Mass lass was estimated using graphical analysis as discussed previously. The duct bottoms and tops were 0.29 cm (0.115 in) thick while the sides were 0.36 cm (0.14 in) thick. Assuming the aluminum density is 2.9 g/cm^3 then the breach mass loss was estimated with reasonable accuracy. The analysis for this enclosure indicated a total of 23 849.0 g mass loss from the top of the duct enclosure. The masses recorded from the electrical conductors are presented in Table 86. Soot and other loose byproducts were removed from the electrical conductors prior to measurement.

Table 85. Experiment Device Mass Measurements from Experiment 2-41 – Duct Enclosure Metal-Cladding

Description	Pre-Experiment Scale 2 (g)	Δ mass (g)
Top	9978.0	- 3594.0
Left Side (front)	9767.5	- 8888.0
Right Side (rear)	9782.0	- 8217.0
Bottom	9990.0	- 2790.0
	Total Mass Loss	- 23 849.0

Table 86. Experiment Device Mass Measurements from Experiment 2-41 – Electrical Conductors [made using Scale 2 with uncertainty of ± 1 g]

Description	Pre-Experiment (g)	Post-Experiment (g)	Mass Loss (g)
Bus Phase A	13 010.0	11 884.0	- 1 126.0
Bus Phase B	13 027.0	11 768.5	- 1 258.5
Bus Phase C	13 032.0	11 927.0	- 1 105.0
		Total Mass Loss	- 3 489.5

Appendix D. Photographs from Experiments

This appendix presents select photographs for each experiment. Additional photographs are presented in the KEMA Laboratories Experimental Report (Appendix F).

D.1. Experiment 2-33A

Fig. 160. Pre-Experiment 2-33A with equipment placed in Test Cell #7. Left – complete lineup, Center – Section ‘A’ internals viewed from front with doors open, Right – SIS wire pulled out to show amount installed in upper wire-way (note wire ends were pushed back into wireway prior to experiment).

Fig. 161. Pre-Experiment 2-33A experimental setup viewed from courtyard (Test Cell #7).

Fig. 162. Post-Experiment 2-33A. Note arc burn-through on side of Enclosure "C" (EV53), melting of vents in lower section and placement of breaker protection cover.

Fig. 163. Post-Experiment 2-33A Conductors. Enclosure ‘C’ (EV53).

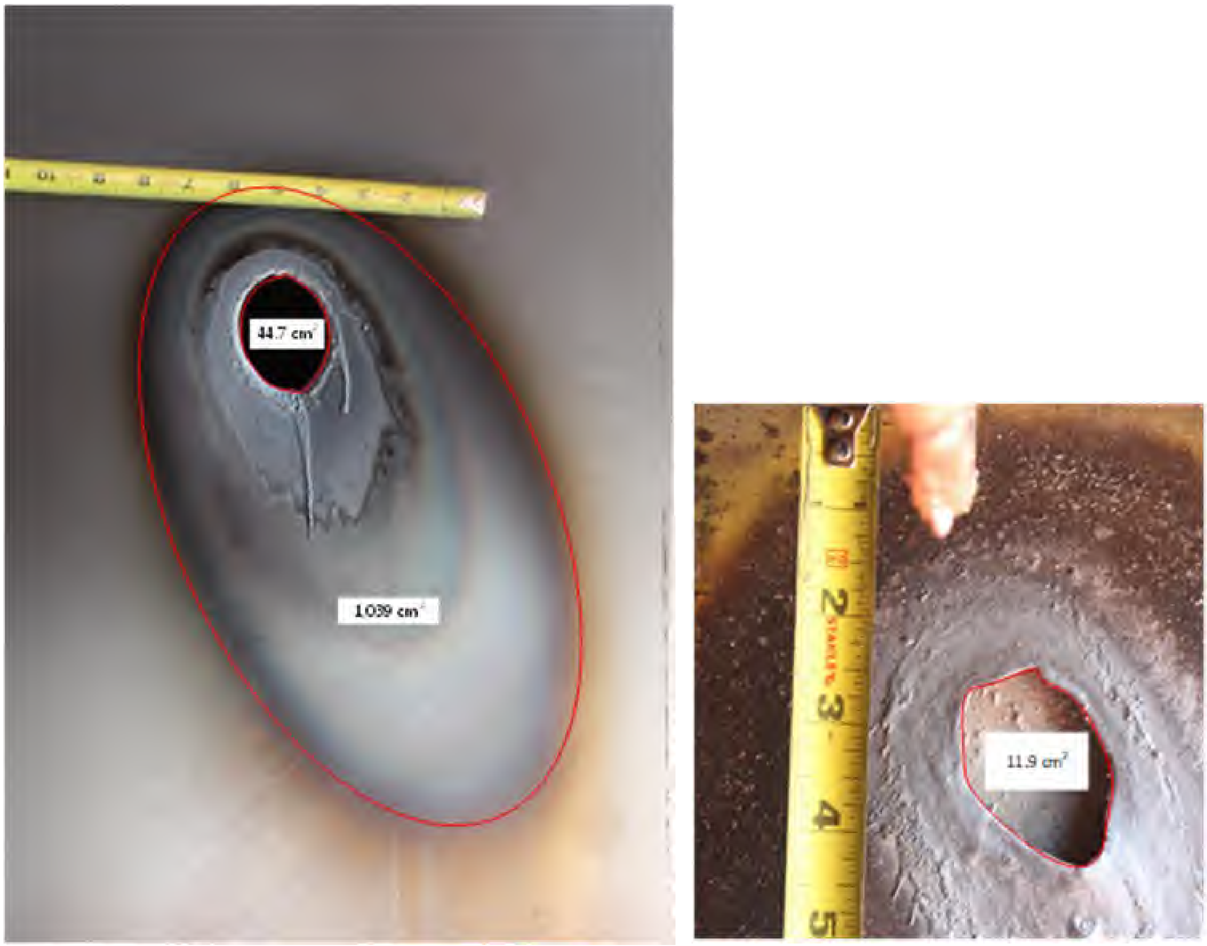

Fig. 164. Enclosure burn-through. Left – exterior panel, Right – internal panel. Total mass loss approximately 91.0 g.

D.2. Experiment 2-33B

The experiment device used in Experiment 2-33B was identical to that used in Experiment 2-33A.

Fig. 165. Pre-Experiment 2-33B. Viewed from side opposite power supply, showing instrumentation rack arrangement surrounding enclosure.

Fig. 166. Pre-Experiment 2-33B in test cell. Left – front corner view, Right – experimental device viewed from rear.

Fig. 167. Post-Experiment 2-33B Left – front corner view, Right – rear corner view.

Fig. 168. Post-Experiment internal view from rear.

Fig. 169. Post-Experiment 2-33B Enclosure 'A' (EV51). Top left – top of breaker viewed from rear of enclosure, Top right – back of breaker, Bottom-left – Front of enclosure with all three cubicle doors open, Bottom-right – top enclosure close-up view.

Fig. 170. Post-Experiment 2-33B Enclosure 'B' (EV52). Top left – upper cubicle internals showing remanence of panel wiring, Top center – middle cubicle with door open showing face of breaker, Top right – lower cubicle showing lower bus bars (all three phases) laying on floor of enclosure, Bottom – view of breaker from rear (note lower breaker stabs showing and lower bus bars are missing).

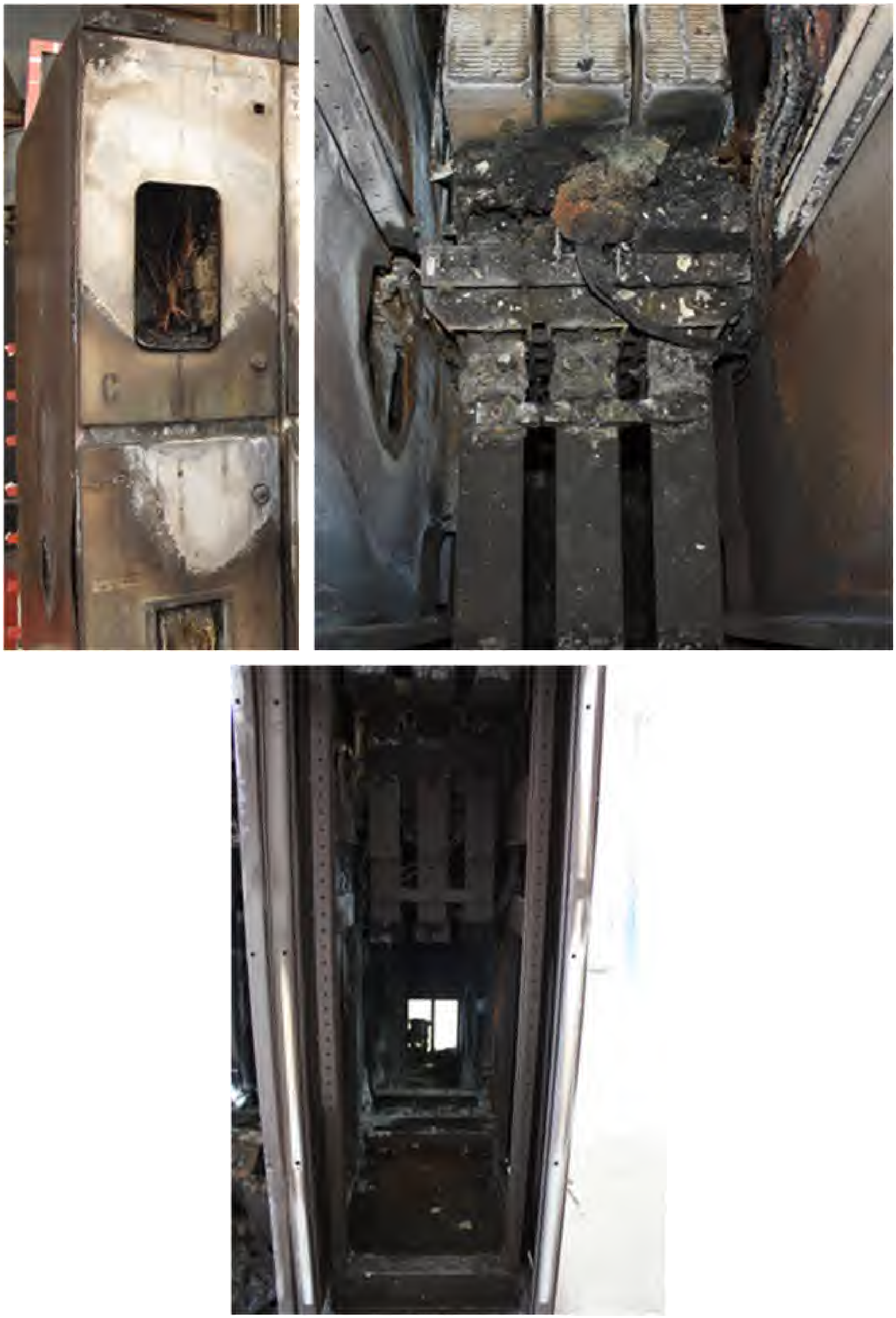

Fig. 171. Post-Experiment 2-33B Enclosure ‘C’ (EV53). Top-left upper cubicle containing remains of panel wiring, Top-right, breaker viewed from rear and above, Bottom – lower cubicle viewed from rear.

Fig. 172. Post-Experiment 2-33B Horizontal Main Bus Conductors.

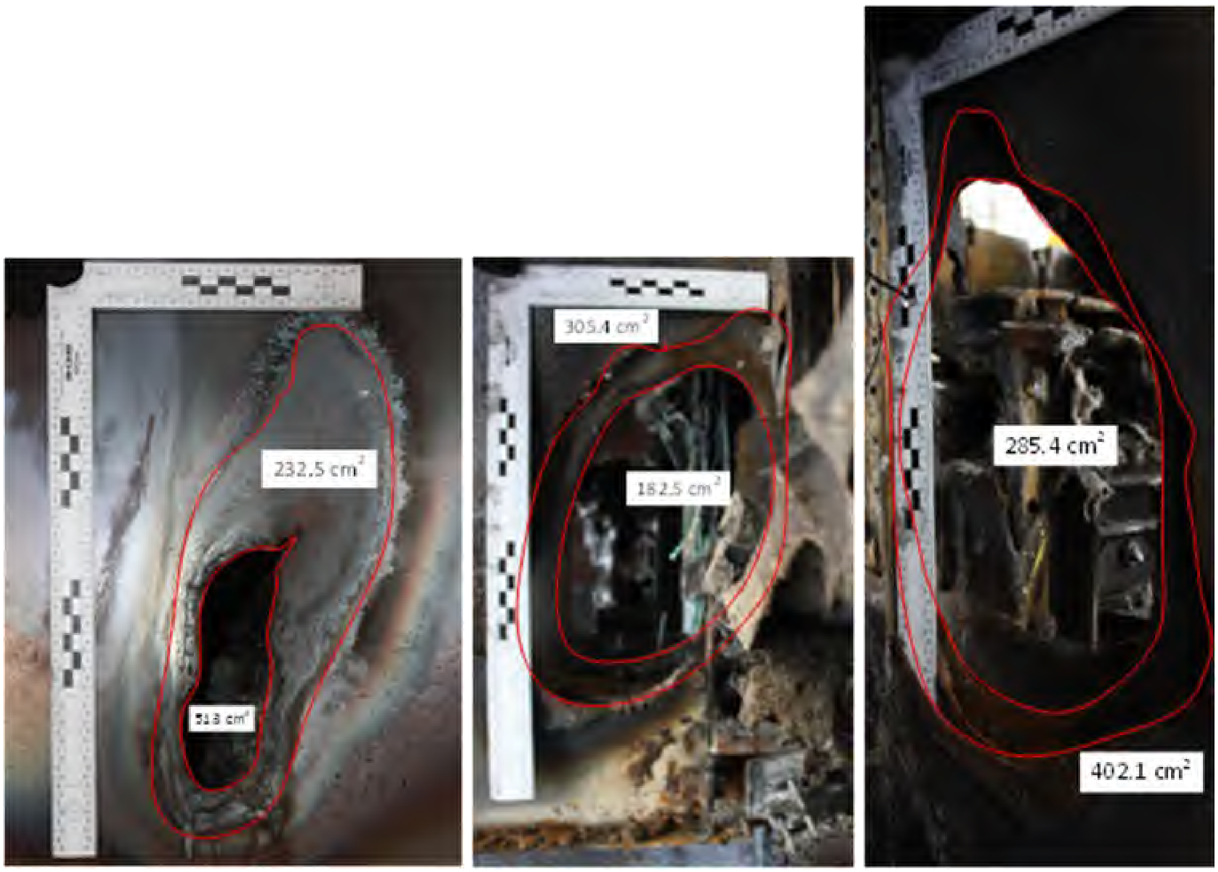

Fig. 173. Post-Experiment 2-33B Enclosure Breach. Left – Exterior breach approximately 82 g, Center – Interior double panel breach between Enclosure ‘A’ & ‘B’ approximately 118 g, Right – Interior double panel breach between Enclosure ‘B’ & ‘C’ approximately 166 g.

D.3. Experiment 2-34

Fig. 174. Pre-Experiment 2-34 Enclosures “D”, “E”, and “F”. Left – front angle view of experimental device, Right – side view of “back-to-back” experimental configuration (note enclosure labled 2-33 on left is not energized).

Fig. 175. Post-Experiment 2-34 Enclosures “D”, “E”, and “F”. Left – front angle view of experimental device, Right – side view of experimental device.

Fig. 176. Post-Experiment 2-34 Conductors.

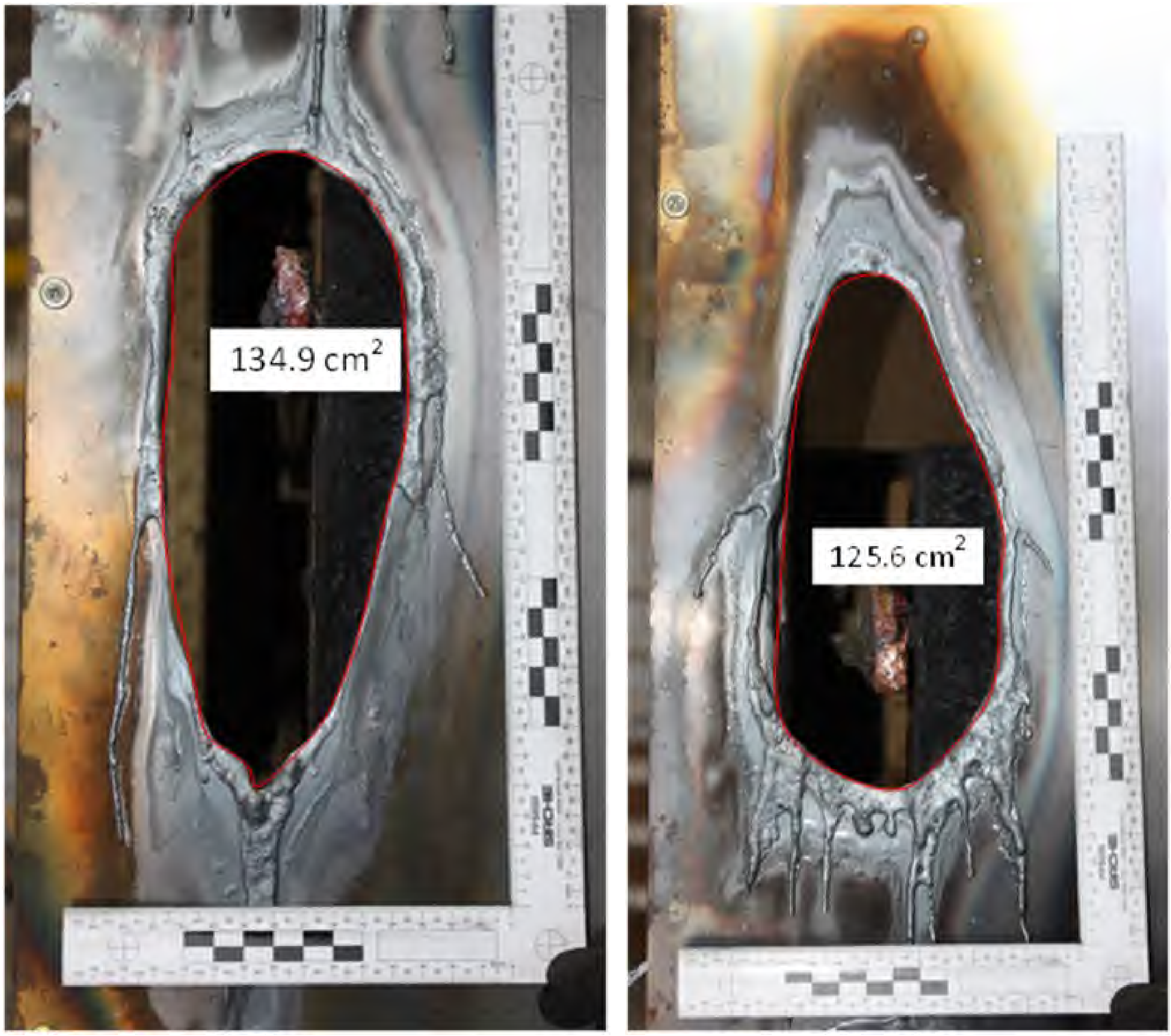

Fig. 177. Post-Experiment 2-34 Enclore “F”. Enclosure Breach. Left – bottom breach area, Right – top breach area.

D.4. Experiment 2-35

Fig. 178. Pre-Experiment 2-35 Enclosures “O” and “P”. Enclosure “O” (left) and “P” (right) front panel, Right – Inside Enclsoure “O” showing main bus where arc was initiated.

Fig. 179. Post-Experiment 2-35 Enclosures “O” and “P”. Left – Enclosure “O” showing incoming power supply and soot on exterior, Right - Enclosure “P” (note breach on upper left panel).

Fig. 180. Post-Experiment 2-35 Enclosures “O” and “P”. Soot and heat damage on front enclosure doors.

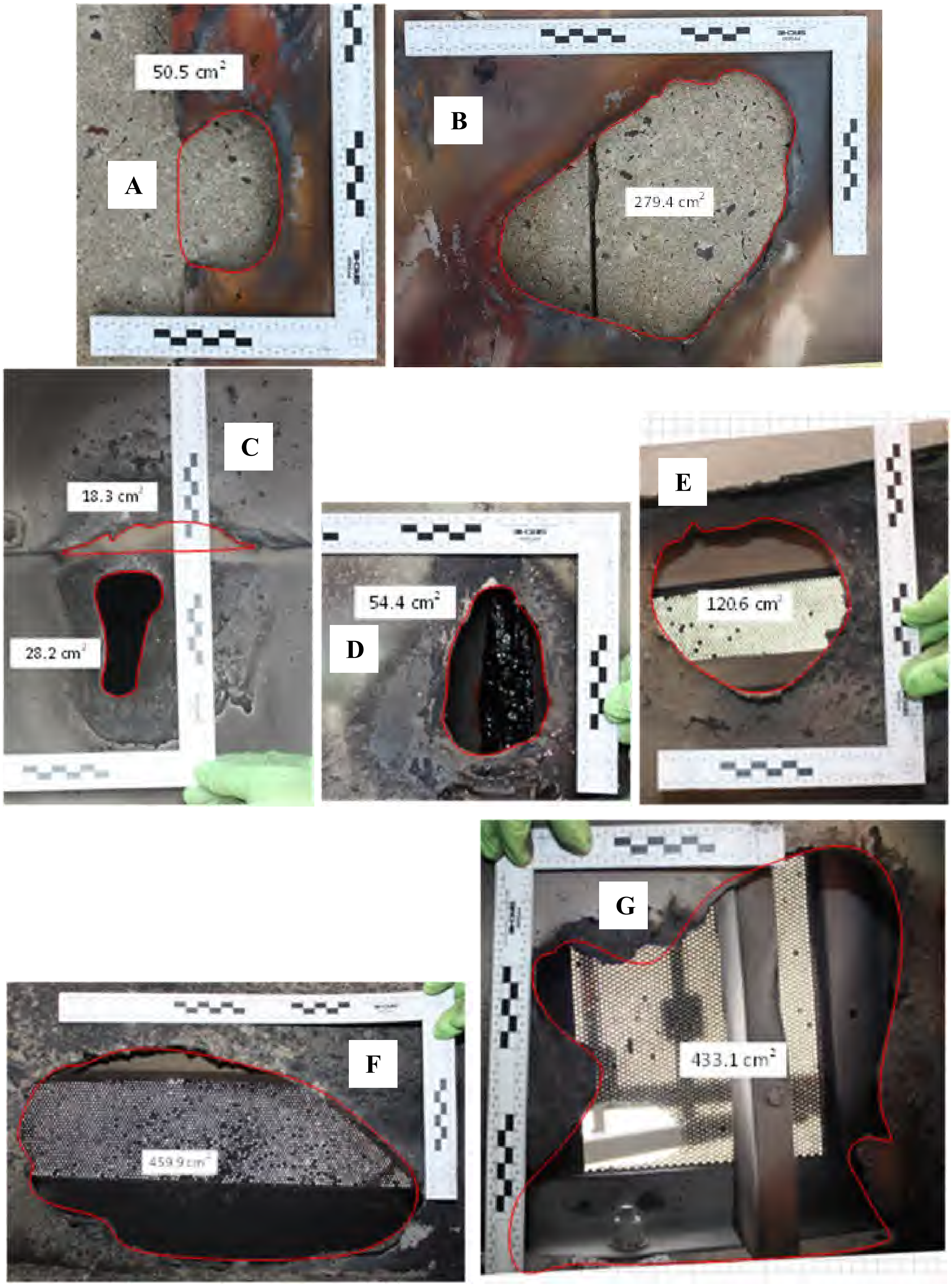

Fig. 181. Post-Experiment 2-35 Enclosure “O” Breaches A-B-C, Internal main bus cover panels, D-E-F-G, Internal panels above breaker.

D.5. Experiment 2-36

Fig. 182. Pre-Experiment 2-36 Enclosures "H" and "N". Left – switchgear mockup at storage warehouse, Right – enclosures prior to experiment showing instrumentation rack locations.

Fig. 183. Post-Experiment 2-36, Enclosure “H”. Top-left – front instrument cubicle, Top-right – lower breaker cubicle, Bottom – exterior showing two panels re-oriented on top of enclosure, one panel on side completely disconnected from enclosure.

Fig. 184. Post-Experiment Enclosure "N". Top-left – front instrumentation and breaker cubicle, Top-right – side showing soot deposit near cover over main bus section of switchgear, Bottom – main bus section showing damage to horizontal copper bus.

Fig. 185. Post-Experiment 2-36, Enclosure “H” breaches.

D.6. Experiment 2-37

Fig. 186. Pre-Experiment 2-37 Enclosures “J” and “I”. Left – off angle view of Enclosure “J” (left) and “I” (right), Right – arc location main bus.

Fig. 187. Post-Experiment 2-37 Breaker. Left - rear angle view, Center – stab close-up, Right - rear angle view.

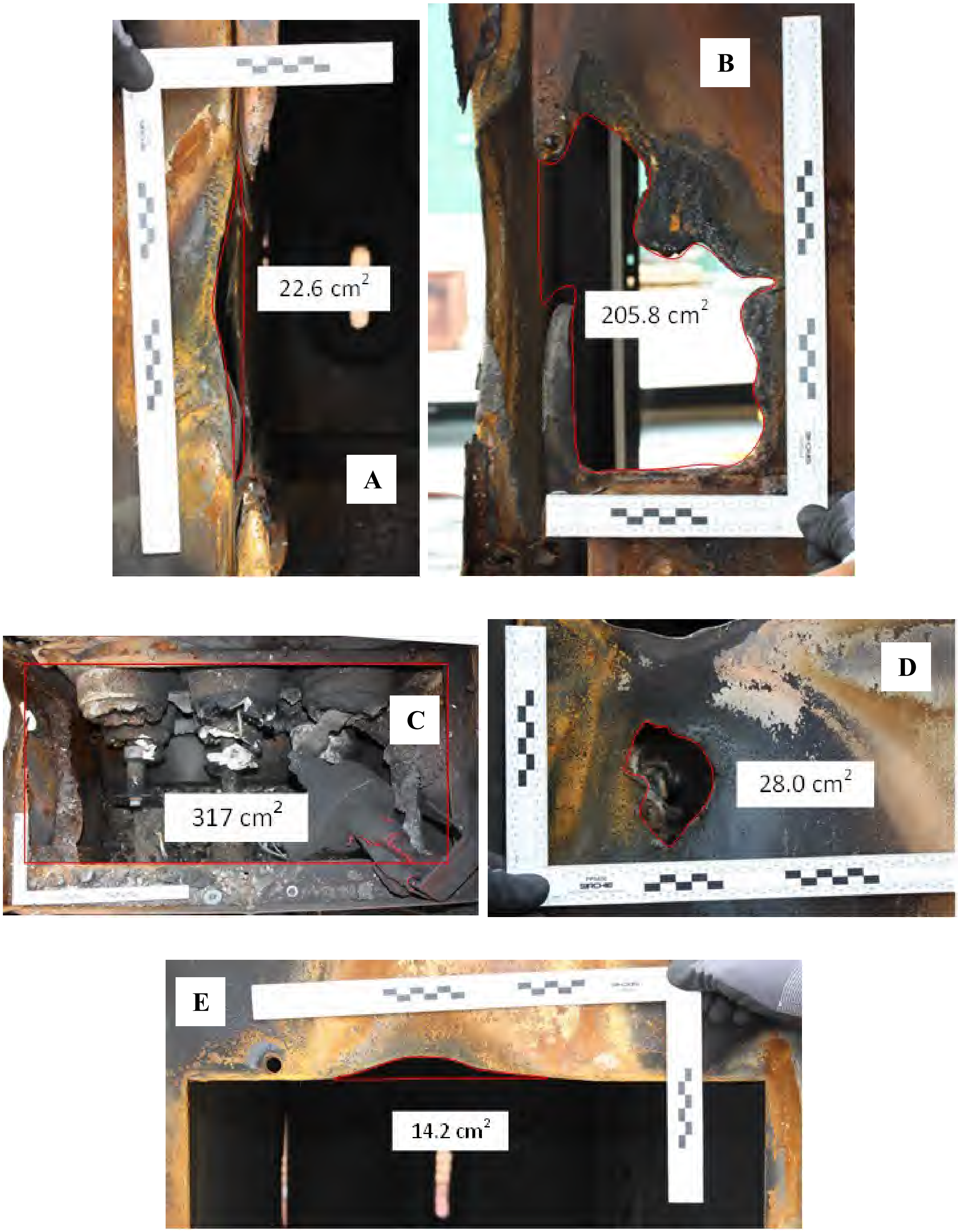

Fig. 188. Post-Experiment 2-37 Enclosure “J” mass loss.

D.7. Experiment 2-38

Fig. 189. Pre-Experiment 2-38 Enclosure “K” and “L”. Left - Enclosure “K” (left) and “L” (right), Right -arc location on main bus Enclosure “K”.

Fig. 190. Pre-Experiment 2-38 Enclosure “K” and “L”. Left – Enclosure “K” (left) and “L” (right). Right – general cross-aisle configuraiotn with Enclosure “M” across from “L” and Enclosure “I” across from “K”.

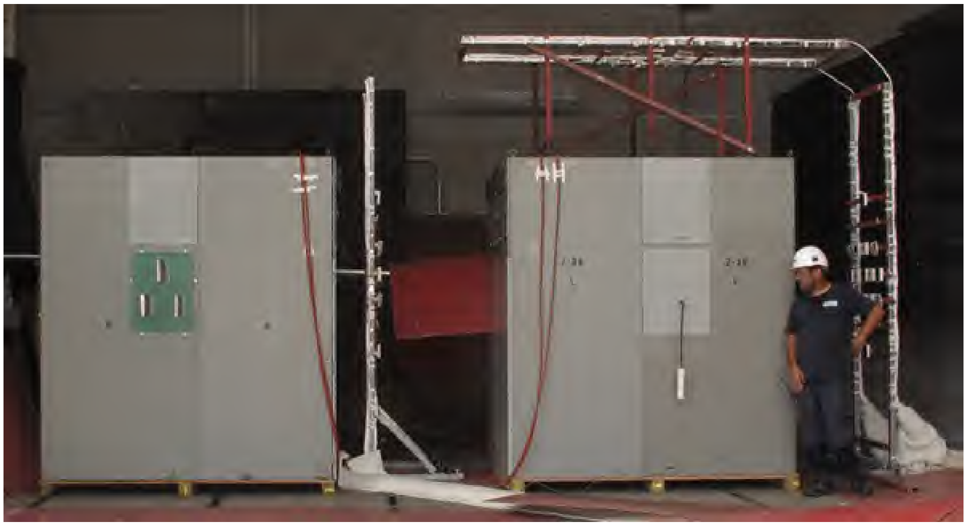

Fig. 191. Pre-experiment 2-38 Enclosure “M” and “L”. Front view of “cross-aisle” configuration. Arc initiated in Enclosure "K” located behind Enclosure “L”.

Fig. 192. Post-Experiment 2-38 Enclosure “M” and “L”. Front view of Enclosure “M” (left) with Enclosure “I” behind, and Enclosure “L” (right) with Enclosure “K” behind (where arc initiated).

Fig. 193. Post-experiment 2-38 Enclosures “L” and “K”. Left - Enclosure "K" rear panel breach due to pressure, Right – measurement of rear internal panel distance from Enclosure “K” corner. Note that both internal panels surrounding main bus were ejected during experiment and located on floor. Farthest panel was approximately 3 m (10 ft) from enclosure, while nearest panel was approximately 0.9 m (3 ft) from enclosure.

Fig. 194. Post-Experiment 2-38 Conductors.

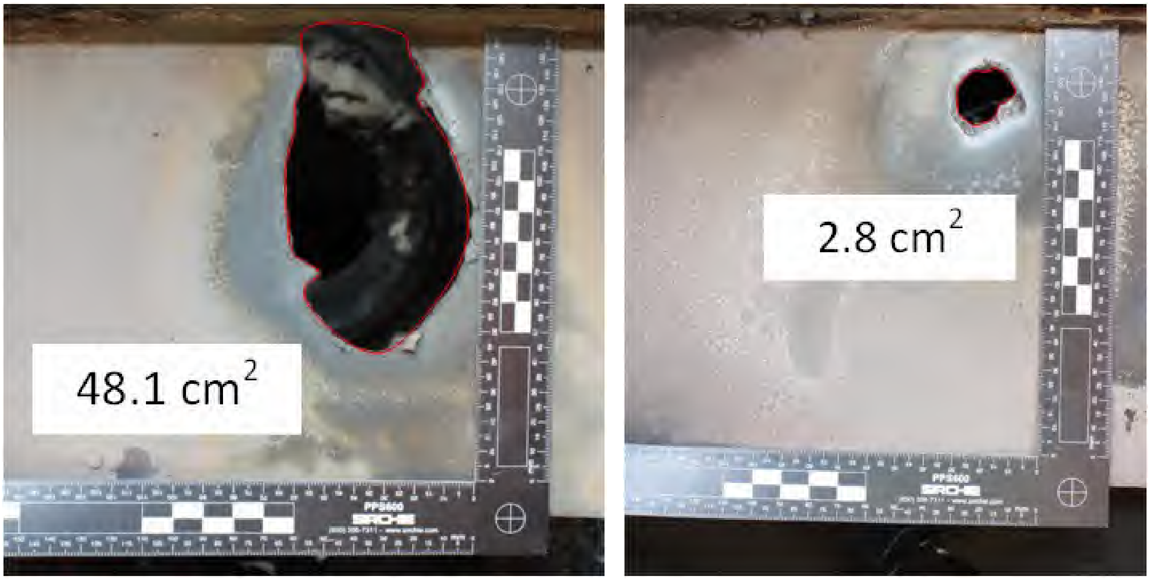

Fig. 195. Post-Experiment 2-38 Internal Breaches Enclosure "L".

D.8. Experiment 2-39

Fig. 196. Pre-Experiment 2-39 Enclosures “I” and “K”. Enclosure “I” (left) and “K” (right), Enclosure “M” is next to Enclosure “I” (behind Enclosure “I” in photo) and Enclosure “L” is next to Enclosure "K" (behind Enclosure “K” in photo).

Fig. 197. Post-Experiment 2-39 Enclosures “M”, “I”, and “K”. Note door to Enclosure “M” is not in photo, instrument rack positioned in front of Enclosure “I” fell to the ground after impact from Enclosure “M” door.

Fig. 198. Post-Experiment 2-39 Enclosure "M" Breaches. Top – internal panels near secondary run-backs, Bottom – internal bottom bus panels.

Fig. 199. Post-Experiment 2-37 Enclosure "M" Breaker. Left - rear angle view, Center – stab close-up, Right - rear angle view.

D.9. Experiment 2-40

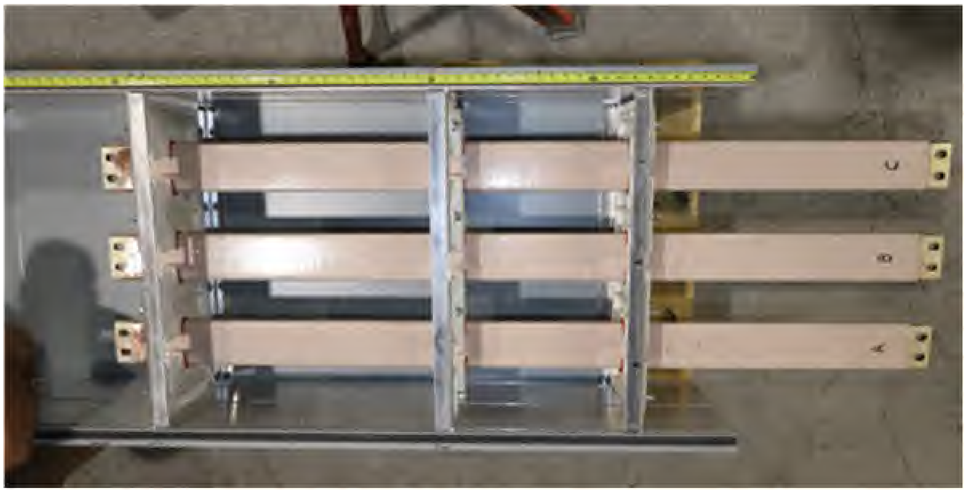

Fig. 200. Pre-Experiment 2-40 Bus Duct. Bus duct cover removed showing arc location (left – end of bars) and power supply connection (right - end of bars with phase alphabetical lettering).

Fig. 201. Pre-Experiment 2-40 Bus Duct. Duct and instrument rack configuration prior to experiment, arc initiated at arrow.

Fig. 202. Post-Experiment 2-40 Bus Duct. Duct severed with a portion resting on the support structure.

Fig. 203. Post-Experiment 2-40 Bus Duct. Left – horizontal duct with copper bars at support, Right – end of severed duct as viewed from incomming power side.

Fig. 204. Post-Experiment 2-40 Duct Enclosure Breach.

D.10. Experiment 2-41

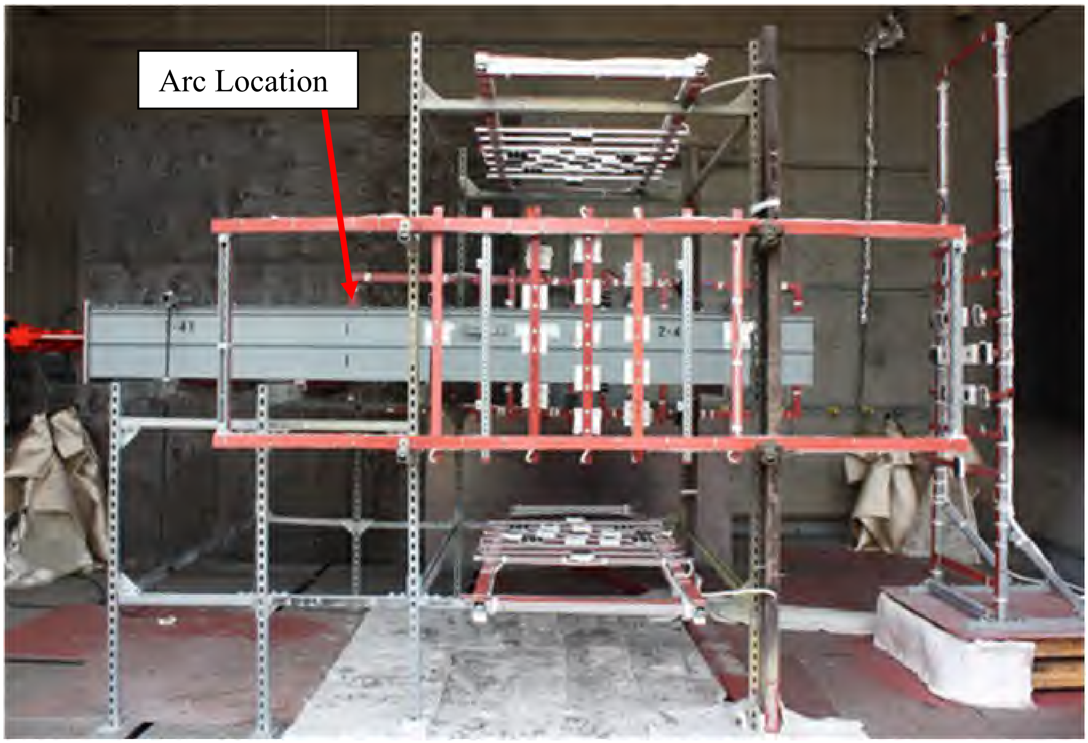

Fig. 205. Pre-Experiment 2-41 Bus Duct. Duct and instrument rack configuration prior to experiment.

Fig. 206. Post-Experiment 2-41 Bus Duct. View of remaining duct from power side.

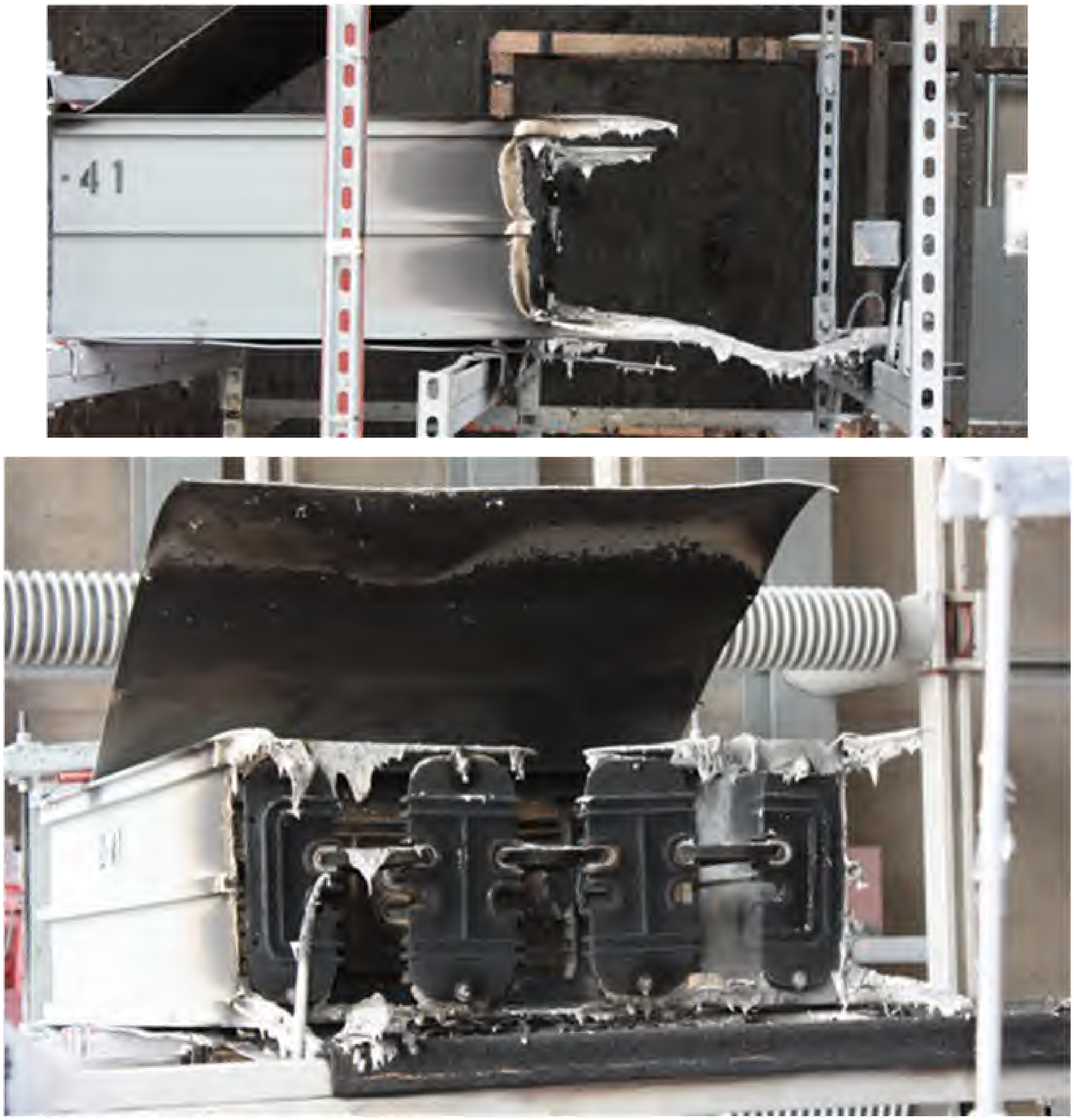

Fig. 207. Post-Experiment 2-41 Bus Duct. Top – side view of enclosure close to power supply, Bottom – end view of remaining bus bars and bus bar supports inside duct.

Fig. 208. Post-Experiment 2-41 Bus Duct. Remaining bus duct enclosure located on ground after experiment.

Appendix E. Low-Voltage Arc Hold Trial Experiments

This appendix describes trial experiments performed on low-voltage gear to explore the ability of the equipment to sustain a HEAF for an expected period of time.

E.1. Background and Need

Experiments performed during the Phase 1 of the OECD program [6], along with experiments performed by the U.S. Nuclear Regulatory Commission [17], demonstrated a limited ability of low-voltage equipment to sustain an arc for an expected duration (2 to 10 s). Table 87 presents a summary of the low-voltage experiment results. The experiments were classified as a success or failure based on the ability of the arc to sustain for at least 50 percent of the "target arc duration." Of the 19 experiments presented below, 11 were classified as failures representing 58 percent of the experiment population.

Table 87. Summary of Low-Voltage HEAF Experiments

Experiment ID / #	Nominal Voltage (V)	Nominal Current (kA)	Duration (s) Target / Actual	Location	Duration Success / Failure
Phase 1 / # 1	480	42	2.0 / 2.1	Vertical bus	Success
Phase 1 / # 2	480	42	4.0 / 4.1	Vertical bus	Success
Phase 1 / # 3	480	42	8.0 / 8.1	Vertical bus	Success
Phase 1 / # 4	480	50	3.0 / 0.009	Horizontal run backs	Failure
Phase 1 / # 5	480	50	4.0 / 0.3	Vertical bus	Failure
Phase 1 / # 6	480	50	4.0 / 0.3	Vertical Bus	Failure
Phase 1 / # 7	480	50	4.0 / 0.4	Vertical Bus	Failure
Phase 1 / # 23	480	40	10.0 / 7.1	Disconnect – Main Bus	Success
Phase 1 / # 24	480	40	10.0 / 0.013	Horizontal run backs	Failure
Phase 1 / # 25	480	40	10.0 / 3.0	Vertical bus	Failure
NRC / # 2-13A	480	13.5	2.0 / 0.9	Vertical bus	Failure
NRC / # 2-13B	600	13.5	2.0 / 0.4	Vertical bus	Failure
NRC / # 2-13C	600	13.5	2.0 / 0.4	Vertical bus	Failure
NRC / # 2-13D	600	13.5	2.0 / 0.9	Vertical bus	Failure
NRC / # 2-13E	600	13.5	2.0 / 2.1	Breaker stabs	Success
NRC / # 2-13F	480	13.5	2.0 / 1.6	Vertical bus	Success
NRC / # 2-13G	600	13.5	2.0 / 2.0	Vertical bus	Success
NRC / # 2-18A	480	25.0	8.0 / 2.0	Vertical bus	Failure
NRC / # 2-18B	600	25.0	8.0 / 8.3	Vertical bus	Success

From the information presented above, HEAF experiments performed at a low-voltage were slightly less likely to sustain an arc for the planned arcing duration than not. These insights raised the question of the benefits of performing the remaining OECD HEAF 2 low-voltage experiment program. The program specified 12 experiments, of which, only 2 (Experiments 2-13 and 2-18) were performed. Therefore, 10 low-voltage experiments would be required to complete the low-voltage portion of the OECD HEAF 2 program. Additionally, the remaining equipment available for experiments was similar to the DS equipment used in 15 of the 19 experiments, which had a 73% failure rate to sustain an arc for that subset of equipment.

From a program execution standpoint, price increases in raw materials and support services caused the resource burden to increase from pricing prior to 2020. Given the limited budget of the OECD HEAF 2 program, performing all the low-voltage experiments would reduce the funding and available number of medium-voltage experiments. Recent risk information from applications of updated HEAF methods also indicated that low-voltage scenario risk was typically lower than that of medium-voltage scenarios.

With the information presented above, the research team was uncertain of the benefit of performing the entire low-voltage experiment program. They suggested that a limited number of trial experiments be performed to evaluate the ability of the low-voltage equipment to sustain an arc for the planned arc duration, then use those results to influence the final experimental matrix.

E.2. Objective

The objective of this effort was to perform a limited number of experiments to explore low-voltage equipment capability to sustain a high energy arc fault for planned durations.

E.3. Approach

A simplified approach was used to minimize cost and meet the objectives of this exercise. Two vertical sections of low-voltage switchgear were prepared for use. This included closing most openings on the switchgear (floor and side openings), shorting current transformers (to eliminate secondary fire hazards), overriding breaker trip linkage, and extending main bus bar connections outside of each unit to allow connection to the KEMA laboratories power supply connections. Isometric drawings of the used devices are presented in Fig. 209.

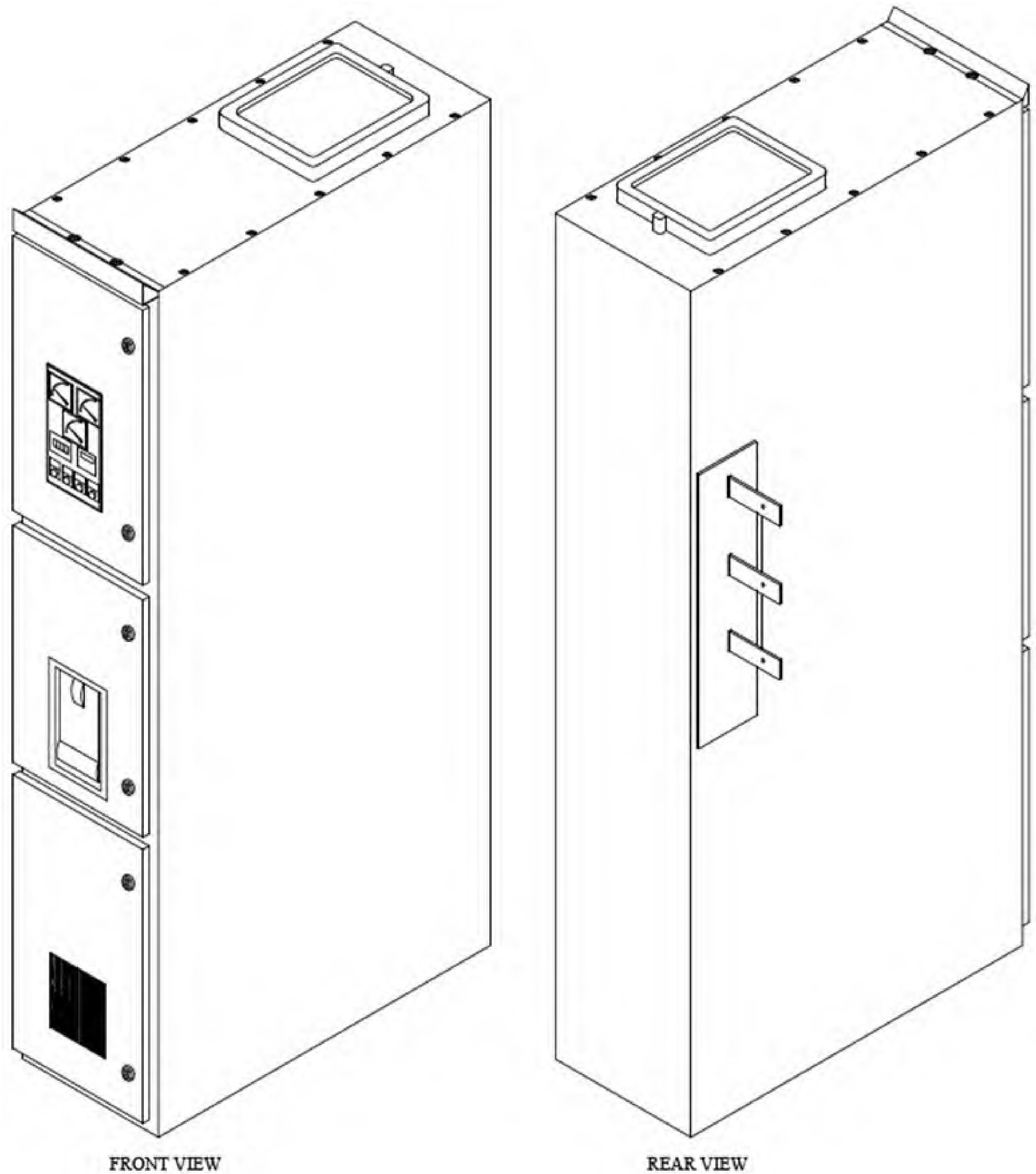

Fig. 209. Isometric drawings of used gear.

Fig. 210 provides a drawing of the internal components of the experiment object. Two arc locations were selected as possible arcing locations, as shown in the figure. Arc Location #1 was at the end of the bus where the primary cable connections were made. This experiment configuration was considered a load consideration, consistent with IEEE guidance [20] to locate the arc at the farther location from the incoming power to minimize arc migration. There were no cables connected for these experiments. Arc Location #2 was on the line side of the breaker. In this configuration, the arc was impeded from migrating via a physical conduction path due to the breaker.

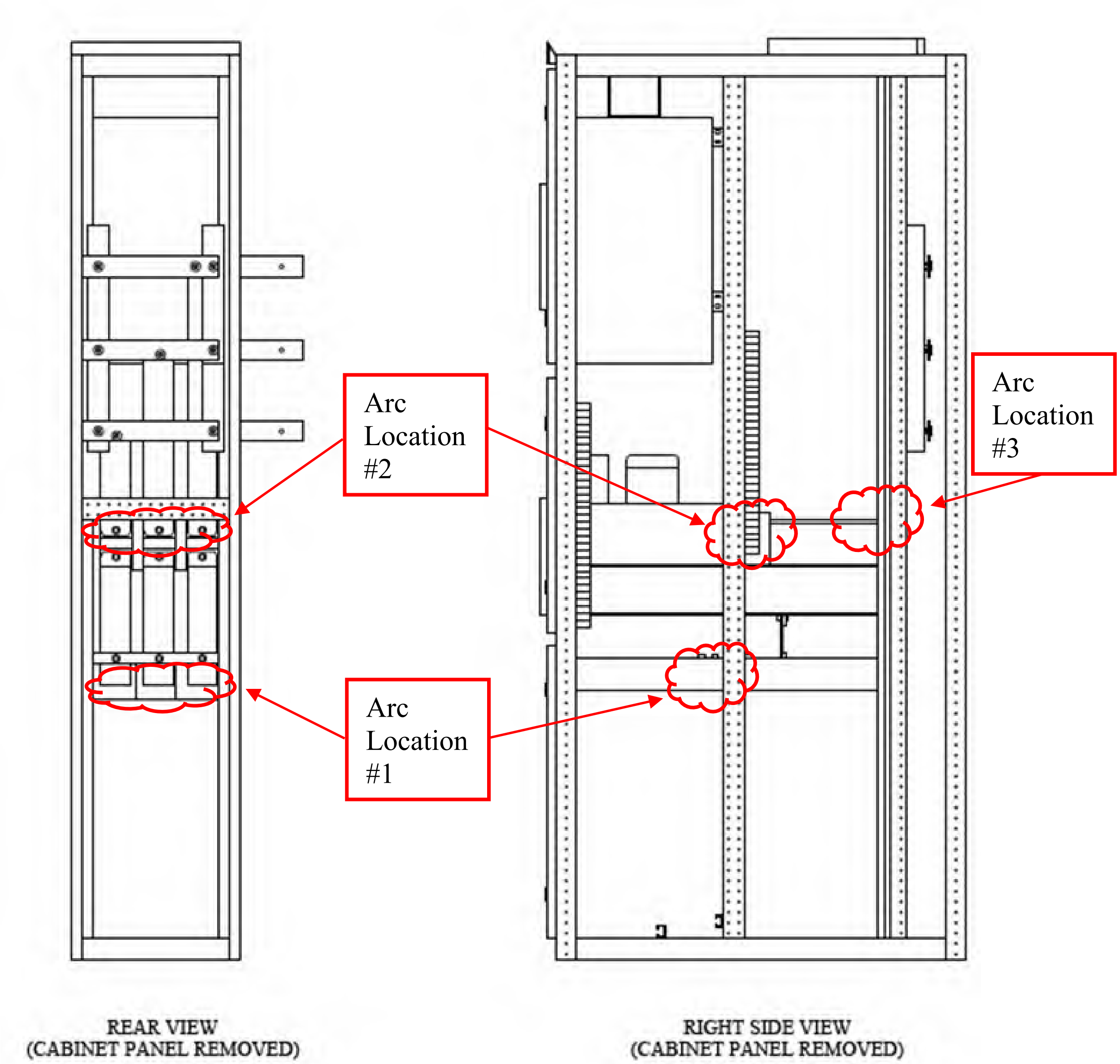

Fig. 210. CAD drawings showing internal components of equipment. Note Arc Location #3 was not used.

The design of experiments was developed with an iterative approach. Initial experiments were performed in a manner to support arc sustainability and subsequent changes were made based on the results. This concept is presented in Fig. 211. Note that Arc Location #3 was not used since the arc was sustained at Arc Location #2.

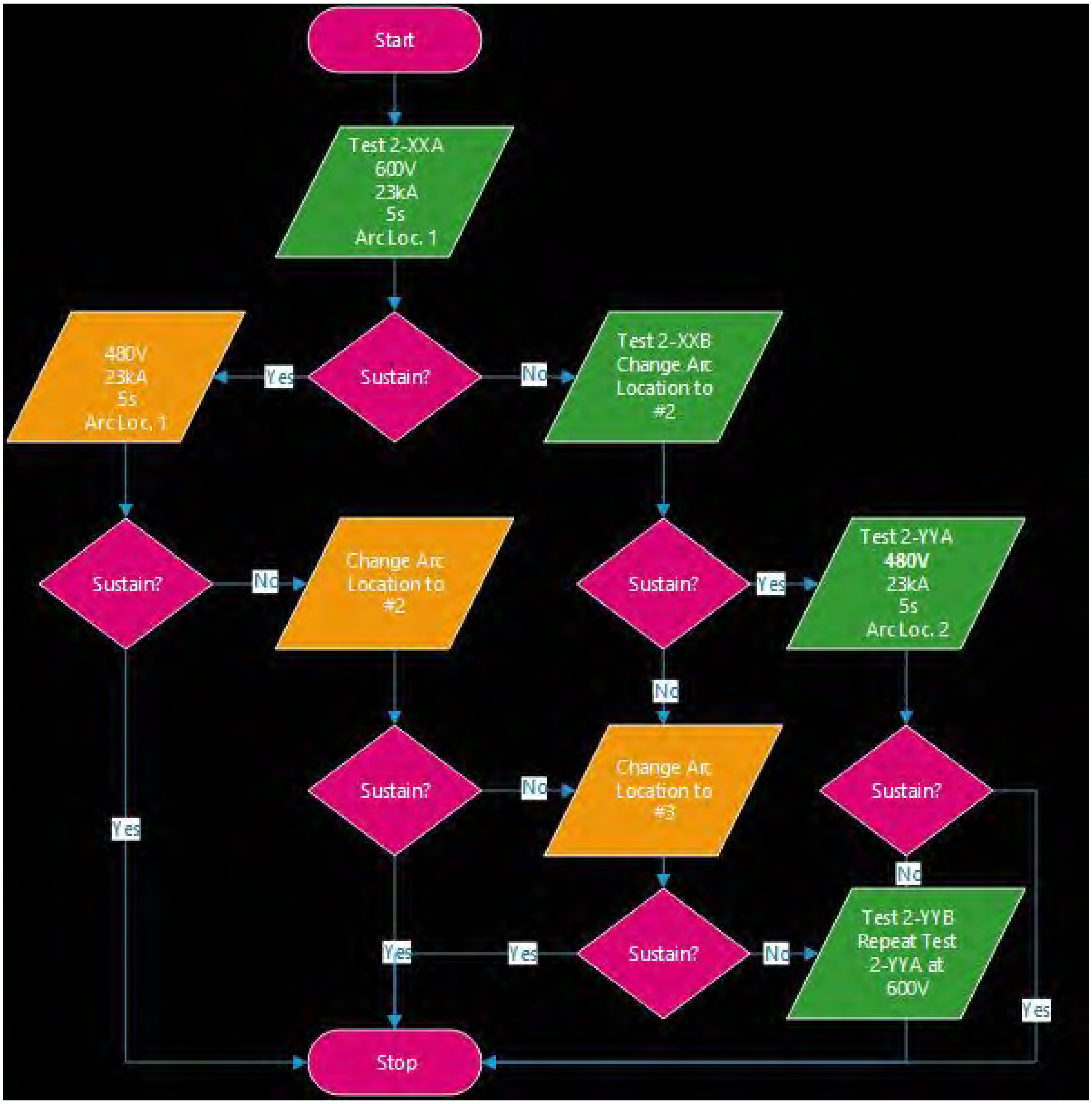

Fig. 211. Flow Chart of Experimental Progression. Green path shows actual experiment progression.

Ultimately, four experiments were performed between March 9th and 10th, 2023, specifically;
Experiment 2-XXA: 600 V, 2 3kA, 5 seconds, Arc Location #1
Experiment 2-XXB: 600 V, 23 kA, 5 seconds, Arc Location #2
Experiment 2-YYB: 480 V, 23 kA, 5 seconds, Arc Location #2
Experiment 2-YYB: 600 V, 23 kA, 5 seconds, Arc Location #2

Instrumentation for these trial experiments were also minimal. Four ASTM style slug calorimeters were used. The slugs were mounted to a laboratory supplied instrumentation stand. Two stands were used with two slugs per stand. The layout is shown in Fig. 212. In addition to the slugs, minimal videography and thermal imaging was used to document the experiments. Four high-definition video cameras and one infrared thermal imager was used.

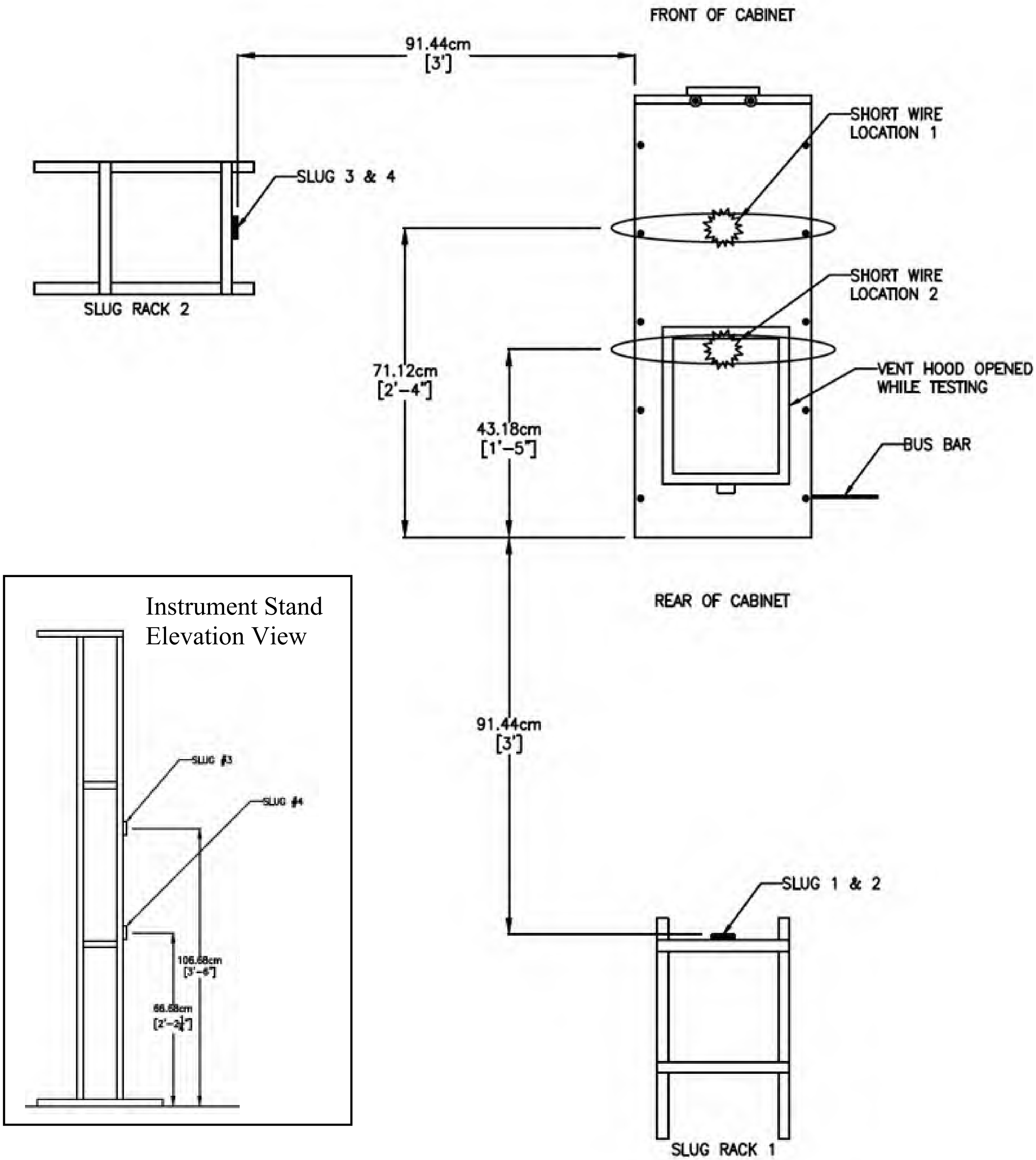

Fig. 212. ASTM slug calorimeter instrumentation layout.

E.4. Results

The results from the trial experiments are presented in this section.

E.4.1. Experiment 2-XXA 600 V, 23 kA, 5 s Duration, Arc Location #1

Experiment 2-XXA was performed on Thursday March 9, 2023, at 9:58 AM. The atmospheric conditions were fair with a temperature of approximately 3 °C (38 °F), winds approximately 16 km/h (10 mi/hr) out of the NNW, relative humidity of approximately 57 percent and atmospheric pressure approximately 101.5 kPa (29.96 in). A single size 10 American wire gauge (AWG) ASTM Class k strand conductor was used as the arcing wire and connected across all three phases, as shown in Fig. 213. This size was consistent with guidance provided in IEEE C37.20.7. This experiment used Arc Location #1.

Fig. 213. Pre-Experiment 2-XXA. Arcing wire location.

The experiment did not last the expected 5 second duration, but self-extinguished at 0.781 seconds, representing an energy release of 6.1 MJ. The electrical data is presented in Fig. 214, which is summarized below.

Arc Duration : 0.781 s

Arc Voltage: 422 $V_{l\text{-}l}$

Arc Current: 23.1 kA

Energy: 6.1 MJ

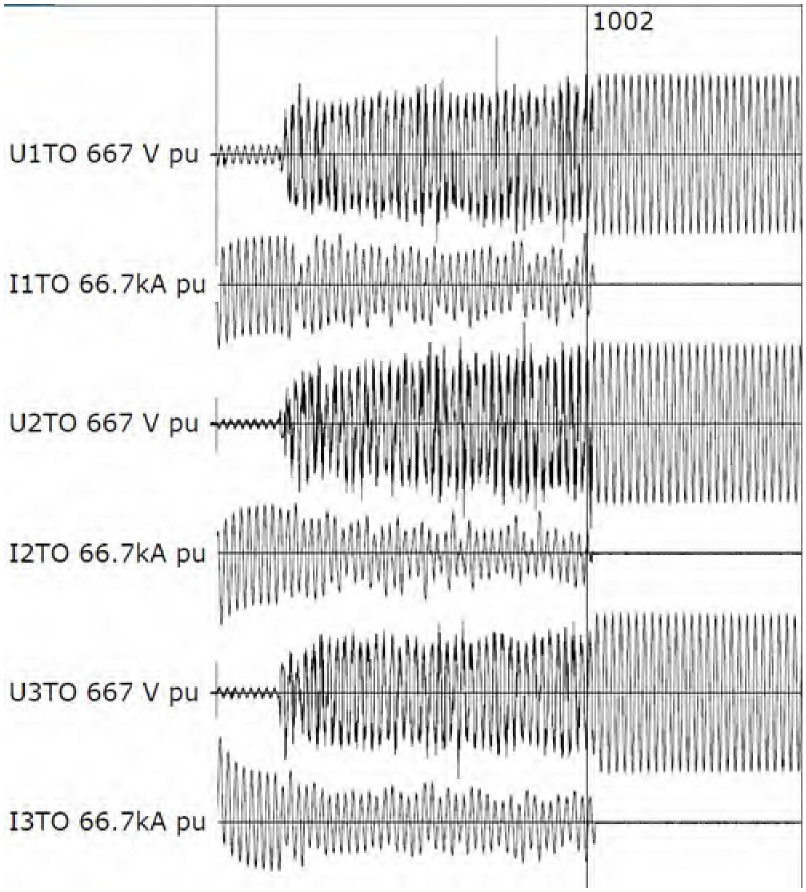

Fig. 214. Post-Experiment 2-XXA. Electrical data readout.

The arc energy caused an enclosure breach on the right side of the gear (opposite side of incoming power). This damage is shown in Fig. 215.

Fig. 215. Post-Experiment 2-XXA. Left – enclosure breach on right side of gear (cladding 1.5 mm [0.060 in] thick), Right – internal bus bar condition at arcing location.

A summary of the ASTM slug calorimeters is presented in Table 88.

Table 88. Summary of ASTM slug calorimeters, Experiment 2-XXA

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment
1	1	Top	18	12	
1	2	Bottom	12	152	
2	3	Top	27	6	
2	4	Bottom	18	5	

E.4.2. Experiment 2-XXB 600 V, 23 kA, 5 s Duration, Arc Location #2

Experiment 2-XXB was performed on Thursday March 9, 2023, at 11:12 AM. The atmospheric conditions were fair with a temperature of approximately 7 °C (44 °F), winds approximately 24 km/h (15 mi/hr) out of the NW, relative humidity of approximately 49 percent and atmospheric pressure approximately 101.4 kPa (29.94 in). A single size 10 AWG ASTM Class k strand conductor was used as the arcing wire and connected across all three phases, as shown in Fig. 216. This size was consistent with guidance provided in IEEE C37.20.7. This experiment used Arc Location #2.

Fig. 216. Pre-Experiment 2-XXB. Arcing wire location.

The experiment did last the planned 5 second duration, representing an energy release of approximately 51 MJ. The electrical data is presented in Fig. 217, which is summarized below.

Arc Duration : 5.04 s

Arc Voltage: 377 V_{l-l}

Arc Current: 18.8 kA_{l-n}

Energy: 51 MJ

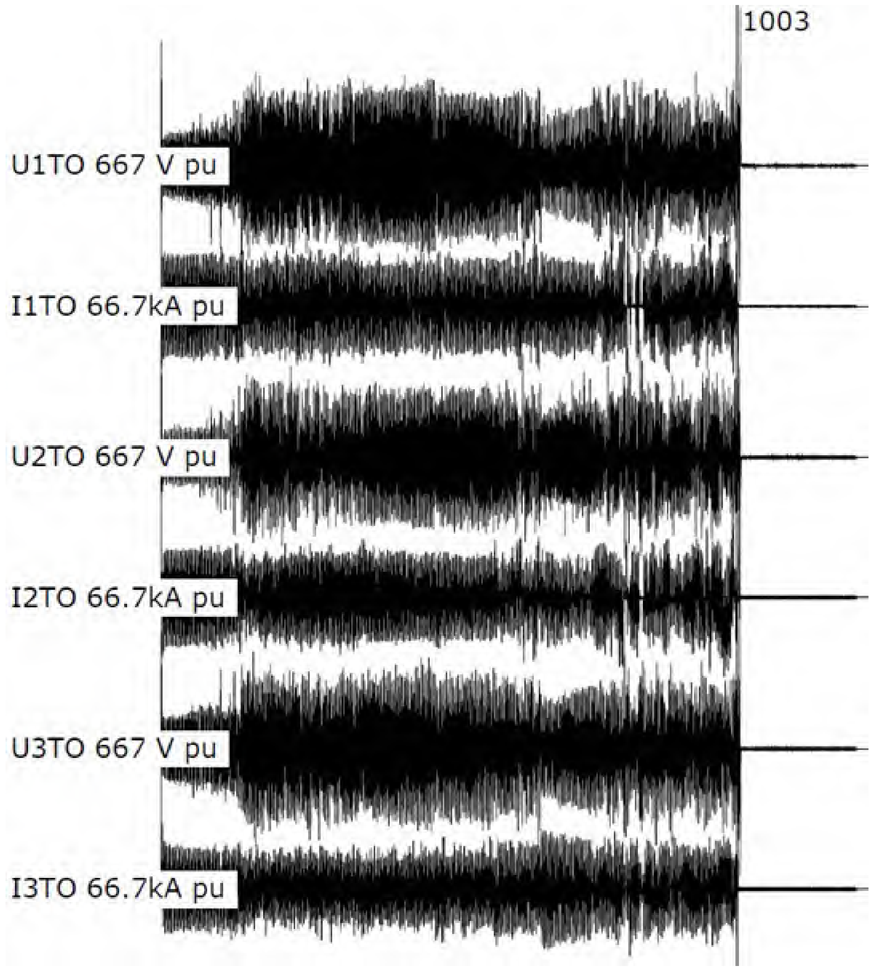

Fig. 217. Experiment 2-XXB. Electrical data readout.

The arc energy caused an enclosure breach at multiple locations on both sides of the equipment. On the right side of the enclosure (opposite side of incoming power) four breaches were observed. Three were in alignment with the horizontal bus bars near the rear of the enclosure. The other breach was located at the lower portion of the enclosure near the load bus bars. A near symmetrical opening was observed on the left side (same side of incoming power). This damage is shown in Fig. 218.

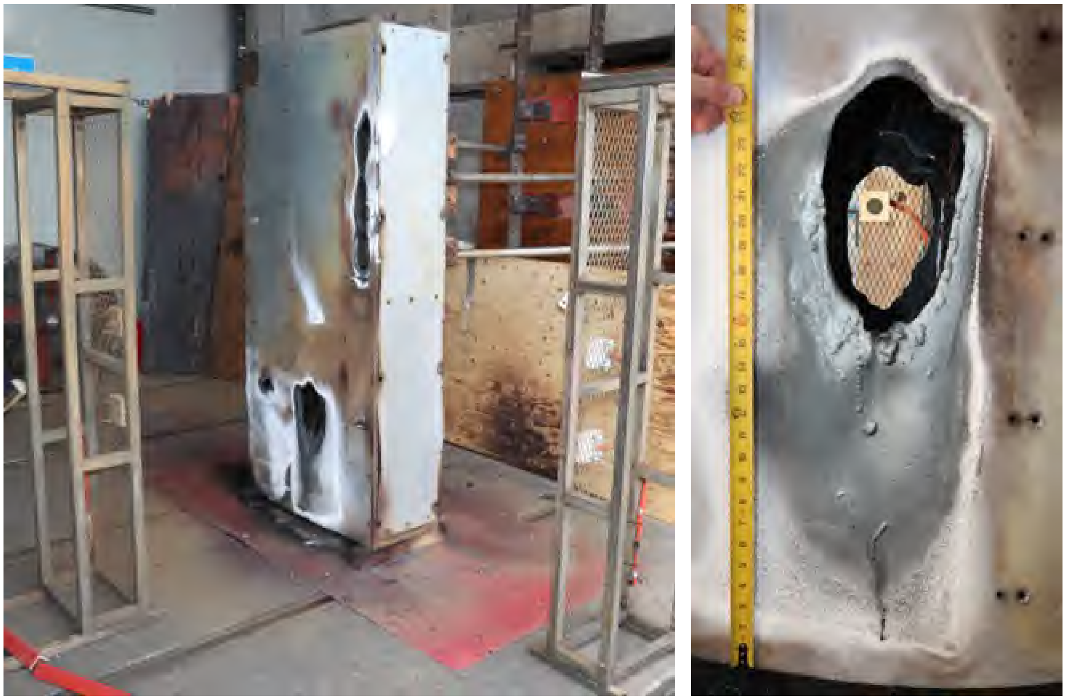

Fig. 218. Post-Experiment 2-XXB Enclosure Damage. Left – rear side view showing multiple breach locations and relative locations of ASTM slugs, Right – Single breach location on incoming power side.

A summary of the ASTM slug calorimeters is presented in Table 89.

Table 89. Summary of ASTM slug calorimeters, Experiment 2-XXB

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3 %	Comment
1	1	Top	168	80	
1	2	Bottom	192	80	
2	3	Top	388	76	
2	4	Bottom	517	80	

E.4.3. Experiment 2-YYA 480 V, 23 kA, 5 s Duration, Arc Location #2

Experiment 2-YYA was performed on Thursday March 9, 2023, at 1:45 PM. The atmospheric conditions were partly cloudy with a temperature of approximately 9 °C (49 °F), winds approximately 22 km/h (14 mi/hr) out of the NNW, relative humidity approximately 44 percent and atmospheric pressure approximately 101.3 kPa (29.91 in). A single size 10 AWG ASTM

Class k strand conductor was used as the arcing wire and connected across all three phases, as shown in Fig. 216. This size was consistent with guidance provided in IEEE C37.20.7. This experiment used Arc Location #2. Given the successful sustainment of the arc in the previous experiment (Experiment 2-XXB), the experiment voltage was lowered to a nominal voltage of 480 V.

Fig. 219. Pre-Experiment 2-YYA arcing wire location.

The experiment did not last the planned 5 second duration, but self-extinguished at 1.15 seconds, representing an energy release of 8.6 MJ. The electrical data is presented in Fig. 220, which is summarized below.

Arc Duration : 1.15 s

Arc Voltage: 272 V_{l-l}

Arc Current: 18.75 kA

Energy: 8.6 MJ

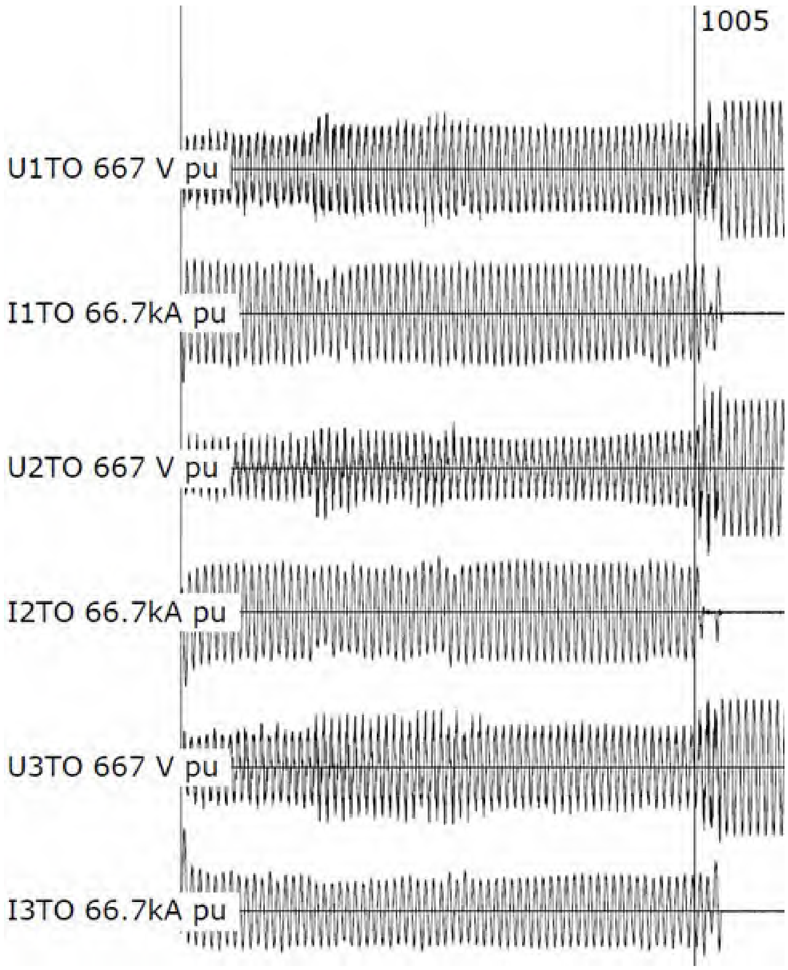

Fig. 220. Experiment 2-YYA Electrical data readout.

The arc energy did not result in a breach of the electrical enclosure. Post-experiment photographs are presented in Fig. 221.

Fig. 221. Post-Experiment 2-YYA. Left – Enclosure heat damage on right side (opposite incoming power supply), Center – bus bars at arc initiation location, Right – Enclosure heat damage on left side (incoming power supply side).

A summary of the ASTM slug calorimeters is presented in Table 90.

Table 90. Summary of ASTM slug calorimeters, Experiment 2-YYA

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) Greater of ± 18 kJ/m^2 or ± 4 %	Comment
1	1	Top	4	
1	2	Bottom	4	
2	3	Top	22	
2	4	Bottom	19	

E.4.3.1. Experiment 2-YYB 600 V, 23 kA, 5 s Duration, Arc Location #2

Experiment 2-YYB was performed on Friday March 10, 2023, at 7:54 AM. The atmospheric conditions were fair with a temperature of approximately 0 °C (32 °F), winds were calm, relative humidity approximately 73 percent, and atmospheric pressure approximately 101.1 kPa (29.86 in). A single size 10 AWG ASTM Class k strand conductor was used as the arcing wire and connected across all three phases, as shown in Fig. 222. This size was consistent with guidance provided in IEEE C37.20.7. This experiment used Arc Location #2. Based on the results from the previous experiments (Experiment 2-YYA), the voltage was increased to 600 V.

Fig. 222. Pre-Experiment 2-YYA. Arcing wire location.

The experiment did not last the planned 5 second duration, but self-extinguished at 3.68 seconds, representing an energy release of approximately 37.9 MJ. The electrical data is presented in Fig. 223, which is summarized below.

Arc Duration : 3.68 s

Arc Voltage: 436 V_{l-l}

Arc Current: 18.76 kA

Energy: 37.94 MJ

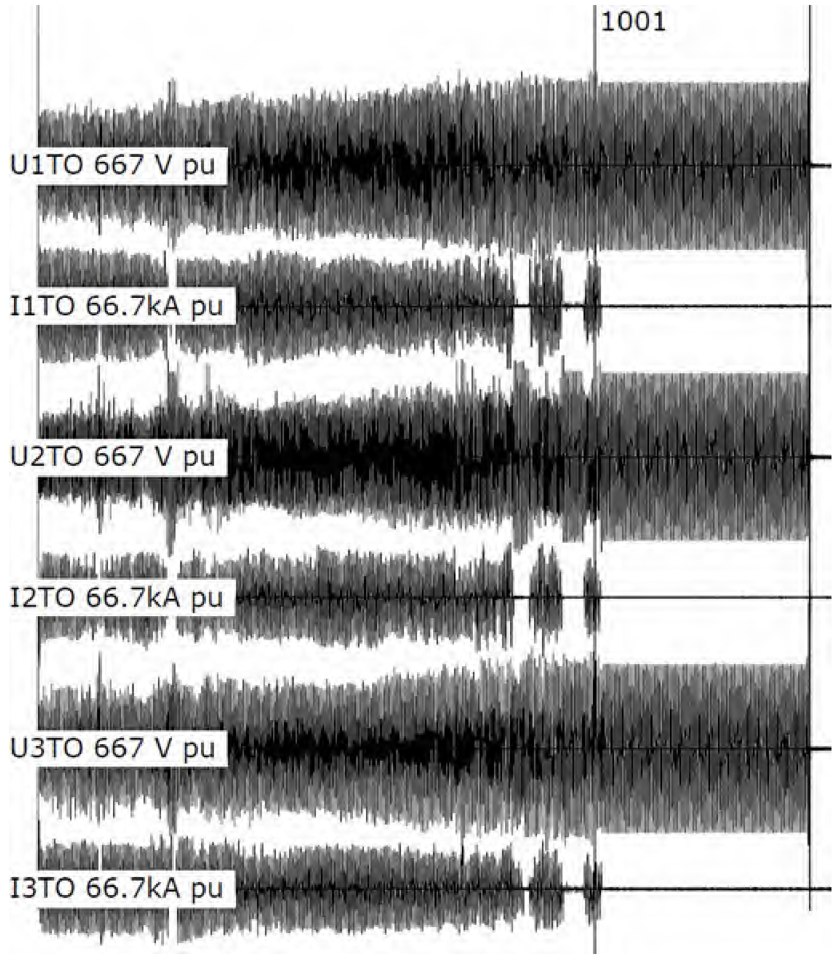

Fig. 223. Experiment 2-YYB. Electrical data readout.

The arc energy caused an enclosure breach on both sides of the electrical enclosure, adjacent to the arc initiation location. This damage is shown in Fig. 224. Damage was not observed near the horizontal bus bars supplying power to the unit, which was different from the Experiment 2-XXB observations.

Fig. 224. Post-Experiment 2-YYB Enclosure Breaches. Left - enclosure breach on right side of enclosure (opposite incoming power supply), Right – enclosure breach on left side of enclosure (incoming power supply side). (cladding 1.5 mm [0.060 in] thick).

E.5. Summary

Four high energy arcing fault (HEAF) experiments were performed between March 9 and 10, 2023. Two of the three arc locations were explored for their ability to sustain the arc. Arc Location #3 was not evaluated since it was similar to Arc Location #2, and the magnetic influence would likely cause the arc to migrate to Arc Location #2.

Arc Location #2 represented an incoming power supply to a supply breaker and was found to sustain the arc for more than 50 percent of the planed arc duration (an ad hoc metric used to evaluate prior experimental results). In Experiment 2-XXB, the full 5 s arc duration was achieved at Arc Location #2, while a 3.68 s arc duration was achieved (74 percent of planned duration) during Experiment 2-YYB. It appeared that Arc Location #1 would not be capable of sustaining the arc. In addition, this exploration determined that 480 V was not sufficient to sustain the arc for this equipment configuration. This is not to imply HEAFs at 480 V are not possible, but that sustainment was not achievable for the equipment configuration used.

Appendix F. KEMA Experiment Report

Appendix F is attached and contains a copy of KEMA Laboratories' experimental report.

KEMA TEST REPORT

25349

Object	Low Voltage Switchgear
Type	- **Serial No.** -
	600 V – 1250 A - 45 kA – 3 phase - 60 Hz
Client	Nuclear Regulatory Commission, 11555 Rockville Pike 20852-273 Rockville, United Stated
Tested by	KEMA-Powertest LLC 4379 County Line Road Chalfont, PA 18914, USA
Date of tests	9 and 10 March 2023
Test specification	The tests have been carried out in accordance with the client's instructions.
Disclaimers	This report applies only to the individual object tested. KEMA-Powertest LLC ("KEMA") makes no representations or warranties with respect to any device other than the object tested. It is the responsibility of the applicable device manufacturer to ensure that any other devices or units having the same name and descriptions as the test object are identical. No certificate of performance or other report issued by KEMA for the purpose of confirming the performance of a test object in relation to the testing requirements of a national or international standard, or in relation to any other testing specification, shall constitute a warranty as to the adequacy or quality of the design or construction of the test object. No other document issued by KEMA for the purpose of reporting, explaining or describing any engineering or consulting services performed by KEMA shall constitute a warranty as to the adequacy or quality of the design or construction of any apparatus or system that is the subject of the document.

This report consists of 91 pages in total.

May 19, 2023

Frank Cielo
Director
KEMA-Powertest, LLC

INFORMATION SHEET

1 KEMA Type Test Certificate

A KEMA Type Test Certificate contains a record of a series of (type) tests carried out in accordance with a recognized standard. The object tested has fulfilled the requirements of this standard and the relevant ratings assigned by the manufacturer are endorsed by KEMA Labs. In addition, the object's technical drawings have been verified and the condition of the object after the tests is assessed and recorded.
The Certificate contains the essential drawings and a description of the object tested. A KEMA Type Test Certificate signifies that the object meets all the requirements of the named subclauses of the standard. It can be identified by gold-embossed lettering on the cover and a gold seal on its front sheet.
The Certificate is applicable to the object tested only. KEMA Labs is responsible for the validity and the contents of the Certificate. The responsibility for conformity of any object having the same type references as the one tested rests with the manufacturer.
Detailed rules on types of certification are given in KEMA Labs' Certification procedure applicable to KEMA Labs.

2 KEMA Report of Performance

A KEMA Report of Performance is issued when an object has successfully completed and passed a subset (but not all) of test programmes in accordance with a recognized standard. In addition, the object's technical drawings have been verified and the condition of the object after the tests is assessed and recorded. The report is applicable to the object tested only. A KEMA Report of Performance signifies that the object meets the requirements of the named subclauses of the standard. It can be identified by silver-embossed lettering on the cover and a silver seal on its front sheet.
The sentence on the front sheet of a KEMA Report of Performance will state that the tests have been carried out in accordance with …… The object has complied with the relevant requirements.

3 KEMA Test Report

A KEMA Test Report is issued in all other cases.

4 Official and uncontrolled test documents

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5 Accreditation of KEMA Labs

KEMA Labs is accredited in accordance with ISO/IEC 17025 by the respective national accreditation bodies. KEMA Labs Arnhem, the Netherlands, is accredited by RvA under nos. L020, L218, K006 and K009. KEMA Labs Chalfont, United States, is accredited by A2LA under no. 0553.01. KEMA Labs Prague, the Czech Republic, is accredited by CAI as testing laboratory no. 1035.

REVISION OVERVIEW

Rev. No	Date of issue	Reason for issue
0	05/19/2023	Final issue

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11 Instrumentation Information Sheet........90

End of Document [1 PAGE]

1 IDENTIFICATION OF THE OBJECT TESTED

1.1 Ratings/characteristics of the object tested

Voltage	600 V
Rated current	1250 A
Number of phases	3
Frequency	60 Hz
Main circuit	
• short-time withstand current	45 kA
• duration of short-circuit	5 s

1.2 Description of the object tested

Three phase low voltage metal enclosed switchgear incorporating a circuit breaker

1.3 Travel recorder

No travel recorder fitted.

1.4 List of drawings

No drawing was submitted by the client.

2 GENERAL INFORMATION

2.1 The tests were witnessed by

The following persons witnessed the tests at the KEMA premises:

Name	**Company**
Gabriel Taylor Nick Melly	Nuclear Regulatory Commission 11555 Rockville Pike 20852-273 Rockville, United Stated
Christopher Brown Lucy Fox Anthony Putorti	National Institute of Standards and Technology (NIST) 100 Bureau Dr. Gaithersburg, MD 20899

2.2 The tests were carried out by

Name	**Company**
Luiz Almada	KEMA-Powertest LLC, Chalfont, PA, USA

2.3 Accuracy of measurement

The guaranteed uncertainty in the figures mentioned, taking into account the total measuring system, is less than 3%, unless mentioned otherwise. Measurement uncertainty can be verified by reviewing the instrument calibration records. The instruments used are calibrated on a regular basis and are traceable to the National Institute of Standards and Technology.

2.4 Notes

Low Voltage Switchgears removed from service and donated to NRC for Internal Arc Fault tests.

3 LEGEND

Phase indications
If more than one phase is recorded on oscillogram, the phases are indicated by the digits 1, 2 and 3. These phases 1, 2 and 3 correspond to the phase values in the columns of the accompanying table, respectively from left to right.

Explanation of the letter symbols and abbreviations on the oscillograms

pu	Per unit (the reference length of one unit is represented by the black bar on the oscillogram)
I1TO	Current through test object
I2TO	Current through test object
I3TO	Current through test object
Itank	Tank current test object
U1TO	Voltage across test object
U2TO	Voltage across test object
U3TO	Voltage across test object

4 CHECKING OF THE PROSPECTIVE CURRENT

Standard and date

Standard	Client's instructions
Test date	9 March 2023

Serial No.

-

4.1 Condition before test

The prospective circuit was verified with a shorting bar connected to the test object inputs.

4.2 Test results and oscillograms

Overview of test numbers

230309-1001

Remarks

Prospective circuit was verified at a reduced voltage of 300 V.

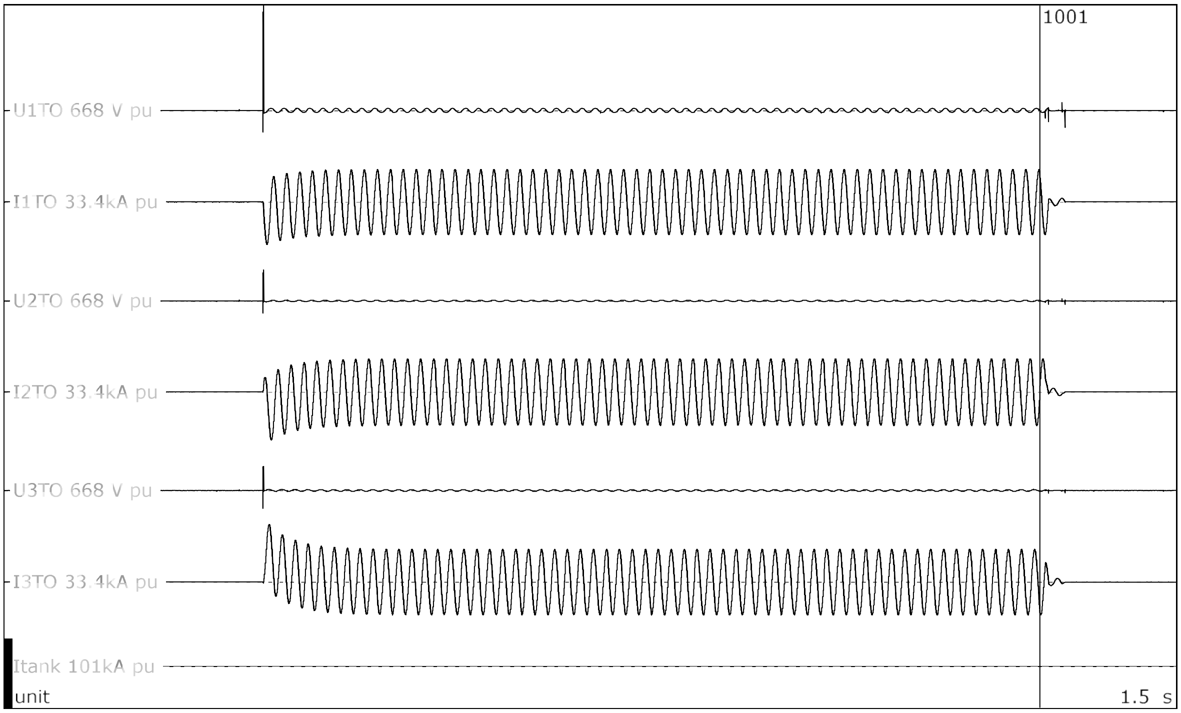
The full level pro-rated available circuit to be applied on the Internal Arc test will be:

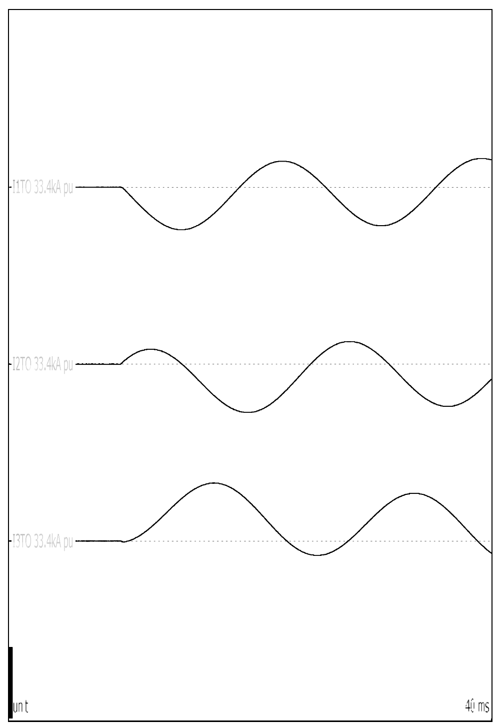
OCV = 630 V

Isym = 23kA

Ipeak = 57kA

Checking of the prospective current





Test number: **230309-1001**

Phase		A	B	C
Current	kA_{peak}	-20.2	-22.9	27.3
Current, a.c. component, beginning	kA_{RMS}	11.0	11.2	11.1
Current, a.c. component, middle	kA_{RMS}	11.0	11.2	11.0
Current, a.c. component, end	kA_{RMS}	11.0	11.2	11.0
Current, a.c. component, average	kA_{RMS}	11.0	11.2	11.0
Current, a.c. component, three-phase average	kA_{RMS}	11.1		
Duration, current	s	1.00	1.00	1.00
Equivalent RMS value and duration		11 kA during – 1.0 s		

Observations:	No visible disturbance. Reduced level test for calibration purposes, performed at OCV 300 V. Full level available circuit will be: OCV = 630 V Isym = 23kA Ipeak = 57kA

5 INTERNAL ARC TEST – TEST 1 – NRC TEST 2 - XXA

Standard and date

Standard	Client's instructions
Test date	9 March 2023

Serial No.

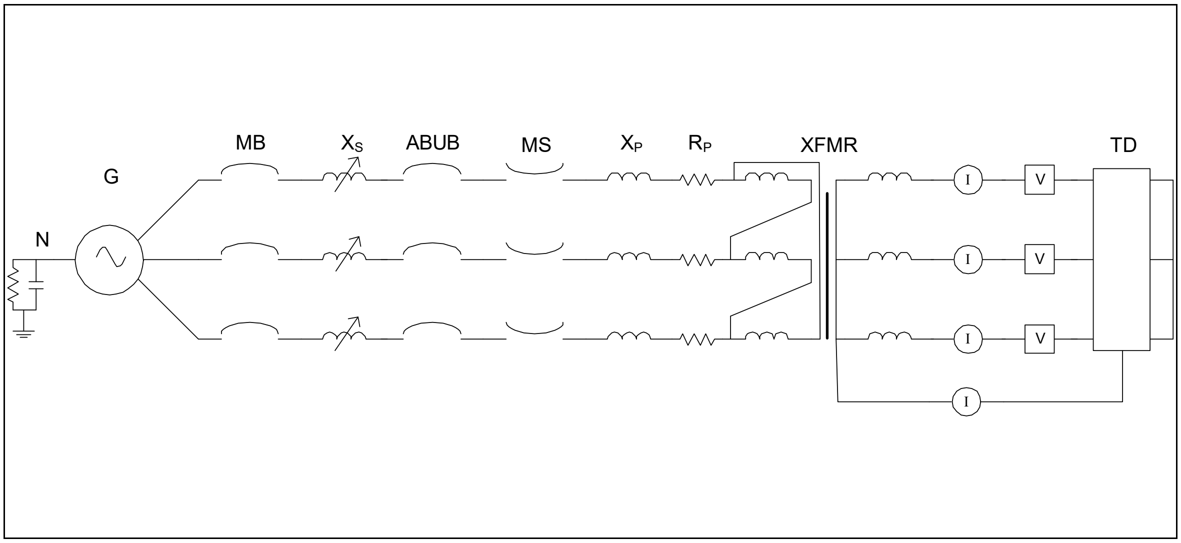
Sample 2-XX

5.1 Condition before test

Arc wire was located at the end of the load side of the circuit breaker.

Two calorimeters placed 3' away from back side of the unit.
CAL 1 - Top
CAL 2 - Bottom
Two calorimeters placed 3' away from right side of the unit.
CAL 3 - Top
CAL 4 - Bottom

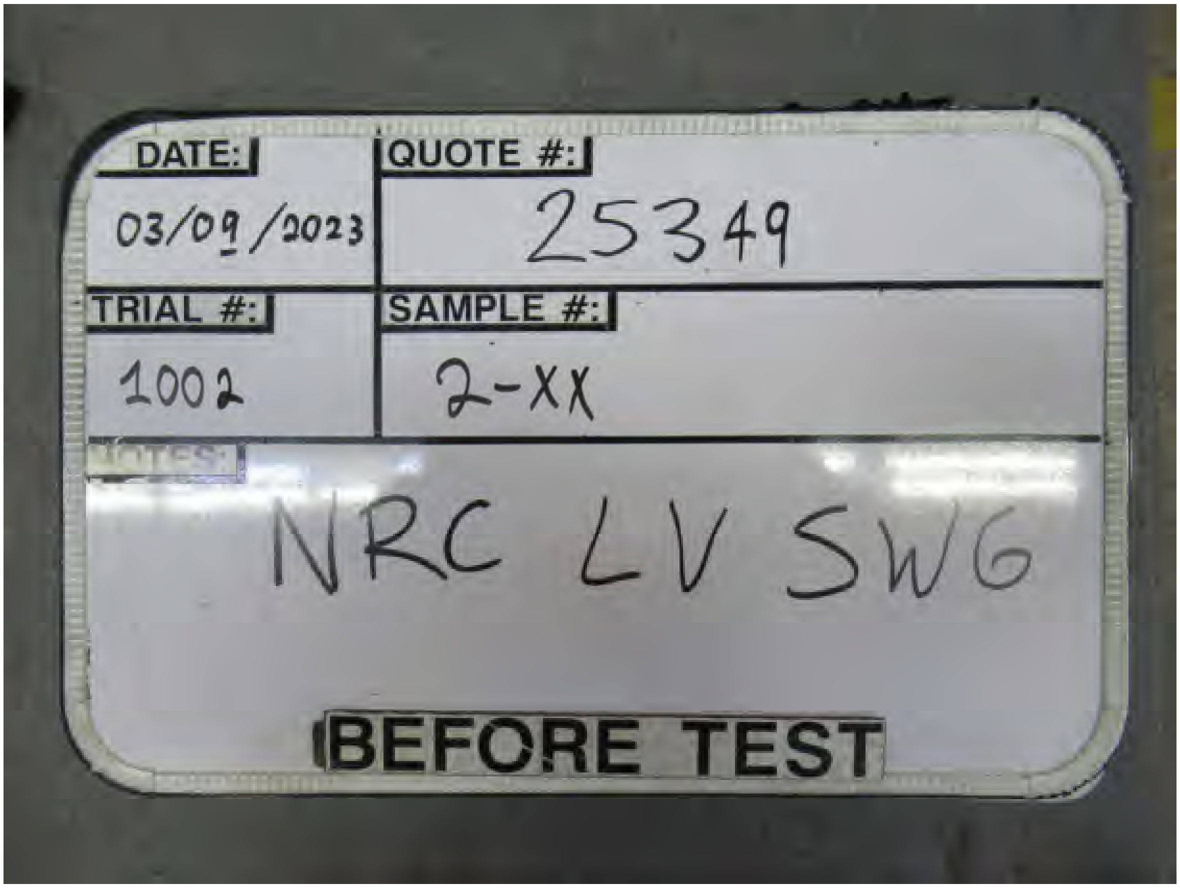
5.2 Test circuit S01

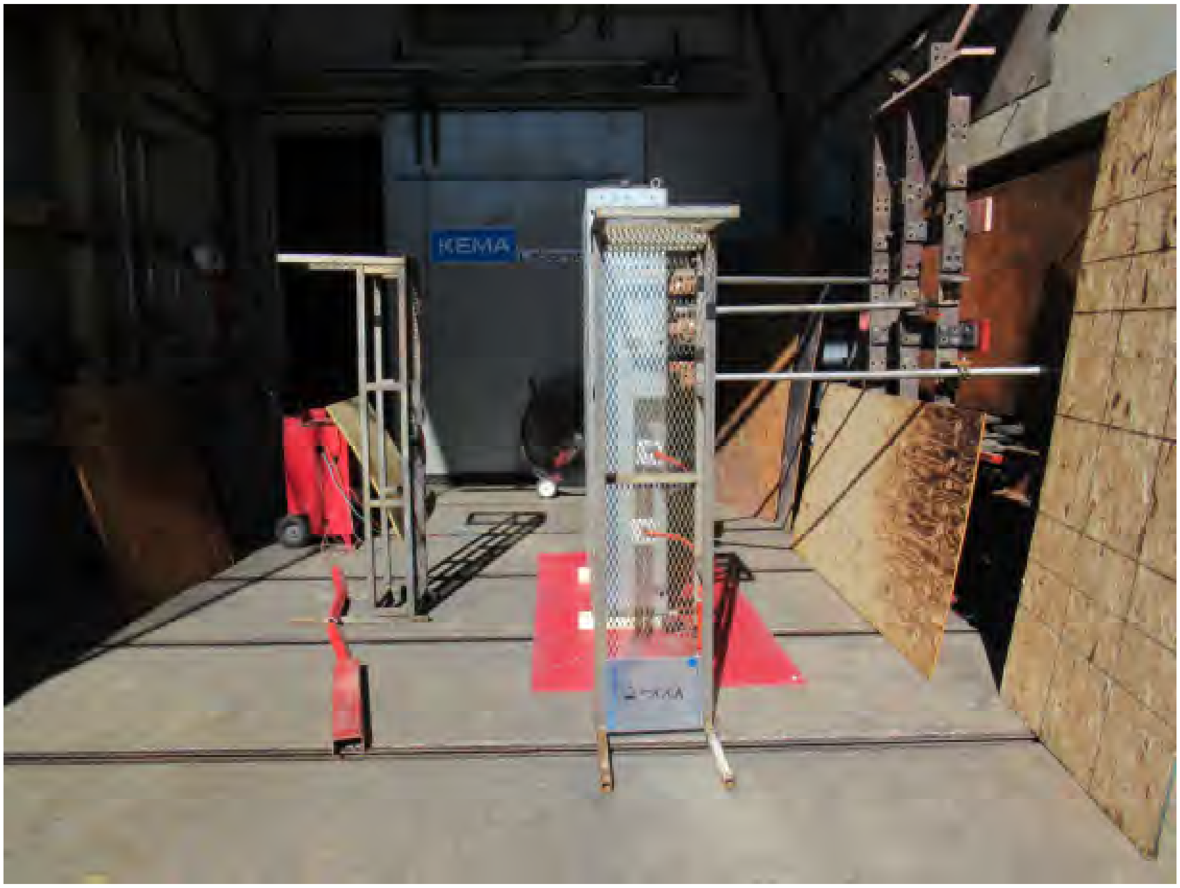


G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	C	= Capacitance
MB	= Main Breaker	TD	= Test Device	U	= Voltage Measurement
MS	= Make Switch	X	= Inductance	I	= Current Measurement

Supply		
Power	MVA	23.9
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.6
Current	kA	23
Impedance	Ω	0.0151
Power factor		< 0,1
Neutral		earthed

5.3 Photograph before test

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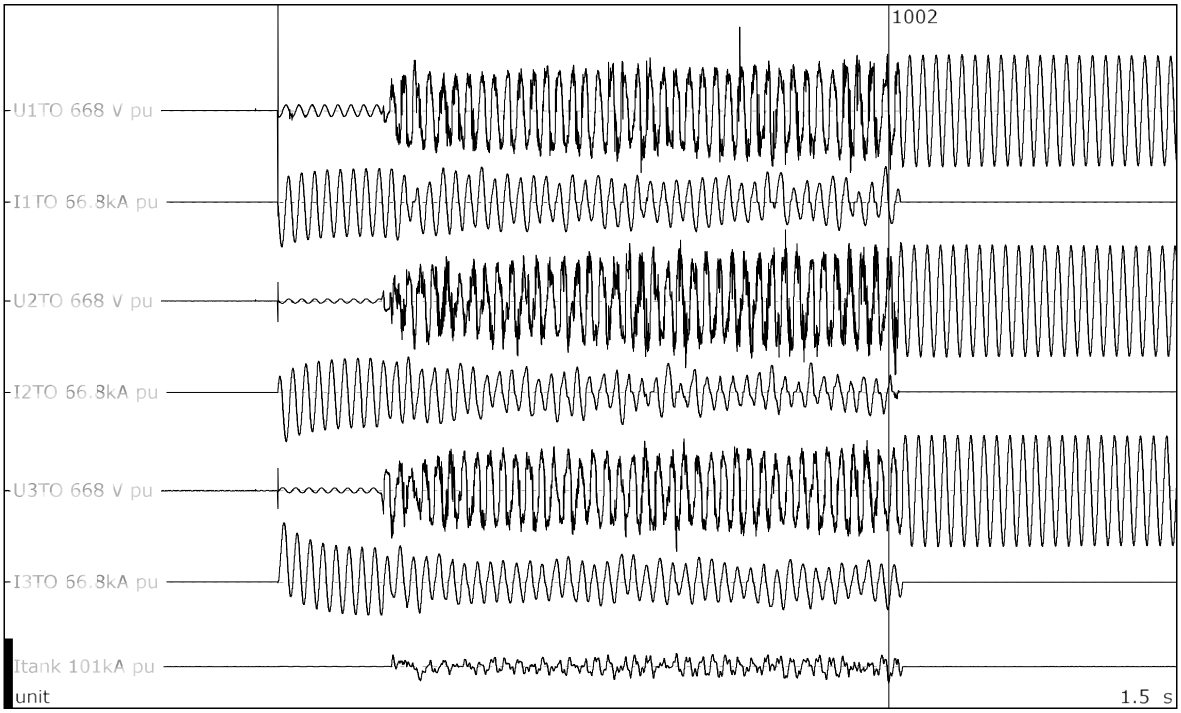
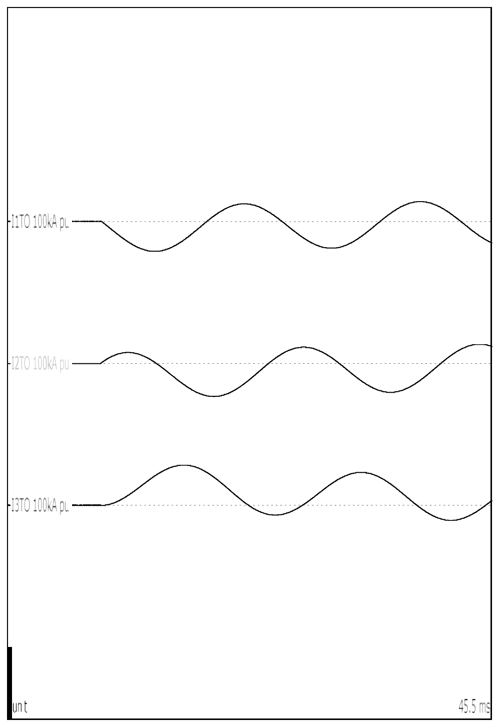
5.4 Test results and oscillograms

Overview of test numbers
230309-1002

Remarks

Internal arc test





Test number: **230309-1002**

Phase		A	B	C
Current	kA_{peak}	-42.6	-47.0	56.7
Current, a.c. component, beginning	kA_{RMS}	22.8	23.3	22.8
Current, a.c. component, middle	kA_{RMS}	14.4	11.5	13.1
Current, a.c. component, end	kA_{RMS}	10.6	10.4	10.4
Current, a.c. component, average	kA_{RMS}	18.2	17.4	17.0
Current, a.c. component, three-phase average	kA_{RMS}	17.5		
Duration, current	s	0.796	0.796	0.796
Equivalent RMS value and duration		23.0 kA during 5.00 s		
I2t	10E6 A^2s	248	201	210
E	MJ	2.67	1.72	1.83

Observations:	Sample 2-XX. Large display with smoke and flames visible. Enclosure tank current of 7.534 kA was detected starting at 145 ms after current initiation. Arc wire was located at the end of the load side of the circuit breaker.

5.5 Condition / inspection after test

See table below with Calorimeters' data results.

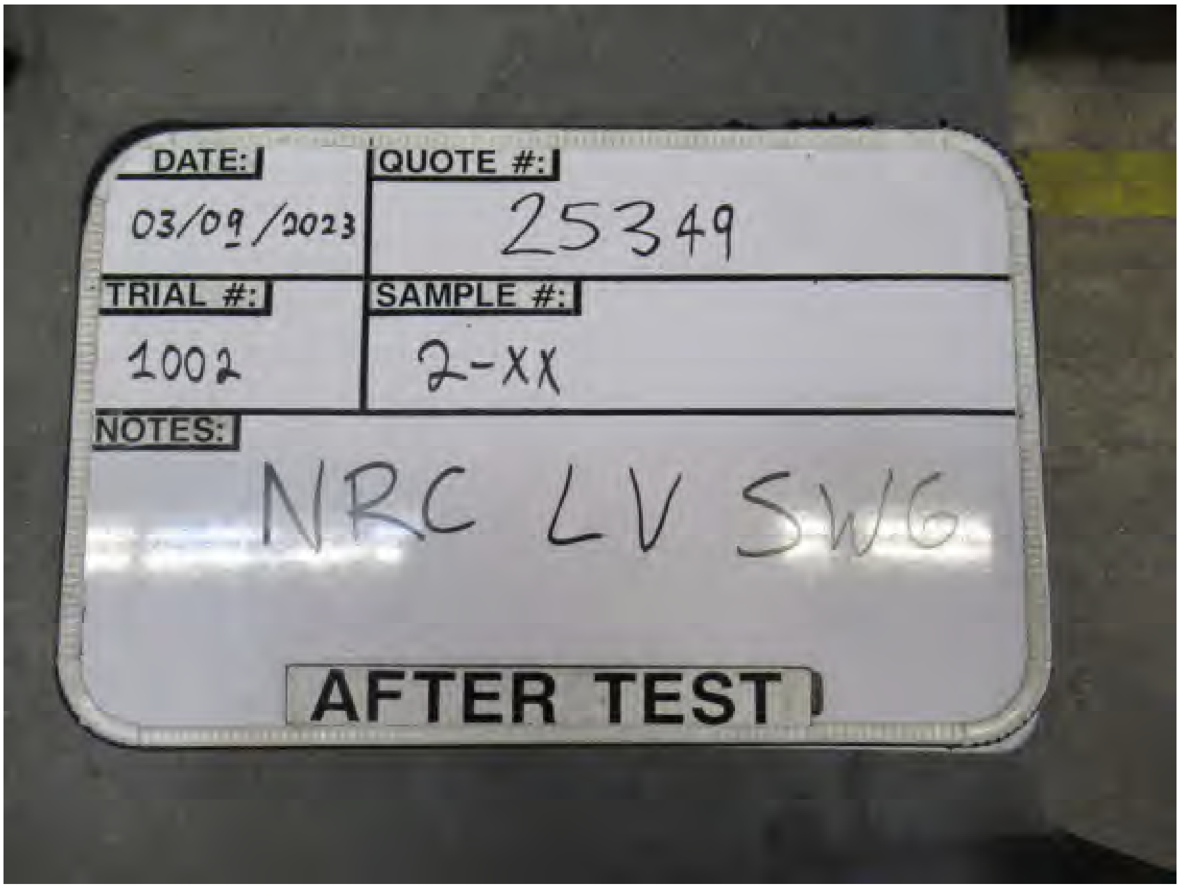
230309-1002

*Calorimeters' data and calculations

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Back Top	15.785	0.09176	16.411	0.09178	0.345
Back Bottom	15.013	0.09174	15.593	0.09176	0.319
Right Top	10.101	0.0916	13.302	0.09169	1.759
Right Bottom	10.804	0.09162	15.798	0.09176	2.745

Calorimeters belong to NRC and its results are for information only. Calorimeters were built and calibrated by KEMA Powertest.

5.6 Photograph after test

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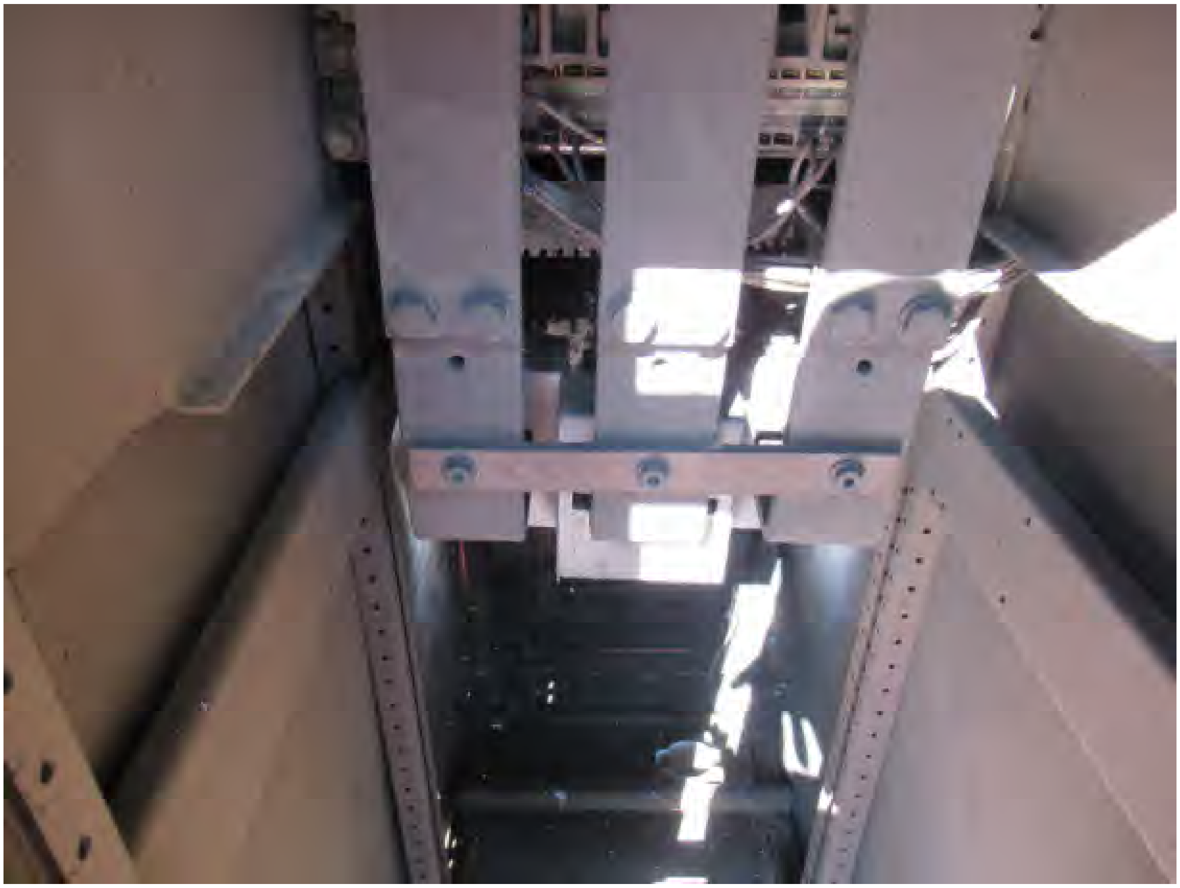


6 INTERNAL ARC TEST – TEST 2 – NRC TEST 2 - XXB

Standard and date

Standard	Client’s instructions
Test date	9 March 2023

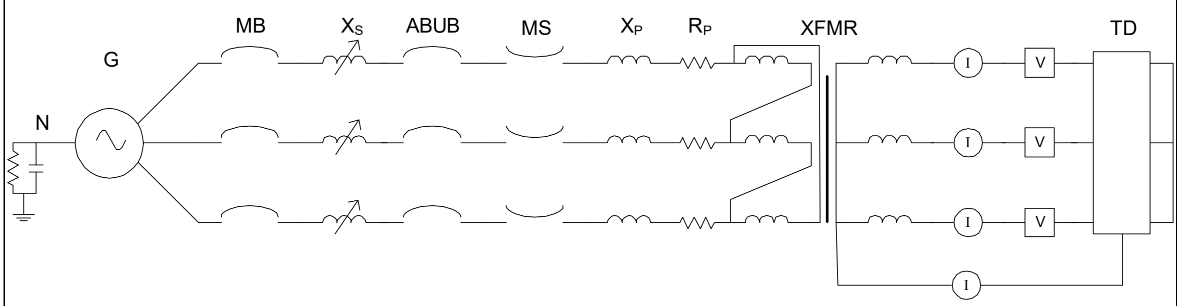
Serial No.
Sample 2-XX

6.1 Condition before test

Arc wire was located on the stabs on line side of circuit breaker.

Two calorimeters placed 3' away from back side of the unit.
CAL 1 - Top
CAL 2 - Bottom
Two calorimeters placed 3' away from right side of the unit.
CAL 3 - Top
CAL 4 - Bottom

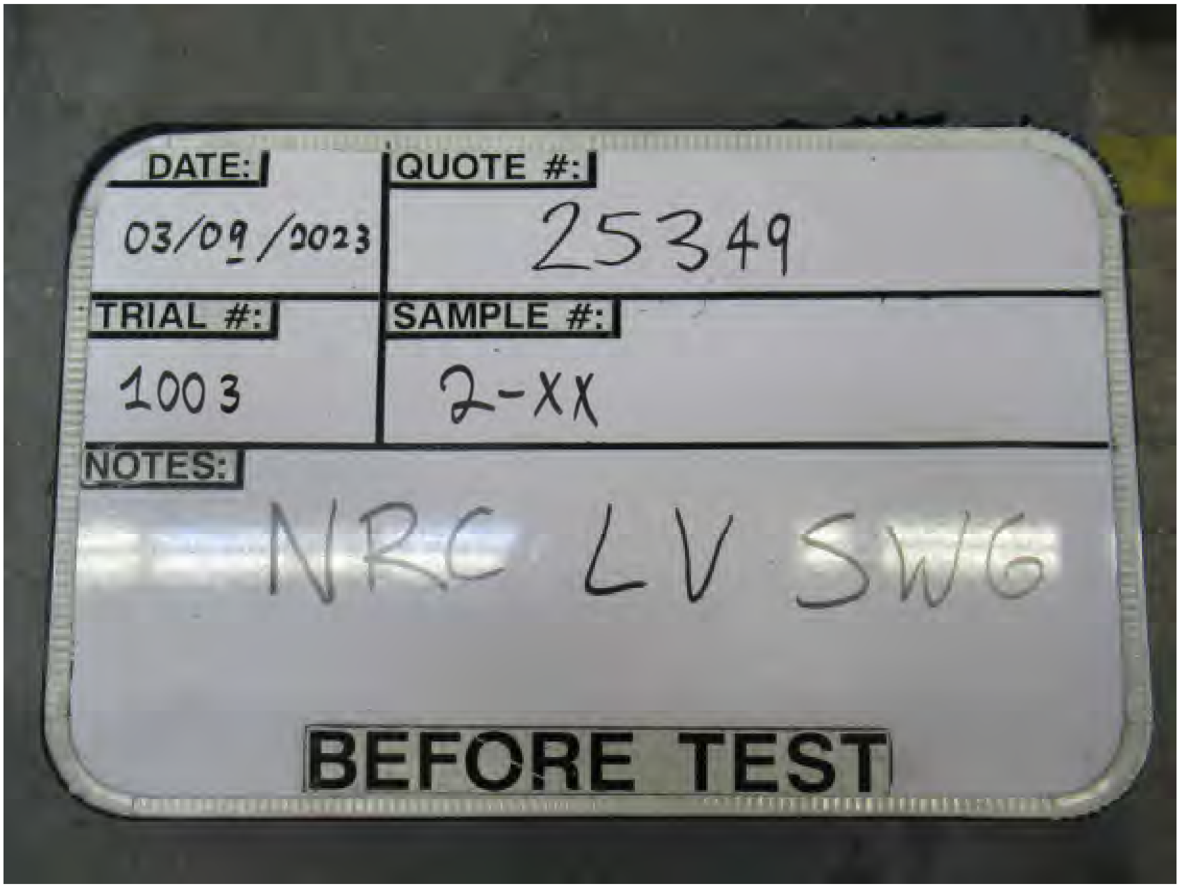
6.2 Test circuit S01



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	C	= Capacitance
MB	= Main Breaker	TD	= Test Device	U	= Voltage Measurement
MS	= Make Switch	X	= Inductance	I	= Current Measurement

Supply		
Power	MVA	23.9
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.6
Current	kA	23
Impedance	Ω	0.0151
Power factor		< 0,1
Neutral		earthed

6.3 Photograph before test

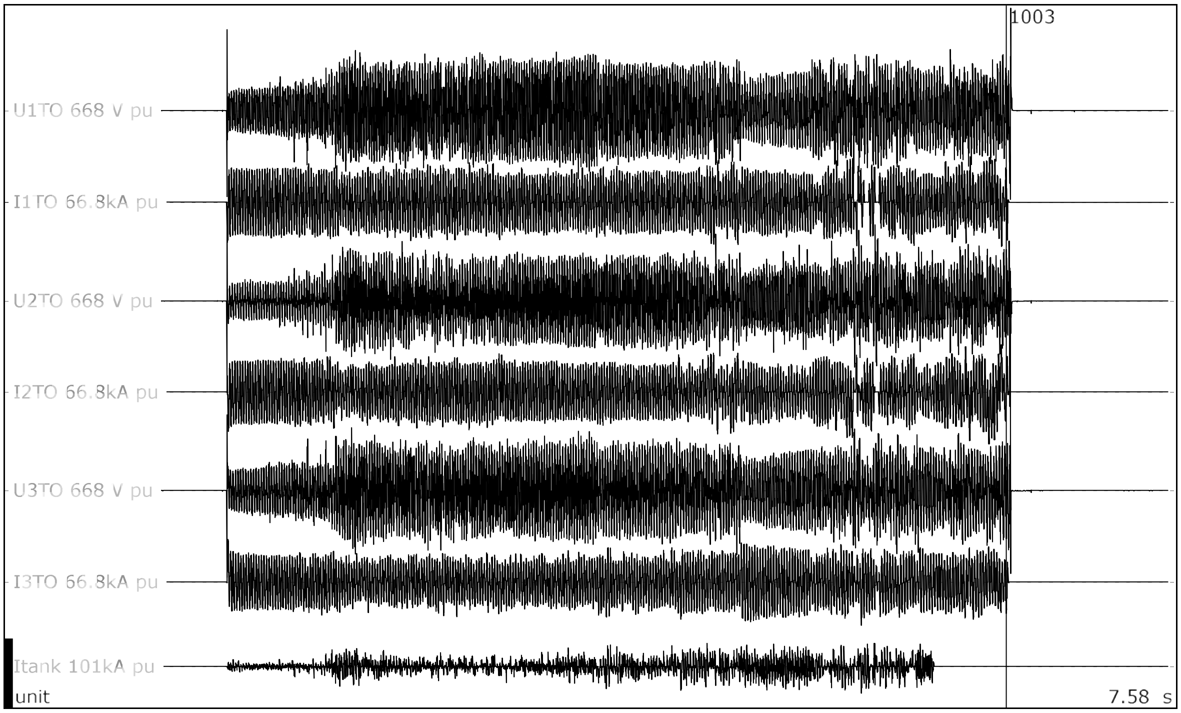


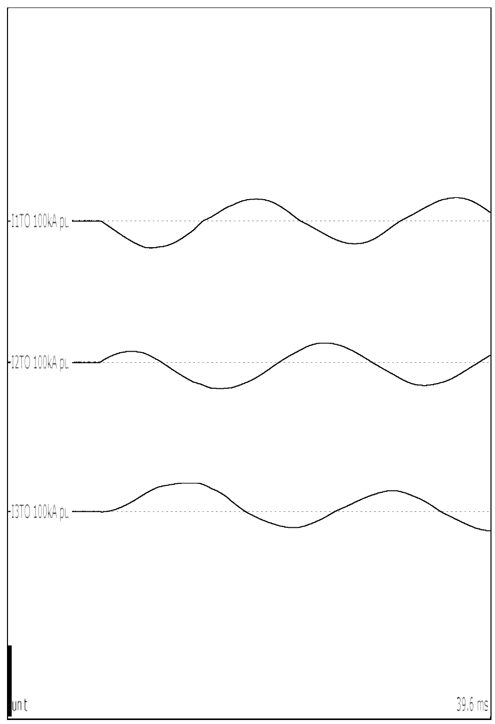
6.4 Test results and oscillograms

Overview of test numbers
230309-1003

Remarks

Internal arc test





Test number: **230309-1003**

Phase		A	B	C
Current	kA_{peak}	33.3	24.8	30.5
Current, a.c. component, beginning	kA_{RMS}	23.4	22.0	20.5
Current, a.c. component, middle	kA_{RMS}	21.4	20.1	16.2
Current, a.c. component, end	kA_{RMS}	20.6	22.2	17.7
Current, a.c. component, average	kA_{RMS}	19.5	19.2	19.8
Current, a.c. component, three-phase average	kA_{RMS}	19.5		
Duration, current	s	5.05	5.05	5.05
Equivalent RMS value and duration		23.0 kA during 5.00 s		
I2t	10E6 A^2s	1963	1829	1527
E	MJ	20.5	15.1	15.5

Observations: Sample 2-XX. Large display with smoke and flames visible. Enclosure tank current of 8.291kA was detected together with current initiation.
Arc wire was located on the stabs on line side of circuit breaker.

6.5 Condition / inspection after test

See table below with Calorimeters' data results.

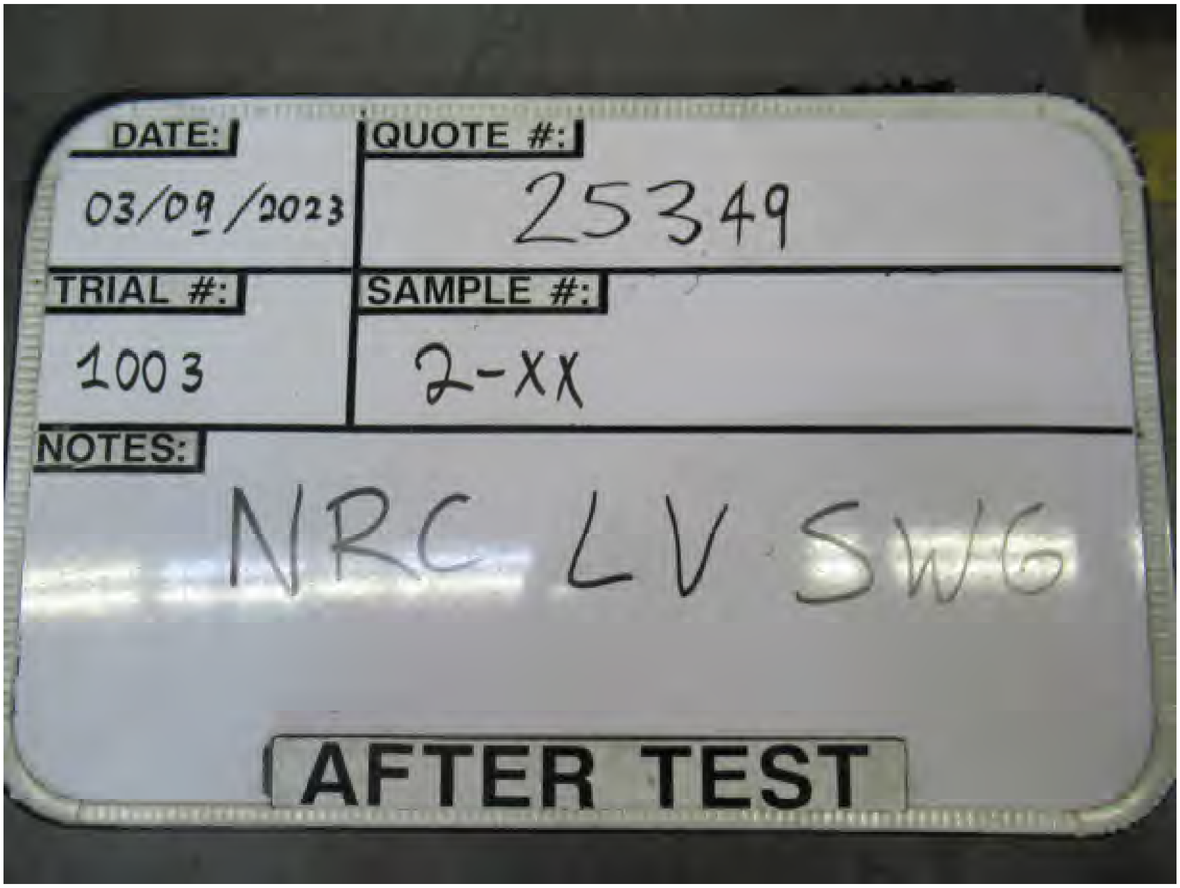
230309-1003

*Calorimeters’ data and calculations

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Back Top	12.801	0.09167	41.995	0.09256	16.123
Back Bottom	12.867	0.09168	46.094	0.09268	18.363
Right Top	11.608	0.09164	79.697	0.09372	37.834
Right Bottom	12.225	0.09166	101.881	0.09439	50.002

Calorimeters belong to NRC and its results are for information only. Calorimeters were built and calibrated by KEMA Powertest.

6.6 Photograph after test

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7 CHECKING OF THE PROSPECTIVE CURRENT

Standard and date

Standard	Client's instructions
Test date	9 March 2023

Serial No.

7.1 Condition before test

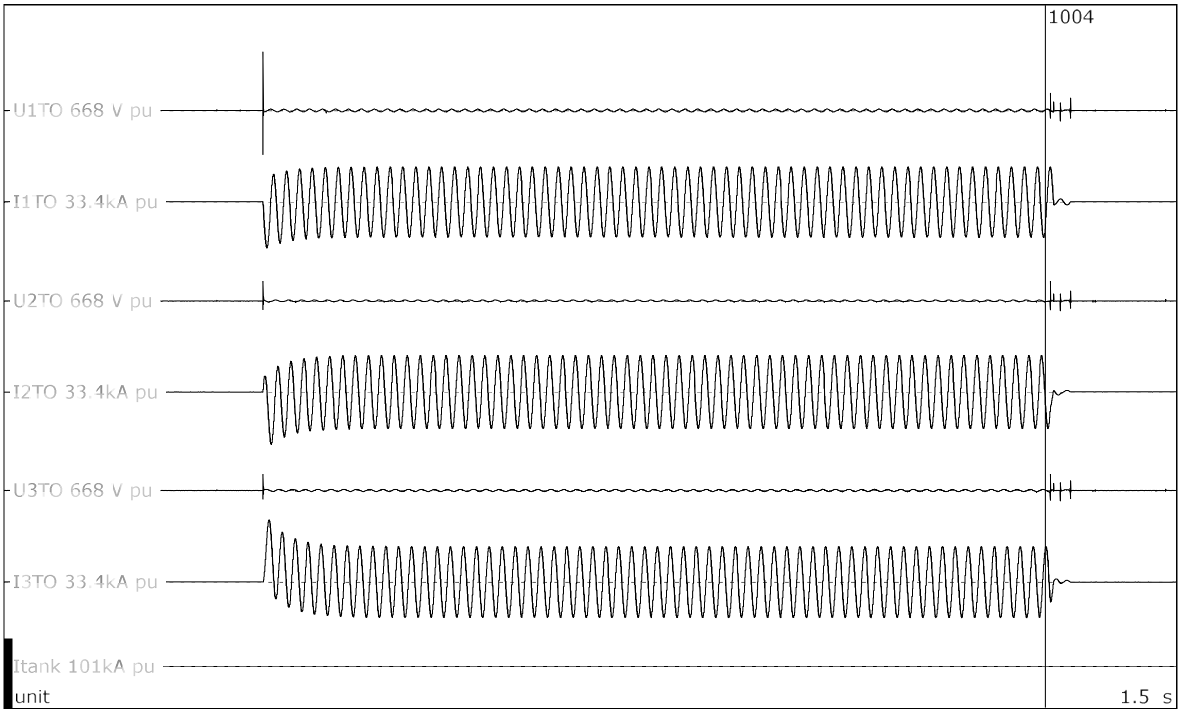
The prospective circuit was verified with a shorting bar connected to the test object inputs.

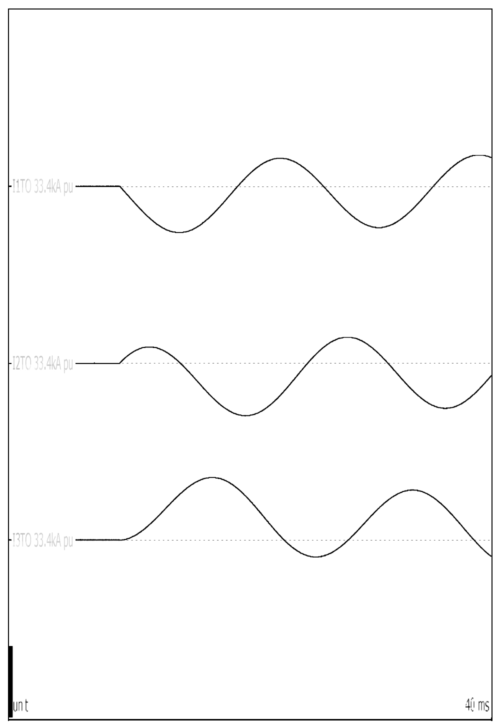
7.2 Test results and oscillograms

Overview of test numbers
230309-1004

Remarks
Prospective circuit was verified at a reduced voltage of 240 V.
The full level pro-rated available circuit to be applied on the Internal Arc test will be:
OCV = 480 V
Isym = 24kA
Ipeak = 59kA

Checking of the prospective current





Test number: **230309-1004**

Phase		**A**	**B**	**C**
Current	kA peak	-21.9	-24.8	29.5
Current, a.c. component, beginning	kA RMS	11.9	12.3	12.0
Current, a.c. component, middle	kA RMS	11.8	12.3	11.9
Current, a.c. component, end	kA RMS	11.8	12.3	11.9
Current, a.c. component, average	kA RMS	11.8	12.3	12.0
Current, a.c. component, three-phase average	kA RMS	12.0		
Duration, current	s	1.00	1.00	1.000
Equivalent RMS value and duration		12 kA during – 1.0 s		
I2t	10E6 A^2s	-		
E	MJ	-		

Gas pressure at 20 °C - MPa

Observations: No visible disturbance. Reduced level test for calibration purposes. Full level available circuit will be:
OCV = 480 V
Isym = 24kA
Ipeak = 59kA

8 INTERNAL ARC TEST – TEST 3 – NRC TEST 2 - YYA

Standard and date

Standard	Client's instructions
Test date	9 March 2023

Serial No.

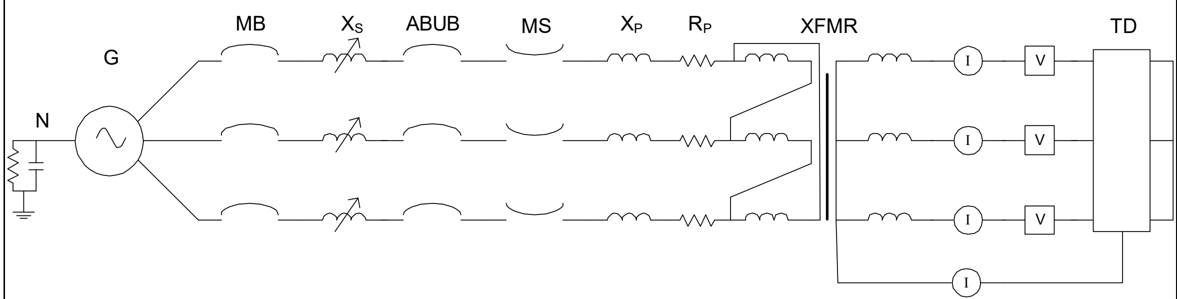
Sample 2-YY

8.1 Condition before test

Arc wire was located on the line side of the circuit breaker.

Two calorimeters placed 3' away from back side of the unit.
CAL 1 - Top
CAL 2 - Bottom
Two calorimeters placed 3' away from right side of the unit.
CAL 3 - Top
CAL 4 - Bottom

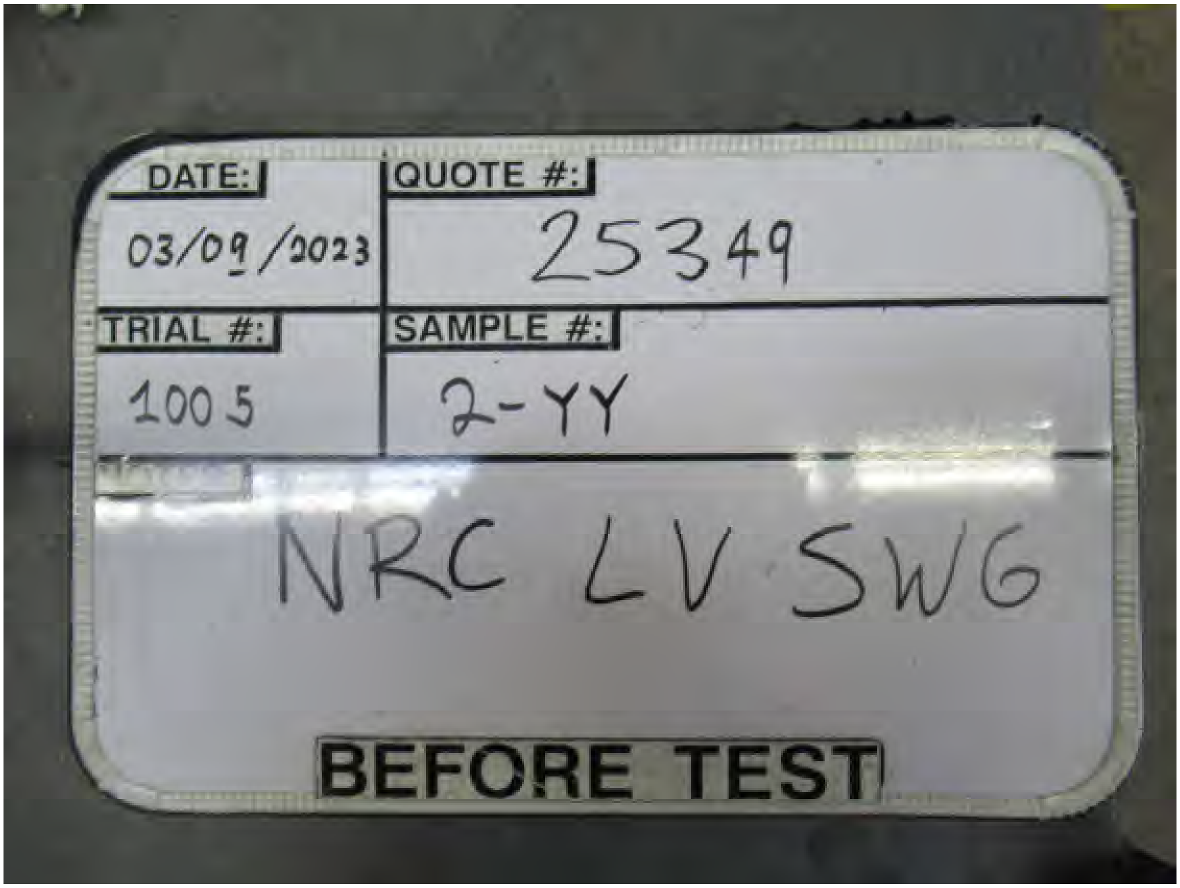
8.2 Test circuit S02



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	C	= Capacitance
MB	= Main Breaker	TD	= Test Device	U	= Voltage Measurement
MS	= Make Switch	X	= Inductance	I	= Current Measurement

Supply		
Power	MVA	19.12
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.48
Current	kA	23
Impedance	Ω	0.012
Power factor		< 0,1
Neutral		earthed

8.3 Photograph before test

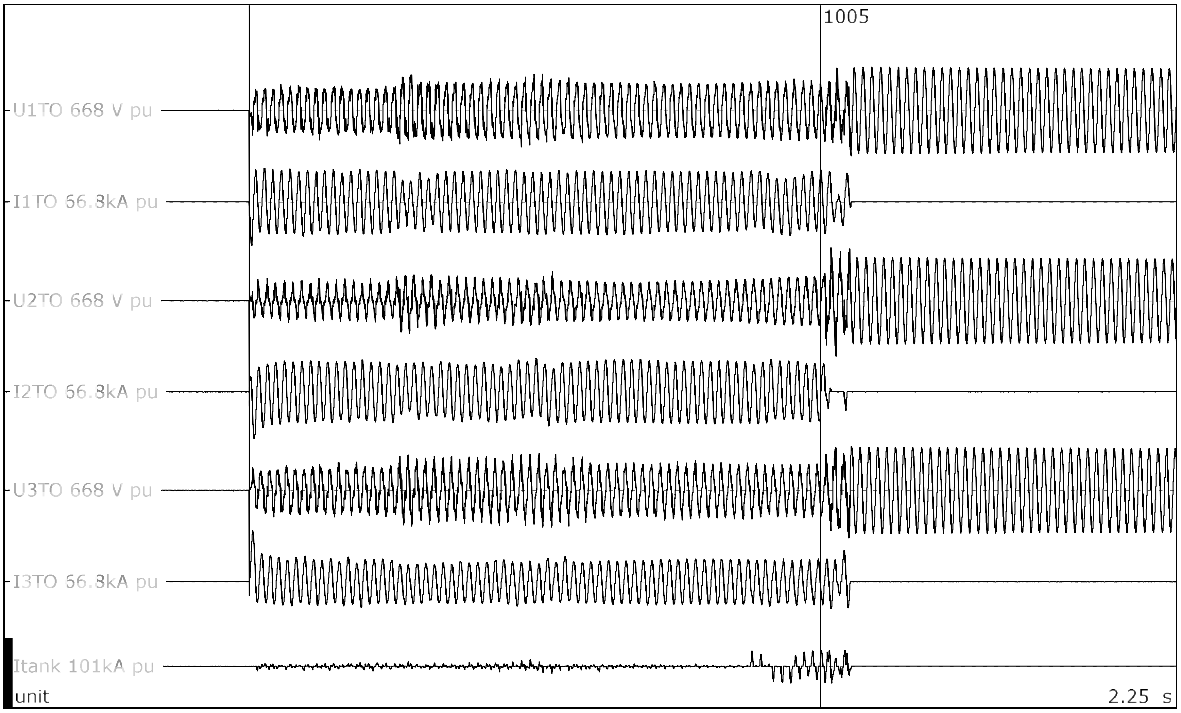


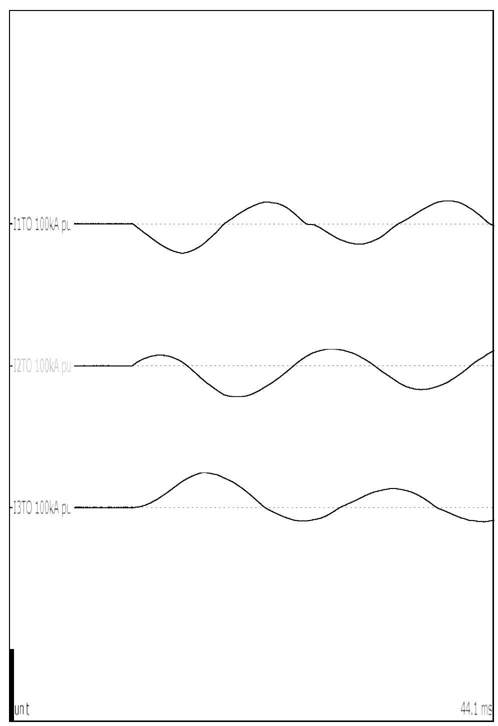
8.4 Test results and oscillograms

Overview of test numbers
230309-1005

Remarks

Internal arc test





Test number: **230309-1005**

Phase		**A**	**B**	**C**
Current	kA_{peak}	-41.5	-44.4	49.2
Current, a.c. component, beginning	kA_{RMS}	23.1	22.3	20.1
Current, a.c. component, middle	kA_{RMS}	20.9	18.8	13.3
Current, a.c. component, end	kA_{RMS}	2.67	19.5	15.3
Current, a.c. component, average	kA_{RMS}	21.1	20.3	14.8
Current, a.c. component, three-phase average	kA_{RMS}	18.7		
Duration, current	s	1.10	1.10	1.09
Equivalent RMS value and duration		23.0 kA during 5.00 s		
I2t	10E6 A^2s	450	460	256
E	MJ	3.76	2.50	2.35

Observations: Sample 2-YY. Large display with smoke and flames visible. Enclosure tank current of 1.78 kA was detected. Arc wire was located on the line side of the circuit breaker.

8.5 Condition / inspection after test

See table below with Calorimeters' data results.

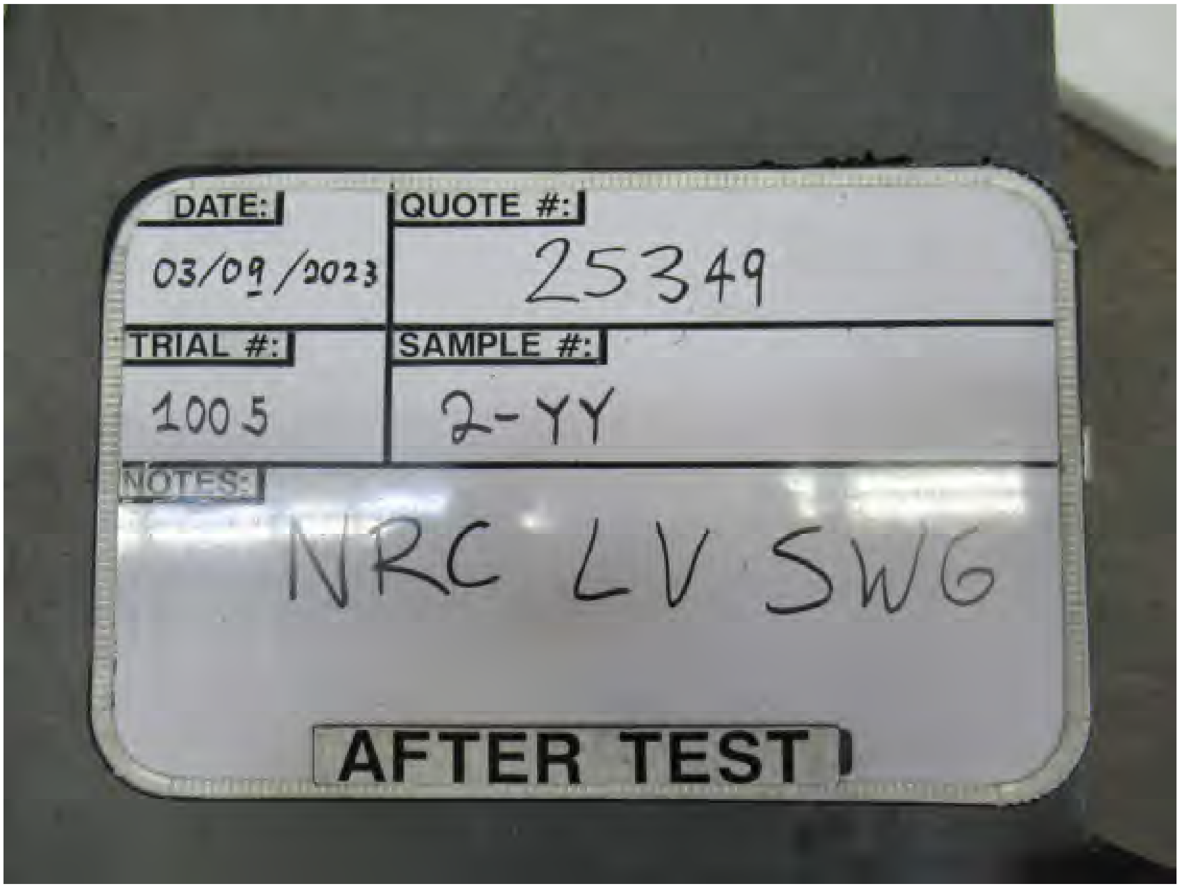
230309-1005

*Calorimeters' data and calculations

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Back Top	10.952	0.09162	11.674	0.09164	0.397
Back Bottom	11.096	0.09162	11.815	0.09165	0.395
Right Top	10.962	0.09162	14.867	0.09173	2.146
Right Bottom	11.064	0.09162	14.949	0.09174	2.135

Calorimeters belong to NRC and its results are for information only. Calorimeters were built and calibrated by KEMA Powertest.

8.6 Photograph after test

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9 INTERNAL ARC TEST – TEST 4 – NRC TEST 2 - YYB

Standard and date

Standard	Client’s instructions
Test date	10 March 2023

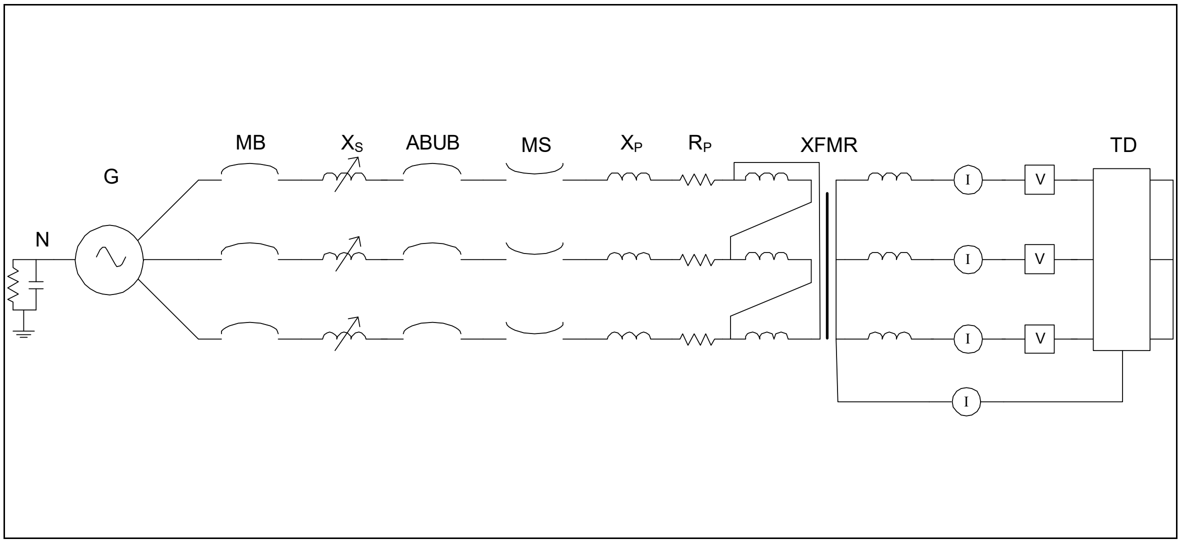
Serial No.
Sample 2-YY

9.1 Condition before test

Client requested KEMA to apply the 600 V / 23 kA prospective circuit – trial 230309-1001.
Arc wire was located on the line side of the circuit breaker.

Two calorimeters placed 3' away from back side of the unit.
CAL 1 - Top
CAL 2 - Bottom
Two calorimeters placed 3' away from right side of the unit.
CAL 3 - Top
CAL 4 - Bottom

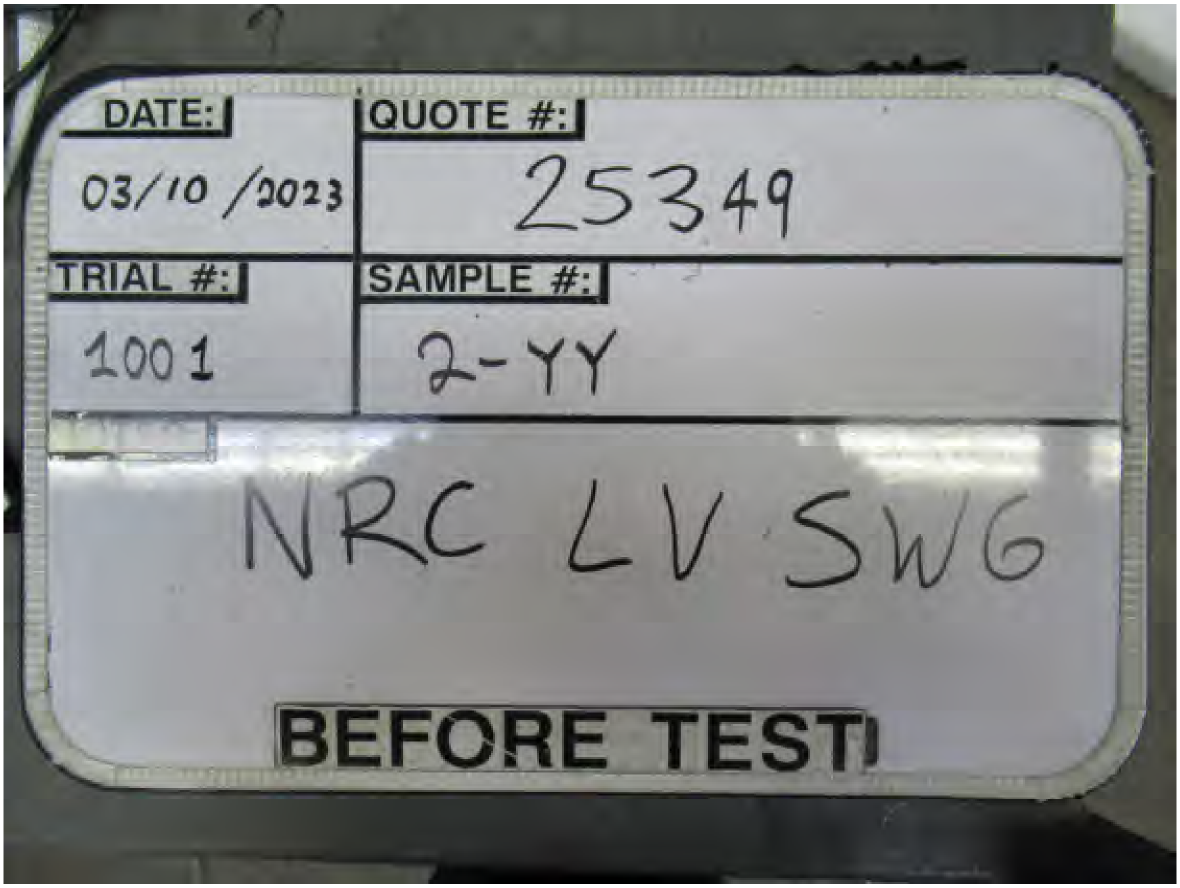
9.2 Test circuit S01



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	C	= Capacitance
MB	= Main Breaker	TD	= Test Device	U	= Voltage Measurement
MS	= Make Switch	X	= Inductance	I	= Current Measurement

Supply		
Power	MVA	23.9
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.6
Current	kA	23
Impedance	Ω	0.0151
Power factor		< 0,1
Neutral		earthed

9.3 Photograph before test

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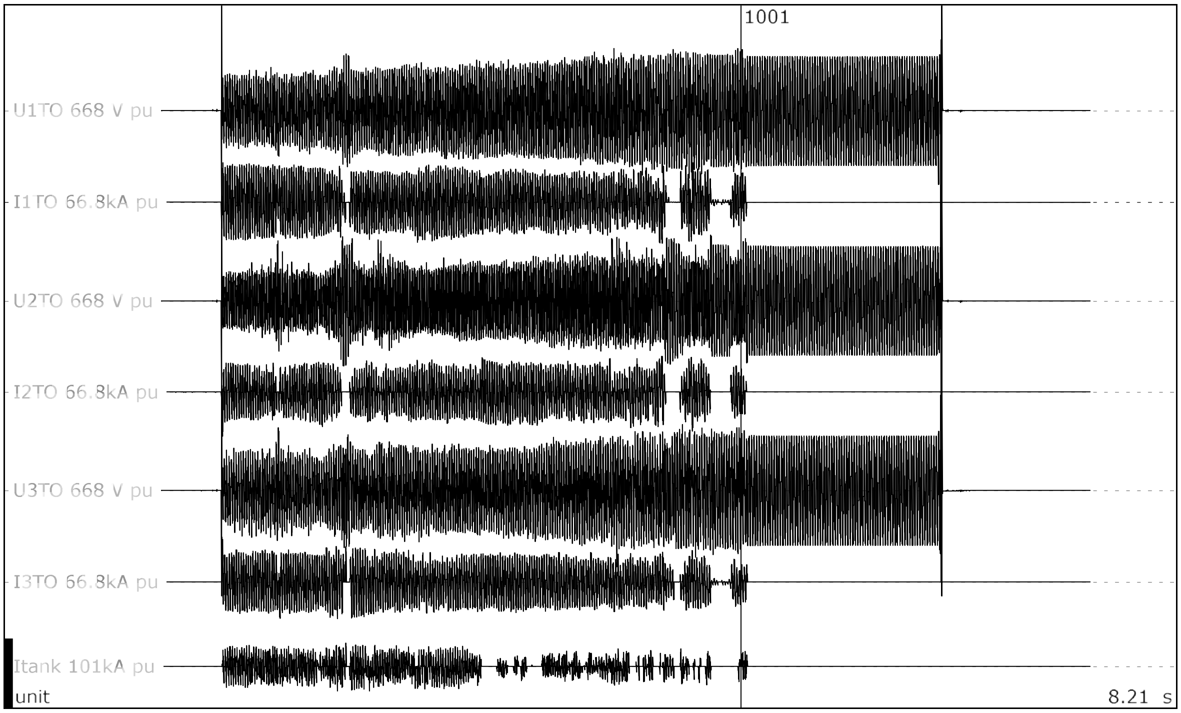
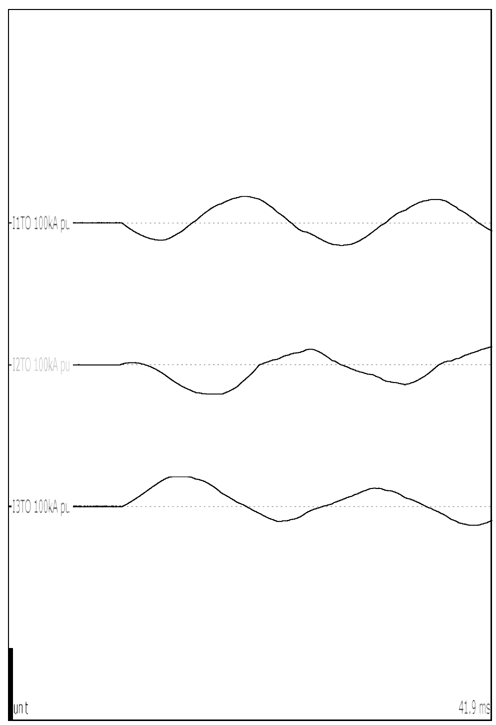
9.4 Test results and oscillograms

Overview of test numbers
230310-1001

Remarks

Internal arc test





Test number: **230310-1001**

Phase		A	B	C
Current	kA_{peak}	-33.3	24.7	-27.4
Current, a.c. component, beginning	kA_{RMS}	23.0	20.1	19.5
Current, a.c. component, middle	kA_{RMS}	18.0	19.1	15.4
Current, a.c. component, end	kA_{RMS}	15.7	15.9	1.54
Current, a.c. component, average	kA_{RMS}	18.7	17.3	15.6
Current, a.c. component, three-phase average	kA_{RMS}	17.2		
Duration, current	s	3.68	3.68	3.68
Equivalent RMS value and duration		23.0 kA during 5.00 s		
I2t	10E6 A^2s	1328	887	951
E	MJ	15.1	10.8	12.0

Observations:	Sample 2-YY. Client requested KEMA to apply the 600 V / 23 kA prospective circuit – trial 230309-1001. Large display with smoke and flames visible. Enclosure tank current of 13.2 kA was detected. Arc wire was located on the line side of the circuit breaker.

9.5 Condition / inspection after test

See table below with Calorimeters' data results.

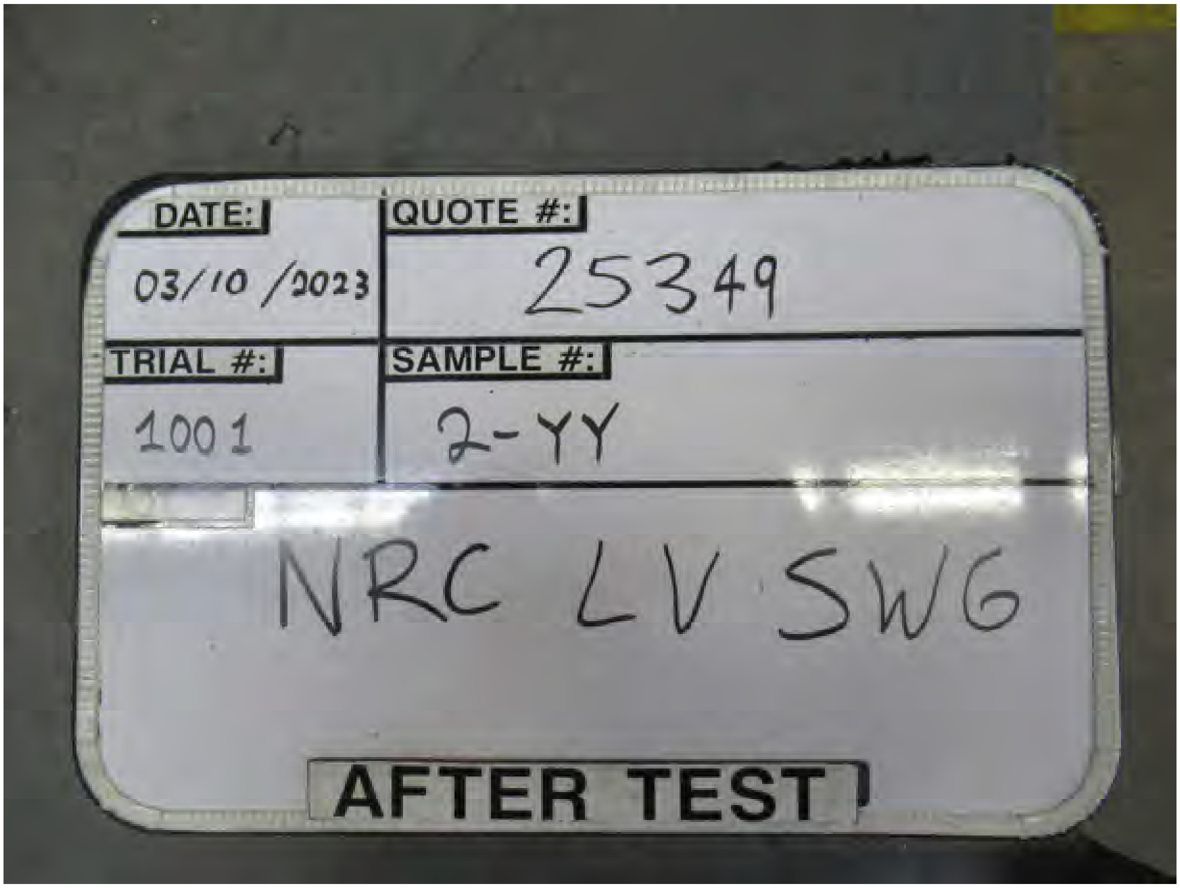
230310-1001

*Calorimeters' data and calculations

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Back Top	3.238	0.0914	22.005	0.09195	10.315
Back Bottom	3.09	0.09139	20.971	0.09192	9.826
Right Top	2.758	0.09139	73.526	0.09353	39.228
Right Bottom	2.737	0.09138	51.833	0.09286	27.116

Calorimeters belong to NRC and its results are for information only. Calorimeters were built and calibrated by KEMA Powertest.

9.6 Photograph after test




KEMA
Laborator


KEMA

11 INSTRUMENTATION INFORMATION SHEET

CODE#	TYPE	MANUFACTURER	MODEL#	SERIAL#	CALIBRATION LAST	CALIBRATION DUE
TEM91	TEMP.LOGGER	DEWESoft	KRYPTONi	D05980F2EA	3/3/2023	9/19/2023
DAS23	DAS	NI/DEWETRON	DEWE-30-16	56111512	9/21/2022	4/9/2023
ISO167	ISO AMP	DEWETRON	HIS-LV	371018	9/21/2022	4/9/2023
ISO158	ISO AMP	DEWETRON	HIS-LV	371009	9/21/2022	4/9/2023
ISO166	ISO AMP	DEWETRON	HIS-LV	371017	9/21/2022	4/9/2023
ISO160	ISO AMP	DEWETRON	HIS-LV	371011	9/21/2022	4/9/2023
ISO161	ISO AMP	DEWETRON	HIS-LV	371012	9/21/2022	4/9/2023
ISO162	ISO AMP	DEWETRON	HIS-LV	371013	9/21/2022	4/9/2023
ISO163	ISO AMP	DEWETRON	HIS-LV	371014	9/21/2022	4/9/2023
CTX218	ROGOWSKI CT	PEM	SDS0680-4p	0005-0103A	3/17/2023	10/3/2023
CTX219	ROGOWSKI CT	PEM	SDS0680-4p	0005-0103B	3/17/2023	3/27/2023
CTX220	ROGOWSKI CT	PEM	SDS0680-4p	0005-0103C	3/17/2023	10/3/2023
CTX221	ROGOWSKI CT	PEM	SDS0680-4p	0005-0103N	3/17/2023	10/3/2023
VDR17	RES VOL.DIV	POWERTEST	NON DIFF	17	3/17/2023	10/3/2023
VDR18	RES VOL.DIV	POWERTEST	NON DIFF	18	3/17/2023	10/3/2023
VDR19	RES.VOL.DIV	POWERTEST	NON DIFF.	19	3/17/2023	10/3/2023

END OF DOCUMENT

KEMA TEST REPORT

28012

Object	Switchgear		
Type	High Energy Arcing Fault tests	**Serial No.**	2-33, 2-34, 2-35, 2-36, 2-37, 2-38, 2-39, 2-40, 2-41
	6.9 kV – 8 - 30 kA – 60 Hz		
Client	Nuclear Regulatory Commission 11555 Rockville Pike Rockville, MD 20852-273 USA		
Manufacturer	U. S. Nuclear Regulatory Commission Washington, DC 20555-0001		
Tested by	KEMA-Powertest LLC 4379 County Line Road Chalfont, PA 18914, USA		
Date of tests	7, 8, 9, 10, 11, 14, 15, 17 and 18 August 2023		
Test specification	The arc tests have been carried out in accordance with the client's instructions.		

Disclaimers

This report applies only to the individual object tested. KEMA-Powertest LLC (“KEMA”) makes no representations or warranties with respect to any device other than the object tested. It is the responsibility of the applicable device manufacturer to ensure that any other devices or units having the same name and descriptions as the test object are identical.

No certificate of performance or other report issued by KEMA for the purpose of confirming the performance of a test object in relation to the testing requirements of a national or international standard, or in relation to any other testing specification, shall constitute a warranty as to the adequacy or quality of the design or construction of the test object. No other document issued by KEMA for the purpose of reporting, explaining or describing any engineering or consulting services performed by KEMA shall constitute a warranty as to the adequacy or quality of the design or construction of any apparatus or system that is the subject of the document.

This report consists of 240 pages in total.

December 8, 2023

Frank Cielo
Director
KEMA Powertest, LLC

INFORMATION SHEET

1 KEMA Type Test Certificate

A KEMA Type Test Certificate contains a record of a series of (type) tests carried out in accordance with a recognized standard. The object tested has fulfilled the requirements of this standard and the relevant ratings assigned by the manufacturer are endorsed by KEMA Labs. In addition, the object's technical drawings have been verified and the condition of the object after the tests is assessed and recorded.
The Certificate contains the essential drawings and a description of the object tested. A KEMA Type Test Certificate signifies that the object meets all the requirements of the named subclauses of the standard. It can be identified by gold-embossed lettering on the cover and a gold seal on its front sheet.
The Certificate is applicable to the object tested only. KEMA Labs is responsible for the validity and the contents of the Certificate. The responsibility for conformity of any object having the same type references as the one tested rests with the manufacturer.
Detailed rules on types of certification are given in KEMA Labs' Certification procedure applicable to KEMA Labs.

2 KEMA Report of Performance

A KEMA Report of Performance is issued when an object has successfully completed and passed a subset (but not all) of test programmes in accordance with a recognized standard. In addition, the object's technical drawings have been verified and the condition of the object after the tests is assessed and recorded. The report is applicable to the object tested only. A KEMA Report of Performance signifies that the object meets the requirements of the named subclauses of the standard. It can be identified by silver-embossed lettering on the cover and a silver seal on its front sheet.
The sentence on the front sheet of a KEMA Report of Performance will state that the tests have been carried out in accordance with …… The object has complied with the relevant requirements.

3 KEMA Test Report

A KEMA Test Report is issued in all other cases.

4 Official and uncontrolled test documents

The official test documents of KEMA Labs are issued in bound form. Uncontrolled copies may be provided as a digital file for convenience of reproduction by the client. The copyright has to be respected at all times.

5 Accreditation of KEMA Labs

KEMA Labs is accredited in accordance with ISO/IEC 17025 by the respective national accreditation bodies. KEMA Labs Arnhem, the Netherlands, is accredited by RvA under nos. L020, L218, K006 and K009. KEMA Labs Chalfont, United States, is accredited by A2LA under no. 0553.01. KEMA Labs Prague, the Czech Republic, is accredited by CAI as testing laboratory no. 1035.

REVISION OVERVIEW

Rev. No	Date of issue	Reason for issue
0	12/8/2023	Final issue

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1. Total heat energy results [10 PAGES]

End of Document [1 PAGE]

1 IDENTIFICATION OF THE OBJECT TESTED

1.1 Ratings/characteristics of the object tested

Voltage	6.9 kV
Number of phases	3
Frequency	60 Hz
Internal arc classification	
• three-phase arc fault current	8 - 30 kA
• arc fault duration	up to 17.5s s

1.2 Description of the object tested

Switchgear

1.3 Travel recorder

Not applicable.

1.4 List of drawings

No drawings are included in this report.

2 GENERAL INFORMATION

2.1 The tests were witnessed by

The following persons witnessed the tests at the KEMA premises:

Name	Company
Anthony D. Putorti Jr.	National Institute of Standards and Technology
Stephen Fink	100 Bureau Dr.
Christopher U. Brown	Gaithersburg, MD 20899
Albert J. Wavering	
A. Kirk Dohne	
Michael Heck	
Scott Bareham	
Wai Cheong Tam	
Lucy Fox	
Austin Glover	Sandia National Laboratorie, New Mexico
Alvaro Cruz-Cabrera	1515 Eubank SE
Ryan Flanagan	Albuquerque, NM 87185
Mark Henry Salley	U. S. Nuclear Regulatory Commission
Kenneth A. Hamburger	Washington, DC 20555-0001
Kenn Miller	
Gabriel J. Taylor	
Nicholas B. Melly	

2.2 The tests were carried out by

Name	Company
Emmanuel Ankrah (14, 15, 17 August 2023)	KEMA-Powertest LLC,
Samuel Andris (7, 8, 9, 10, 11 August 2023)	Chalfont, PA, USA

2.3 Accuracy of measurement

The guaranteed uncertainty in the figures mentioned, taking into account the total measuring system, is less than 3%, unless mentioned otherwise. Measurement uncertainty can be verified by reviewing the instrument calibration records. The instruments used are calibrated on a regular basis and are traceable to the National Institute of Standards and Technology.

2.4 Notes

Tests objects were tested as installed by client.

3 LEGEND

Phase indications

If more than one phase is recorded on oscillogram, the phases are indicated by the digits 1, 2 and 3. These phases 1, 2 and 3 correspond to the phase values in the columns of the accompanying table, respectively from left to right.

Explanation of the letter symbols and abbreviations on the oscillograms

pu	Per unit (the reference length of one unit is represented by the black bar on the oscillogram)
I1TO	Current through test object
I2TO	Current through test object
I3TO	Current through test object
PT1	Pressure
PT2	Pressure
U1TO	Voltage across test object
U2TO	Voltage across test object
U3TO	Voltage across test object

4 CHECKING CIRCUIT PARAMETERS

Standard and date

Standard	Client's instructions
Test date	7 August 2023

Serial No.
n/a

4.1 Condition before test

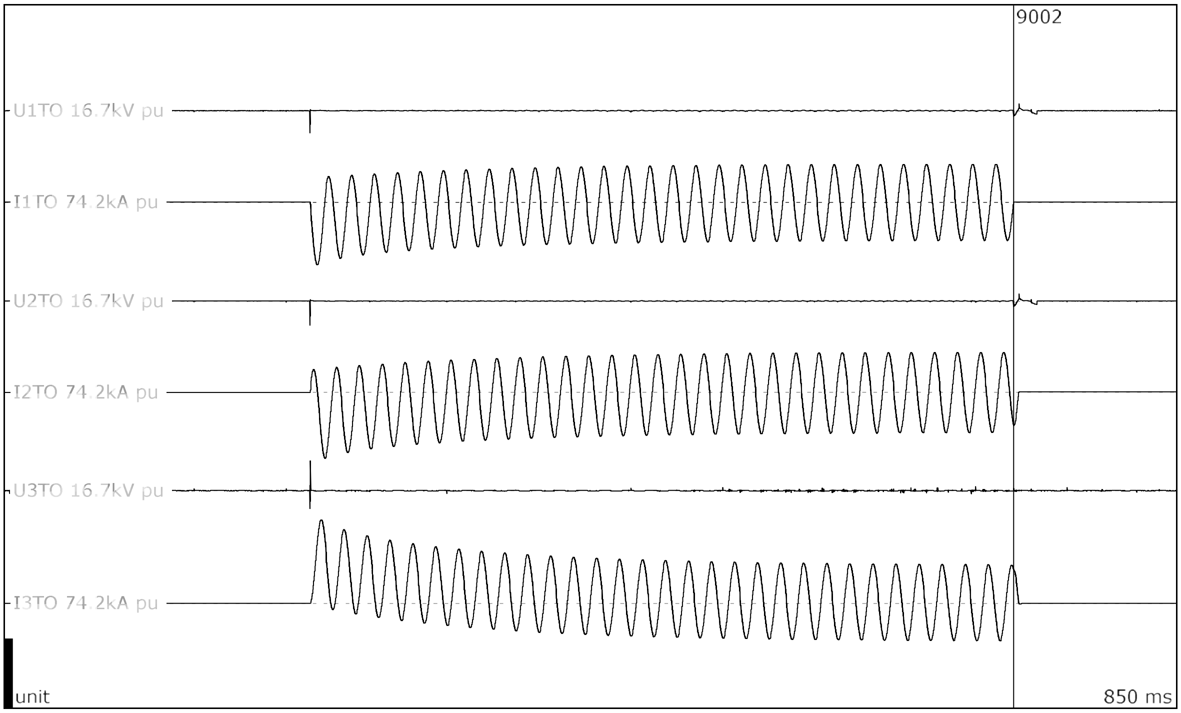
Shorting bar connected to input terminals of test device.

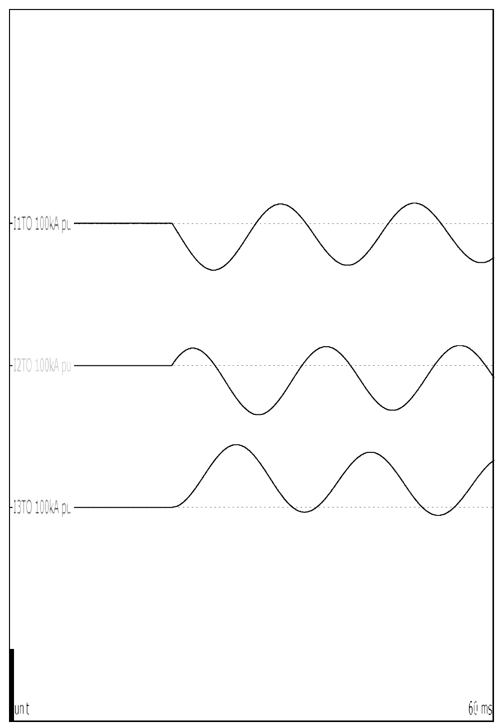
4.2 Test results and oscillograms

Overview of test numbers
230807-9002

Remarks
-

Checking circuit parameters





Test number: **230807-9002**

Phase		**AØ**	**BØ**	**CØ**
Current	kA peak	-66.2	-70.1	88.3
Current, a.c. component, beginning	kA RMS	31.8	33.7	31.8
Current, a.c. component, middle	kA RMS	28.7	30.1	28.6
Current, a.c. component, end	kA RMS	28.6	30.0	28.5
Current, a.c. component, average	kA RMS	29.3	30.9	29.3
Current, a.c. component, three-phase average	kA RMS	29.8		
Duration, current	s	0.510	0.510	0.510

Observations:	Applied open circuit voltage of 4160 V. Circuit parameters will be pro-rated to 4190 V, 30 kA.

4.3 Condition / inspection after test

See observations for test details.

5 ARC TEST 2-40: 30KA, 4S, CU

Standard and date

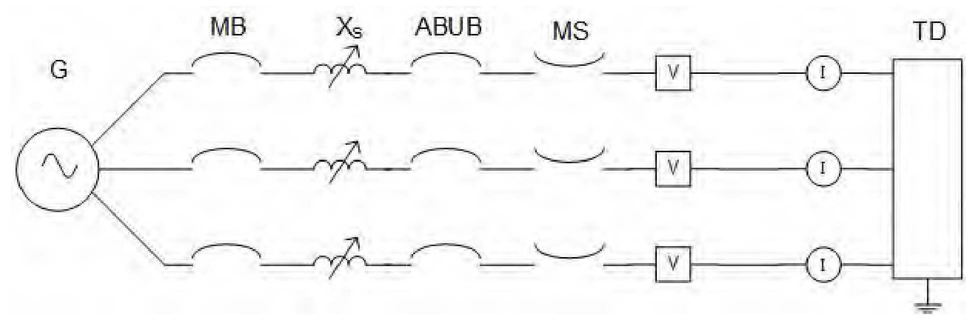
Standard	Client’s instructions
Test date	7 August 2023

Serial No.
2-40

5.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire on the bus bar 53 inches, from the flange, on the source side of the bus duct enclosure.

5.2 Test circuit S01



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	216
Frequency	Hz	60
Phase(s)		3
Voltage	kV	4.19
Current	kA	30
Impedance	Ω	0.0801
Power factor		< 0.1
Neutral		not earthed

5.3 Photograph before test


08/07/2023 14:09


08/07/2023 14:15


08/07/2023 14:41


08/07/2023 14:41

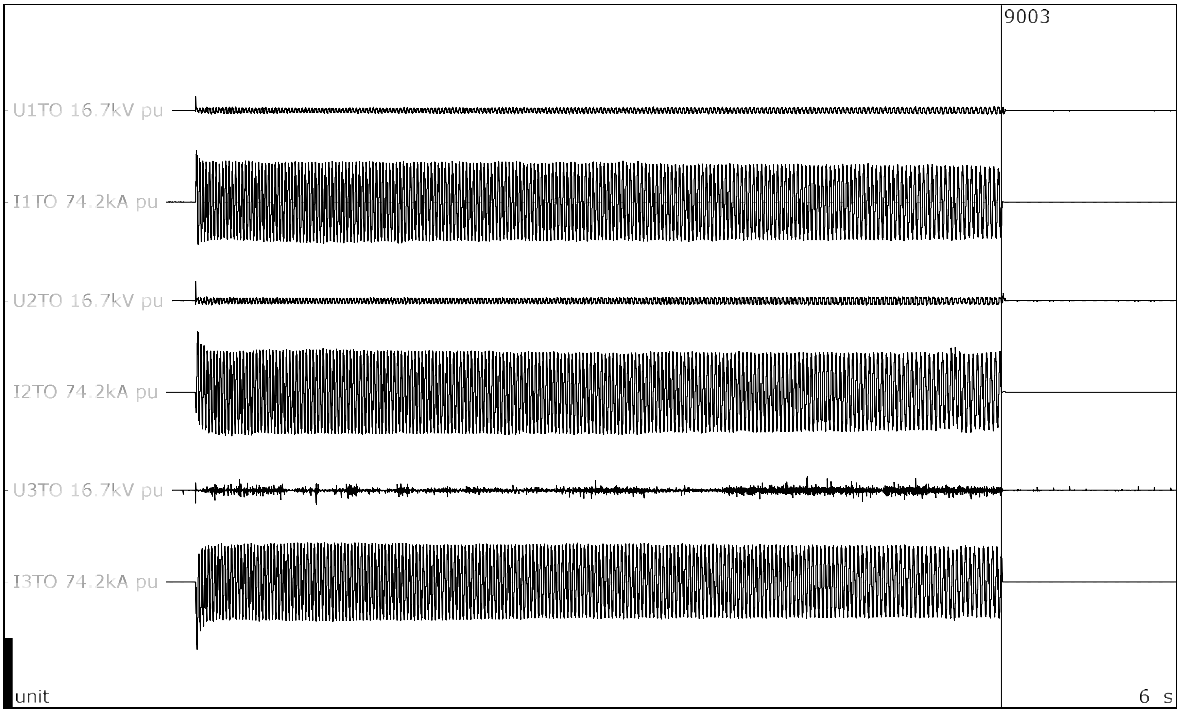

08/07/2023 14:43

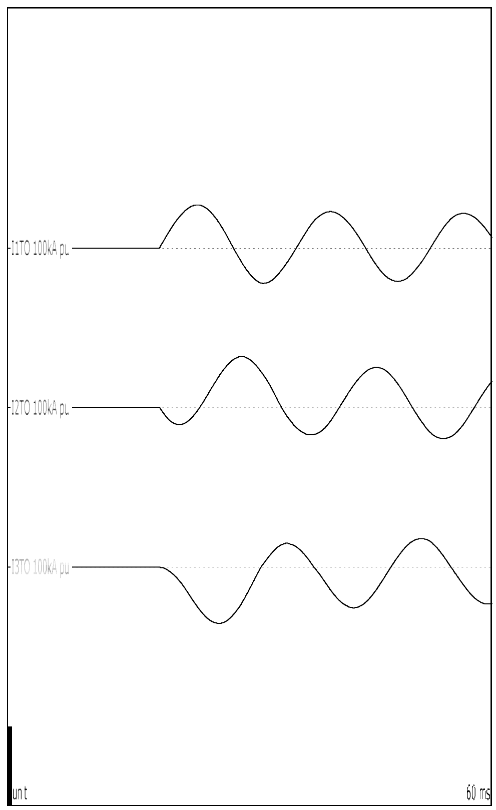
5.4 Test results and oscillograms

Overview of test numbers
230807-9003

Remarks
-

Arc Test 2-40: 30kA, 4s, CU





Test number: **230807-9003**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	2.42	2.42	2.42
Applied voltage, phase-to-phase	kV_{RMS}		4.19	
Making current	kA_{peak}	54.1	64.0	-71.1
Current, a.c. component, beginning	kA_{RMS}	33.4	32.5	32.1
Current, a.c. component, middle	kA_{RMS}	28.8	29.8	27.6
Current, a.c. component, end	kA_{RMS}	26.6	29.0	26.5
Current, a.c. component, average	kA_{RMS}	29.5	30.3	28.3
Current, a.c. component, three-phase average	kA_{RMS}		29.4	
Duration	s	4.12	4.12	4.12
Arc energy	MJ		-	

Observations:	Emission of flames and gas observed. CØ voltage divider has excess noise. This is causing incorrect energy calculation on CØ.

5.5 Condition / inspection after test

Heavy damage to the bus duct. Majority of enclosure vaporized.

5.6 Photograph after test


08/07/2023 15:10


08/07/2023 15:05


08/07/2023 15:11


08/07/2023 15:08


08/07/2023 15:11


08/07/2023 15:11


08/07/2023 15:12


2-40
08/07/2023 15:12


08/07/2023 15:08


08/07/2023 15:05

6 ARC TEST 2-41: 30KA, 4S, AL

Standard and date

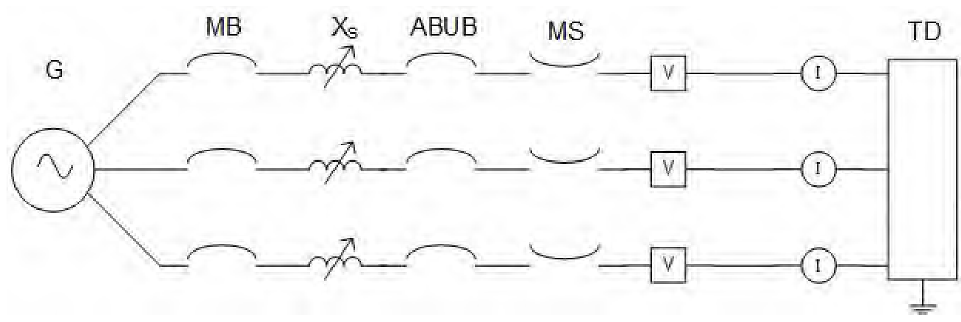
Standard	Client’s instructions
Test date	8 August 2023

Serial No.
2-41

6.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire on the bus bar 53 inches, from the flange, on the source side of the bus duct enclosure.

6.2 Test circuit S01



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	216
Frequency	Hz	60
Phase(s)		3
Voltage	kV	4.19
Current	kA	30
Impedance	Ω	0.0801
Power factor		< 0.1
Neutral		not earthed

6.3 Photograph before test


08/08/2023 11:38


08/08/2023 11:33


08/08/2023 11:39


08/08/2023 11:39

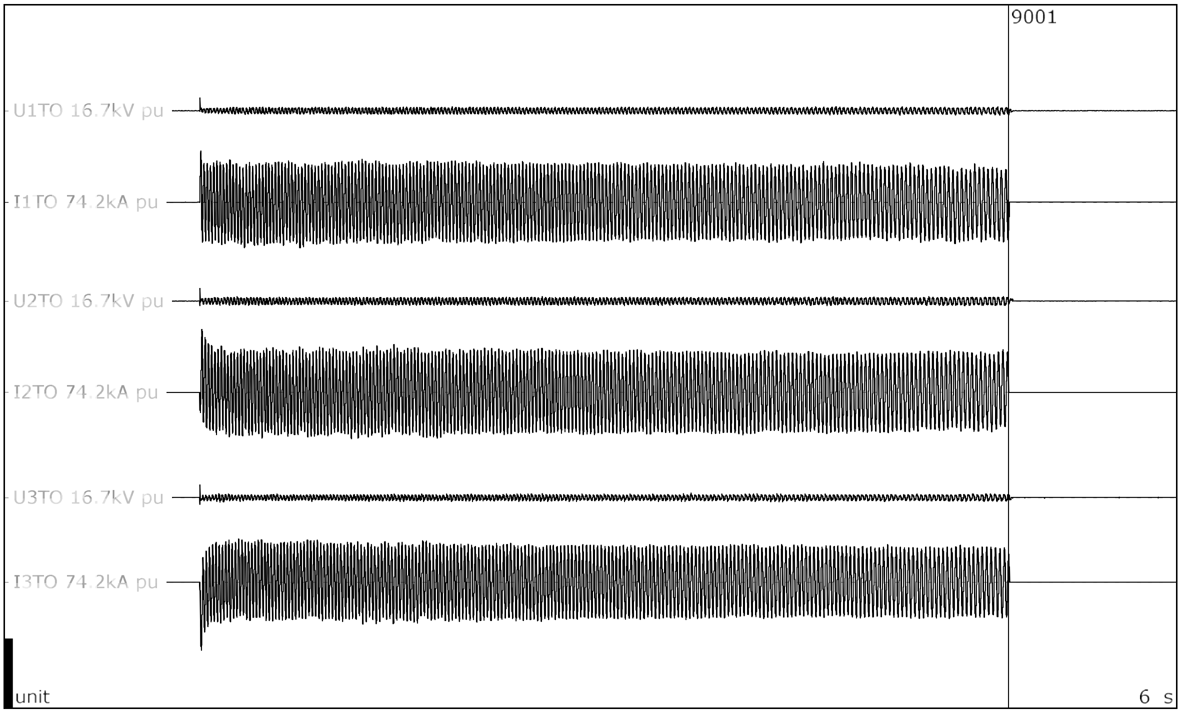

2-41
08/08/2023 11:34

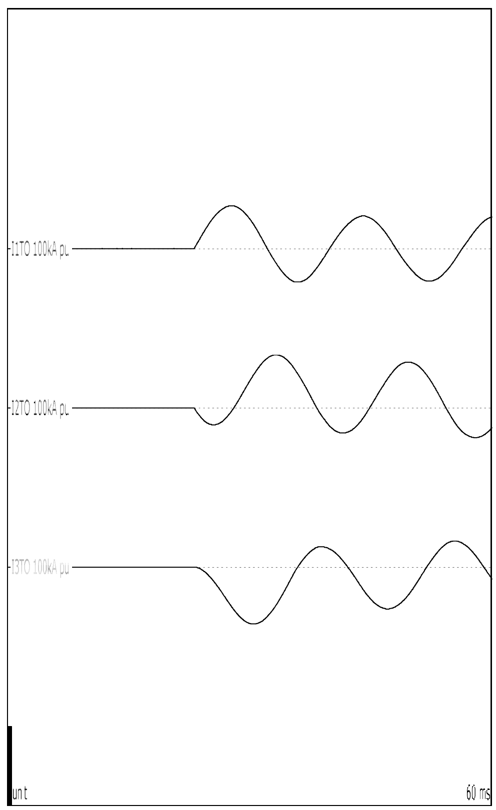
6.4 Test results and oscillograms

Overview of test numbers
230808-9001

Remarks
Calorimeter 1 not reading correct value before test. Data not valid.

Arc Test 2-41: 30kA, 4s, Al





Test number: **230808-9001**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	2.42	2.42	2.42
Applied voltage, phase-to-phase	kV_{RMS}	4.19		
Making current	kA_{peak}	53.8	66.8	-72.0
Current, a.c. component, beginning	kA_{RMS}	31.8	33.0	31.1
Current, a.c. component, middle	kA_{RMS}	28.3	30.6	27.1
Current, a.c. component, end	kA_{RMS}	26.9	28.4	25.6
Current, a.c. component, average	kA_{RMS}	29.3	30.7	28.0
Current, a.c. component, three-phase average	kA_{RMS}	29.3		
Duration	s	4.14	4.14	4.14
Arc energy	MJ	157		

Observations: Emission of flames and gas observed.

6.5 Condition / inspection after test

Heavy damage to the bus duct. Majority of enclosure vaporized.

6.6 Photograph after test


08/08/2023 11:56


08/08/2023 11:55


08/08/2023 11:55


08/08/2023 11:56


08/08/2023 11:56


2-41
08/08/2023 11:56


08/08/2023 11:57


08/08/2023 11:57


08/08/2023 11:57


08/08/2023 11:56


08/08/2023 11:56

7 CHECKING CIRCUIT PARAMETERS

Standard and date

Standard	Client's instructions
Test date	9 August 2023

Serial No.

n/a

7.1 Condition before test

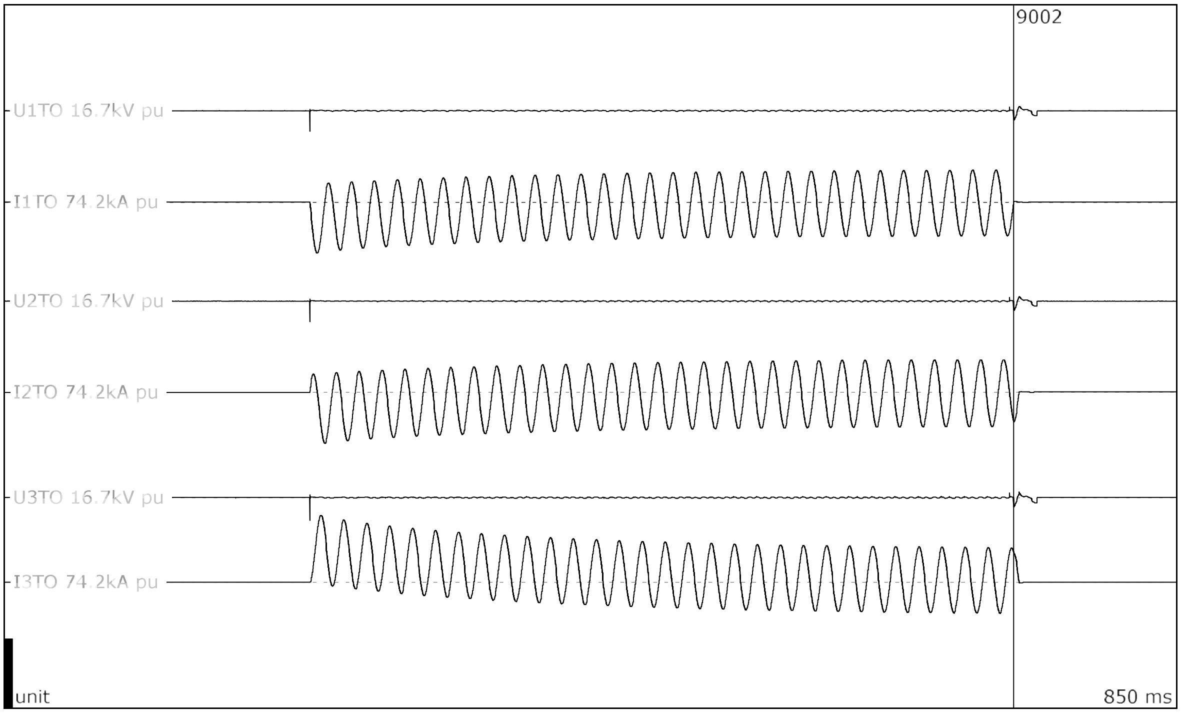
Shorting bar connected to input terminals of test device.

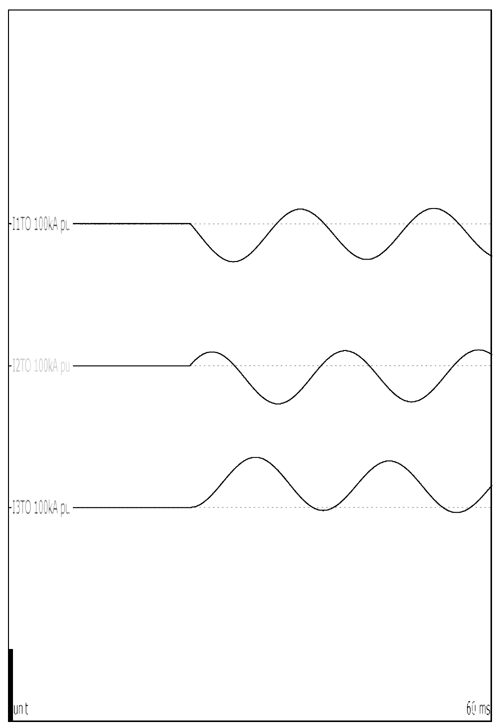
7.2 Test results and oscillograms

Overview of test numbers
230809-9002

Remarks
-

Checking circuit parameters





Test number: **230809-9002**

Phase		AØ	BØ	CØ
Current	kA_{peak}	-54.0	-54.3	70.8
Current, a.c. component, beginning	kA_{RMS}	25.7	26.3	25.7
Current, a.c. component, middle	kA_{RMS}	24.6	25.1	24.5
Current, a.c. component, end	kA_{RMS}	24.6	25.1	24.6
Current, a.c. component, average	kA_{RMS}	24.8	25.3	24.8
Current, a.c. component, three-phase average	kA_{RMS}	25.0		
Duration, current	s	0.510	0.510	0.510

Observations: Circuit parameters are 6.97 kV, 25 kA.

7.3 Condition / inspection after test

See observations for test details.

8 ARC TEST 2-35: 25KA, 4S, CU

Standard and date

Standard	Client's instructions
Test date	9 August 2023

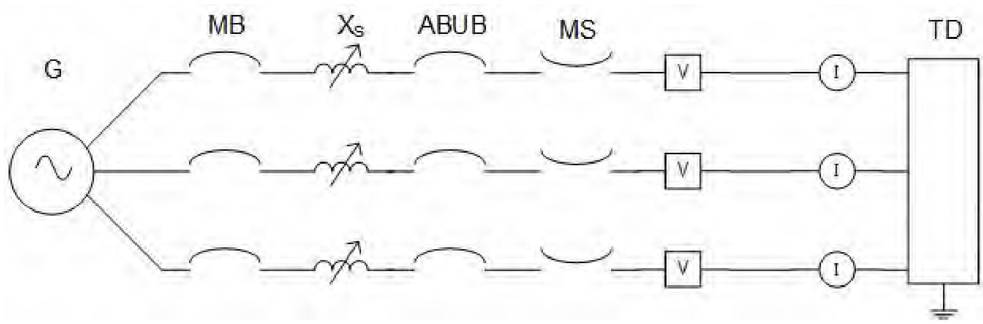
Serial No.

2-35

8.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire in the front upper left compartment on the main bus.
Pressure transducer 1 located on the left side of the compartment containing the arc wire.
Pressure transducer 2 located on the right side of the switchgear.

8.2 Test circuit S02



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	302
Frequency	Hz	60
Phase(s)		3
Voltage	kV	6.97
Current	kA	25
Impedance	Ω	0.161
Power factor		< 0.1
Neutral		not earthed

8.3 Photograph before test


08/09/2023 10:49


08/09/2023 11:59


08/09/2023 12:00

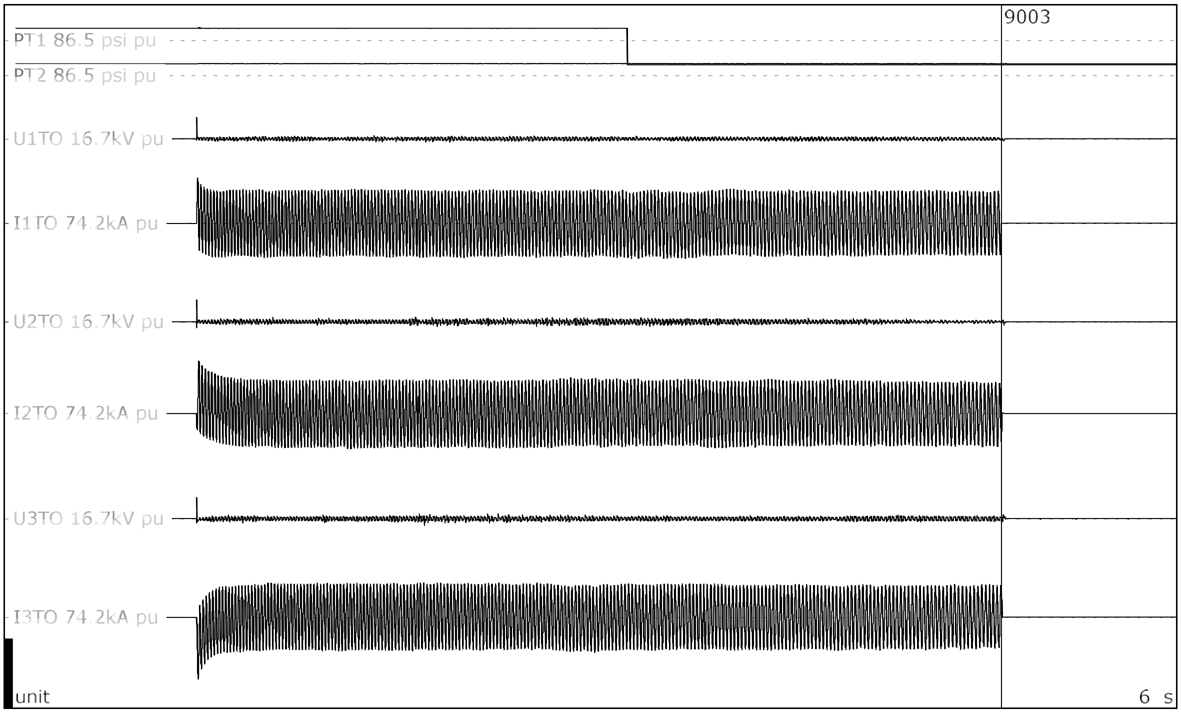

08/09/2023 12:00

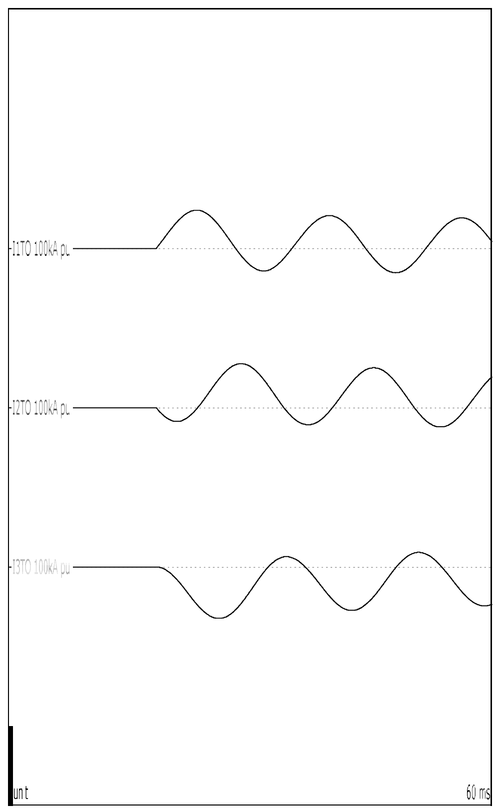
8.4 Test results and oscillograms

Overview of test numbers
230809-9003

Remarks
-

Arc Test 2-35: 25kA, 4s, CU





Test number: **230809-9003**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	48.2	55.4	-65.1
Current, a.c. component, beginning	kA_{RMS}	25.9	26.5	25.7
Current, a.c. component, middle	kA_{RMS}	24.2	24.9	24.3
Current, a.c. component, end	kA_{RMS}	23.5	23.3	23.3
Current, a.c. component, average	kA_{RMS}	24.6	24.9	24.4
Current, a.c. component, three-phase average	kA_{RMS}		24.6	
Duration	s	4.12	4.12	4.12
Arc energy	MJ		83.1	

Observations: Emission of flames and gas observed.
PT#1 1.6 psi above atmospheric
PT #2 0.68 psi above atmospheric

8.5 Condition / inspection after test

Interior and sides of the sample exterior were heavily burned.
Front door containing the arc wire blew open.
Fire in the test gear burned for about 15 minutes before being extinguished.

8.6 Photograph after test


08/09/2023 13:40


2-35
P
08/09/2023 13:34


2-35
08/09/2023 13:40


08/09/2023 13:38


08/09/2023 13:36


08/09/2023 13:35


WARNING
08/09/2023 13:35
WARNING


08/09/2023 13:35


08/09/2023 13:34


08/09/2023 13:34

9 ARC TEST 2-37: 25KA, 4S, CU

Standard and date

Standard	Client's instructions
Test date	10 August 2023

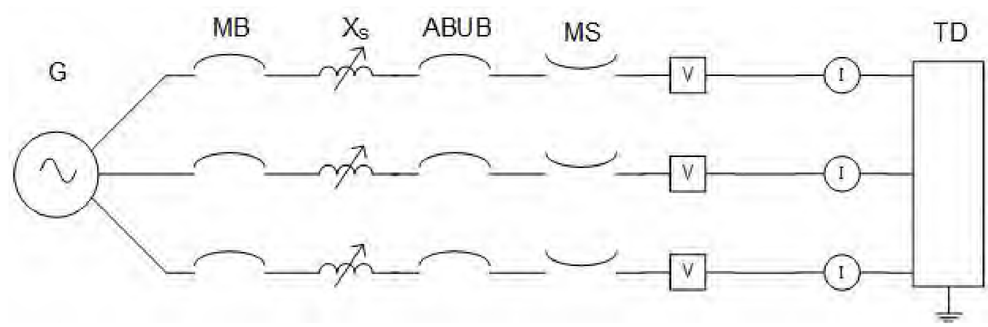
Serial No.

2-37

9.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire on the line side of the breaker in the bottom left compartment..
Pressure transducer 1 located on the left side of the compartment containing the arc wire.
Pressure transducer 2 located on the right side of the switchgear.

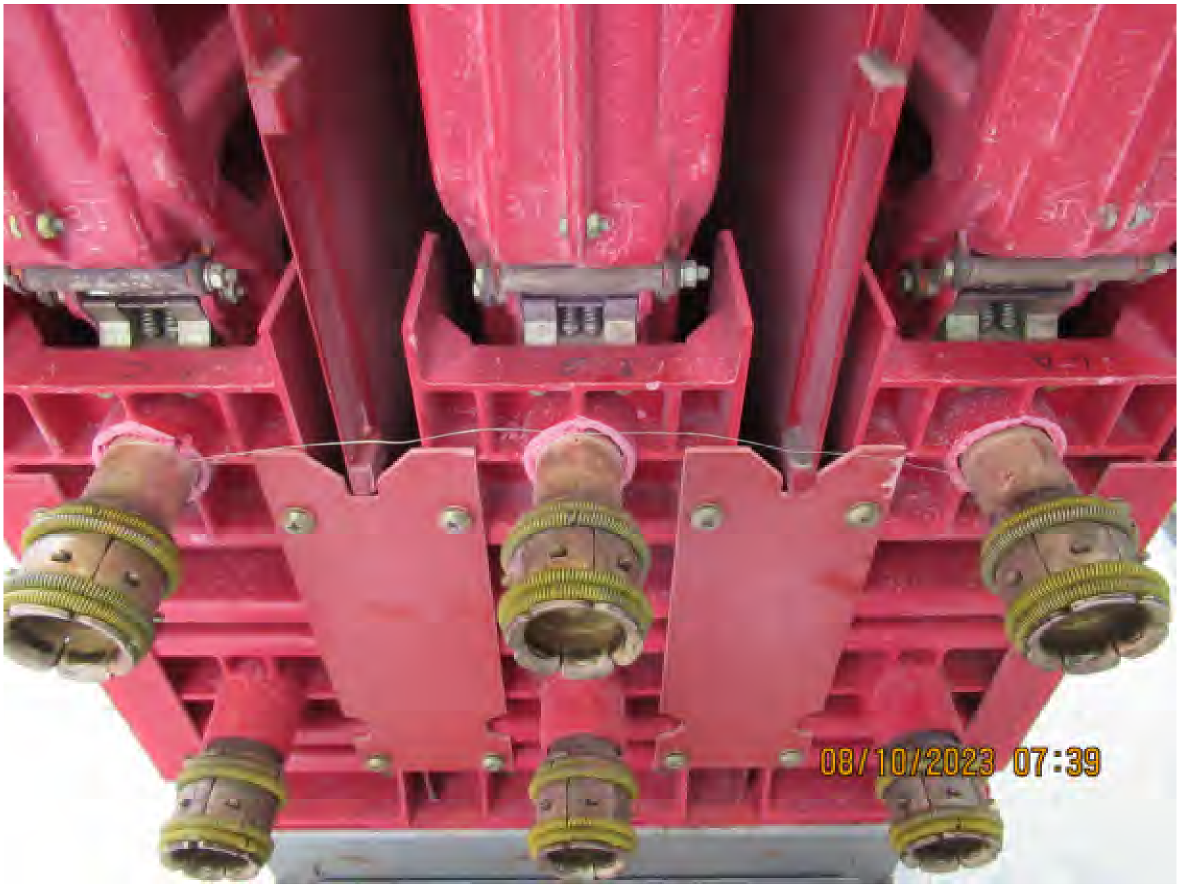
9.2 Test circuit S02



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	302
Frequency	Hz	60
Phase(s)		3
Voltage	kV	6.97
Current	kA	25
Impedance	Ω	0.161
Power factor		< 0.1
Neutral		not earthed

9.3 Photograph before test




08/10/2023 10:54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08/10/2023 11:03

9.4 Test results and oscillograms

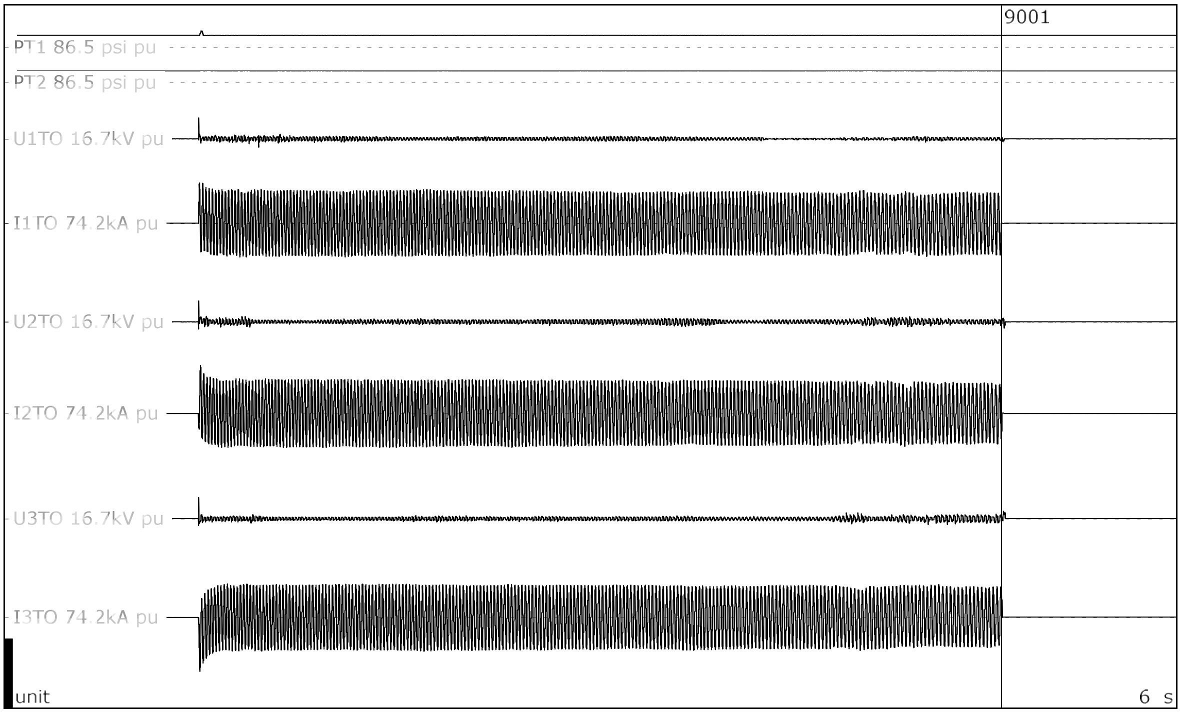
Overview of test numbers

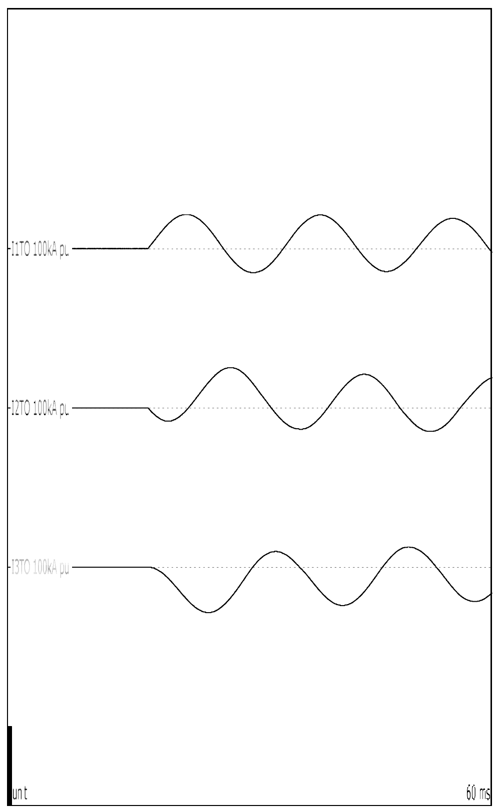
230810-9001

Remarks

-

Arc Test 2-37: 25kA, 4s, CU





Test number: **230810-9001**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}	6.97		
Making current	kA_{peak}	42.9	50.6	-57.3
Current, a.c. component, beginning	kA_{RMS}	25.8	25.6	25.6
Current, a.c. component, middle	kA_{RMS}	23.7	24.1	23.7
Current, a.c. component, end	kA_{RMS}	22.7	22.3	22.4
Current, a.c. component, average	kA_{RMS}	24.0	24.4	24.0
Current, a.c. component, three-phase average	kA_{RMS}	24.1		
Duration	s	4.11	4.11	4.11
Arc energy	MJ	93.3		

Observations:	Emission of flames and gas observed. PT#1 6.16 psi above atmospheric PT #2 0.5 psi above atmospheric

9.5 Condition / inspection after test

Interior and sides of the sample exterior were heavily burned.
Front door containing the arc wire ejected. Front door of the breaker blew out of the switchgear.
Fire in the test gear self-extinguished.

9.6 Photograph after test


08/10/2023 11:32


08/10/2023 11:29


08/10/2023 11:28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08/10/2023 11:28


08/10/2023 11:31


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08/10/2023 11:30


08/10/2023 11:30


08/10/2023 11:29


08/10/2023 11:29


08/10/2023 11:29

10 ARC TEST 2-36: 25KA, 4S, CU

Standard and date

Standard	Client’s instructions
Test date	11 August 2023

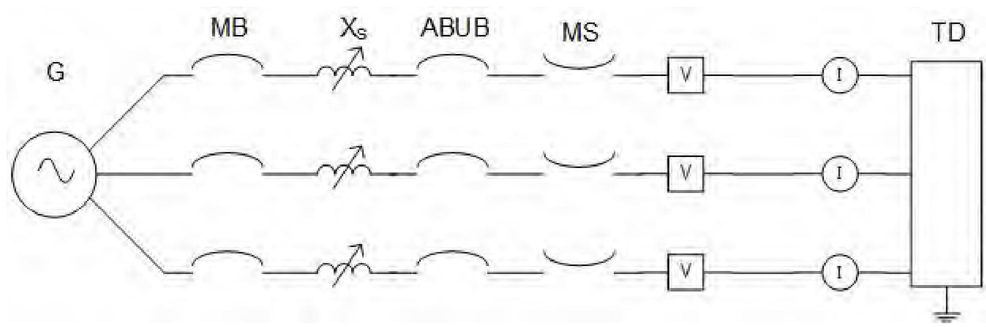
Serial No.

2-36

10.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire on the line side of the breaker in the bottom left compartment.
Pressure transducer 1 located on top of the unit above the cabinet containing the arc.
Pressure transducer 2 located on the unit on above the cabinet on the right side.

10.2 Test circuit S02



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	302
Frequency	Hz	60
Phase(s)		3
Voltage	kV	6.97
Current	kA	25
Impedance	Ω	0.161
Power factor		< 0.1
Neutral		not earthed

10.3 Photograph before test


08/11/2023 10:23
2-36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2-36
08/11/2023 10:25

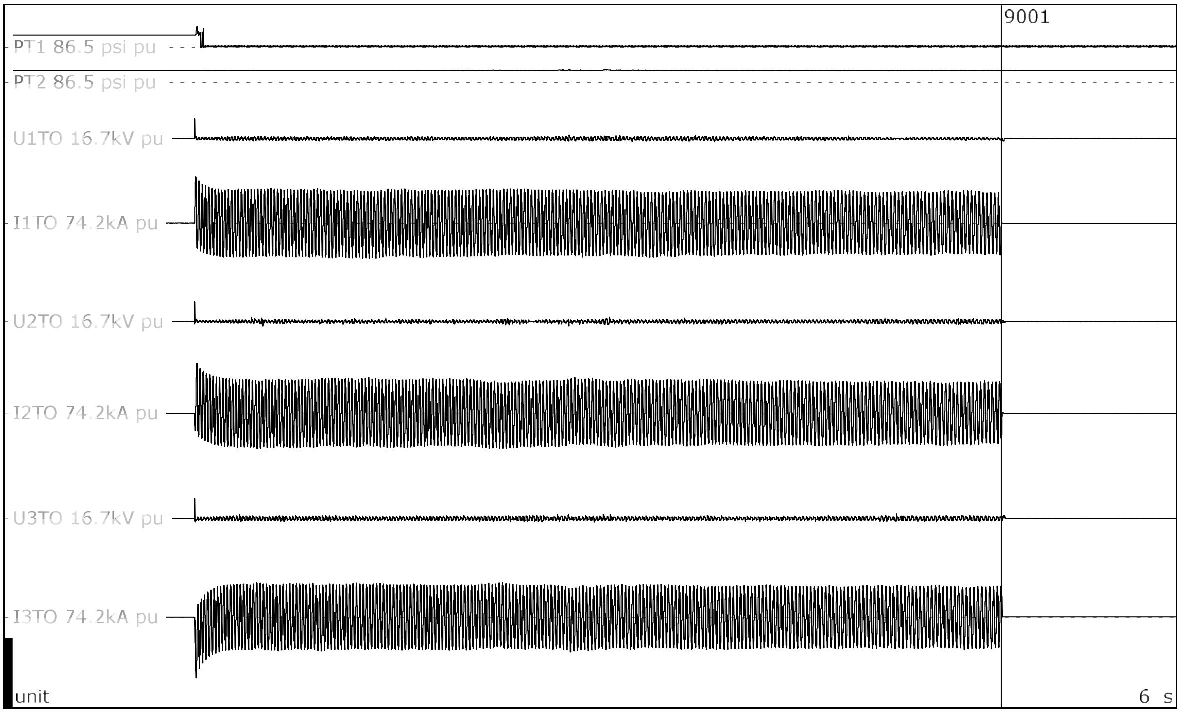

08/11/2023

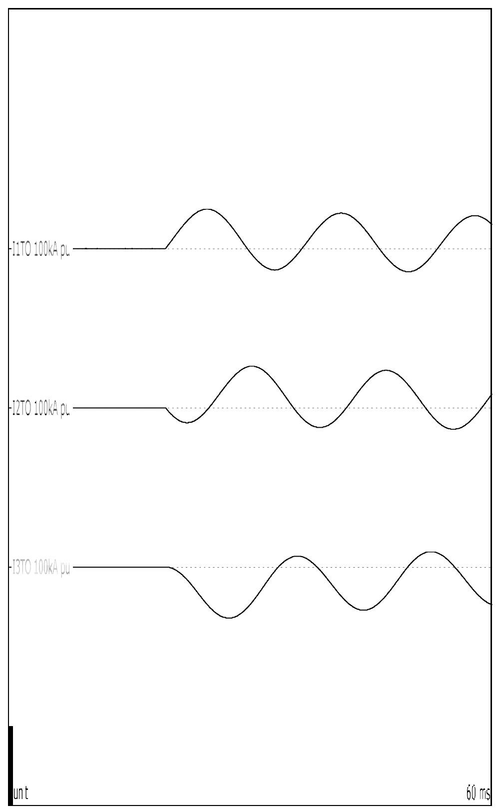
10.4 Test results and oscillograms

Overview of test numbers
230811-9001

Remarks
Calorimeter 4 data invalid due to bad connection before test.

Arc Test 2-36: 25kA, 4s, CU





Test number: **230811-9001**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	49.6	52.4	-64.4
Current, a.c. component, beginning	kA_{RMS}	26.2	26.2	25.8
Current, a.c. component, middle	kA_{RMS}	23.9	24.4	23.4
Current, a.c. component, end	kA_{RMS}	22.9	22.9	23.1
Current, a.c. component, average	kA_{RMS}	24.5	24.6	24.1
Current, a.c. component, three-phase average	kA_{RMS}		24.4	
Duration	s	4.13	4.13	4.13
Arc energy	MJ		74.9	

Observations: Emission of flames and gas observed.
PT#1 10.8 psi above atmospheric
PT #2 0.4 psi above atmospheric

10.5 Condition / inspection after test

Interior and sides of the sample exterior were heavily burned.
Fire in the test gear burned for about 20 minutes before being extinguished.
Pressure transducer 1 found on the ground with the rubber tube cut and transducer dislodged from PVC tubing,

10.6 Photograph after test


08/11/2023 11:22


08/11/2023 11:23


08/11/2023 11:24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08/11/2023 11:25


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08/11/2023 11:23


08/11/2023 11:23

11 ARC TEST 2-38: 25KA, 4S, CU

Standard and date

Standard	Client's instructions
Test date	14 August 2023

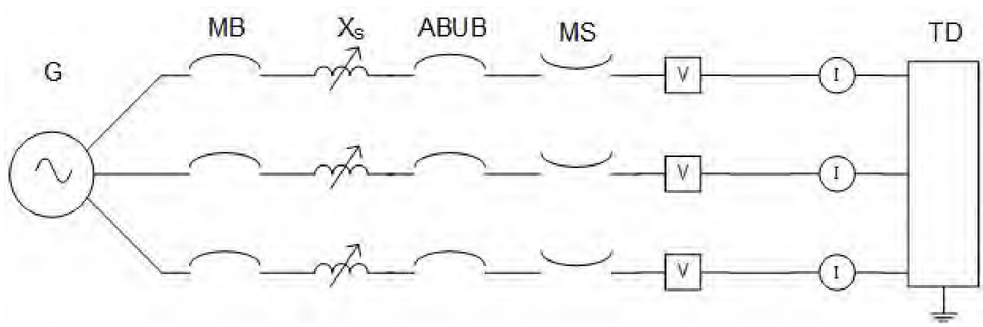
Serial No.

2-38

11.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #24 AWG wire on the line side of the breaker in the bottom left compartment.
Pressure transducer 1 located on cabinet containing the arc wire.
Pressure transducer 2 located on the compartment adjacent to the compartment containing the arc.

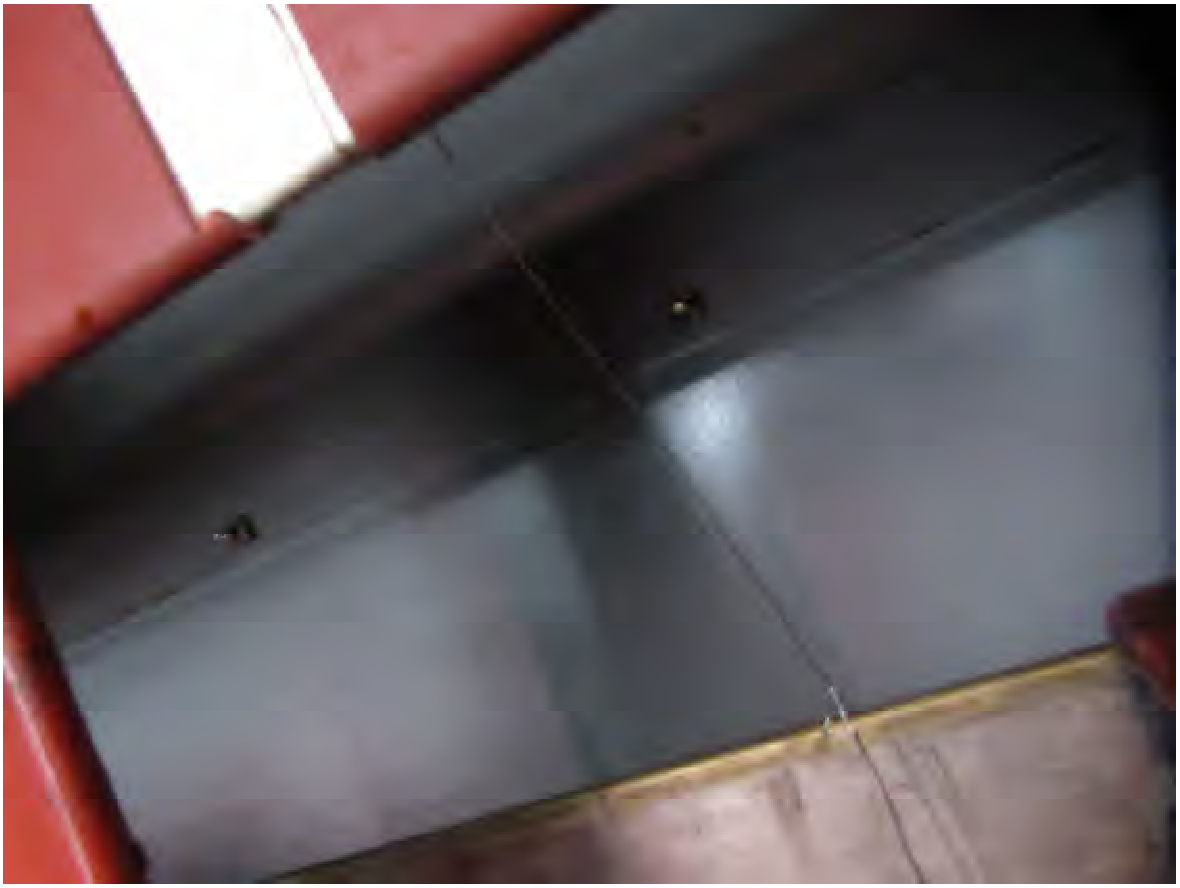
11.2 Test circuit S02

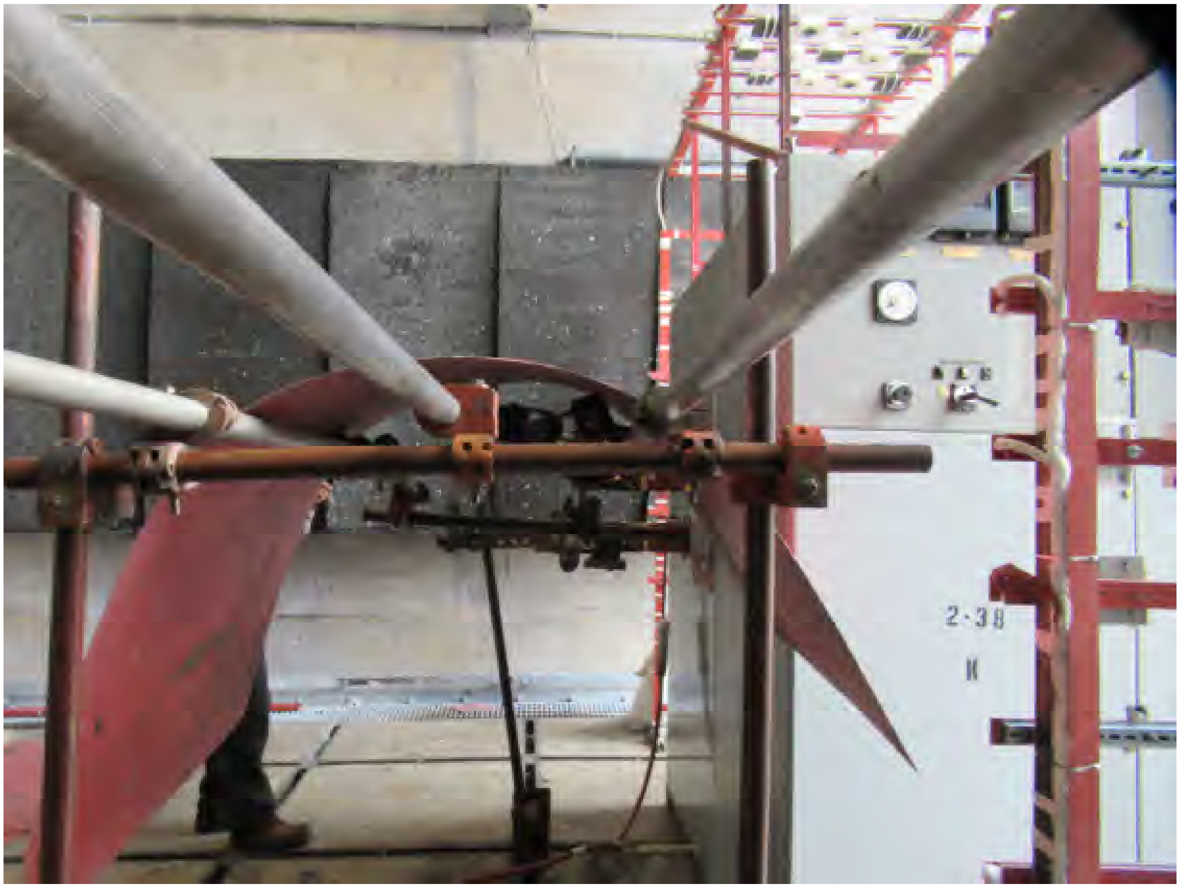


G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

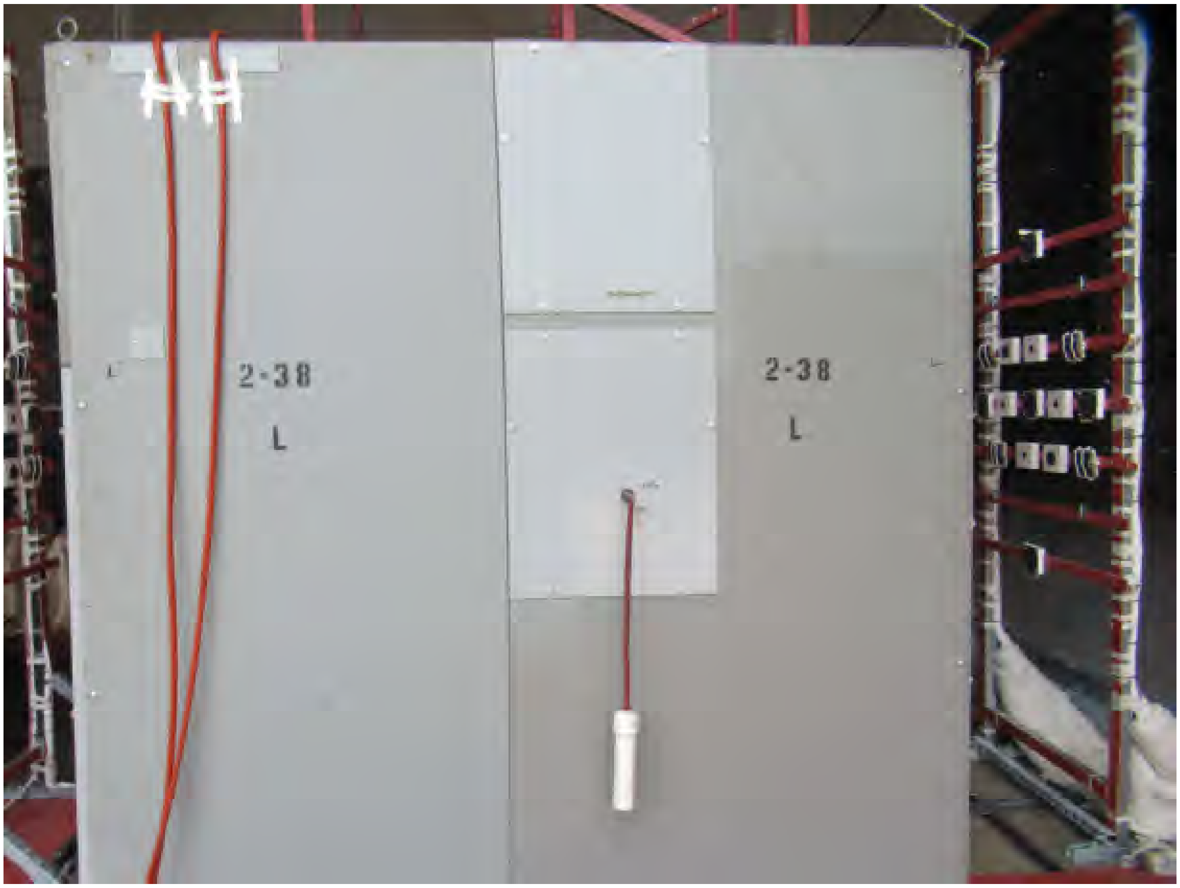
Supply		
Power	MVA	302
Frequency	Hz	60
Phase(s)		3
Voltage	kV	6.97
Current	kA	25
Impedance	Ω	0.161
Power factor		< 0.1
Neutral		not earthed

11.3 Photograph before test




2-38


2-38
K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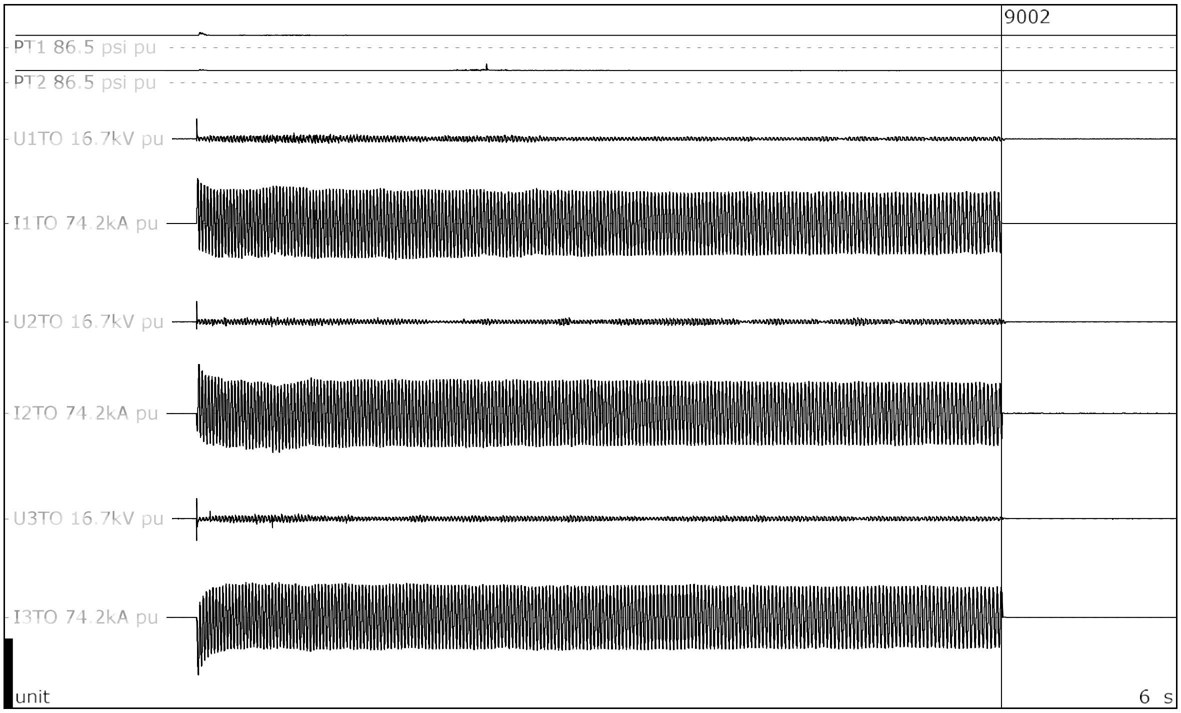
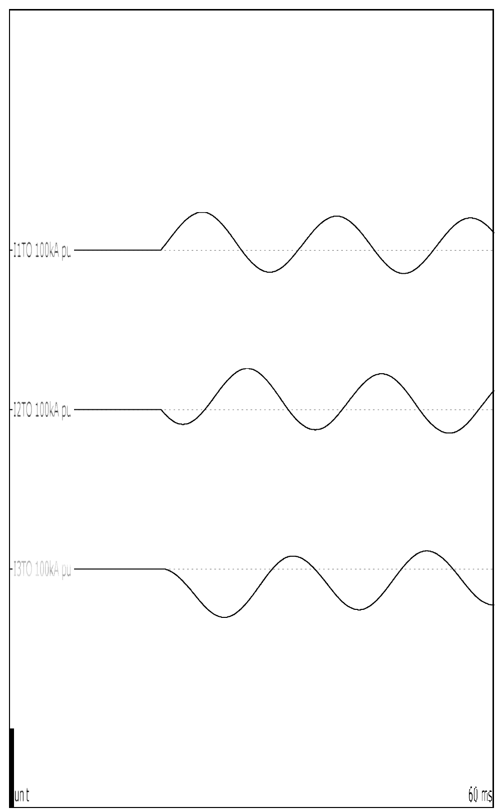
11.4 Test results and oscillograms

Overview of test numbers
230814-9002

Remarks
-

Arc Test 2-38: 25kA, 4s, CU





Test number: **230814-9002**

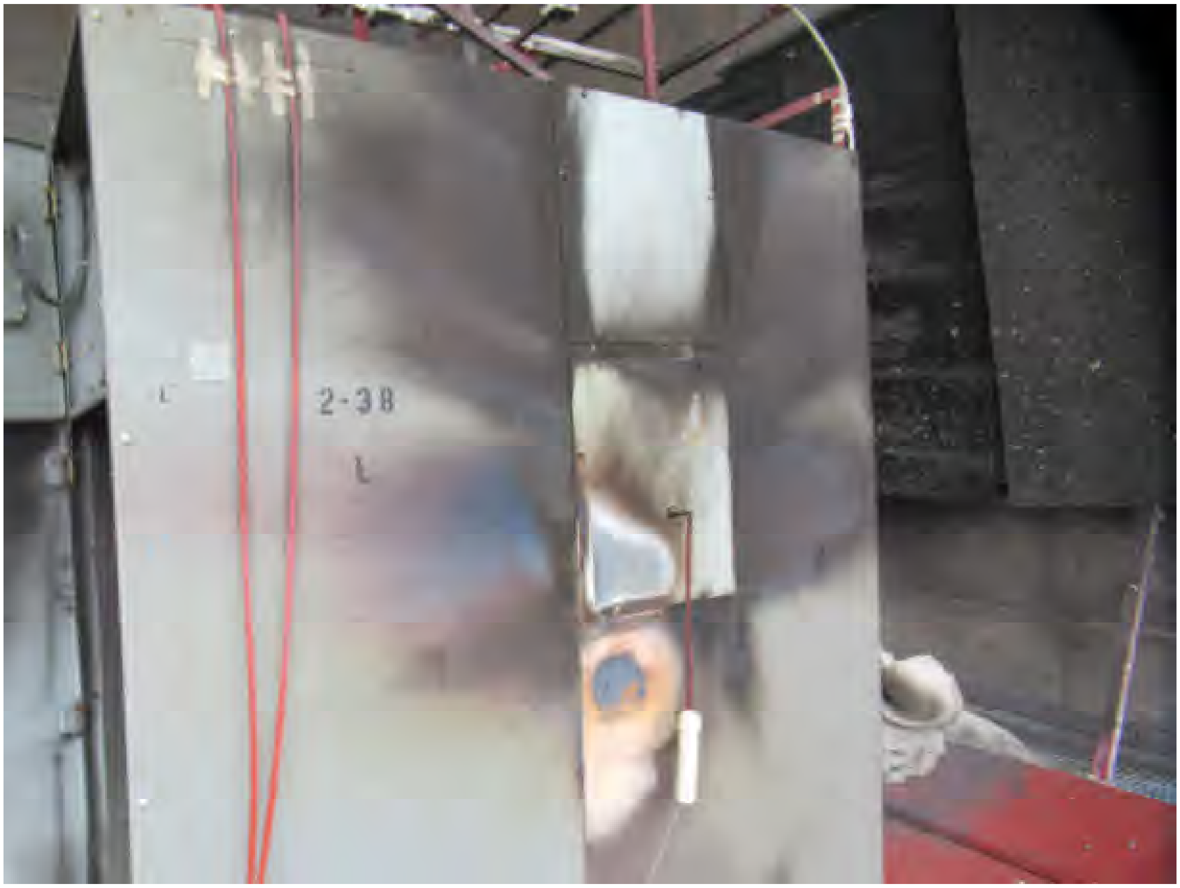
Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.99	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.90	
Making current	kA_{peak}	47.6	51.6	-61.2
Current, a.c. component, beginning	kA_{RMS}	25.8	26.1	25.6
Current, a.c. component, middle	kA_{RMS}	23.9	24.1	23.5
Current, a.c. component, end	kA_{RMS}	22.4	22.9	22.7
Current, a.c. component, average	kA_{RMS}	24.3	24.4	23.9
Current, a.c. component, three-phase average	kA_{RMS}		24.2	
Duration	s	4.12	4.12	4.12
Arc energy	MJ		93.6	

Observations: Emission of flames and gas observed.
PT#1 3.85 psi above atmospheric.
PT#2 1.18 psi above atmospheric.

11.5 Condition / inspection after test

No burn throughs of enclosure observed.
Internal enclosure panels found laying on ground after test.

11.6 Photograph after test


2-38

12 ARC TEST 2-39: 25KA, 4S, CU

Standard and date

Standard	Client’s instructions
Test date	15 August 2023

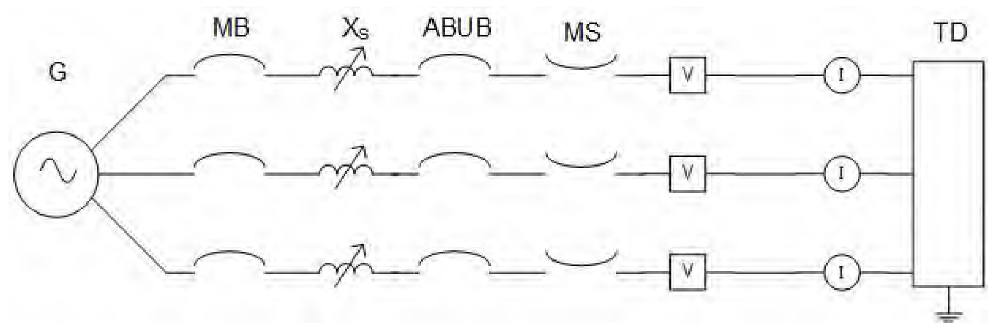
Serial No.

2-39

12.1 Condition before test

Enclosure grounded.
Test sample new. All adjacent enclosures were used in prior tests and re-conditioned for this test.
Arc initiated by #24 AWG wire on the line side of the breaker in the bottom left compartment.
Pressure transducer 1 located on the right side of cabinet K.
Pressure transducer 2 located on the side of compartment containing the arc.

12.2 Test circuit S02

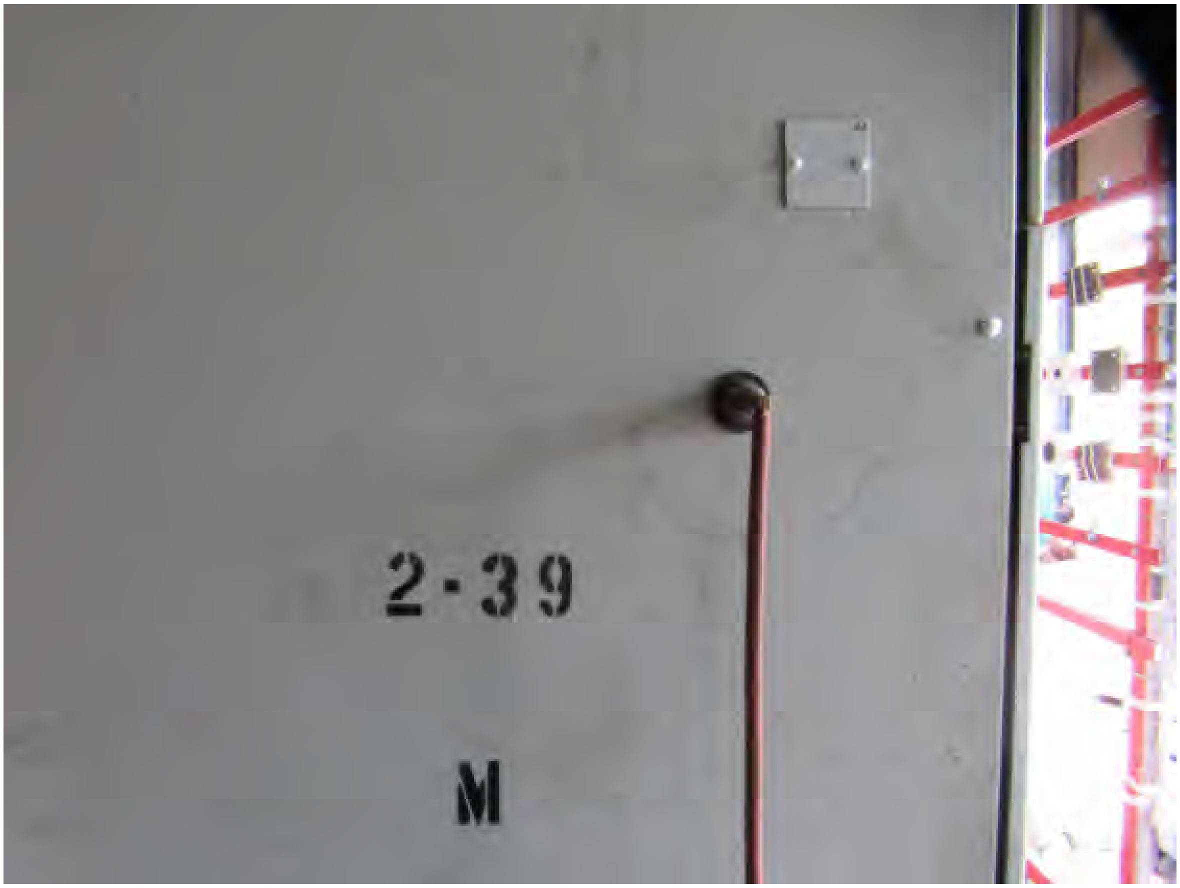


G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	302
Frequency	Hz	60
Phase(s)		3
Voltage	kV	6.97
Current	kA	25
Impedance	Ω	0.161
Power factor		< 0.1
Neutral		not earthed

12.3 Photograph before test


2-39
-39

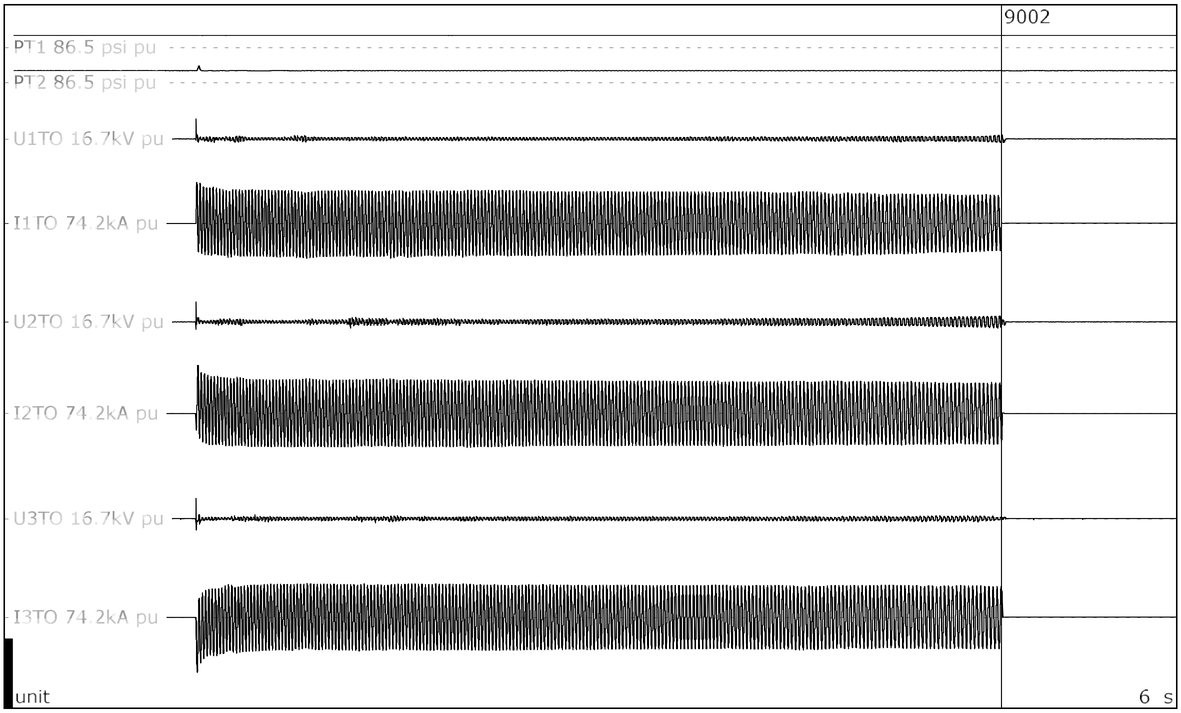

2-39
M

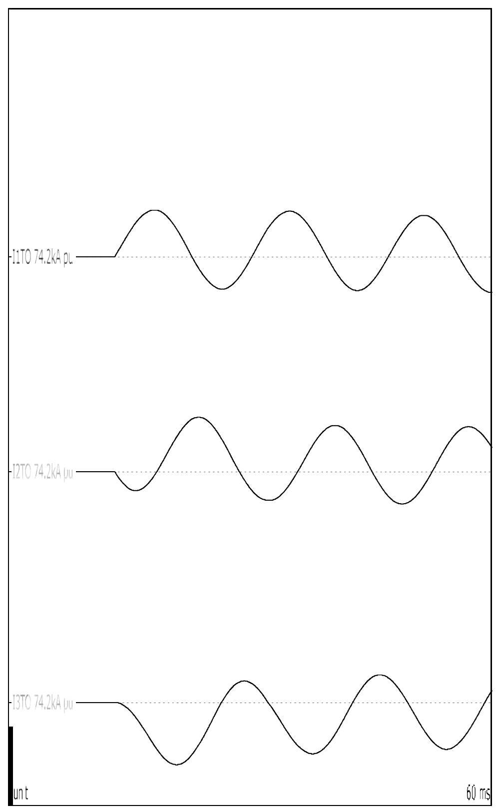
12.4 Test results and oscillograms

Overview of test numbers
230815-9002

Remarks
-

Arc Test 2-39: 25kA, 4s, CU





Test number: **230815-9002**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	kV_{RMS}	4.02	4.03	4.02
Applied voltage, phase-to-phase	kV_{RMS}		6.97	
Making current	kA_{peak}	43.6	50.7	-58.1
Current, a.c. component, beginning	kA_{RMS}	26.0	25.7	25.8
Current, a.c. component, middle	kA_{RMS}	23.7	24.1	23.9
Current, a.c. component, end	kA_{RMS}	20.8	23.0	23.1
Current, a.c. component, average	kA_{RMS}	24.1	24.5	24.3
Current, a.c. component, three-phase average	kA_{RMS}		24.3	
Duration	s	4.12	4.12	4.12
Arc energy	MJ		104	

Observations: Emission of flames and gas observed.
PT#1 0.57 psi above atmospheric
PT#2 6.04 psi above atmospheric

12.5 Condition / inspection after test

Door of breaker cabinet in which arc was initiated blew off.
Fire was allowed to burn for about 14 minutes before opening cabinet K top and bottom front doors.
Fire continued to burn after opening and eventually extinguished using water.

Arc blast knocked off instrument rack in front of cabinet K.

12.6 Photograph after test


B

13 CHECKING CIRCUIT PARAMETERS

Standard and date

Standard	Client's instructions
Test date	17 August 2023

Serial No.

n/a

13.1 Condition before test

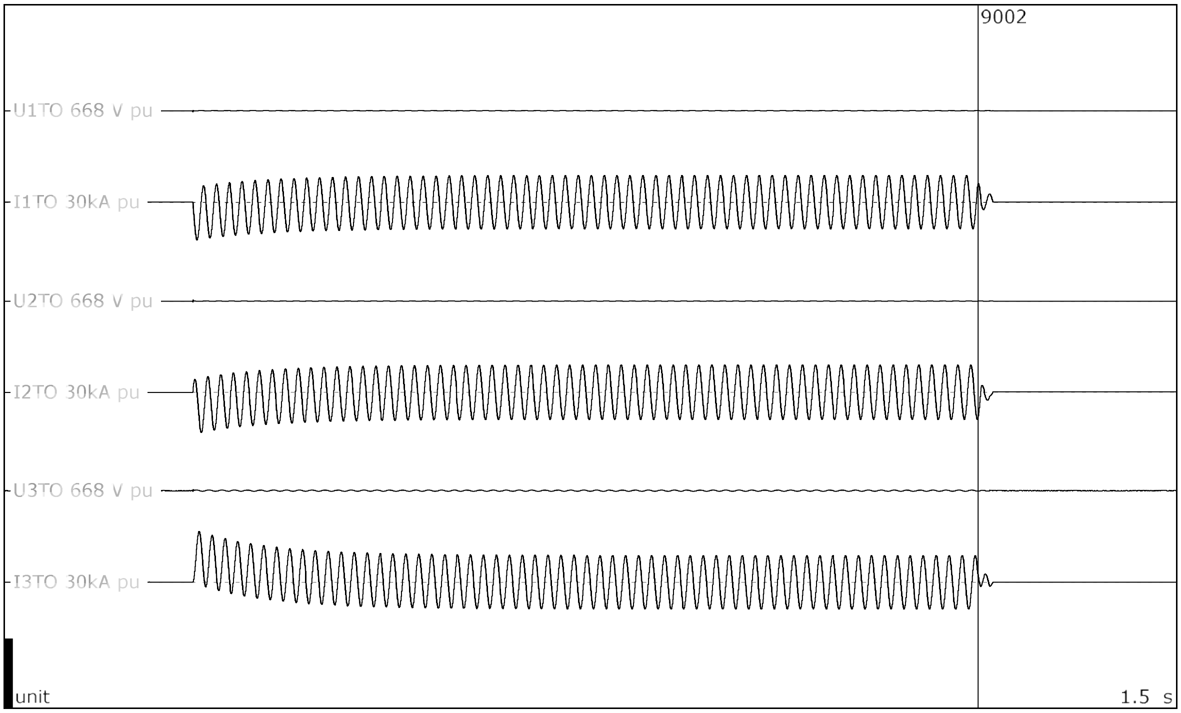
Shorting bar connected to input terminals of test device.

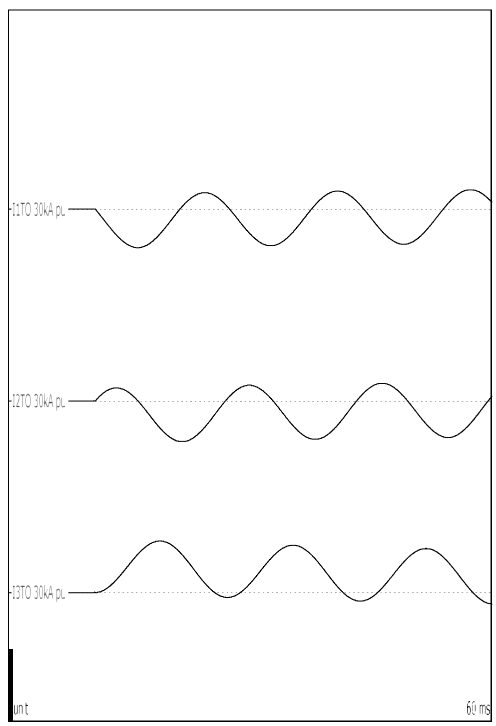
13.2 Test results and oscillograms

Overview of test numbers
230817-9002, 9003

Remarks
-

Checking circuit parameters



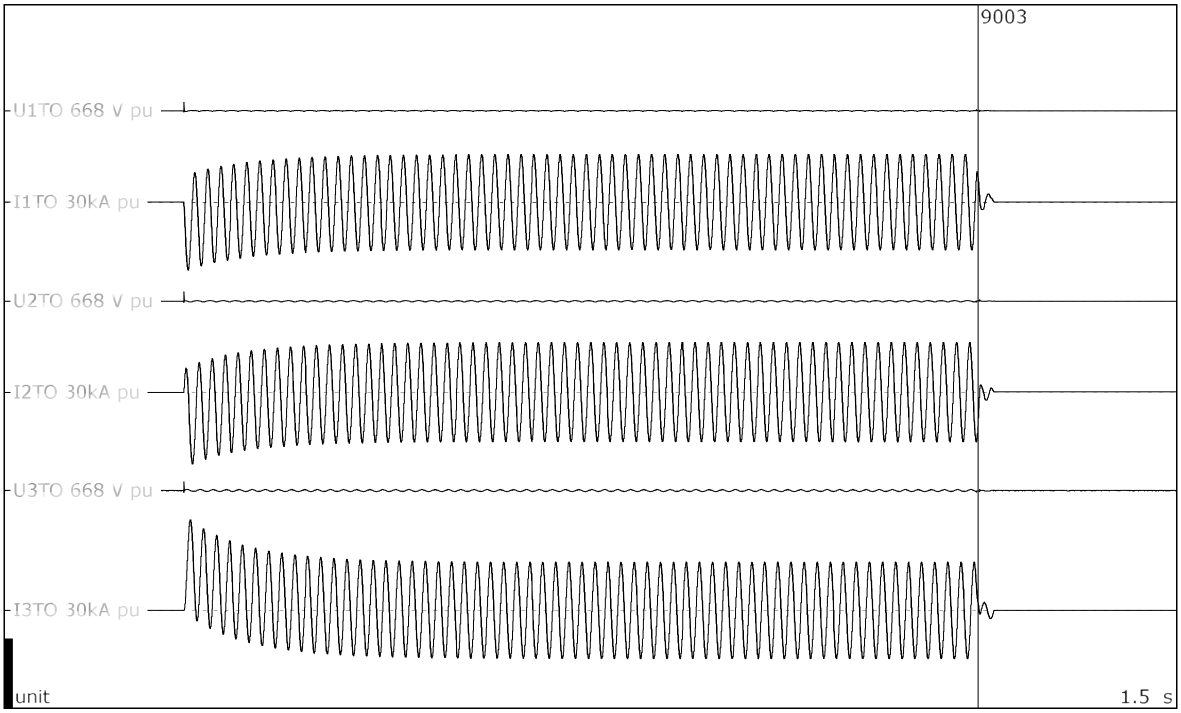


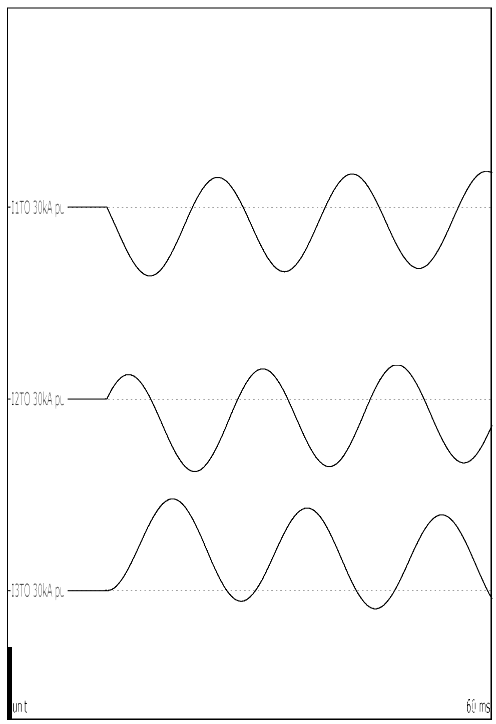
Test number: **230817-9002**

Phase		AØ	BØ	CØ
Current	kA_{peak}	-16.2	-17.3	21.8
Current, a.c. component, beginning	kA_{RMS}	8.08	8.25	8.08
Current, a.c. component, middle	kA_{RMS}	8.07	8.26	8.11
Current, a.c. component, end	kA_{RMS}	8.09	8.28	8.13
Current, a.c. component, average	kA_{RMS}	8.08	8.26	8.10
Current, a.c. component, three-phase average	kA_{RMS}		8.15	
Duration, current	s	1.00	1.00	1.00

Observations:	Checking of circuit parameters with open circuit voltage of 625 V. Full pro-rated circuit parameters: 614 V, 8 kA

Checking circuit parameters





Test number: **230817-9003**

Phase		AØ	BØ	CØ
Current	kA_{peak}	-29.0	-30.8	38.8
Current, a.c. component, beginning	kA_{RMS}	14.4	14.9	14.6
Current, a.c. component, middle	kA_{RMS}	14.4	15.0	14.6
Current, a.c. component, end	kA_{RMS}	14.5	15.0	14.6
Current, a.c. component, average	kA_{RMS}	14.4	15.0	14.6
Current, a.c. component, three-phase average	kA_{RMS}		14.7	
Duration, current	s	1.02	1.02	1.02

Observations:	Checking of circuit parameters with open circuit voltage of 600 V. Full pro-rated circuit parameters: 613 V, 15 kA

13.3 Condition / inspection after test

See observations for test details.

14 ARC TEST 2-33A: 15KA, 8S, CU

Standard and date

Standard	Client's instructions
Test date	17 August 2023

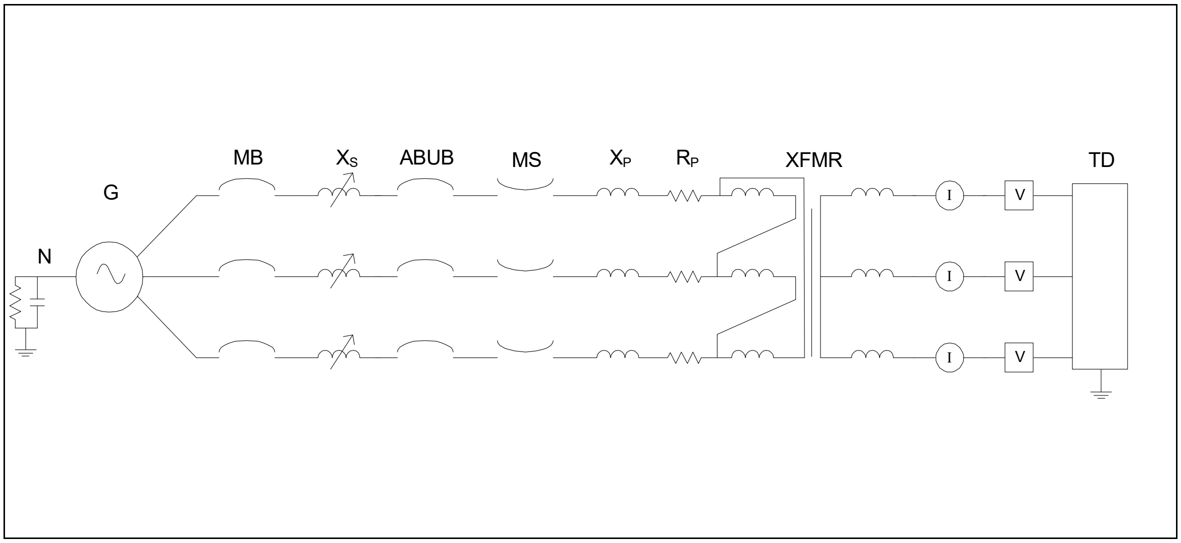
Serial No.

2-33A

14.1 Condition before test

Enclosure grounded.
Test sample new.
Arc initiated by #10 AWG wire on the load side of the breaker in the cabinet farthest from KEMA source.
Pressure transducer 1 located on the left side of compartment containing the arc.
Pressure transducer 2 located on the rear side of compartment containing the arc.

14.2 Test circuit S03



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	15.93
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.613
Current	kA	15
Impedance	Ω	0.02360
Power factor		< 0.2
Neutral		not earthed

14.3 Photograph before test


2-33

14.4 Test results and oscillograms

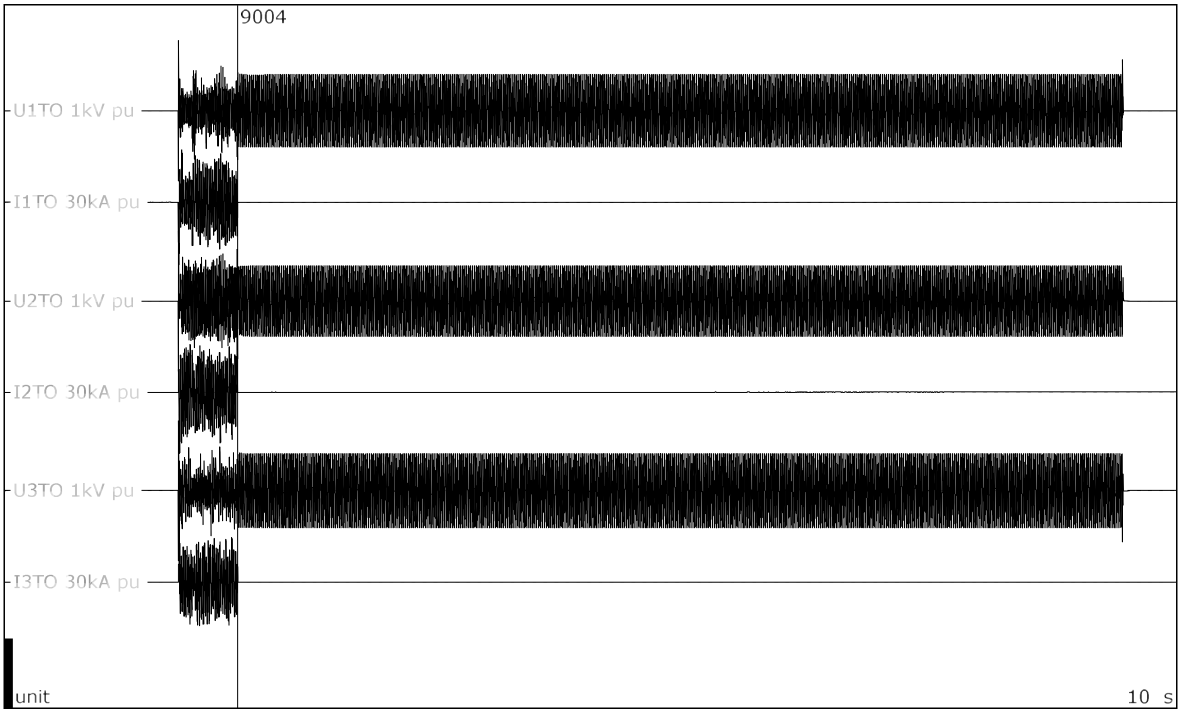
Overview of test numbers

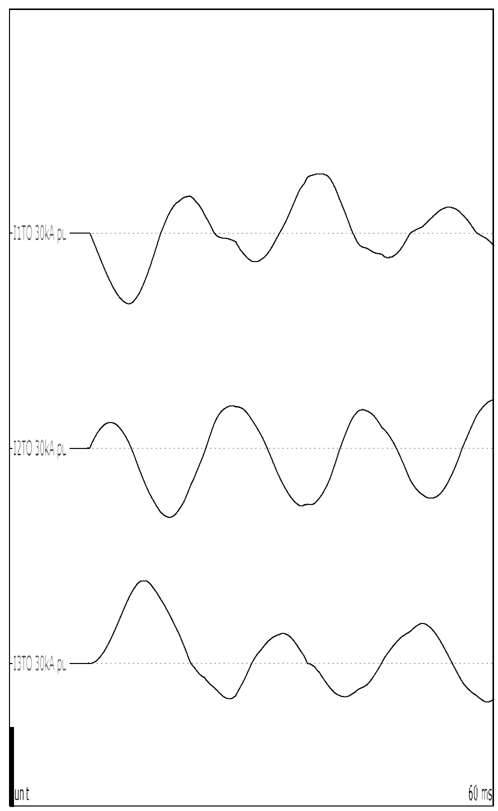
230817-9004

Remarks

-

Arc Test 2-33A: 15kA, 8s, CU





Test number: **230817-9004**

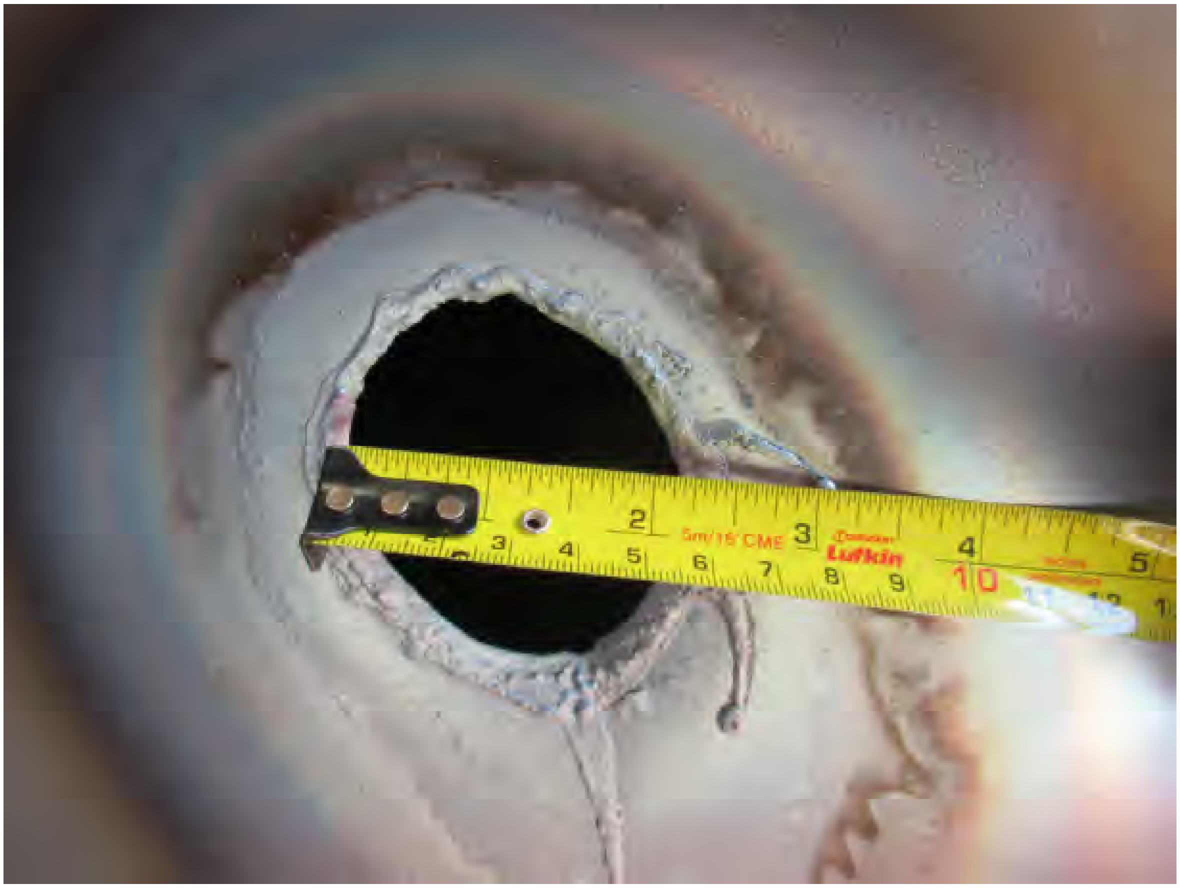
Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}	613		
Making current	kA_{peak}	-26.7	-26.1	31.2
Current, a.c. component, beginning	kA_{RMS}	11.7	13.7	11.4
Current, a.c. component, middle	kA_{RMS}	10.8	12.2	12.2
Current, a.c. component, end	kA_{RMS}	10.1	12.2	9.60
Current, a.c. component, average	kA_{RMS}	10.6	11.0	10.8
Current, a.c. component, three-phase average	kA_{RMS}	10.8		
Duration	s	0.504	0.504	0.504
Arc energy	MJ	3.33		

Observations: Emission of flames and gas observed.
Arc self-extinguished. Test source voltage held on for 8 seconds.
PT#1 0.47 psi above atmospheric.
PT#2 1.09 psi above atmospheric.

14.5 Condition / inspection after test

Burn-through of enclosure on the side of the cabinet in which arc was initiated.

14.6 Photograph after test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15 ARC TEST 2-33B: 15KA, 8S, CU

Standard and date

Standard	Client's instructions
Test date	17 August 2023

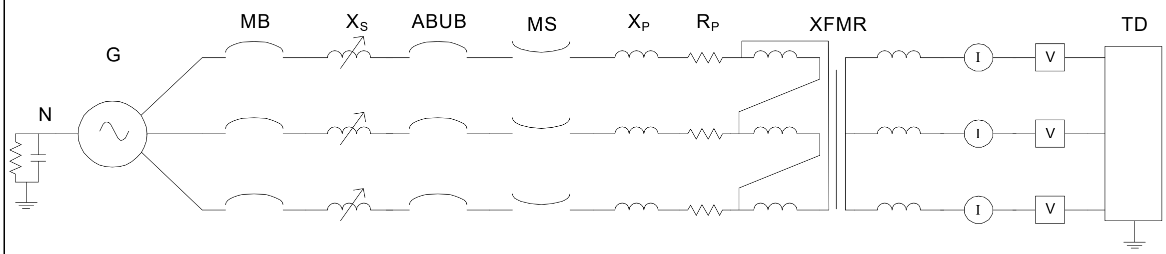
Serial No.

2-33B

15.1 Condition before test

Enclosure grounded.
Test sample in the same condition as after test 2-33A.
Arc initiated by #10 AWG wire on the line side of the breaker in the middle cabinet.
Pressure transducer 1 located on the left side of the leftmost compartment.
Pressure transducer 2 located on the rear side of leftmost compartment.

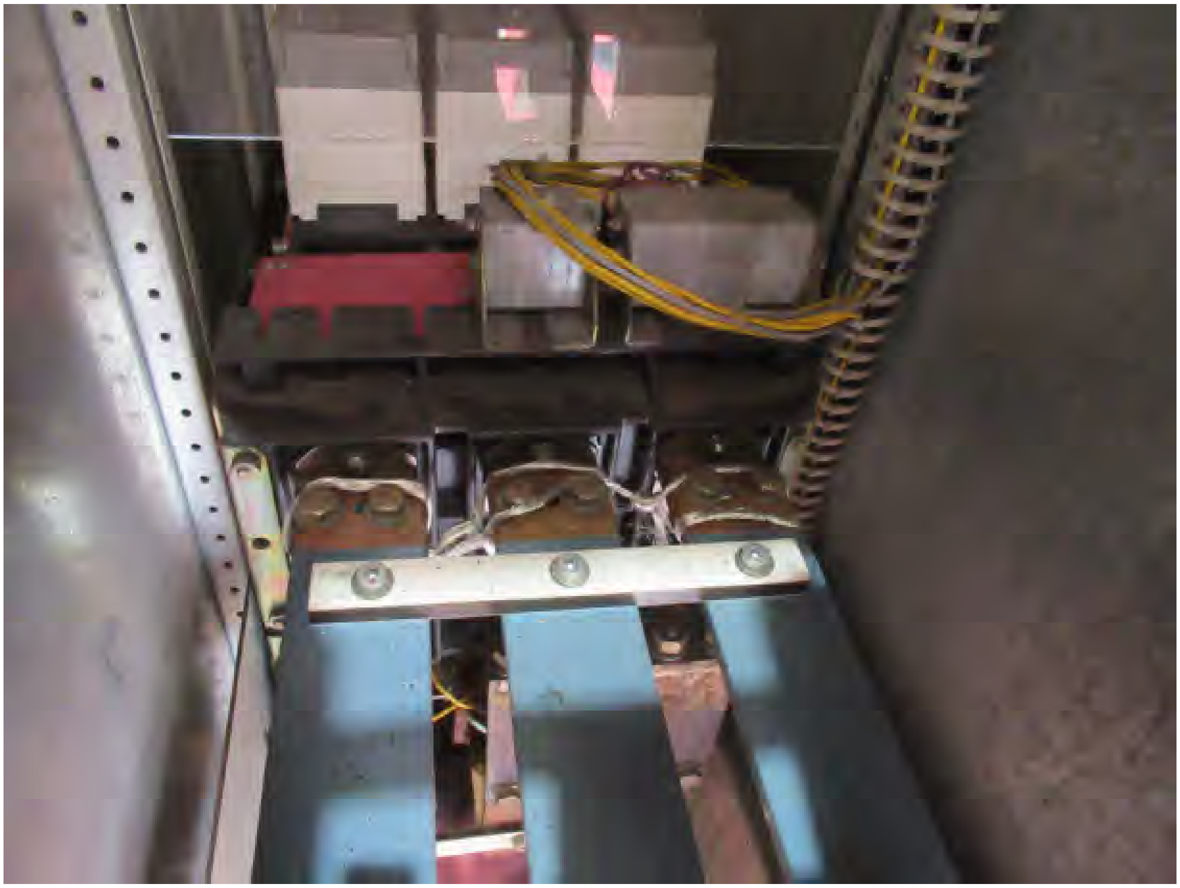
15.2 Test circuit S03



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	15.93
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.613
Current	kA	15
Impedance	Ω	0.02360
Power factor		< 0.2
Neutral		not earthed

15.3 Photograph before test

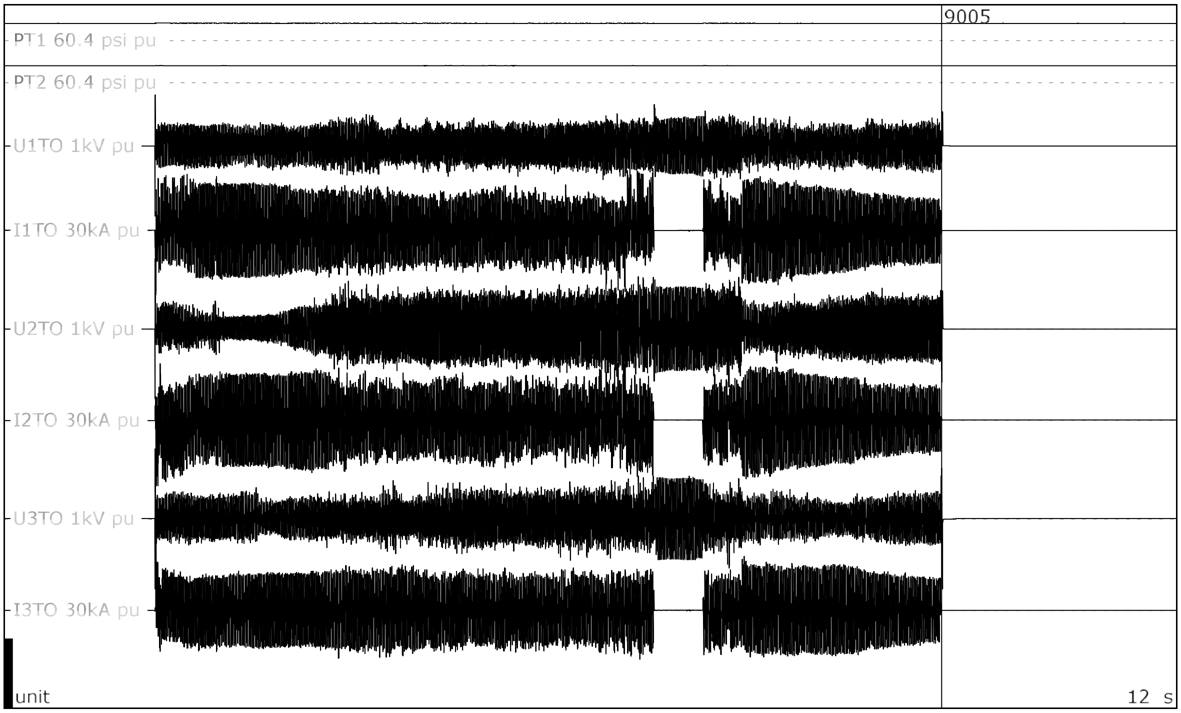


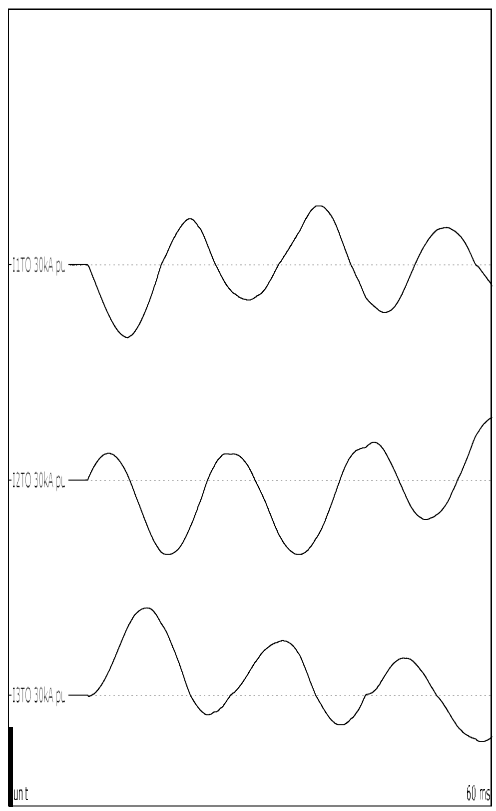
15.4 Test results and oscillograms

Overview of test numbers
230817-9005

Remarks
-

Arc Test 2-33B: 15kA, 8s, CU





Test number: **230817-9005**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}	613		
Making current	kA_{peak}	16.7	-15.4	-18.0
Current, a.c. component, beginning	kA_{RMS}	10.8	10.4	12.0
Current, a.c. component, middle	kA_{RMS}	12.0	12.0	11.5
Current, a.c. component, end	kA_{RMS}	9.43	9.77	9.33
Current, a.c. component, average	kA_{RMS}	11.4	11.8	11.5
Current, a.c. component, three-phase average	kA_{RMS}	11.6		
Duration	s	8.00	8.00	8.00
Arc energy	MJ	52.1		

Observations:	Emission of flames and gas observed. Arc self-extinguished approximately 5 seconds into test and re-established after 0.5 seconds. PT#1: 0.587 psi above atmospheric. PT#2: 0.3306 psi above atmospheric.

15.5 Condition / inspection after test

Burn-through of enclosure (halfway through the length) on the side of the cabinet farthest from KEMA source.

15.6 Photograph after test

16 ARC TEST 2-34: 8KA, 17.5S, CU

Standard and date

Standard	Client's instructions
Test date	18 August 2023

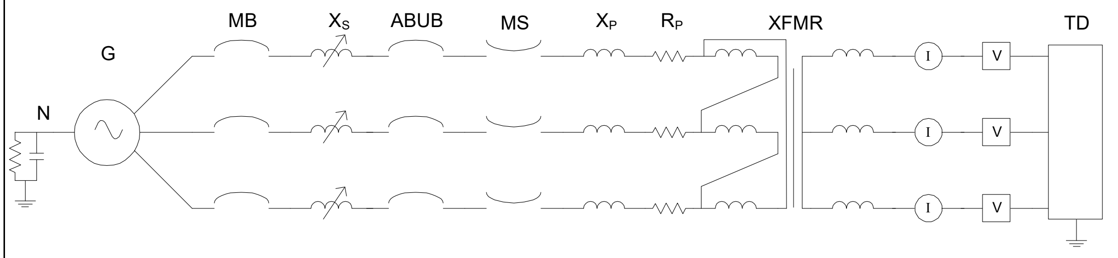
Serial No.

2-34

16.1 Condition before test

Enclosure grounded.
Test sample within which arc was initiated is new. Test sample from previous test was connected at the back of the new one.
Arc initiated by #10 AWG wire on the line side of the breaker in the middle cabinet.
Pressure transducer 1 located on the left side of the leftmost compartment and positioned about 7 inches from the front of the compartment.
Pressure transducer 2 located on the left side of the leftmost compartment and positioned about 4 inches from the rear of the compartment.

16.2 Test circuit S04



G	= Generator	ABUB	= Aux. Breaker	R	= Resistance
N	= Neutral	XFMR	= Transformer	V	= Voltage Measurement
MB	= Main Breaker	TD	= Test Device	I	= Current Measurement
MS	= Make Switch	X	= Inductance		

Supply		
Power	MVA	8.508
Frequency	Hz	60
Phase(s)		3
Voltage	kV	0.614
Current	kA	8
Impedance	Ω	0.0443
Power factor		< 0.2
Neutral		not earthed

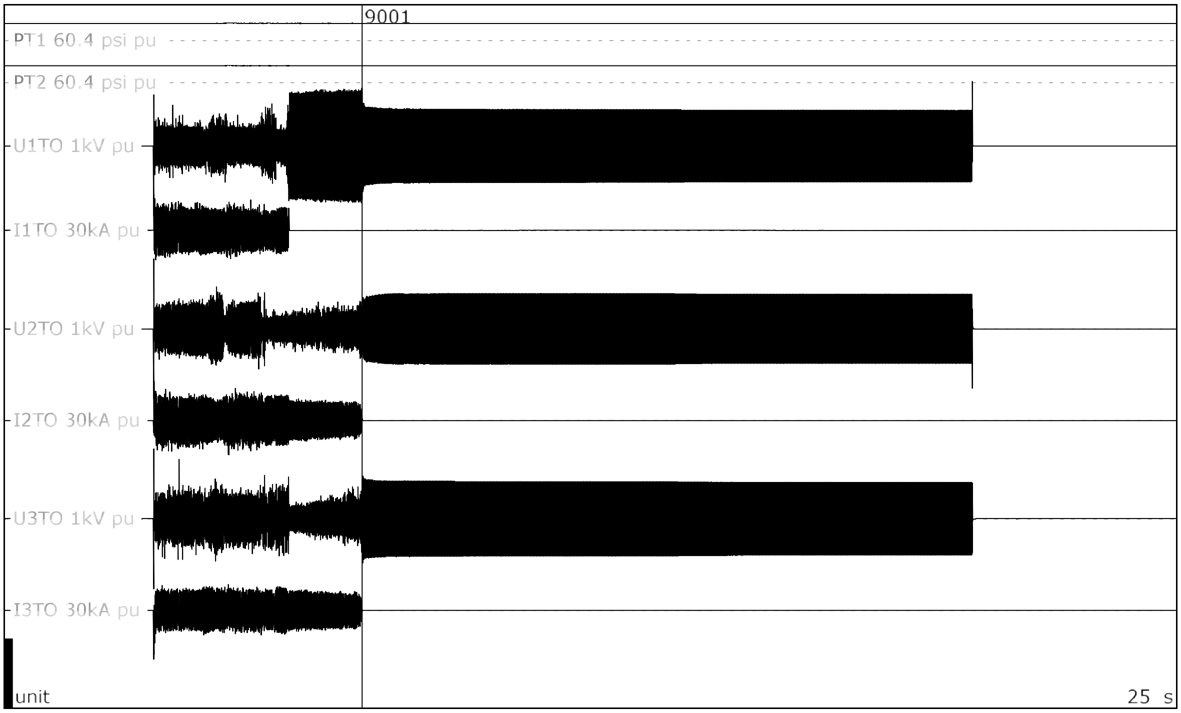
16.3 Photograph before test

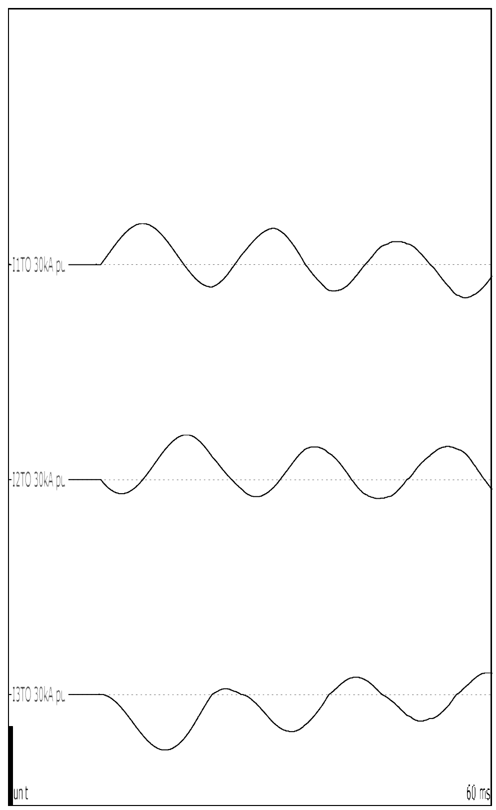
16.4 Test results and oscillograms

Overview of test numbers
230818-9001

Remarks
-

Arc Test 2-34: 8kA, 17.5s, CU





Test number: **230818-9001**

Phase		AØ	BØ	CØ
Applied voltage, phase-to-ground	V_{RMS}	354	354	354
Applied voltage, phase-to-phase	V_{RMS}	614		
Making current	kA_{peak}	15.4	16.9	-21.0
Current, a.c. component, beginning	kA_{RMS}	8.13	8.06	6.54
Current, a.c. component, middle	kA_{RMS}	6.50	6.14	6.20
Current, a.c. component, end	kA_{RMS}	6.59	5.25	5.21
Current, a.c. component, average	kA_{RMS}	6.80	6.85	5.59
Current, a.c. component, three-phase average	kA_{RMS}	6.41		
Duration	s	2.89	4.44	4.44
Arc energy	MJ	13.0		

Observations:	Emission of flames and gas observed. Arc self-extinguished. Test source voltage held on for 17.5 seconds. PT#1 0.114 psi above atmospheric. PT#2 0.121 psi above atmospheric.

16.5 Condition / inspection after test

Burn-through of enclosure on the side of the cabinet in which arc was initiated.

16.6 Photograph after test


F
E
D

17 TEST INSTRUMENTS INFORMATION

Instrument ID	Type	Manufacturer	Model No.	Serial No.	Last Cal.	Cal. Due
TEM89	Data Acquisitio..	DEWESoft	KRYPTONi	D05980DB69	2023-09-15	2024-03-15
TEM91	Data Acquisitio..	DEWESoft	KRYPTONi	D05980F2EA	2023-09-15	2024-03-15
DAS17	Data Acquisitio..	NI/DEWETRON	DEWE-30-16	0195BB69	2023-06-20	2024-06-20
ISO108	Signal Conditio..	DEWETRON	HSI-LV	437704	2023-06-20	2024-06-20
ISO109	Signal Conditio..	DEWETRON	HSI-LV	437707	2023-06-20	2024-06-20
ISO132	Signal Conditio..	DEWETRON	HSI-LV	437720	2023-06-20	2024-06-20
ISO117	Signal Conditio..	DEWETRON	HSI-LV	437702	2023-06-20	2024-06-20
ISO118	Signal Conditio..	DEWETRON	HSI-LV	437708	2023-06-20	2024-06-20
ISO124	Signal Conditio..	DEWETRON	HSI-LV	437736	2023-06-20	2024-06-20
ISO125	Signal Conditio..	DEWETRON	HSI-LV	437727	2023-06-20	2024-06-20
ISO126	Signal Conditio..	DEWETRON	HSI-LV	437710	2023-06-20	2024-06-20
ISO136	Signal Conditio..	DEWETRON	HSI-LV	437706	2023-06-20	2024-06-20
ISO137	Signal Conditio..	DEWETRON	HSI-LV	437709	2023-06-20	2024-06-20
ISO138	Signal Conditio..	DEWETRON	HSI-LV	437721	2023-06-20	2024-06-20
AMP41	Signal Conditio..	AA Lab Systems	AFL-300	1	2023-04-18	2023-11-04
AMP42	Signal Conditio..	AA Lab Systems	AFL-300	2	2023-04-18	2023-11-04
CTX172	Current Transdu..	PEM	SDS0680	0002-0100A	2023-04-25	2023-11-11
CTX173	Current Transdu..	PEM	SDS0680	0002-0100B	2023-04-25	2023-11-11
CTX174	Current Transdu..	PEM	SDS0680	0002-0100C	2023-04-25	2023-11-11
VDR84	Voltage Divider	NORTH STAR	VD-150	1	2023-08-25	2024-08-25
VDR86	Voltage Divider	NORTH STAR	VD-150	3	2023-08-25	2024-08-25
PTX06	Potential Trans..	GE	JVM5	3737435	2022-09-16	2024-09-16
PTX07	Potential Trans..	GE	JVM5	3737433	2022-09-16	2024-09-16
PTX08	Potential Trans..	GE	JVM5	3737432	2022-09-16	2024-09-16
VTD10	Voltage Transdu..	LEM	CV3-200	114119404454	2023-03-17	2023-10-03
VTD11	Voltage Transdu..	LEM	CV3-200	114119404456	2023-03-17	2023-10-03
VTD12	Voltage Transdu..	LEM	CV3-200	114119404457	2023-03-17	2023-10-03

Instrument ID	Type	Manufacturer	Model No.	Serial No.	Last Cal.	Cal. Due
CTX214	Current Transdu..	PEM	SDS0680	0004-0102A	2023-06-07	2023-12-08
CTX215	Current Transdu..	PEM	SDS0680	0004-0102B	2023-06-07	2023-12-08
CTX216	Current Transdu..	PEM	SDS0680	0004-0102C	2023-06-07	2023-12-08
VDR92	Voltage Divider	NORTH STAR	PVM-11	1716317	2023-07-13	2024-07-13
VDR93	Voltage Divider	NORTH STAR	PVM-11	1716417	2023-07-13	2024-07-13
VDR94	Voltage Divider	NORTH STAR	PVM-11	1716517	2023-07-13	2024-07-13
VDR88	Voltage Divider	NORTH STAR	VD-150	5	2023-08-25	2024-08-25
ISO127	Signal Conditio..	DEWETRON	HSI-LV	437714	2023-06-20	2024-06-20
VDR90	Voltage Divider	NORTH STAR	VD-150	7	2023-08-25	2024-08-25

18 ATTACHMENTS

1. Total heat energy results [10 PAGES]

Test 33A

Name		Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1		30.843	0.09221	32.807	0.09227	1.086
Al A-2		30.866	0.09221	36.262	0.09238	2.986
Al A-3		30.177	0.09219	30.443	0.09220	0.147
Al A-4		28.938	0.09216	29.118	0.09216	0.099
Al A-5		29.776	0.09218	31.826	0.09224	1.133
Al A-6		29.834	0.09218	32.506	0.09226	1.477

Test 33B

Name		Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1		32.335	0.09226	88.064	0.09397	31.112
Al A-2		33.247	0.09229	102.893	0.09442	38.980
Al A-3		30.445	0.09220	56.669	0.09301	14.560
Al A-4		29.536	0.09217	50.936	0.09283	11.868
Al A-5		31.052	0.09222	54.449	0.09294	12.986
Al A-6		30.916	0.09222	59.363	0.09309	15.802

Test 34

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	32.335	0.09226	88.064	0.09397	31.112
Al A-2	33.247	0.09229	102.893	0.09442	38.980
Al A-3	30.445	0.09220	56.669	0.09301	14.560
Al A-4	29.536	0.09217	50.936	0.09283	11.868
Al A-5	31.052	0.09222	54.449	0.09294	12.986
Al A-6	30.916	0.09222	59.363	0.09309	15.802

Test 35

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	48.016	0.09274	74.380	0.09355	14.724
Al A-2	44.601	0.09264	67.659	0.09335	12.855
Al A-3	45.514	0.09266	59.684	0.09310	7.891
Al A-4	41.281	0.09253	47.441	0.09272	3.421
Al A-5	30.789	0.09221	119.752	0.09492	49.905
Al A-6	33.374	0.09229	121.230	0.09496	49.316

Test 36

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	47.731	0.09273	47.994	0.09274	0.146
Al A-2	43.998	0.09262	1200.000	0.13540	790.161
Al A-3	46.239	0.09269	132.900	0.09530	48.835
Al A-4	41.432	0.09254	130.184	0.09522	49.953
Al A-5	27.325	0.09211	77.273	0.09364	27.813
Al A-6	27.606	0.09212	59.186	0.09309	17.532

Test 37

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	47.731	0.09273	47.994	0.09274	0.146
Al A-2	43.998	0.09262	1200.000	0.13540	790.161
Al A-3	46.239	0.09269	132.900	0.09530	48.835
Al A-4	41.432	0.09254	130.184	0.09522	49.953
Al A-5	27.325	0.09211	77.273	0.09364	27.813
Al A-6	27.606	0.09212	59.186	0.09309	17.532

Test 38

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	31.214	0.09223	112.306	0.09470	45.440
Al A-2	35.723	0.09236	76.787	0.09363	22.895
Al A-3	32.698	0.09227	34.492	0.09233	0.992
Al A-4	30.440	0.09220	32.017	0.09225	0.872
Al A-5	31.506	0.09223	86.251	0.09392	30.549
Al A-6	31.358	0.09223	66.100	0.09330	19.322

Test 39

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	32.415	0.09226	33.323	0.09229	0.502
Al A-2	33.972	0.09231	35.915	0.09237	1.076
Al A-5	31.217	0.09223	40.263	0.09250	5.010
Al A-6	30.804	0.09221	49.486	0.09279	10.361

Test 40

Name ▲	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	41.780	0.09255	480.282	0.10251	256.406
Al A-2	38.012	0.09243	634.710	0.10538	353.833
Al A-3	41.725	0.09255	479.166	0.10249	255.759
Al A-4	36.910	0.09240	324.389	0.09980	165.630
Al A-5	29.245	0.09217	611.081	0.10489	343.692
Al A-6	29.496	0.09217	715.082	0.10731	409.969
Al A-7	28.876	0.09215	396.222	0.10109	212.802
Al A-8	28.954	0.09216	847.486	0.11166	500.107
Al B-1	29.101	0.09216	194.702	0.09696	93.882
Al B-2	29.167	0.09216	207.315	0.09727	101.164

Test 41

Name	Avg. Start Temp. (°C)	Initial Heat Cap. (cal/g°C)	Max Temp. (°C)	Final Heat Cap. (cal/g°C)	Total Heat Energy (J/cm^2)
Al A-1	31.870	0.09225	32.153	0.09225	0.156
Al A-2	37.058	0.09240	135.168	0.09536	55.223
Al A-3	39.020	0.09246	623.892	0.10515	346.472
Al A-4	35.765	0.09236	472.247	0.10238	254.806
Al A-5	26.790	0.09209	764.865	0.10874	444.355
Al A-6	26.893	0.09209	876.710	0.11288	522.162
Al A-7	26.226	0.09207	506.657	0.10296	280.884
Al A-8	26.557	0.09208	1199.878	0.13539	800.081
Al B-1	26.892	0.09209	411.617	0.10136	223.105
Al B-2	26.881	0.09209	375.778	0.10074	201.679

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