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REPORT ON HIGH ENERGY ARCING FAULT EXPERIMENTS

Experimental Results from Low-Voltage Switchgear Enclosures

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Prepared by:
G. Taylor
Office of Nuclear Regulatory Research

A.D. Putorti Jr.
National Institute of Standards and Technology

Mark Henry Salley, NRC Project Manager

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Disclaimer

NIST Technical Note 2197

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Anthony Putorti
Scott Bareham
Christopher Brown
Wai Cheong Tam
Edward Hnetkovsky
Andre Thompson
Michael Selepak
Philip Deardorff
National Institute of Standards and Technology

Kenneth Hamburger
Nicholas Melly
Kenneth Miller
Gabriel Taylor
U.S. Nuclear Regulatory Commission

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Abstract

This report documents an experimental program designed to investigate High Energy Arcing Fault (HEAF) phenomena for low-voltage metal enclosed switchgear containing aluminum conductors. This report covers full-scale laboratory experiments using representative nuclear power plant (NPP) three-phase electrical equipment. Electrical, thermal, and pressure data were recorded for each experiment and documented in this report. This report covers experiments performed on two low-voltage switchgear units with each unit consisting of two vertical sections. The data collected supports characterization of the low-voltage HEAF hazard, and these results will be used to support potential improvements in fire probabilistic risk assessment (PRA) methods.

The experiments were performed at KEMA Labs located in Chalfont, Pennsylvania. The experimental design, setup, and execution were completed by staff from the NRC, the National Institute of Standards and Technology (NIST), Sandia National Laboratories (SNL) and KEMA. In addition, representatives from the Electric Power Research Institute (EPRI) observed some of the experimental setup and execution.

The HEAF experiments were performed between August 26 and August 29, 2019 on near-identical Westinghouse Type DS low-voltage metal-enclosed indoor switchgear. A three-phase arcing fault was initiated on the aluminum main bus or in select cases on the copper bus stabs near the breaker. These experiments used either nominal 480 V (AC) or 600 V (AC). Durations of the experiments ranged from approximately 0.4 s to 8.3 s with fault currents ranging from approximately 9.2 kA to 19.3 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, radiometers, and slug calorimeters at various locations around the electrical enclosures. Environmental measurements of breakdown, conductivity, and electromagnetics were also taken. The experiments were documented with normal and high-speed videography, infrared imaging, and photography.

The results, while limited, indicated the difficulty in maintaining and sustaining low-voltage arcs on aluminum components of sufficient duration and at a single point as observed from operating experience [1].

Key words

High Energy Arcing Fault, Arc Flash, Electrical Enclosure, Electric Arc, Fire Probabilistic Risk Assessment

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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 do aluminum components involved in high energy arcing faults influence the hazard to external targets?

RESEARCH OVERVIEW

Operating experience has shown that high energy arcing faults pose a hazard to the safe operation of nuclear facilities. Current regulations and probabilistic risk assessment methods were developed using limited information, and these uncertainties required the use of safety margins to bound the hazard. Experiments aimed at providing additional data to improve realism identified a concern that high energy arcing faults involving aluminum may increase the hazard potential. Due to the limited number of experiments where this phenomenon was observed, the NRC pursued additional experimental studies focused on assessing the specific impact of aluminum on the hazard. This report documents a set of experiments performed in 2019.

A series of low-voltage metal enclosed indoor switchgear arcing experiments were performed. Each experiment consisted of an arcing fault initiated within the switchgear unit on either the aluminum main bus work or the copper bus stabs. Numerous measurements were taken to characterize the environment within and surrounding the box, including external heat flux, external incident energy, electromagnetic field, air conductivity, and air breakdown strength. Time resolved electrical measurements of the fault conditions were also recorded.

This report documents the experiments performed, including the experimental methods, test facility, test device, 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 will be documented in subsequent report(s).

KEY FINDINGS

This research yields a data set of information to characterize the effects of electrical arcing faults involving aluminum electrodes. The results from this research include:

- Low-voltage arc faults were difficult to sustain in the configurations studied.
- Arc migration away from the initiation point was evident in several of the experiments and consistent with observations from Phase 1 testing [2]. The inability to sustain the arc in one location reduces the possibility of breaching the enclosure and exposing external targets to HEAF-generated thermal energy.

- Sustaining an arc on copper bus bars was easier than on aluminum bus bars, even though the phase-to-phase separation distances are larger for copper than aluminum buses. The location of the arc for the copper experiments and internal combustible materials resulted in an ensuing fire which required manual intervention to extinguish.
- Measured pressure increases within the enclosure were small and didn’t result in deformation of the enclosure panels or cause doors to open.
- Air conductivity and breakdown strength measurements were made during a number of experiments. For the experimental conditions and locations investigated, the results indicated that the conductive cloud was unlikely to cause equipment arc over.
- For the experimental conditions and locations investigated, the electromagnetic interference measurements showed that the EMI signature was small and not likely to impact sensitive plant equipment.

WHY THIS MATTERS

This report provides empirical evidence to assist U.S. NRC staff 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 high energy arcing fault 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 scientist advancing hazard and fire probabilistic risk assessment methods should focus on Section 3 and 4 of this report.

LEARNING AND ENGAGEMENT OPPORTUNITIES

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

Nuclear Energy Agency (NEA) HEAF Project to conduct experiments in order 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) joint nuclear safety project report 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

This report was prepared by the following:

National Institute of Standards and Technology (NIST)
Engineering Laboratory; Fire Research Division
Gaithersburg, Maryland 20899
Anthony D. Putorti Jr.
Scott Bareham
Christopher Brown
Wai Cheong Tam
Edward Hnetkovsky
Andre Thompson
Michael Selepak
Phil Deardorff

U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
Kenneth Hamburger
Nicholas Melly
Kenneth Miller
Gabriel Taylor

ABBREVIATIONS AND ACRONYMS

AC	alternating current
ASTM	American Society of Testing and Materials
AWG	American Wire Gauge
DAQ	data acquisition
DC	direct current
DIN	Deutsches Institut für Normung
EMI	electro-magnetic interference
EPRI	Electric Power Research Institute
GI	generic issue
GIRP	Generic Issue Review Panel
HEAF	high energy arcing fault
HD	high definition
IEEE	Institute of Electrical and Electronic Engineers
IN	information notice
IR	infra-red
MD	management directive
NEA	Nuclear Energy Agency
NEC	National Electric Code
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
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
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 larger degree of uncertainty, requiring significant safety margins in plant analyses.

One such hazard comprises an electrical arcing fault involving electrical distribution equipment and components comprised of aluminum. While the electrical faults and subsequent fires are considered in existing fire protection programs, recent research [1] has indicated that the presence of aluminum during the electrical fault can exacerbate the damage potential of the event. The extended damage capacity 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 ensu 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 OECD/NEA report [1] 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 Testing." The results of these experiments [2] uncovered a potential increase in hazard posed by aluminum components in or near electrical equipment, as well as unanalyzed equipment failure mechanisms.

In response to this new information, the NRC performed a thorough review of U.S. operating experience with a focus on instances where HEAF-like events have occurred in the presence of aluminum. This review uncovered six events where aluminum effects like those observed in the experiments were present. An 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 Testing 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 [6]. The Generic Issue Review Panel (GIRP) completed its screening evaluation [7] for the proposed Generic Issue (GI) PRE-GI-018, "High-Energy Arc Faults

(HEAFs) Involving Aluminum," and concluded that the proposed issue met all seven screening criteria outlined in Management Directive (MD) 6.4, "Generic Issues Program." Therefore, the GIRP recommended that this issue continue into the Assessment Stage of the GI program. The GIRP has completed an assessment plan, issued August 23, 2018 [8]. Though the HEAF research project will result in updated fire PRA guidance for all arcing faults, much of the HEAF research program exists to resolve PRE-GI-018 in accordance with the assessment plan.

These actions resulted in the identification of a need for more data to better understand the hazard. The NRC developed an experimental plan in collaboration with its international collaborative partners under the OECD/NEA program and based on information from a Phenomena Identification and Ranking Table (PIRT) exercise performed in 2017 [9].

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 and document the experiments and results.

1.3. Scope

The scope of this research includes evaluating the HEAF hazard on low-voltage electrical equipment containing aluminum components. This characterization involves measurement and documentation of electrical and thermal parameters, along with physical evidence. 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 [2, 10]. Specifically, the test device (low-voltage switchgear) was faulted between the three phases. The testing laboratory provided electrical energy to the test device at the specified experimental parameters (system voltage, current, duration). Measurements internal and external to the gear were made using robust measurement devices fielded by the National Institute of Standards and Technology (NIST) and Sandia National Laboratories (SNL). 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 test facility, the test device, and the various instrumentation that were used.

[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 standardized 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.

2.1. Experiment Planning

The experimental plan was developed over an extended period with input provided by numerous stakeholders. Lessons learned from the Phase 1, results from the Phenomena Identification and Ranking Table (PIRT) exercise, and the literature were used to develop the initial experimental plan. The experimental plan is a living document and has undergone several revisions over time as new information is brought to light. Subsequent review and feedback by the OECD/NEA and other stakeholders resulted in changes to the plan. Support on this front from stakeholders and collaborative research partners such as the Electric Power Research Institute (EPRI) has greatly enhanced the experimental plan moving forward. The key central component of the experimental plan is the experimental matrix which specifies the key parameters for each experiment. A graphical experimental matrix for electrical enclosures is presented in Fig. 1. The experiments shown in blue are sponsored jointly by the NRC and OECD/NEA member countries, while the experiments highlighted in orange are sponsored solely by the NRC to support the resolution of the Pre-GI. This report covers Test 2-13 and Test 2-18. The key parameters that are evaluated in this experimental campaign are arc duration and arcing current.

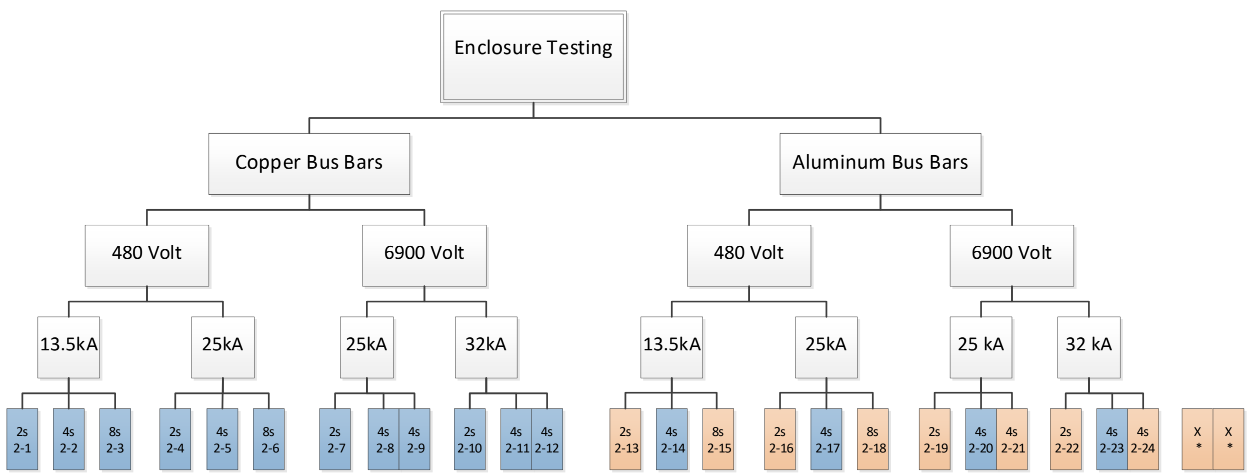


Fig. 1. Graphical Phase 2 Experimental Matrix for Electrical Enclosure

2.2. Experiment Facility

The full-scale experiments were performed at KEMA Labs (referred to in the remainder of this report as “KEMA”), located in Chalfont, Pennsylvania. One round of experiments was performed in August of 2019. The test 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 subject enclosures and to permit fire conditions for a period after completion of the HEAF experiment. KEMA provided the electrical measurements required to quantify the characteristics of the power supplied to the enclosures during the arcing experiments. KEMA also provided radiant energy measurements.

The experimental test cell was composed of 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 test cell faces the operator control room, with a courtyard area 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 test cell leads to a protected space where NIST and SNL data acquisition equipment was located and operated.

Test Cell #7 was used during this experiment series to perform the low-voltage experiments. The test cell is shown in Fig. 2. Detailed drawings of the facility are provided in Appendix A. Drawings of the test cell are courtesy of KEMA.

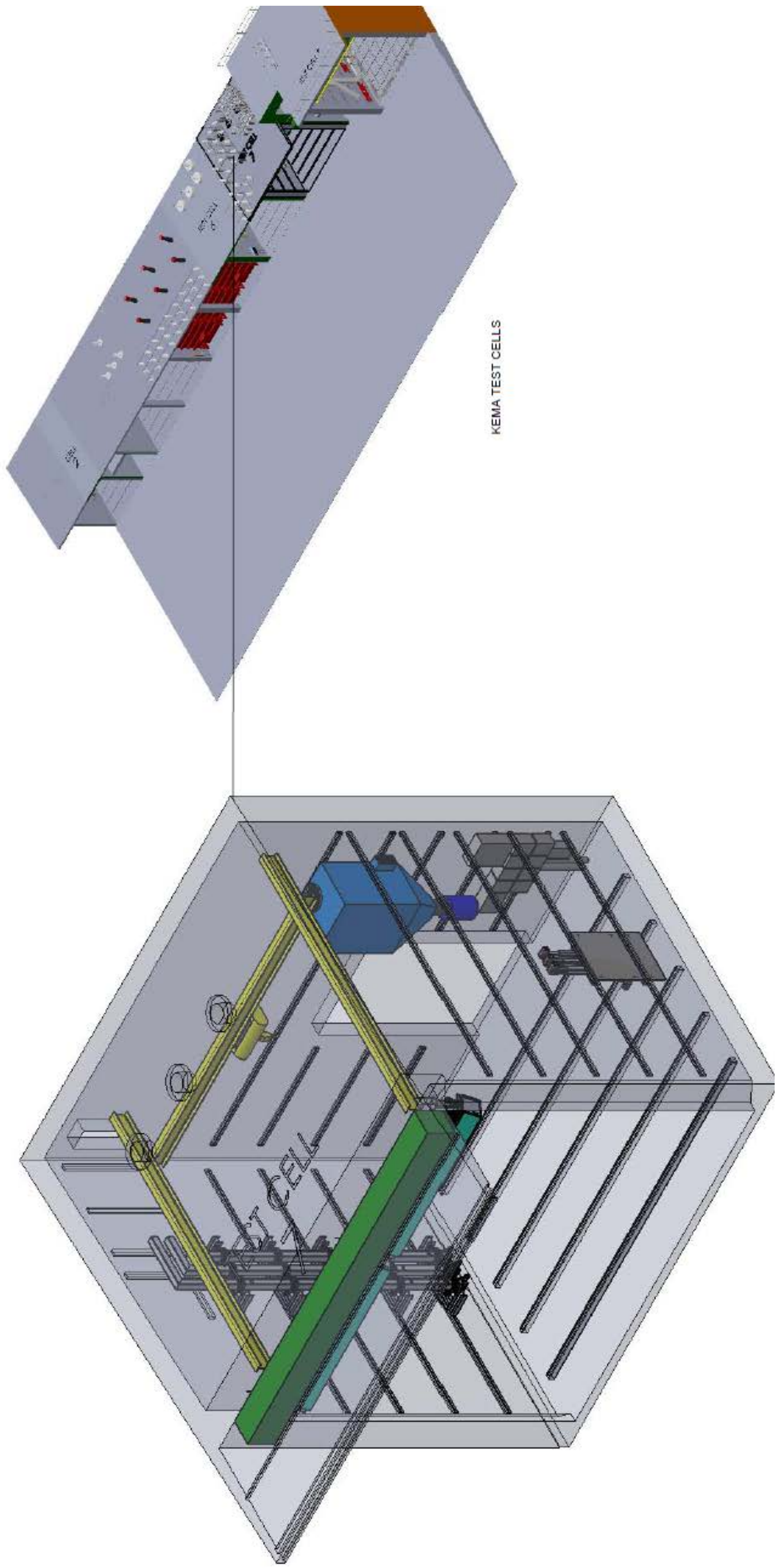


Fig. 2. Isometric drawing of Test Cell #7 (left) and Location of Test Cell #7 with respect to KEMA facility (right).

2.3. Test Device

Two Westinghouse DS-type low-voltage indoor metal enclosed switchgear units were used in the experiments. Both switchgear were identical to each other, consisting of two vertical sections with four cubicles per vertical section. Each vertical section was 53 cm (21 in) wide, 233 cm (92 in) high, and an overall depth of 170 cm (67 in). The top cubicles in each section were configured as an auxiliary cubicle containing metering, switching, relaying, and protection circuitry. The other cubicles were configured as breaker cubicles. A supply cubicle housed a DS-416 supply breaker while other cubicles housed DS-206 breakers that were racked in, but not closed. The supply breaker was the only breaker closed during the experiment. The switchgear was configured such that the laboratory's power supply was connected to the supply breaker run back, with the supply breaker closed and the main bus energized. The switchgear is shown in Fig. 3 through Fig. 5. The experiment test matrix is presented in Table 1.

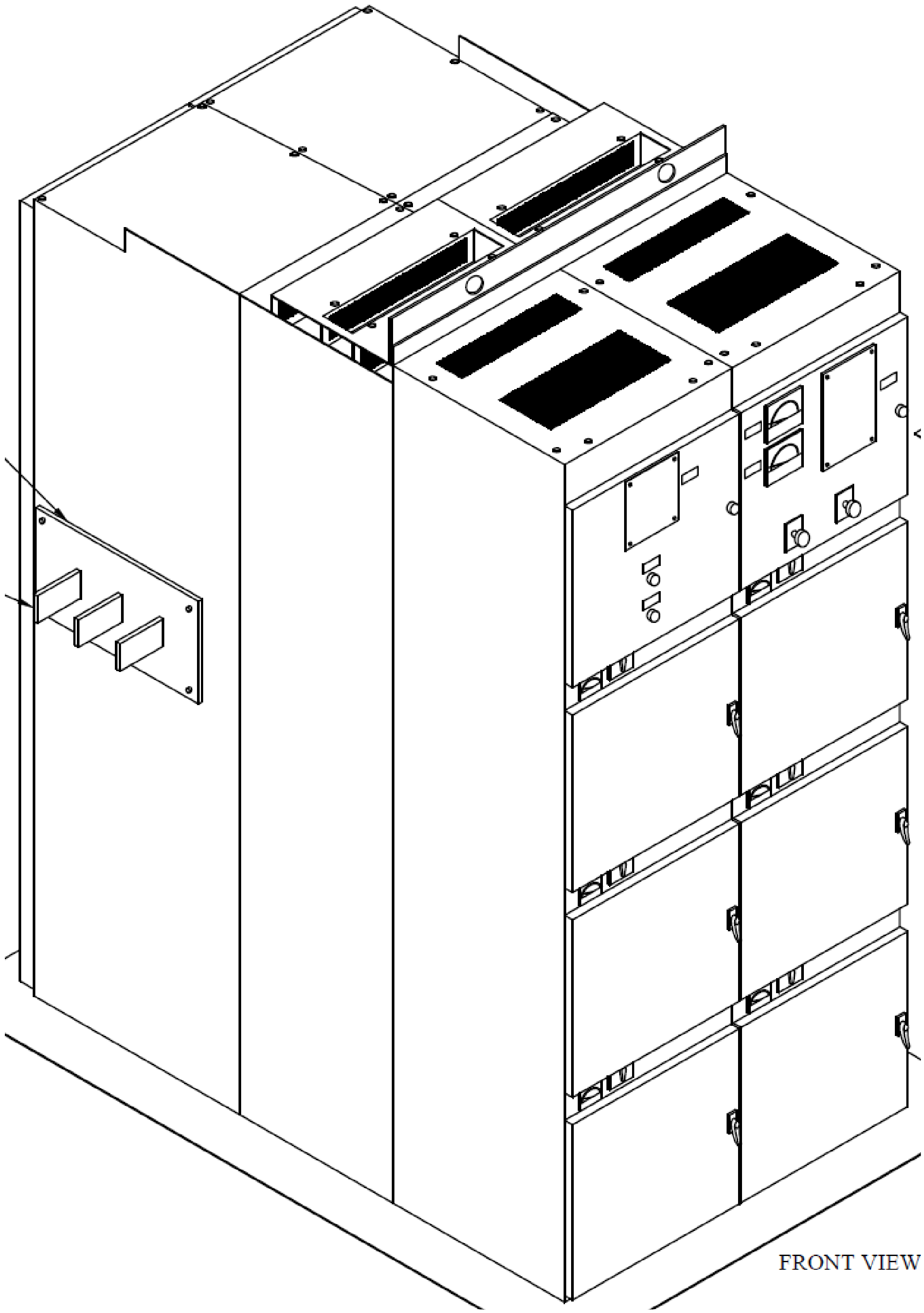


Fig. 3. Isometric drawing of low-voltage metal enclosed switchgear.

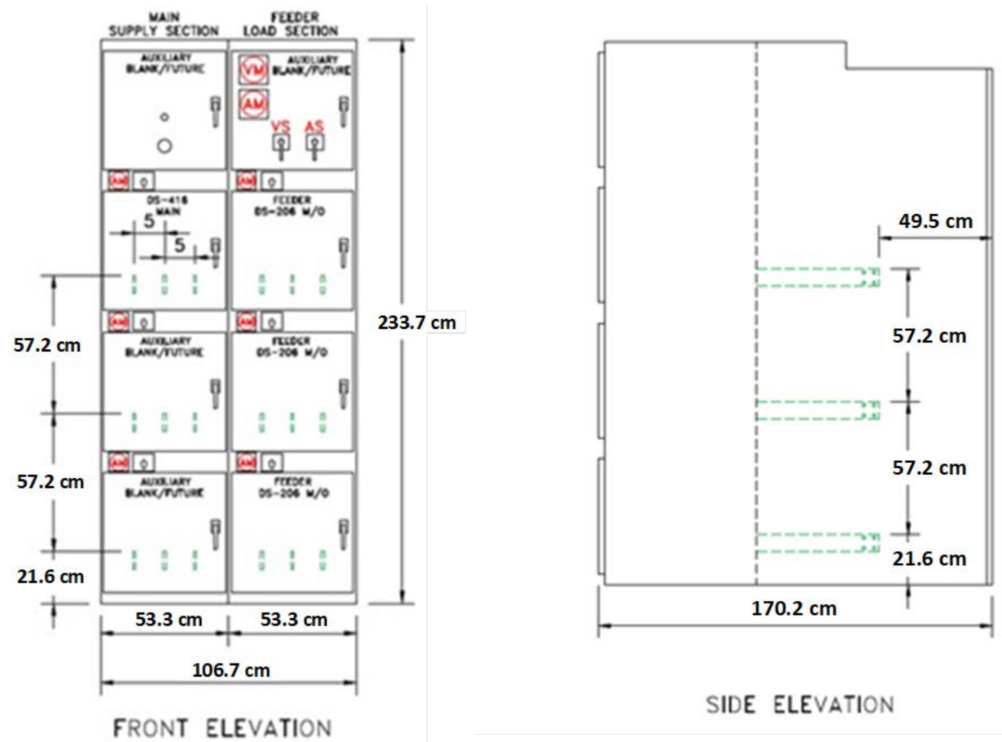


Fig. 4. Drawing of DS Switchgear as procured (all drawing dimensions in "centimeters")

Fig. 5. Photo of DS switchgear. (front (left); side and front (center); opposite side (right)).

Table 1. Experimental Matrix Low-voltage DS Switchgear Experiments.

Test #	Bus Material	Voltage (V)	Current (kA)	Duration (s)
2-13	Aluminum	480	13.5	2
2-18	Aluminum	480	25.0	8

2.4. Instrumentation

A variety of measurement equipment was used during the low-voltage DS switchgear experiments. Table 2 lists the measurement devices and the measurement that each device provides. The instruments were arranged around the cell. A general configuration is shown in Fig. 6 followed by a photograph of the configuration in Fig. 7. A brief description of each device follows. Thermal, pressure, electromagnetic, conductivity, and electrical measurements were made using a variety of instruments and techniques. This section provides an overview of each, along with the methods and locations of measurement.

Table 2. List of measurement equipment.

Measurements	Instrument / Technique
Temperature	Infrared (IR) Imaging, Plate Thermometer (PT)
Electromagnetic Interference	Free-field d-Dot Sensors
Air Conductivity	Planar conductivity sensors
Air Breakdown Strength	Breakdown Sensors
Heat flux (time-varying)	Plate Thermometer (PT)
Heat flux (average)	Plate Thermometer (PT), Thermal Capacitance Slug (T_{cap} slug), Radiometer
Incident Energy	ASTM F1959 Slug calorimeter (slug), Thermal Capacitance Slug (T_{cap} slug)
Arc plasma / fire dimensions	Videography, IR Imaging
Surface deposit analysis	Sample collection (carbon tape), post-experiment laboratory analysis (energy dispersive spectroscopy)
Qualitative information	high speed / high dynamic range imaging, cable samples

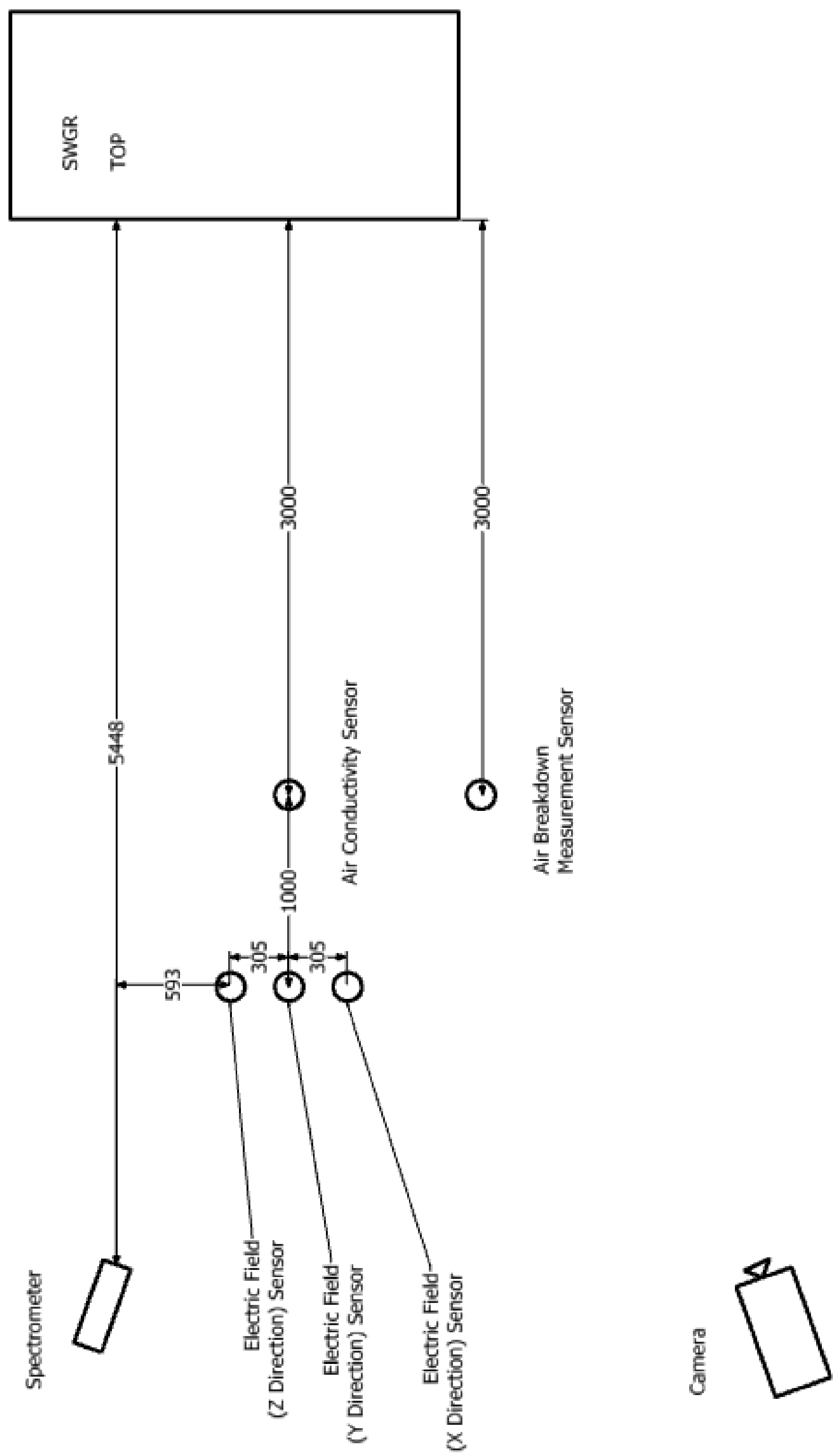


Fig. 6. Plan view of SNL instrumentation locations (note that locations are approximate, and instruments used varied by experiment. Illustration is not to scale). See details in Appendix A.2.

Fig. 7. Photograph of instrumentation cluster (from Left-to-right, air breakdown, radiometer, d-dot, air conductivity, high speed IR and visible videography

2.4.1. Photometrics

NIST and SNL fielded numerous imaging technologies during this experimental series to provide high-speed quantitative and qualitative imaging of the HEAF experiment evolution. The measurement methods included visible high-speed and high-definition imaging, high-speed high dynamic range visible imaging, and high-speed thermal imaging. The equipment fielded by NIST is like that used in the Phase 1 Testing [2] and experiments performed in 2018 [10] to capture high-definition visible and high-speed thermal images. Equipment fielded by SNL was a subset of equipment fielded in the 2018 experimental series [10]. The equipment selection was scaled down based on results and lessons learned. SNL reports document the approach, uncertainties, and results in greater detail [11].

The processed images can be accessed from the NRC RIL website[2]:
https://www.nrc.gov/reading-rm/doc-collections/research-info-letters/index.html

[2] The RIL website can be accessed by visiting http://www.NRC.gov, selecting the "NRC Library" >> "Document Collections" >> "Research Information Letters".

2.4.2. High-Definition Videography

High-definition (HD) video imaging was used to provide additional view angles for each experiment. Two types of camera were used. In the cell, action cameras were placed in protective housings and located on the floor or attached to the test cell wall. Their wide view angle and proximity provided a high resolution and detail of the early portion of the experiments. However, as the experiment progressed the effluent quickly obscured the view and detail these cameras could provide. The second set of HD cameras were located approximately 27 m from the front of the cell adjacent to thermal imaging cameras. The placement and zoom used on these cameras allowed for a macroscopic view of the entire cell or an area surrounding the box. These cameras were 90-degrees orthogonal to the action camera placed on the test cell wall. One-half of these cameras were equipped with IR pass filters to better image the plasma / fire from the HEAF to allow improve image capture during arcing event.

2.4.3. Thermography

Up to four thermal imaging cameras were used per experiment. Two of the cameras were supplied by NIST, while the other two were provided by SNL. The camera settings ranged in frame-rate, thermal calibration range, and resolution. The cameras were also placed in different locations. The NIST cameras were located outside the test cell approximately 26.5 m from and orthogonal to the KEMA cell roll up door opening. The SNL cameras were located outside of the cell and were housed within a mechanically ventilated metal enclosure. The thermal imagers used in this series are shown in Fig. 8, with courtyard locations shown in Fig. 9 and Fig. 10.

2.4.3.1. SNL

The SNL thermal imagers were each housed in an enclosure that provided protection of the camera and networking components. An opening in the box allowed for the camera lenses to protrude out of the enclosure. The lenses were protected by locating the cameras at a distance and non-orthogonal axis to the HEAF effluent. Some of the cameras were configured such that the lens was not in direct exposure to the HEAF effluent. This was done by using a mirror and concrete barrier.

2.4.3.2. NIST

The NIST thermal imaging was performed with two main goals. The first goal was to obtain qualitative information about the development and movement of the arc, the development of plumes of hot gases and HEAF products issuing from the open box, the impingement of the arc jets on the targets and thermal transducers, and the penetrations formed in the enclosure. The second goal was to provide quantitative measurements of box temperatures during and after the HEAF event. The thermal imaging measurements were performed by a FLIR model SC8243 imaging system and a Telops MS M350 imaging system.

The FLIR thermal imager is equipped with a 50 mm f/4.0 lens, with an InSb detector that has a nominal response range from 3 µm to 5 µm and a nominal pixel pitch of 18 µm by 18 µm. The imager can operate in full resolution mode of 1024 pixels by 1024 pixels at approximately 125 frames per second and can cover the temperature range of - 20 °C to 1500 °C (- 4 °F to 2732 °F) using dynamic range extension techniques. For these experiments, to compliment the imaging performed by SNL imagers, the resolution was lowered to 319 pixels x 255 pixels, and the temperature range limited to 250 °C to 600 °C so that the frame rate could be increased to approximately 400 Hz.

The Telops thermal imager was equipped with a 50 mm f/2.3 lens, with a detector that has a nominal response range from 3.0 µm to 4.9 µm and a nominal pixel pitch of 16 µm by 16 µm. The imager was operated in full resolution mode of 640 pixels by 512 pixels at approximately 350 frames per second. The video capture was performed using a spinning filter wheel with eight positions, filled with two consecutive series of four different transmittance neutral density filters. A dynamic range extension technique is applied, where the images from each series of four filters are captured, and post-processing software combines the images into one image with an expanded temperature range. After dynamic range extension is applied, the video images are 640 x 512 pixels in size, covering from - 0 °C to 2500 °C (- 4 °F to 4532 °F), with an effective video frame rate of approximately 88 Hz.

The uncertainty of the temperature results from the FLIR and Telops imagers are both specified by the manufacturer as ± 2 °C or ± 2 percent, with a 99 percent confidence interval. Using the NIST Uncertainty Machine [12], the expanded uncertainty in the temperature measurements of the metal surfaces is given in Table 3. Details of the uncertainty analysis can be found in a previous HEAF report [10].

Table 3. Expanded uncertainty for IR imager temperatures

Surface	Mean Emissivity	Temperature (°C)	Uncertainty (°C)	Confidence	Coverage Factor	Approximate Uncertainty Contribution
Paint	0.94	100	± 2.6	95%	1.7	Imager: 30% Emissivity: 70%
Paint	0.94	650	± 10.5	95%	1.9	Imager: 70% Emissivity: 30%
Oxidized Steel	0.80	100	± 3.0	95%	1.8	Imager: 20% Emissivity: 80%
Oxidized Steel	0.80	650	± 11.1	95%	1.9	Imager: 65% Emissivity: 35%

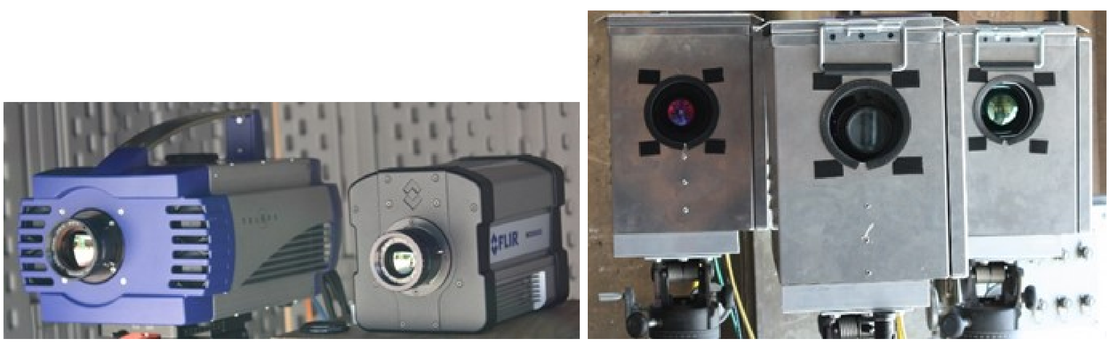


Fig. 8. Thermal imagers (NIST thermal imaging cameras located approximately 26.5 m from test device (let), SNL imaging cameras located approximately 27 m from test device (right), from left to right (thermal, high speed visible, thermal))

Fig. 9. Thermal imagers and high speed imagers are located in the courtyard. Four NIST cameras are in structure, approximately 26.5 m from the test device. Two SNL cameras are located outside the structure, approximately 27.0 m from the test device.

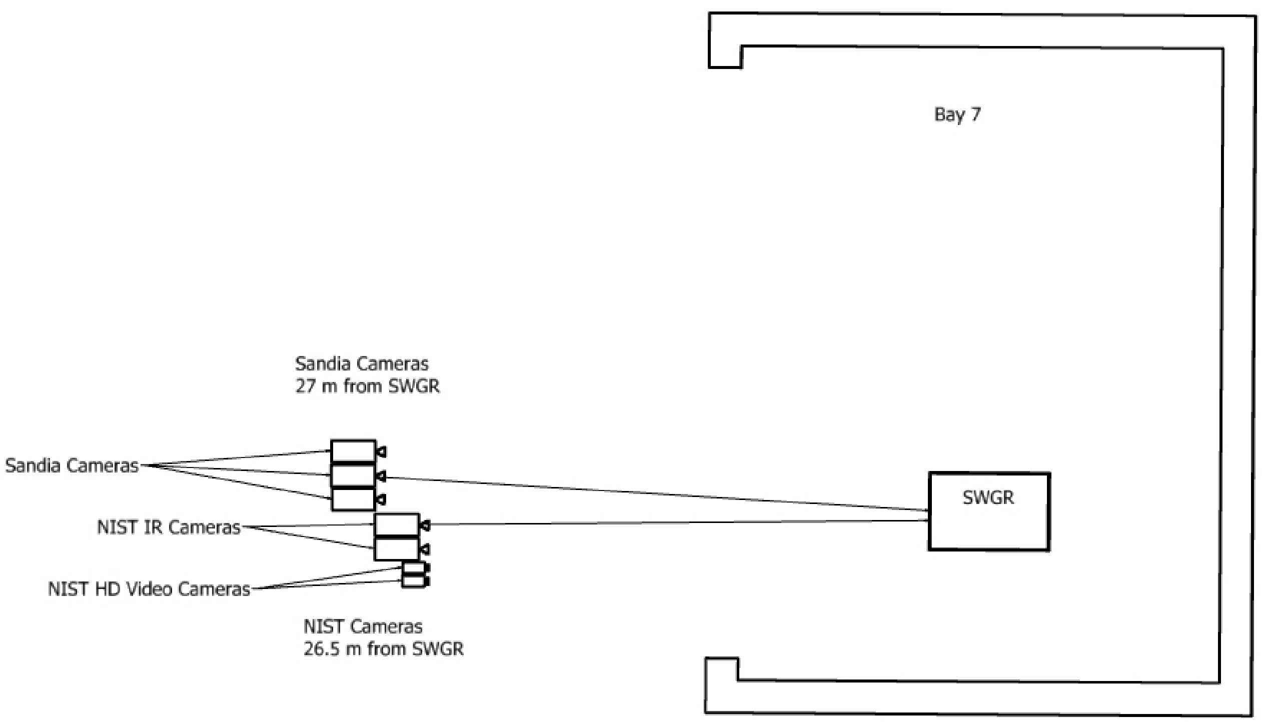


Fig. 10. Plan view of NIST and SNL camera locations (not to scale).

2.4.4. Calorimetry

Several types of calorimeters were used in these experiments. For all experiments, an SNL provided radiometer was used. This device was used in the previous small-scale experiments, and the results obtained during this experimental series provide direct comparisons. During the medium voltage box experiments, several thermal capacitance slug calorimeters and plate thermocouples were used. These devices were made available due to the cancellation of the planned medium voltage bus duct experiments. The types and configurations were selected based on the expected thermal exposure and ability of the device to survive.

2.4.4.1. Plate Thermometer

Modified plate thermometers (PTs) are robust thermal sensors that can survive in hostile HEAF environments [2, 10, 13]. They were chosen for heat flux measurements in the HEAF experiments due to their rugged construction, low cost, lack of cooling water, and known emissivity and convective heat transfer coefficients.

The modified plate thermometer used in the HEAF experiments is shown in Fig. 11. It consists of two 0.51 mm (0.02 in) nominal diameter (24 AWG) Type-K thermocouple wires welded directly to the rear of an 0.787 mm ± 0.051 mm (0.031 in ± 0.002 in, 99 percent confidence interval per manufacturer specifications) thick Inconel 600 plate, approximately 100 mm (3.94 in) by 100 mm (3.94 in) in size. The plate is backed by a mineral fiber blanket approximately 25.4 mm (1.0 in) thick to minimize heat loss. Machine screws with ceramic washers allow for legs to be attached at the rear of the plate thermometer to simplify installation onto instrumentation racks.

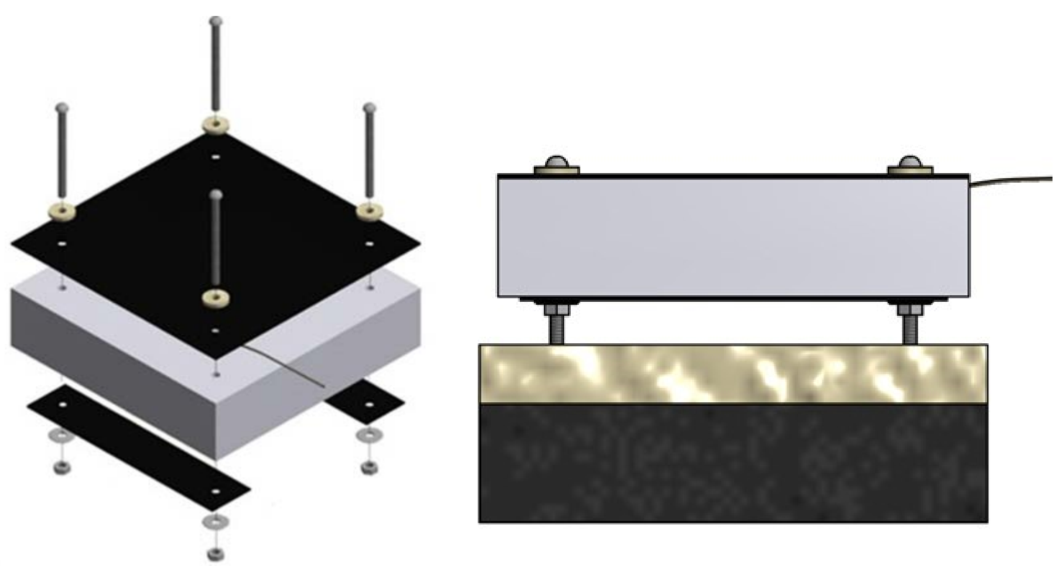


Fig. 11. Exploded view of modified plate thermometer (left); Cross-sectional view of modified plate thermometer placed on cone calorimeter sample holder (right).

The incident heat flux on a plate thermometer can be calculated from a heat balance using the following relation, a rearrangement of Equation 18 from Ingason and Wickstrom [14]:

$$\dot{q}''_{inc} = \sigma \cdot T_{PT}^4 + \frac{(h_{PT} + K_{cond})(T_{PT} - T_\infty)}{\varepsilon_{PT}} + \frac{\rho_{PT} \cdot C_{PT} \cdot \delta \cdot \left(\frac{\Delta T_{PT}}{\Delta t}\right)}{\varepsilon_{PT}} \quad (1)$$

Here $\dot{q}''_{inc}$ is the incident heat flux, σ is the Stefan-Boltzmann Constant, 5.670×10^{-8} W/($m^2\cdot K^4$), T_{PT} is the temperature of the plate (K), h_{PT} is the convection heat transfer coefficient, 10 W/($m^2\cdot K$), K_{cond} is the conduction correction factor determined from NIST cone calorimeter data, 4 W/($m^2\cdot K$), T_∞ is the ambient temperature (K), ε_{PT} is the plate emissivity, 0.85 at 480 °C as rolled and oxidized and specified by the alloy manufacturer, ρ_{PT} is the alloy plate density, 8470 kg/m^3 from the alloy manufacturer, C_{PT} is the alloy plate heat capacity, 502 J/(kg·K) at 300 °C from the alloy manufacturer, δ is the alloy plate thickness, 0.79 mm (0.03 in), and Δt is the data acquisition time step of 0.1 s.

The gauge heat flux can also be calculated and is the heat flux listed in the tables of this report. The gauge heat flux is the heat flux that would be reported by an ideal water-cooled transducer such as a Schmidt-Boelter or Gardon gauge operating at a constant temperature of T_{gauge}. The gauge heat flux, $\dot{q}''_{gauge}$, is calculated from [14]:

$$\dot{q}''_{gauge} = \sigma \cdot T_{PT}^4 + \frac{(h_{PT} + K_{cond})(T_{PT} - T_\infty)}{\varepsilon_{PT}} + \frac{\rho_{PT} \cdot C_{PT} \cdot \delta \cdot \left(\frac{\Delta T_{PT}}{\Delta t}\right)}{\varepsilon_{PT}} - \sigma \cdot T_{gauge}^4 \quad (2)$$

Type A evaluation of uncertainty is performed by the statistical analysis of a series of measurements. Type B evaluation of uncertainty is based on scientific judgement using relevant available information such as manufacturer specifications, calibration data, handbook data, previous experiments, and knowledge of the behaviors of materials and measurement equipment [15, 16, 17].

The plate thermometer temperature increase, ΔT_{PT}, is reported along with the gauge heat flux. The uncertainty in the temperature of the Type-K thermocouple wire is given by the manufacturer as ±1.1 °C or 0.4 percent with a 99 percent confidence interval [18]. The expanded uncertainty in a PT temperature change of 0 °C to 1250 °C is 0.3 percent, with a coverage factor of 2, which corresponds to a confidence interval of 95 percent [15]. The expanded uncertainty in the heat flux measurement is ± 1 kW/m^2 or ± 5 percent, with a coverage factor of 2, which corresponds to a confidence interval of 95 percent. Additional detail on the uncertainty determination can be found in the previous report [10].

2.4.4.2. ASTM Slug Calorimeters (Slug)

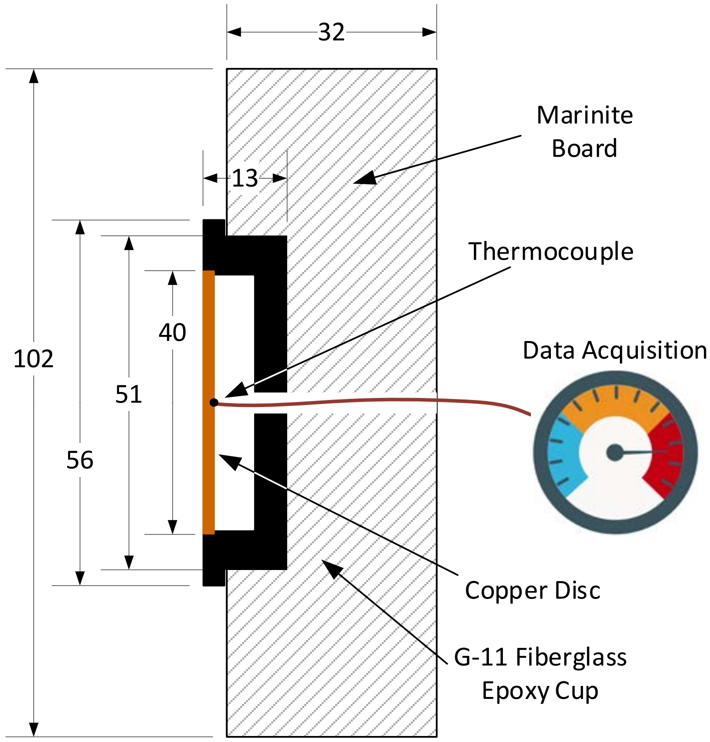
Incident energy was measured using slug calorimeters described in ASTM F1959 [20] and shown in Fig. 12. These instruments are customarily used to measure radiant energy and determine the arc flash hazard to personnel in the area of electrical enclosures. Due to the characteristics of the HEAF phenomena, which can result in convective arc jets, the calorimeters are reacting to convective heat transfer in addition to radiant heat transfer. ASTM slug calorimeters consist of a copper disc with an approximate thickness of 1.6 mm (0.063 in) and diameter of 40 mm (1.6 in). An iron-constantan thermocouple (Type J), composed of two 0.255 mm (0.01 in) nominal diameter (30 AWG) wires, is soldered to in the back of the copper disc using silver solder. The ASTM standard specifies that the copper disc be installed in an insulation board. The KEMA slug calorimeters were installed in a G-11 fiberglass epoxy phenolic cup, which was then placed in a calcium silicate board holder nominally 100 mm by 100 mm by 32 mm thick (4 in by 4 in by 1.25 in nominal thickness) for mounting on instrument rack. The instruments were provided by KEMA. The slug temperatures were reported by the KEMA data acquisition system at a rate of 20 Hz.

The incident energy absorbed by the slug calorimeter during the HEAF experiments is calculated according to the methodology in ASTM F1959 [19]. The method reports the net heat absorbed over the arc duration and assumes that there are no losses from the disc due to re-radiation, convection, or conduction to the disc holder. The absorptivity of the disc is assumed to be one.

The total energy per unit area, Q'', is calculated by:

$$Q'' = \frac{m \cdot \overline{C_p} \cdot (T_f - T_i)}{A} \tag{3}$$

where m is the mass of the copper disc, $\overline{C_p}$ is the average heat capacity of the copper disc, T_f is the temperature of the disc at the end of the arc, T_i is the temperature of the disc before the arc, and A is the front surface area of the disc. The total energy per unit area resulting from the arc is reported in a summary table for each sensor location in each experiment. The ASTM F1959 standard also refers to the total energy per unit area as incident energy (cal/cm^2 or kJ/m^2).



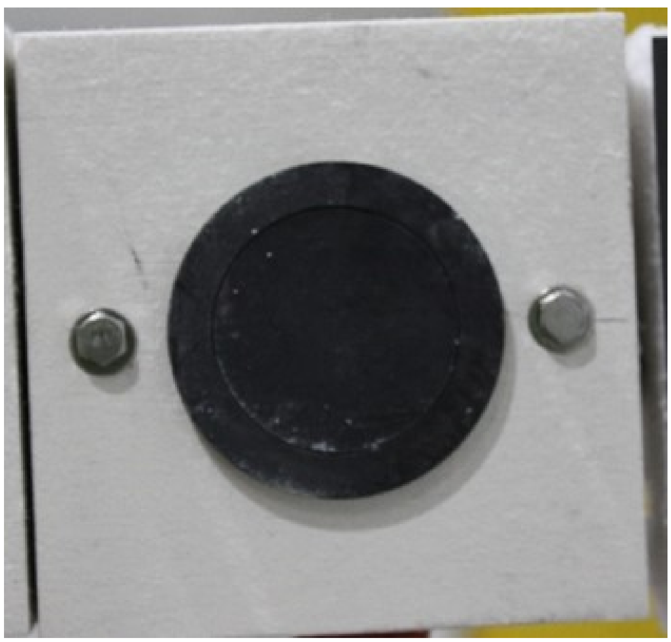


Fig. 12. Cross-section of ASTM Slug (top) nominal dimensions in millimeters, photo of device being prepared in the field (bottom). Note that the two bolts on each side of the device are used for mounting to the DIN rail of the instrumentation rack.

The Type B standard uncertainty in the thermocouple measurement, derived from typical thermocouple manufacturer data, with a coverage factor of 2, is 2.2 °C or 0.75 percent. The ASTM calculation method assumes that the absorptivity of the disc is 1.0; however, inspection of the discs over the course of the experiments suggests that the emissivity may vary from approximately 0.9 to 1.0, in a rectangular probability distribution. The expanded uncertainty in the incident energy measurement is ± 18 kJ/m^2 or ± 4 percent, with a coverage factor of 2, which corresponds to a confidence interval of 95 percent. Additional detail on the uncertainty determination can be found in the previous report [10].

2.4.4.3. Thermal Capacitance Slugs (T_{cap} slug)

Tungsten thermal capacitance slugs (T_{cap} slug) were used to measure the heat flux and incident energy during the HEAF experiment. These sensors were developed as a result of experience gained in Phase 1, where the thermal conditions during some experiments exceeded the measurement capabilities and caused destruction of the ASTM slug calorimeters and modified plate thermometers. A cross section of a T_{cap} slug is shown in Fig. 13, which is a modified example of the thermal capacitance slug described in ASTM E457-08 [21]. The slug is composed of a tungsten cylinder approximately 15 mm (0.59 in) long mounted in calcium silicate board. A type-K thermocouple is attached to the rear of the tungsten to measure the temperature during heating. The development of the T_{cap} is described in the previous report [10].

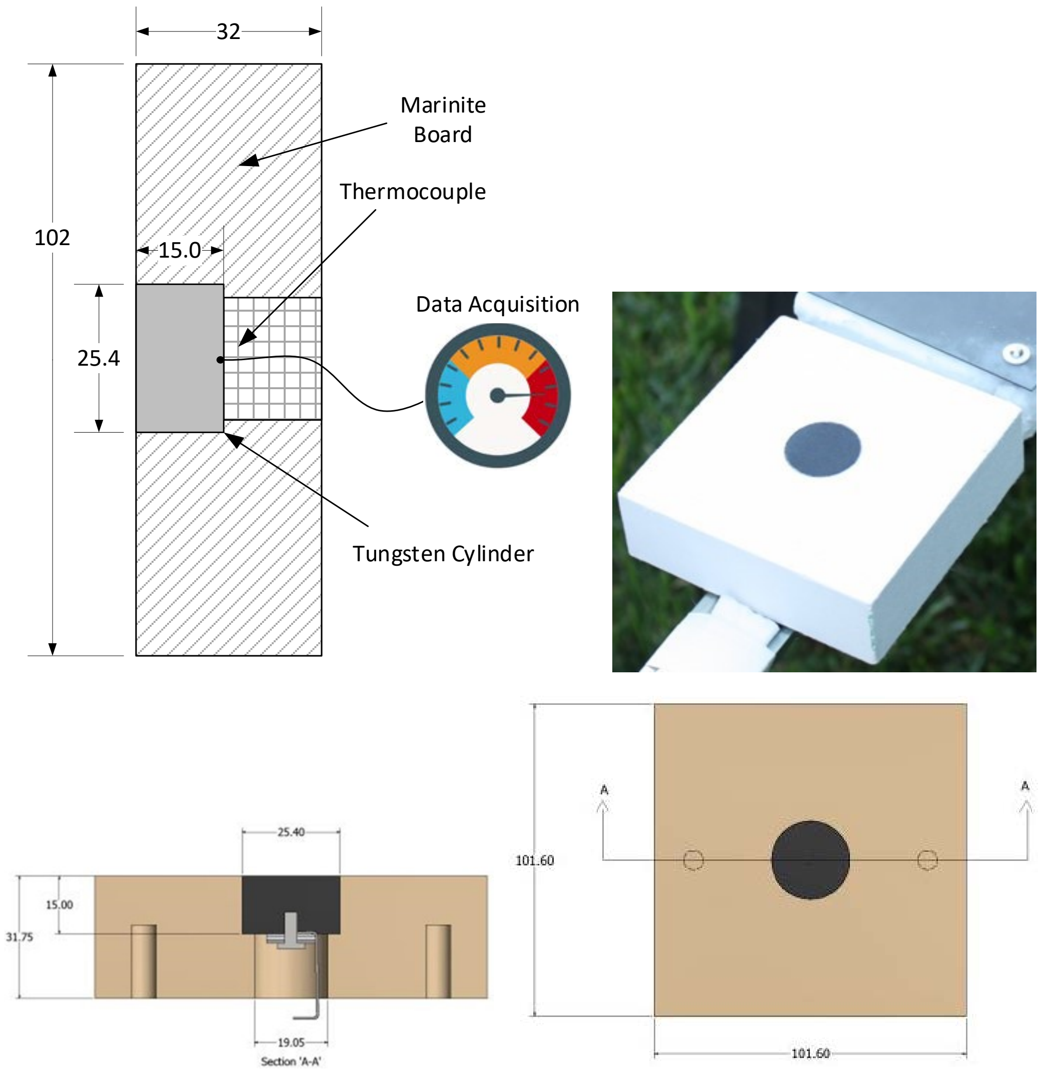


Fig. 13. Thermal capacitance style slug, illustration (top left), photo of device being prepared in the field (top right), dimensional drawings showing internal construction (bottom left and right). All dimensions in mm.

The maximum heat flux was determined from Equation (4), where $(\dot{q}'')$ is the heat flux into the surface of the tungsten slug (kW/m^2), ρ is the density of the tungsten slug (kg/m^3), ($\overline{C_P}$) is the average heat capacity of the tungsten slug (kJ/[kg K]), l is the thickness (m), ΔT is the change in temperature of the tungsten slug (°C), and Δt is the corresponding change in time (s).

$$\dot{q}'' = \rho \cdot \overline{C_P} \cdot l \cdot \left(\frac{\Delta T}{\Delta t}\right) \quad (4)$$

An uncertainty analysis using Type A and Type B components was performed on the T_{cap} slug at 50 kW/m^2 and 5 MW/m^2 using the NIST Uncertainty Machine [12] with cone calorimeter data and fire dynamics simulator (FDS) [19] simulations. The expanded uncertainty in the heat flux measurement is ± 1.5 kW/m^2 or ± 2.9 percent, with a coverage factor of 2, which corresponds to a confidence interval of 95 percent.

The expanded uncertainty of the incident energy over the measurement range is estimated at ± 2.4 kJ/m^2 or ± 5 percent, with a 95 percent confidence interval, which includes the estimated error due to conduction effects. Additional details on the development of the T_{cap} heat transfer analysis, and uncertainty determinations can be found in the previous report [10].

2.4.4.4.Data Acquisition System

The NIST data acquisition system used a combination of shielding, grounding, isolation, and system configuration that reduced the impact of electromagnetic interference (EMI), as shown in Fig. 14. This data acquisition system was used for the plate thermometer and T_{cap} instruments and is described in the literature [2, 10, 13]. A TTL signal with a known delay time was used to synchronize to the KEMA data acquisition and control system.

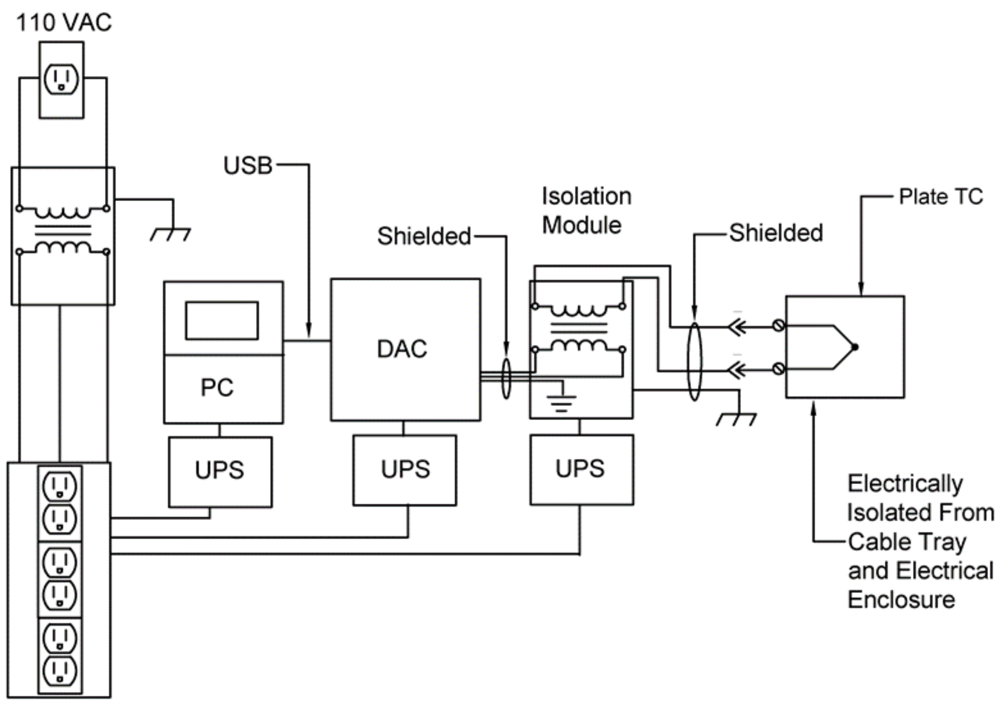


Fig. 14. Data Acquisition System Configuration with EMI rejection.

2.4.5. Pressure Transducer

Pressure measurement methods were improved from the Phase 1 experiments. First, the test laboratory changed the data link cable between the data acquisition cart (located in the test cell) and the data logging station (located in the control room) to a fiber optic cable. This greatly improved the signal to noise ratio and resistance to EMI. Secondly, a magnetic shielding alloy (Mu-metal) was used to shield the sensor. This material is a ferromagnetic alloy with a very high magnetic permeability. The material was installed around the pressure sensor between the sensor and the PVC enclosure. Lastly, piezoelectric-style pressure transducers were used instead of the strain gauge-type in Phase 1. The combination of these three changes greatly improved the electromagnetic interference (EMI) rejection.

The assembly for measuring pressure consisted of a through-bolt that was installed in a hole drilled in the metal cladding of the electrical switchgear enclosure. A 90-degree fitting was connected to the through-bolt on one end, and a pressure hose was connected to the other. The opposite end of the pressure hose was connected to the pressure transducer, which was housed within a white PVC tube for mechanical protection. Within the PVC tube, the Mu-metal was installed. The electrical connection from the transducer exited the PVC tube and was routed to the data collection cart. Prior to the experiments, additional thermal protection was added to the electrical cable by surrounding it with ceramic fiber thermal insulation and secured with fiberglass tape. The configuration is shown in Fig. 15 and Fig. 16. Two general locations were selected. At each location, transducers of different nominal ranges were used. One ranged from 0 kPa (0 psia) to 207 kPa (30 psia), while the other ranged from 0 kPa (0 psia) to 345 kPa (50 psia). Pressure transducers labeled PT3 and PT4 measured the primary cable connection compartment pressure where the arc was initiated, while transducers PT1 and PT2 measured pressure in the breaker cubicle.

Fig. 15. Photos of pressure measurement locations (PT3 and PT4 (left); PT1 and PT2 (right)).

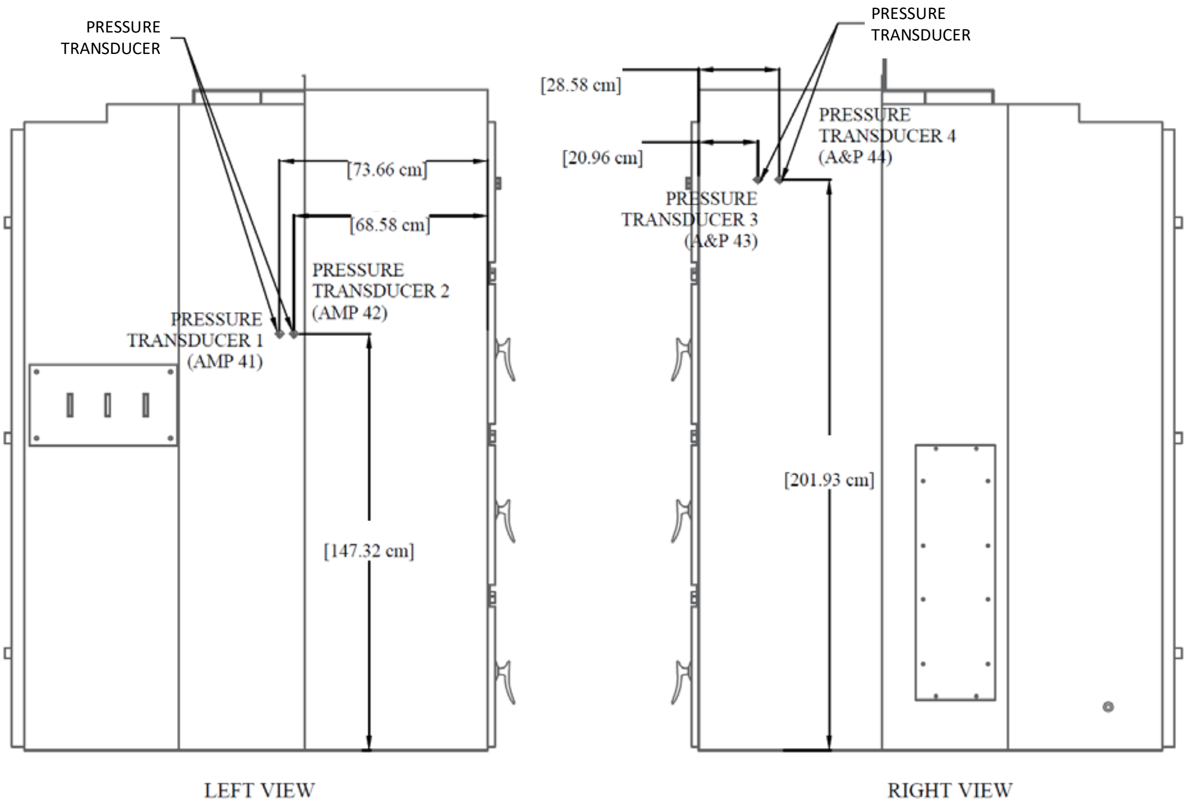


Fig. 16. Drawings showing locations of pressure sensor devices.

2.4.6. Auxiliary Measurements

Several instruments were fielded to characterize the electromagnetic interference, air conductivity, and voltage holdoff strength. These devices are discussed in detail in the previous report [23]. The lack of switchgear enclosure breach or location of breach relative to the instruments resulted in the measured data of no value. As such, these measurements are not reported.

2.4.7. Mass Loss Measurements

Mass loss measurements of electrode and enclosure material were not made. This is due to the large mass of the switchgear main bus, difficulty in separating the main bus from the switchgear, and the uncertainty of the measurement.

2.4.8. Electrical Data Acquisition and Processing

Electrical measurements were made by the KEMA Labs. The measurements included line-to-ground voltages at the generator and just prior to the test device in the test cell and current measurements downstream of the test device (not in the test cell) but downstream of any transformer. The reported voltages in this report are the voltage at the test device and are line-to-ground voltages (unless stated otherwise). The uncertainties in the measurements made by KEMA Labs were ± 3 percent.

2.4.9. Cable Samples

Cable samples (coupons) were provided in every experiment as a passive indication of thermal damage. The inclusion of cable samples was highly recommended by stakeholders during the April 2018 public workshop [24].

The cable coupons were constructed using six or eight segments of cable, approximately 100 mm (4 in) long. The cables were affixed to a square piece of fiberglass reinforced cement board ("Durock™"), measuring approximately 100 mm (4 in) square and nominally 13 mm (0.5 in) thick, using steel wire protected with a glass braid sheath. The wire was also used to connect the cable coupon to the horizontal steel DIN rail. Descriptions and specifications of the cables are listed in Table 4 and Table 5. Face and side views of a typical cable coupon are presented in Fig. 17 and Fig. 18.

Table 4. Manufacturers' descriptions of the cables used in the experiments.

Cable No.	Source‡	Manufacturer	Date	Cable Markings
900	Purchased	Lake Cable	2015	#2582 FT. TPT127 LAKE CABLE 12AWG 7C PE/PVC2010 CONTROL CABLE 600V 75º C 2015 "ROHS 11" REACH MADE IN USA 280547

‡ Note that the CAROLFIRE # refers to the number assigned to that particular cable during the CAROLFIRE program [25]

Table 5. Nominal cable properties.

Cable No.	Insulation Material	Jacket Material	Class.	Conductors	Diameter (mm)	Jacket Thickness (mm)	Insulator Thickness (mm)	Mass per Length (kg/m)	Copper Mass Fraction	Jacket Mass Fraction	Insulation Mass Fraction	Filler Mass Fraction
900	PE	PVC	TP	7	15.9	1.85	1.07	0.38	0.55	0.27	0.10	0.08

Fig. 17. Cable coupon constructed of seven conductor PE / PVC control cable (Cable 900). Front view.

Fig. 18. Cable coupon constructed of seven conductor PE / PVC control cable (Cable 900). Side view.

2.4.10. Instrument Deployment

The majority of the thermal instrumentation devices were located on instrument racks with the faces of the instruments located approximately 0.91 m (3.00 ft) from the exterior sides of the metal clad enclosure. Two instrument racks were also located horizontally above the electrical enclosure (Rack 4 and Rack 5), supported by a reconfigurable steel structure. The sensors on Rack 4 were located approximately 0.91 m (3.00 ft) from the top of the enclosure, while the sensors on Rack 5 were located approximately 1.83 m (6.00 ft) from the top of the enclosure. The location of the upper horizontal rack was horizontally offset by approximately 102 mm (4.0 in) from the lower rack to reduce shadowing from the sensors below. The instrumentation rack configuration for Test 2-13A through Test 2-13G is shown in Fig. 19 and Fig. 20. The instrument rack configuration for Test 2-18A and Test 2-13B is shown in Fig. 21 and Fig. 22. Details of the instrument locations are shown in Fig. 23 through Fig. 29, with a photograph showing the instrumentation racks around the test devices during setup in Fig. 30 and Fig. 31. 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.

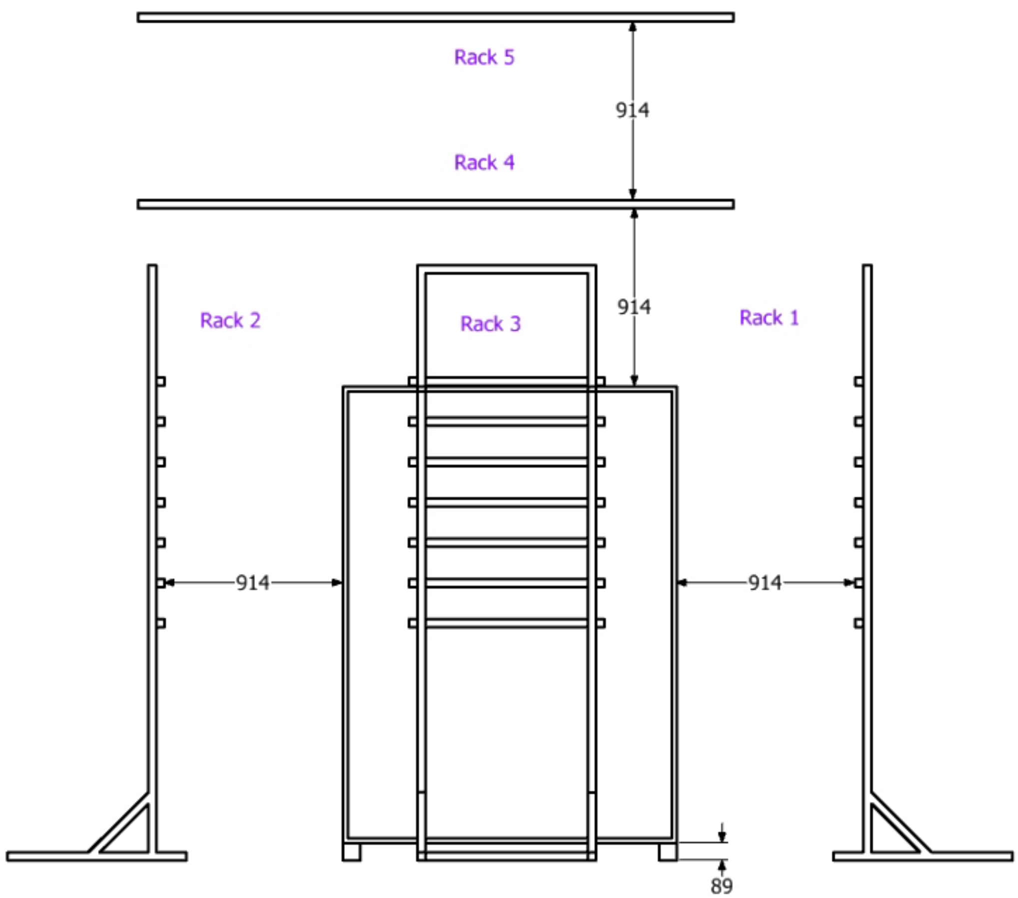


Fig. 19. Elevation view of instrument rack configuration around electrical enclosure for Test 2 13A through 2 13G. Dimensions in mm.

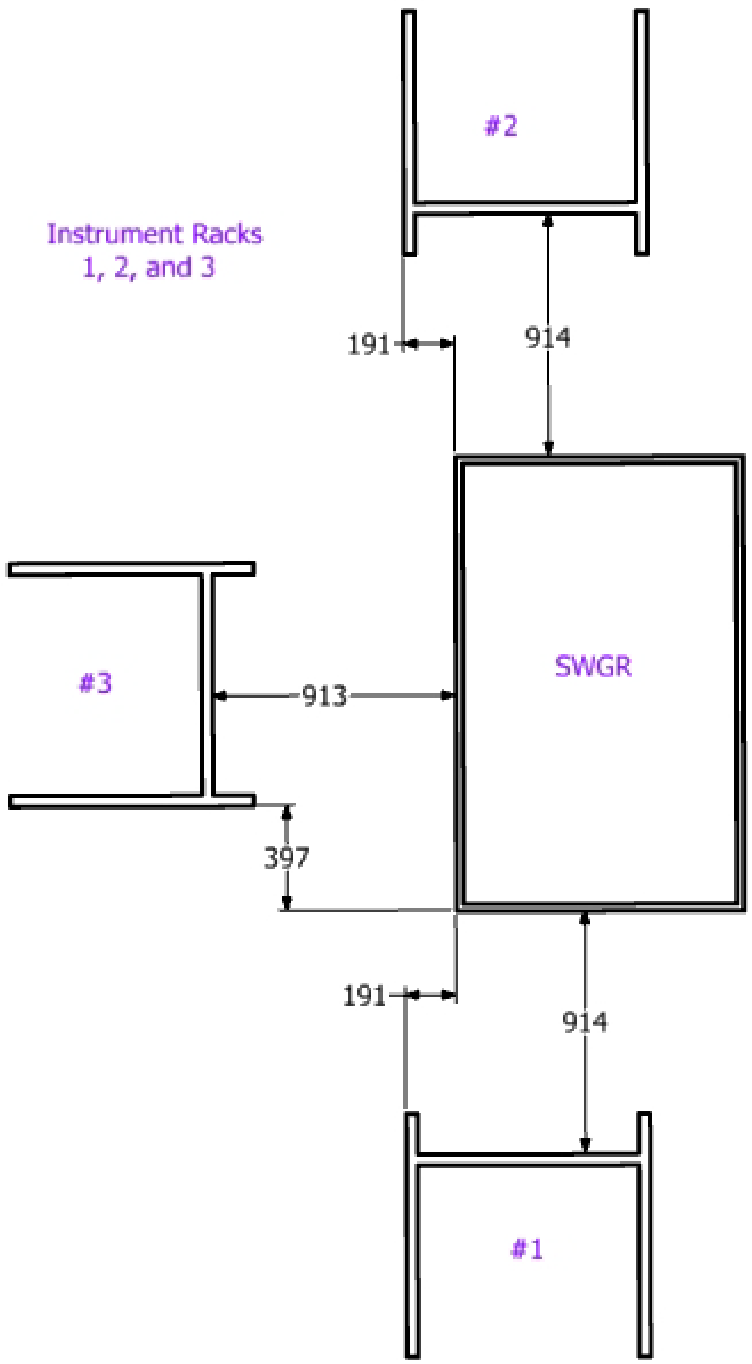


Fig. 20. Plan view of instrument rack configuration around electrical enclosure for Test 2-13A through 2-13G. Dimensions in mm. The switchgear enclosure is approximately 1.080 m (42.5 in) wide, 1.708 m (67.3 in) deep, and 2.337 m (92.0 in) tall.

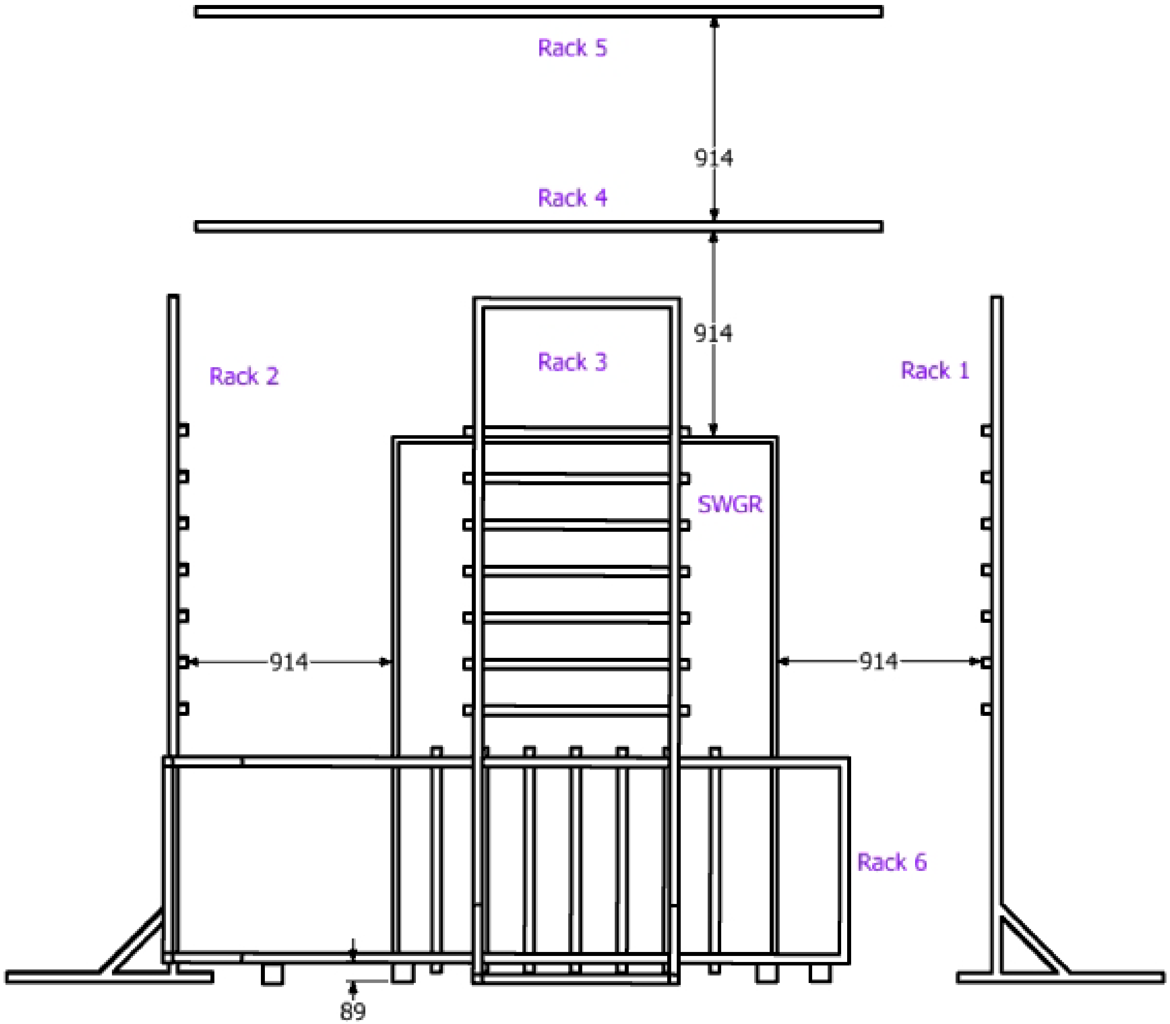


Fig. 21. Elevation view of instrument rack configuration around electrical enclosure for Test 2-18A and 2-18B. Dimensions in mm.

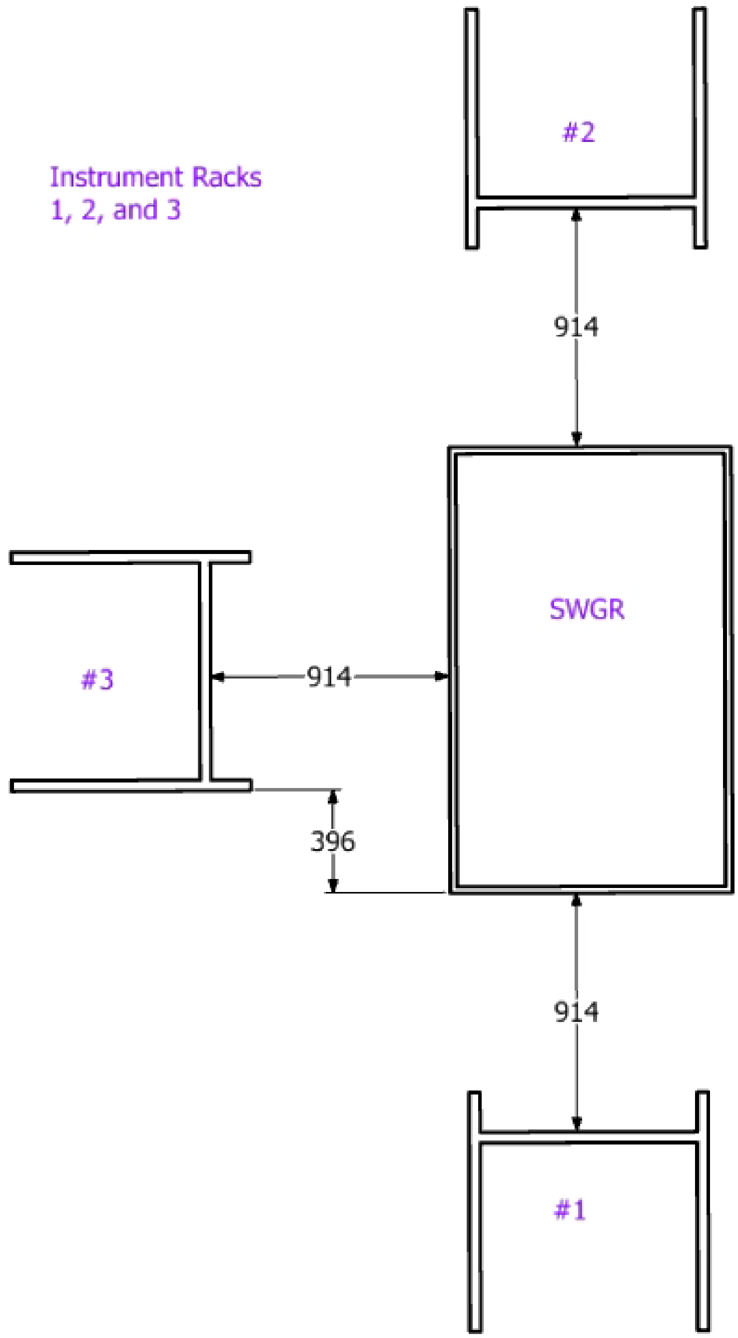


Fig. 22. Plan view of instrument rack configuration around electrical enclosure for Test 2 18A and 2-18B. The enclosure is approximately 1.080 m (42.5 in) wide, 1.708 m (67.3 in) deep, and 2.337 m (92.0 in) tall.

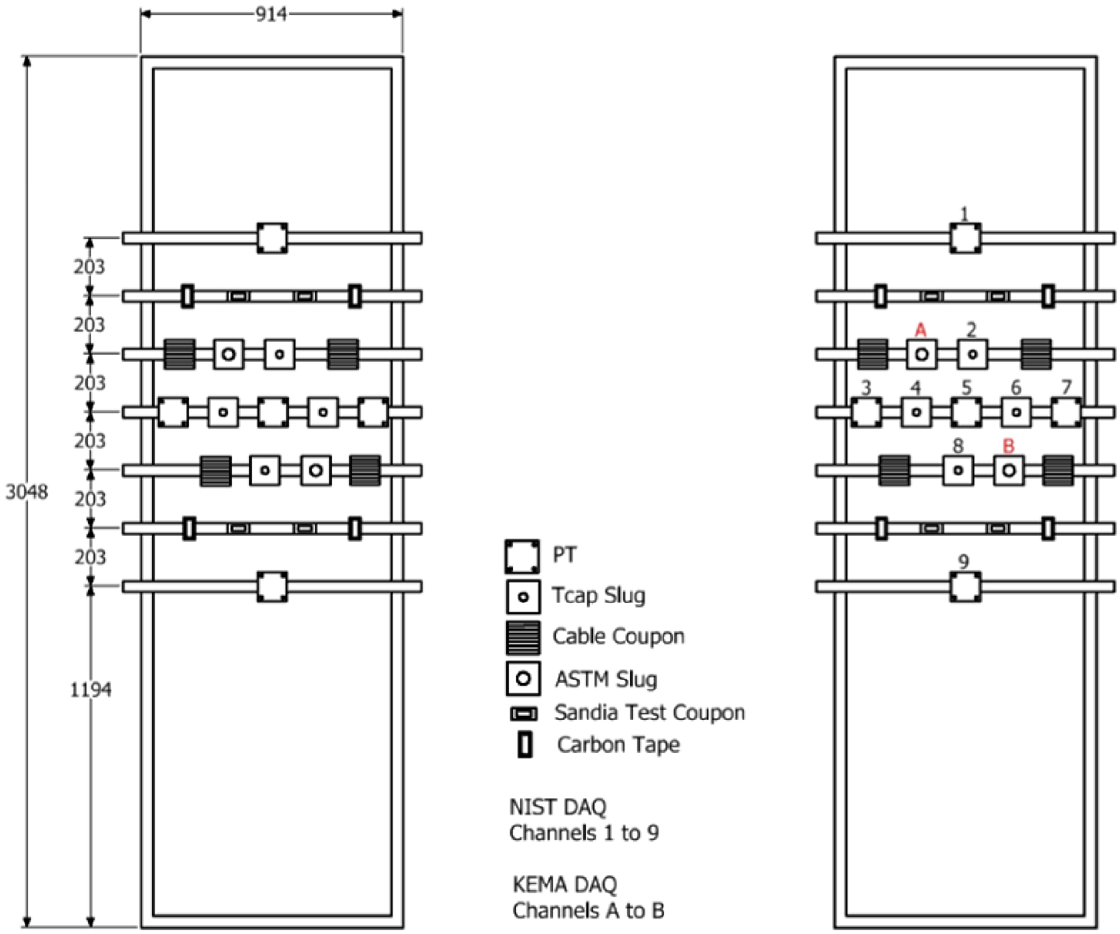


Fig. 23. Illustration of Vertical Instrumentation Rack 1 with data acquisition channels . Dimensions in mm ± 5 mm.

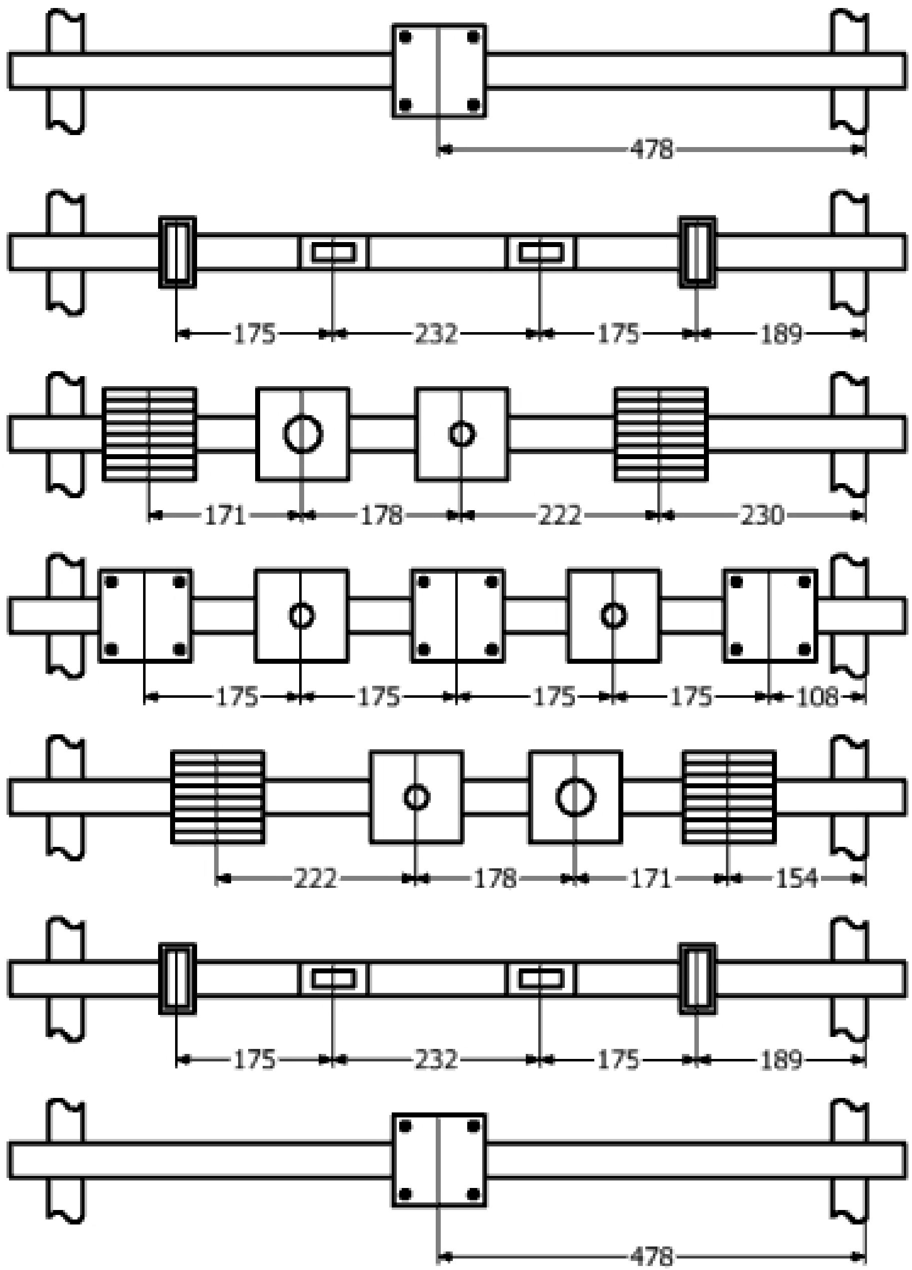


Fig. 24. Detailed Horizontal Locations of Instruments on Instrument Racks 1, 2, 3, 4, 5, and 6. Dimensions in mm ± 5 mm.

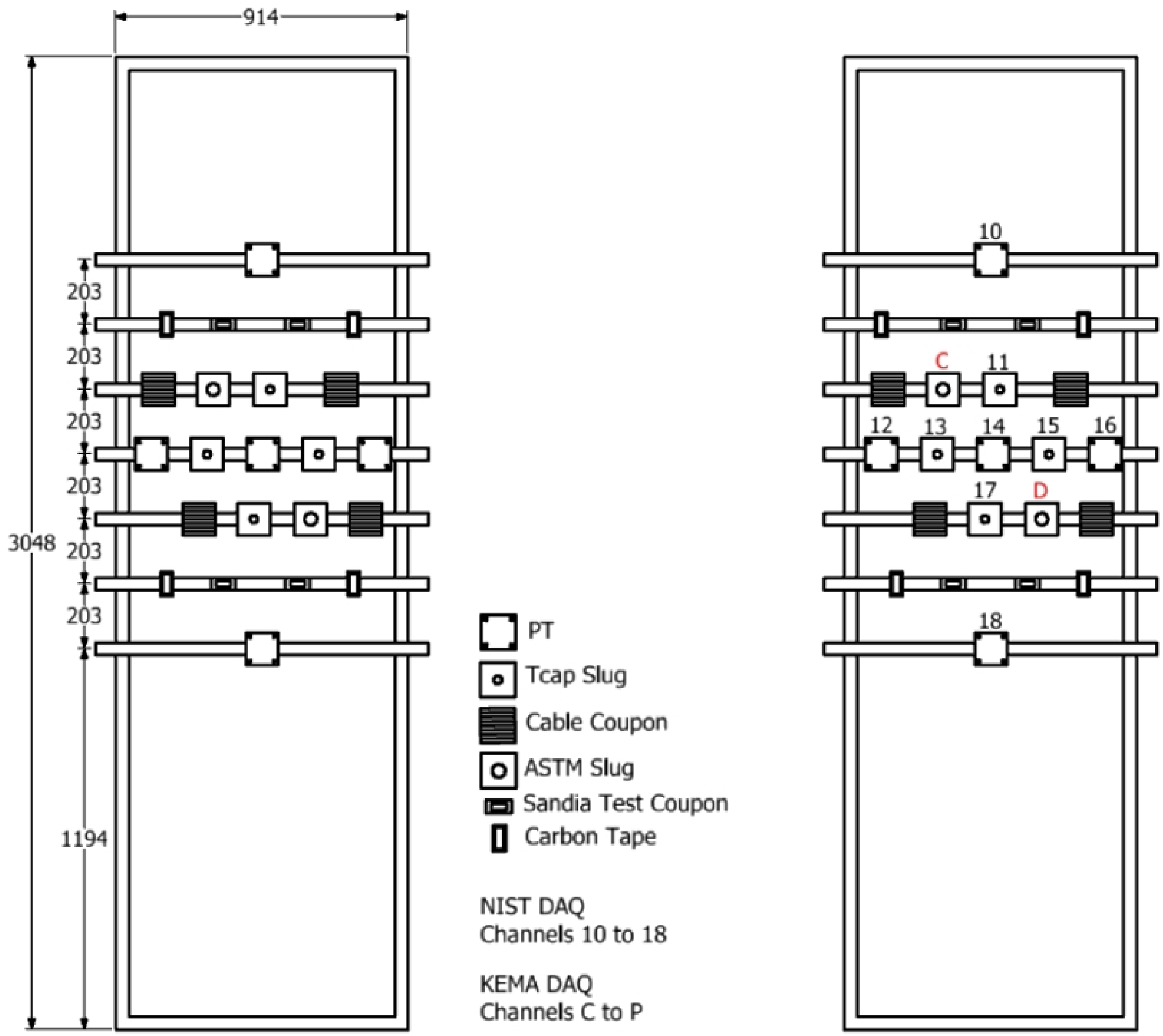


Fig. 25. Illustration of Vertical Instrumentation Rack 2 with data acquisition channels. Dimensions in mm ± 5 mm.

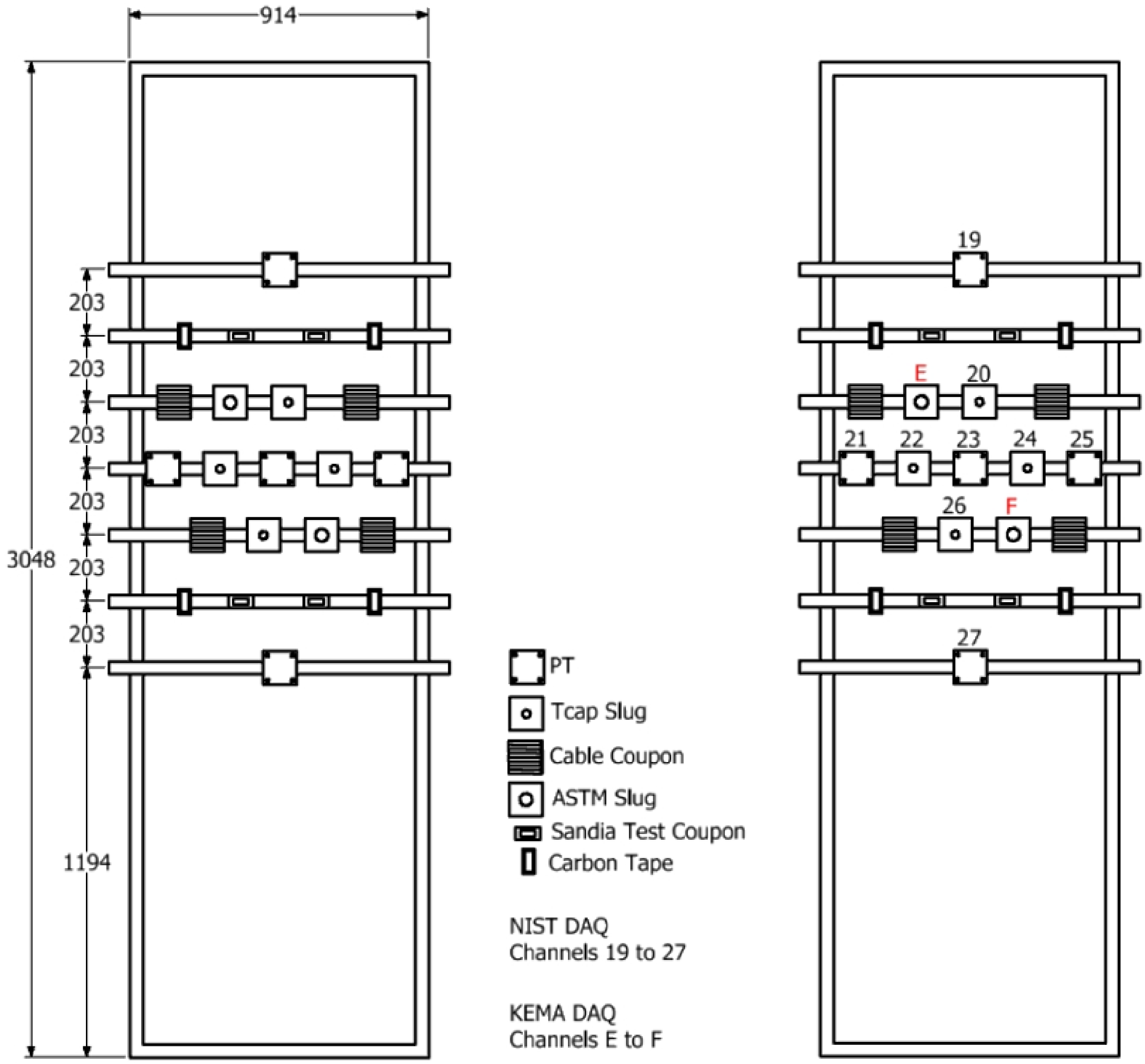


Fig. 26. Illustration of Vertical Instrumentation Rack 3 with data acquisition channels. Dimensions in mm ± 5 mm.

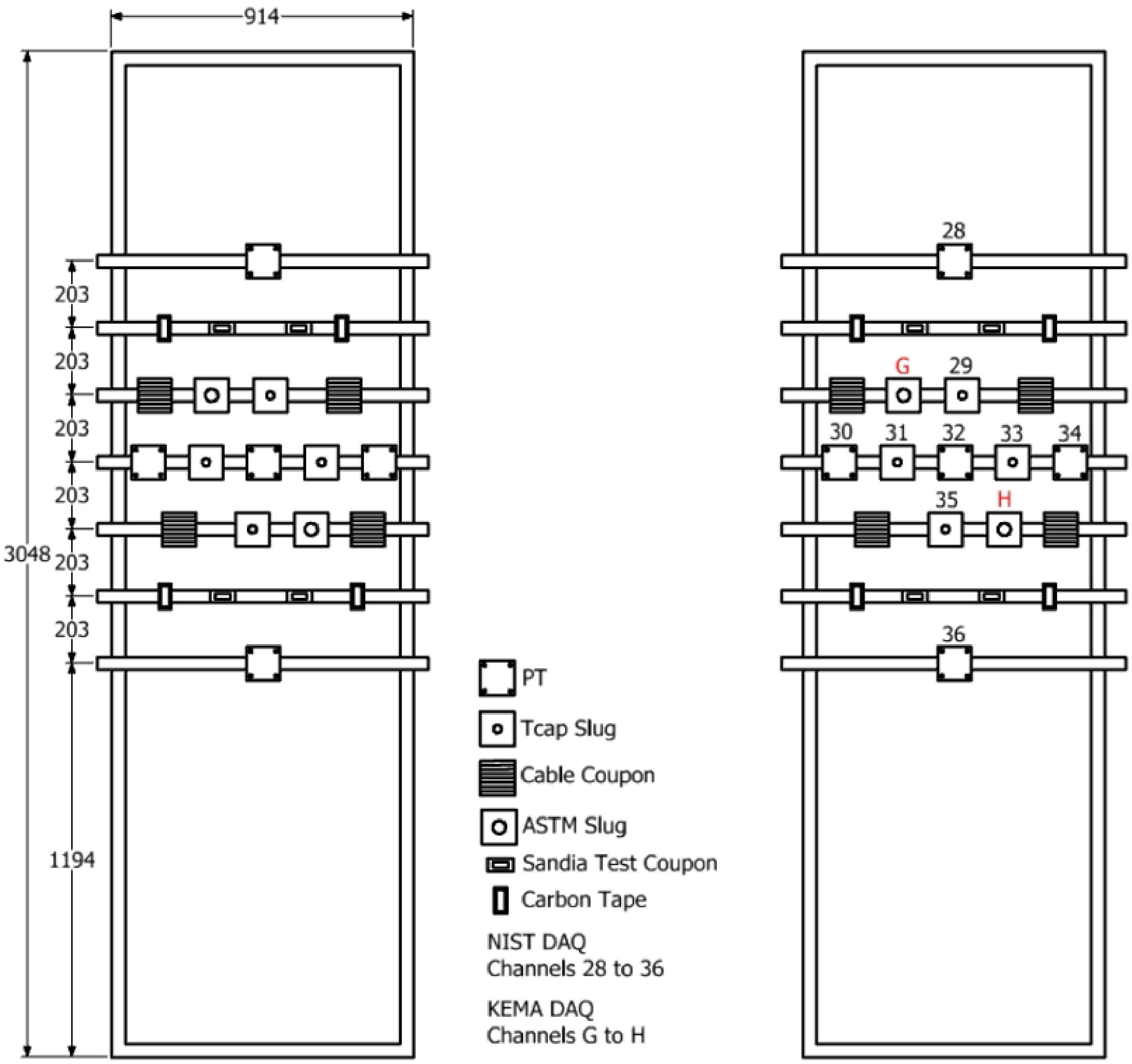


Fig. 27. Illustration of Horizontal Instrumentation Rack 4 with data acquisition channels. Dimensions in mm ± 5 mm. Rack was installed so that the sensors are located approximately 0.91 m (3.00 ft) from the top of the enclosure metal cladding.

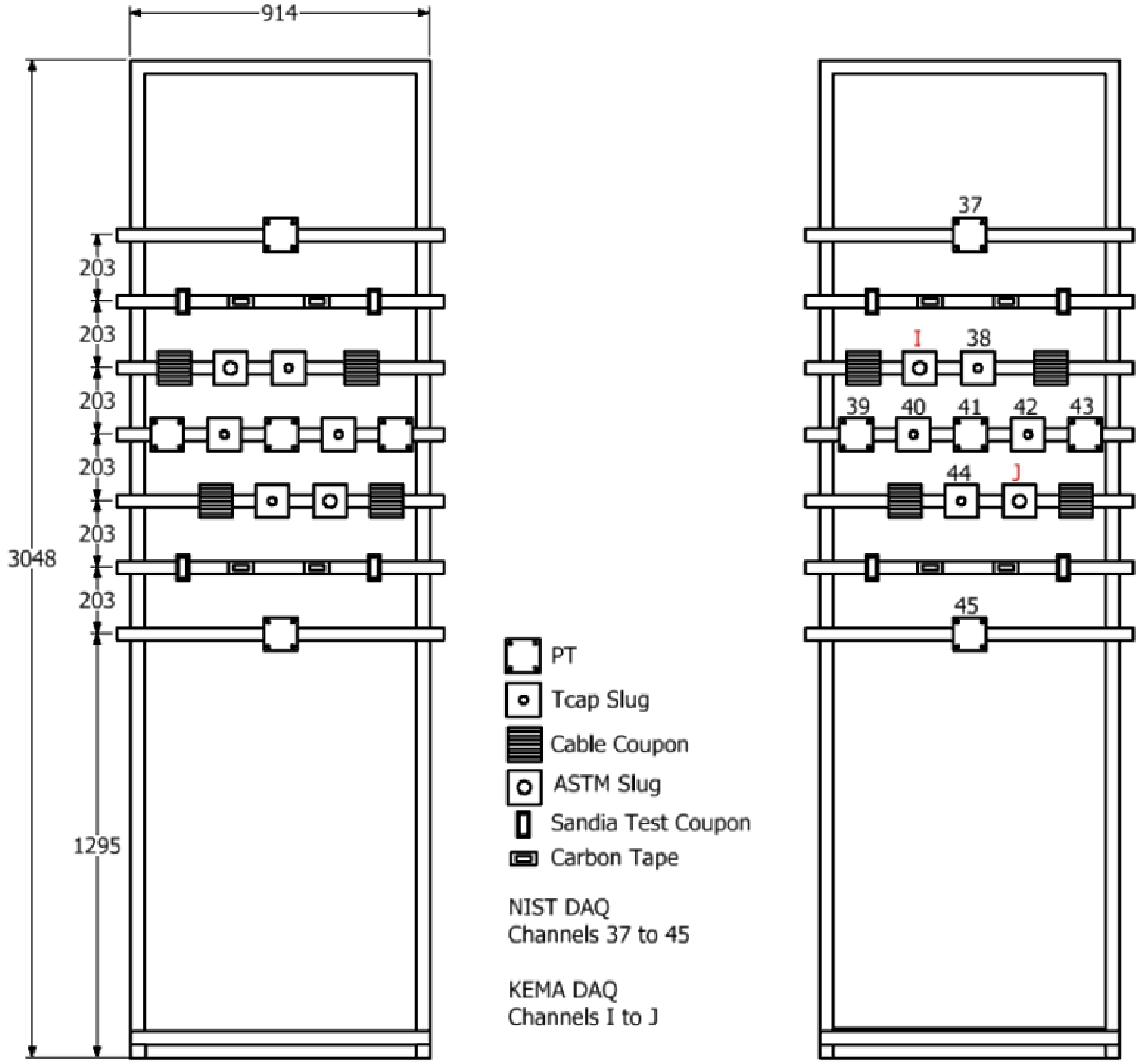


Fig. 28. Illustration of Horizontal Instrumentation Rack 5 with data acquisition channels. Dimensions in mm ± 5 mm. Rack was installed so that the sensors are located approximately 1.83 m (6.00 ft) from the top of the enclosure metal cladding.

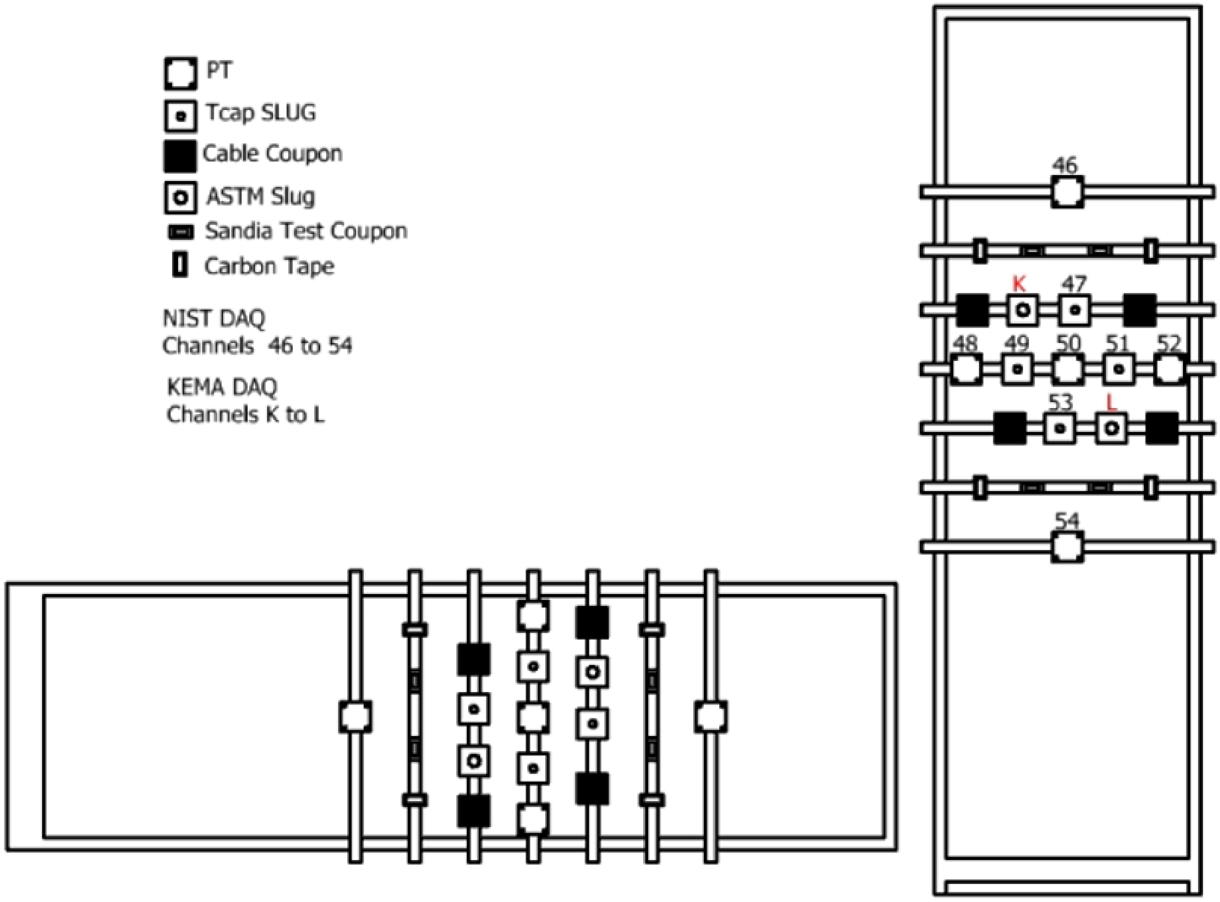


Fig. 29. Illustration of Vertical Instrumentation Rack 6 with data acquisition channels. Dimensions are the same as Instrument Racks 1, 2, 3, 4, and 5. Note that this rack was rotated clockwise 90 degrees as shown on left bottom.

Fig. 30. Photo of Instrumentation Racks for Test 2-13A through Test 2-13G.

Fig. 31. Photo of Instrumentation Racks for Test 2-18A Test 2-18B.

3. Experimental Results

The KEMA Labs performed calibration runs to ensure that the power circuits selected met the desired experimental parameters. The calibrations are measured at a shorting bus within the laboratory's facility, and the actual experimental conditions will be slightly different because of the additional circuit length to the test device and that of the test device. The resulting calibration tests are presented in Table 6, with detail provided in the KEMA report (Appendix C).

Table 6. Circuit Calibration. Measurements are ± 3 percent.

Voltage (V)	Current Sym (kA)	Current Peak (kA)	Circuit
616	13.5	35.6	190826-7001
489	13.5	35.5	190826-7002
619	24.2	52.7	190829-7001
619	25.1	51.0	190829-7002
480	25.7	55.4	190829-7003
480	25.3	34.0	190829-7004

The calibration tests 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 test laboratory's protective device(s). Provided that the arc did not prematurely extinguish prior to the desired arc time, the testing laboratory ensured that the arc duration parameter was met by automatically triggering their protectives devices to open at the specified duration. Because there was a delay in the opening of the circuit (breaker opening time), the actual durations were longer than the desired durations. Table 7 presents the experimental parameter variations performed for these series of experiments.

Table 7. Summary of LV switchgear experiments

Test No. #	Voltage (V) System	Voltage (V) Actual	Voltage (V) Arc	Current (A) Planned	Current (A) Actual	Duration (s) Planned	Duration (s) Actual	Location	Notes
2-13A	480	489	388	13 500	9 800	2.000	0.950	Main bus, top vertical buses, load section	Arc terminated prematurely
2-13B	600	617	421	13 500	9 973	2.000	0.399	Main bus, top vertical buses, load section	Arc terminated prematurely
2-13C	600	617	298	13 500	11 650	2.000	0.413	Main bus, top vertical buses, load section	Arc terminated prematurely
2-13D	600	617	426	13 500	9 266	2.000	0.926	Main bus, top vertical buses, load section	Arc terminated prematurely
2-13E	600	616	305	13 500	10 388	2.000	2.060	Breaker cubicle, middle cube, load section	
2-13F	480	488	302	13 500	9 733	2.000	1.550	Main bus, bottom vertical buses, load section	Arc terminated prematurely
2-13G	600	616	330	13 500	10 707	2.000	2.020	Main bus, bottom vertical buses, supply section	
2-18A	480	427	336	25 000	19 146	8.000	2.020	Main bus, bottom vertical buses, load section	Arc terminated prematurely
2-18B	600	602	415	25 000	19 349	8.000	8.310	Main bus, bottom vertical buses, supply section	

3.1. Test 2-13A – 480 V, 13.5 kA, 2 s duration, main bus top load section

Test 2-13A was performed on August 26, 2019 at 4:55 PM eastern daylight time (EDT). The temperature was approximately 23 °C (73 °F), approximately 51 percent relative humidity and approximately 101.7 kPa of pressure. The weather was mostly cloudy with a 14 km/h (9 mi/h) wind out of the east.

The arc was located near the top of the main bus bar in the load section of the switchgear. The arcing wire installed on the bus and marked up illustrations of the arc wire location is presented in Fig. 32.

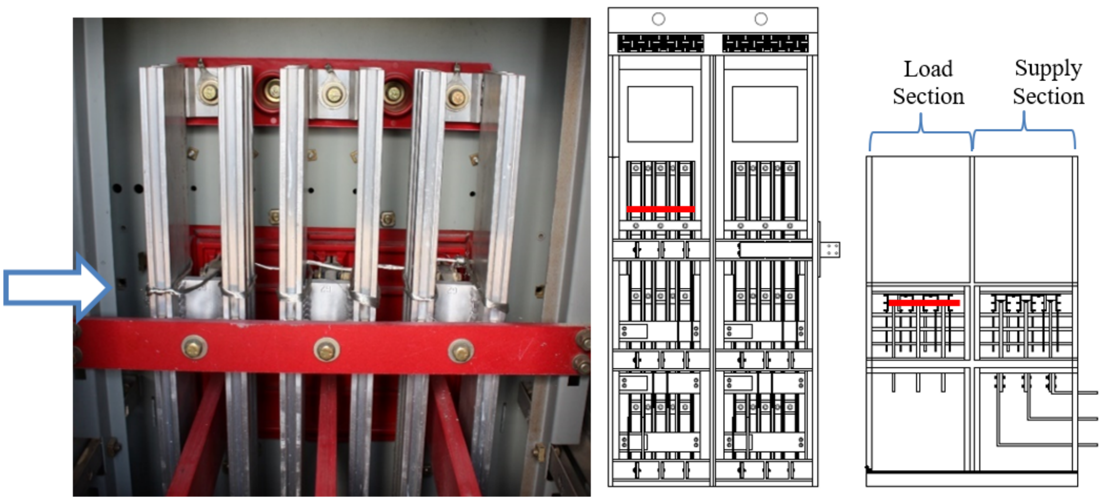


Fig. 32. Shorting wire location Test 2-13A (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right). Shorting location shown in red on illustrations.

3.1.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 8 and include an approximate time reference. Corresponding images are provided in Fig. 33.

The experiment did not arc for the planned 2.0 s. Arcing on all three phases was intermittent for the first 500 ms with a 368 ms phase of no arcing and a brief 62 ms of arcing occurring on phase B and C only. The arcing wire successfully initiated the arc, and the arc moved towards the top of the bars as predicted but it likely extinguished at the top of the bars. There was minimal degradation to the bars themselves and minimal impact on the enclosure and instrument stands.

Table 8. Observations from Test 2-13A

Time (ms)	Observation
0	Initial light observed in top rear louver
50	Particle ejecta observed
150	Particle ejecta reaches first instrument rack immediately above enclosure
250	Luminescent flash zone reaches first instrument rack immediately above enclosure
450	Particle ejecta reaches second instrument rack above enclosure
600	Particle ejecta stream observed on left side of load vertical section extending vertically upward to top instrumentation rack
900	Arc re-strikes
950	Last particle ejecta prior to final arc extinguishment
391 600	NIST data acquisition ends

Fig. 33. Sequence of Images from Test 2-13A (image time stamps are in seconds).

Photograph of the enclosure following the experiment is presented in Fig. 34. The enclosure did not experience a breach.

Fig. 34. Enclosure Post-Test 2-13A.

3.1.1.1.Measurements

Measurements made during Test 2-13A are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.1.1.2.Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 9) and T_{cap} slug measurements (Table 10). The maximum reading is identified with bold text. ASTM Slug Calorimeter measurements are not reported as the data capture did not include pre-test measurements to allow for the calculation of incident energy. This was resolved for future experiments.

Due to the short duration of the arc and no breaching of the exterior skin of the switchgear, the thermal exposures measured outside of the switchgear were very small.

Table 9. Summary of plate thermometer measurements Test 2-13A

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %
1	1	Top	4	1
1	3	Mid-Right	1	0
1	5	Mid-Center	1	0
1	7	Mid-Left	1	0
1	9	Bottom	0	0
2	10	Top	1	0
2	12	Mid-Right	0	0
2	14	Mid-Center	0	0
2	16	Mid-Left	0	0
2	18	Bottom	2	0
3	19	Top	4	1
3	21	Mid-Right	14	0
3	23	Mid-Center	2	0
3	25	Mid-Left	1	0
3	27	Bottom	1	0
4	28	Front	5	1
4	30	Center-Right	**24**	**4**
4	32	Center-Mid	7	3
4	34	Center-Left	4	1
4	36	Back	10.	3

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %
5	37	Front	1	1
5	39	Center-Right	4	2
5	41	Center-Mid	3	1
5	43	Center-Left	2	1
5	45	Back	3	1

Table 10. Summary of T_{cap} slug measurements, Test 2-13A.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	0.2	0.2	1.2
1	4	Mid-Right	0.1	0.0	0.5
1	6	Mid-Left	0.1	0.1	0.6
1	8	Bottom	0.0	0.0	0.4
2	11	Top	0.2	0.0	0.3
2	13	Mid-Right	0.0	0.0	0.1
2	15	Mid-Left	0.2	0.1	0.4
2	17	Bottom	0.0	0.0	0.3
3	20	Top	0.3	0.3	13.0
3	22	Mid-Right	0.2	0.2	11.1
3	24	Mid-Left	0.8	0.2	10.7
3	26	Bottom	0.2	0.0	10.3
4	29	Front	1.6	1.7	14.2
4	31	Center-Right	**3.3**	2.7	21.3
4	33	Center-Left	1.6	1.8	14.3
4	35	Back	2.7	**2.8**	**17.9**
5	38	Front	1.0	0.7	5.1
5	40	Center-Right	1.3	1.1	7.3
5	42	Center-Left	0.9	0.7	4.4
5	44	Back	0.6	0.6	5.1

3.1.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 35. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the main bus compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the primary cable connection compartment is approximately 10 kPa (1.5 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 4 kPa (0.6 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

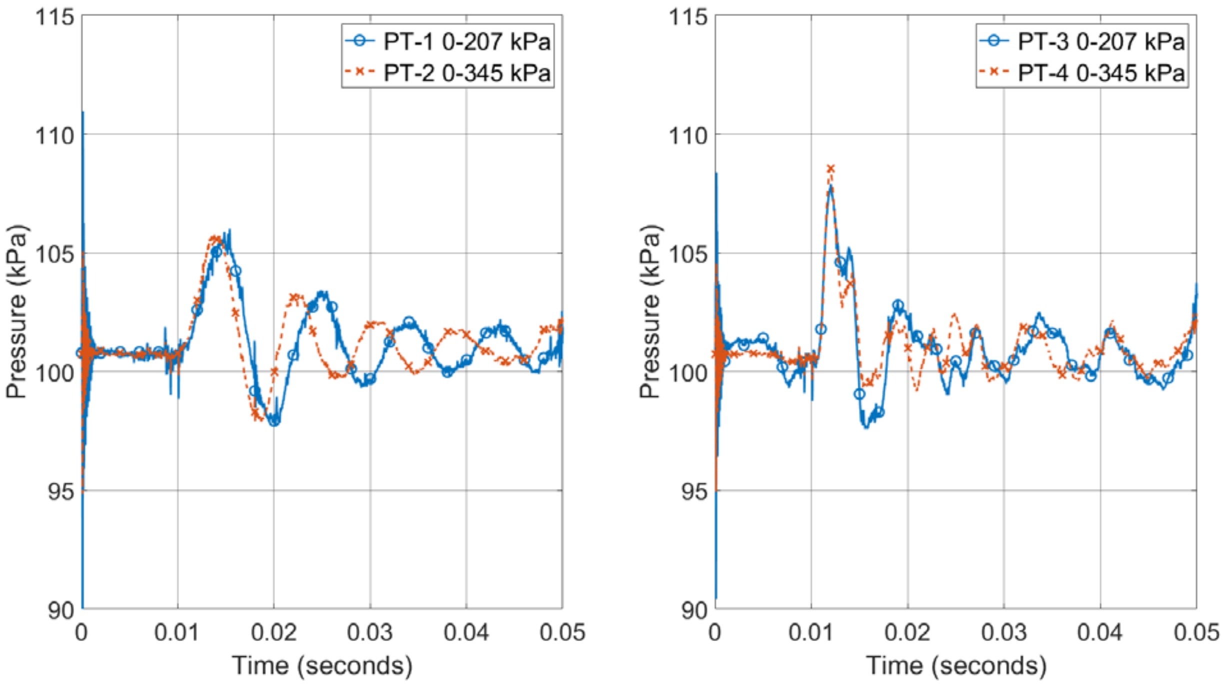


Fig. 35. Pressure measurements from Test 2-13A (breaker compartment (left); Main bus [arcing compartment] – (right)). Measurement uncertainty ± 3 percent.

3.1.1.4. Electrical measurements

Test 2-13A used KEMA circuit S06 and is reported in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.489 kV, 13.5 kA symmetrical, and 35.5 kA peak. The KEMA report (Appendix C) identifies this experiment as 190826-7003. Key experimental measurements are presented in Table 11. Plots of the electrical measurements are presented in Appendix B.

Table 11. Key measurement from Test 2-13A. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	282	282	282
Applied voltage, phase-to-phase	kV_{RMS}		488	
Making current	kA_{peak}	24.0	23.8	-28.7
Current, a.c. component, beginning	kA_{RMS}	10.7	11.9	10.2
Current, a.c. component, middle	kA_{RMS}	7.52	9.15	5.89
Current, a.c. component, end	kA_{RMS}	7.98	4.04	5.44
Current, a.c. component, average	kA_{RMS}	8.78	9.35	7.71
Current, a.c. component, three-phase average	kA_{RMS}		8.61	
Duration	s	0.519	0.519	0.519
Arc Energy	MJ		1.65	

3.2. Test 2-13B – 600 V, 13.5 kA, 2 s duration, main bus top load section

Test 2-13B was performed on August 27, 2019 at 9:01 AM eastern daylight time (EDT). The temperature was approximately 20 °C (68 °F), approximately 73 percent relative humidity and approximately 101.6 kPa of pressure. The weather was cloudy with a 11 km/h (7 mi/h) wind out of the northeast.

The switchgear used in Test 2-13A was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arc was located near the top of the main bus bar in the load section of the switchgear. Two 10 AWG bare stranded conductors were used to initiate the arc. The arcing wire installed on the bus and marked up illustrations of the arc wire location is presented in Fig. 36.

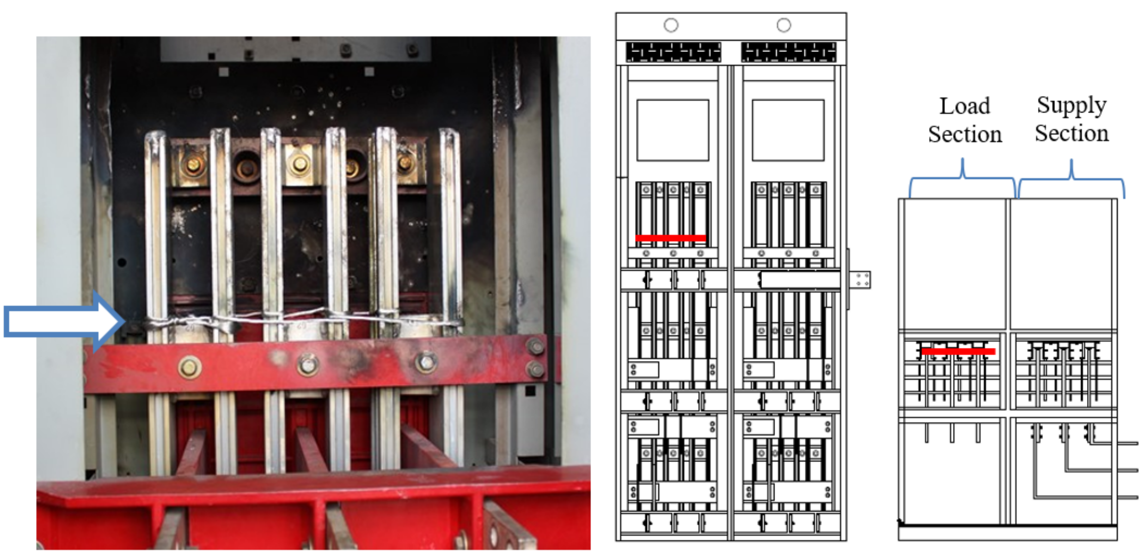


Fig. 36. Shorting wire location Test 2-13B (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), Plan View (right). Shorting location shown in red on illustrations.

3.2.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 12 and include an approximate time reference. Corresponding images are provided in Fig. 37.

The experiment did not arc for the planned 2.0 s. Arcing on all three phases was intermittent for the first 400 ms. The arcing wire successfully initiated the arc, and the arc moved towards the top of the bars as predicted but it likely extinguished at the top of the bars. There was minimal degradation to the bars themselves and minimal impact on the enclosure and instrument stands.

Table 12. Observations from Test 2-13B

Time (ms)	Observation
0	Initial light observed in top rear louver
66	Particle ejecta reaches first instrument rack immediately above enclosure
150	Particle ejecta reaches second instrument rack above enclosure
200	Luminescent flash zone reaches first instrument rack immediately above enclosure
250	Particle ejecta continue to be vertically oriented and localized to left side of load vertical section
333	Particle ejecta stream observed on left and right side of switchgear.
400	Luminescent intensity diminishing
450	Last particle ejecta at arc extinguishment
358 000	NIST data acquisition ends

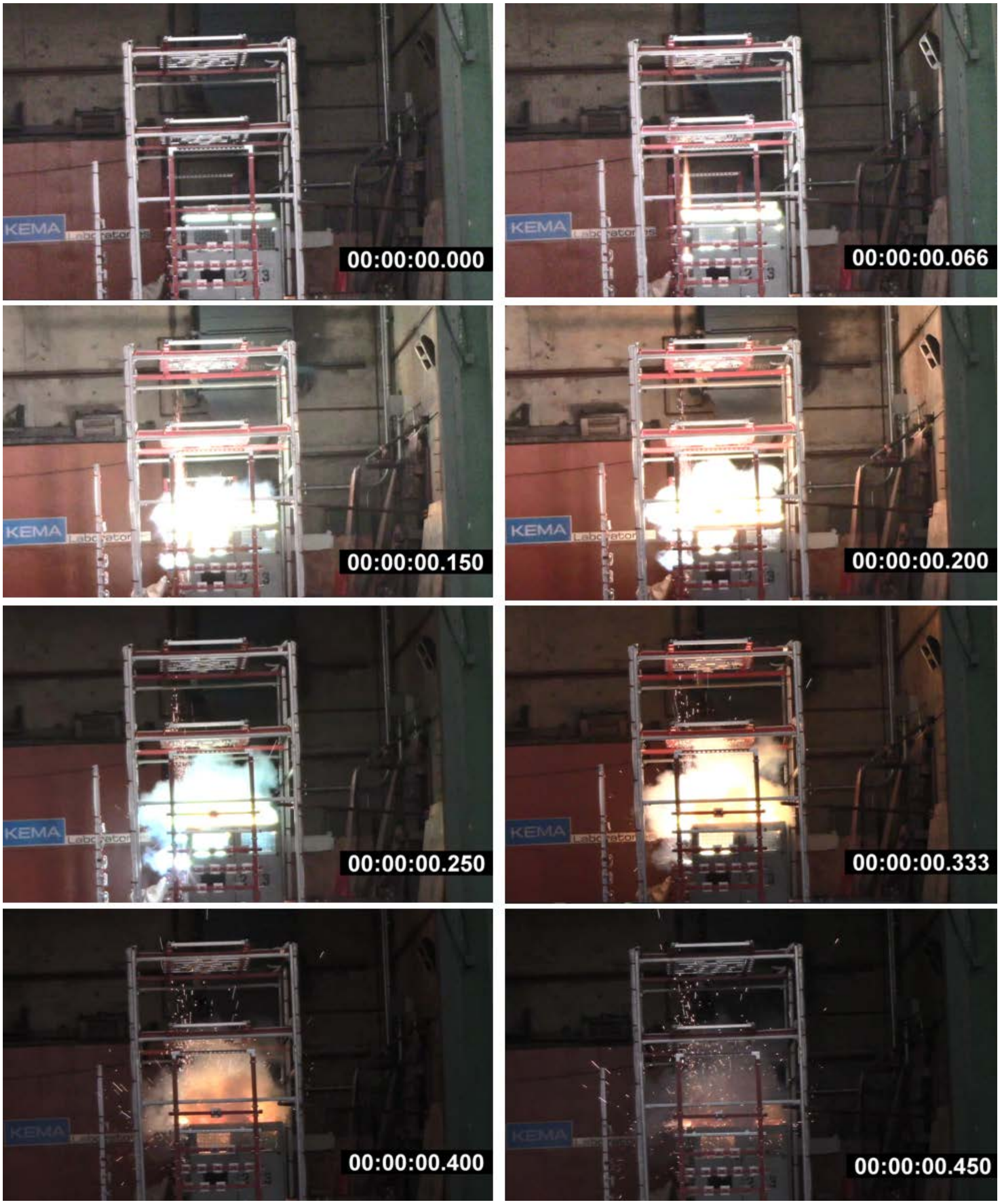


Fig. 37. Sequence of Images from Test 2-13B (image time stamps are in seconds).

Photograph of the enclosure following the experiment is presented in Fig. 38. The enclosure did not experience a breach.

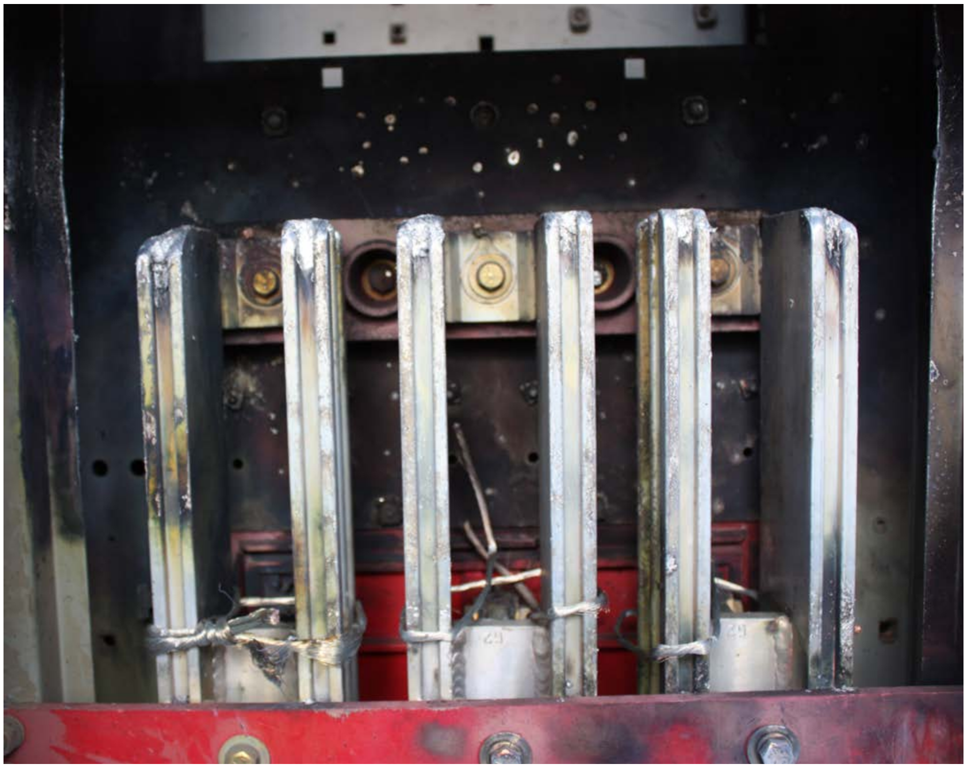


Fig. 38. Enclosure Post-Test 2-13B.

3.2.1.1. Measurements

Measurements made during Test 2-13B are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical
  - Voltage profiles
  - Current profiles
  - Power and energy profiles

3.2.1.2.Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 13), ASTM Slug Calorimeter measurements (Table 14), and T_{cap} slug measurements (Table 15). The maximum reading is identified with bold text. For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

Due to the short duration of the arc and no breaching of the exterior skin of the switchgear, the thermal exposures measured outside of the switchgear were very small.

Table 13. Summary of plate thermometer measurements Test 2-13B.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ±1 kW/m^2 or ± 5 %	Comment
1	1	Top	2	0	
1	3	Mid-Right	9	0	
1	5	Mid-Center	0	0	
1	7	Mid-Left	0	0	
1	9	Bottom	0	0	
2	10	Top	0	0	
2	12	Mid-Right	0	0	
2	14	Mid-Center	0	0	
2	16	Mid-Left	0	0	
2	18	Bottom	0	0	
3	19	Top	5	0	
3	21	Mid-Right	--	0	EMI S/N
3	23	Mid-Center	3	0	
3	25	Mid-Left	1	0	
3	27	Bottom	1	0	
4	28	Front	4	1	
4	30	Center-Right	6	2	
4	32	Center-Mid	**15**	**3**	

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ±1 kW/m^2 or ± 5 %	Comment
4	34	Center-Left	6	1	
4	36	Back	9	2	
5	37	Front	1	1	
5	39	Center-Right	2	1	
5	41	Center-Mid	2	1	
5	43	Center-Left	2	1	
5	45	Back	3	1	

Table 14. Summary of ASTM slug calorimeter measurements, Test 2-13B.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	1	0.6
1	B	Bottom	1	12.6
2	C	Top	1	5.6
2	D	Bottom	1	5.6
3	E	Top	1	17.8
3	F	Bottom	1	17.8
4	G	Rear	6	15.5
4	H	Front	6	18.6
5	I	Rear	4	18.7
5	J	Front	2	5.2

Table 15. Summary of T_{cap} slug measurement, Test 2-13B.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	0.2	0.2	3.6
1	4	Mid-Right	0.1	0.3	2.1
1	6	Mid-Left	0.0	0.0	1.8
1	8	Bottom	0.1	0.1	1.0
2	11	Top	0.2	0.0	0.0
2	13	Mid-Right	0.1	0.0	0.2

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %
2	15	Mid-Left	0.1	0.0	0.1
2	17	Bottom	0.2	0.1	0.2
3	20	Top	0.3	0.5	12.7
3	22	Mid-Right	0.3	0.4	11.4
3	24	Mid-Left	0.3	0.5	12.3
3	26	Bottom	0.1	0.2	8.3
4	29	Front	1.6	3.4	15.7
4	31	Center-Right	1.7	4.2	**19.9**
4	33	Center-Left	**2.1**	4.2	15.4
4	35	Back	1.8	**4.4**	19.4
5	38	Front	0.9	1.3	4.6
5	40	Center-Right	0.7	1.1	4.7
5	42	Center-Left	0.7	1.0	3.4
5	44	Back	0.7	1.1	3.7

3.2.1.3. 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 decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 5 kPa (0.7 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.4 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

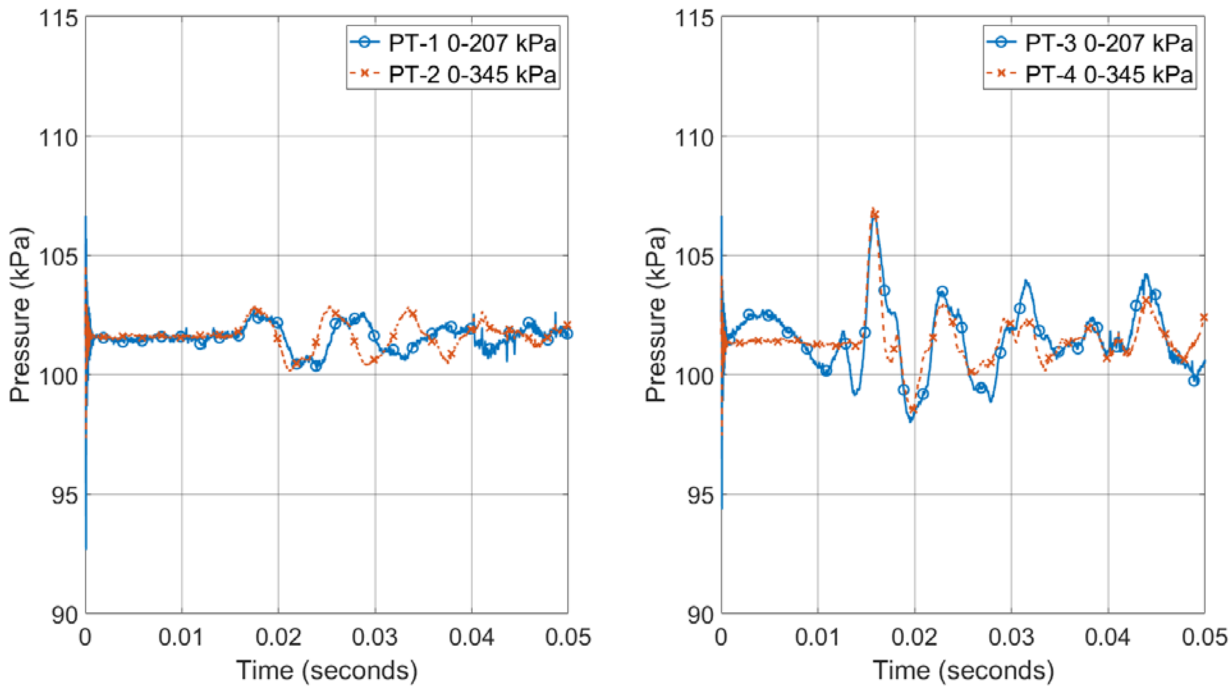


Fig. 39. Pressure measurements from Test 2-13B (breaker compartment (left); Main bus [arcing compartment] (right). Measurement uncertainty ± 3 percent.

3.2.1.4. Electrical measurements

Test 2-13B used KEMA circuit S07 and is reported in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190827-7001. Key experimental measurements are presented in Table 16. Plots of the electrical measurements are presented in Appendix B.

Table 16. Key measurement from Test 2-13B. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	356	356	356
Applied voltage, phase-to-phase	kV_{RMS}	617		
Making current	kA_{peak}	24.7	28.5	-34.3
Current, a.c. component, beginning	kA_{RMS}	13.4	14.0	2.05
Current, a.c. component, middle	kA_{RMS}	8.76	7.33	6.74
Current, a.c. component, end	kA_{RMS}	0.00	0.00	7.95
Current, a.c. component, average	kA_{RMS}	9.91	9.46	8.27
Current, a.c. component, three-phase average	kA_{RMS}	9.22		
Duration	s	0.332	0.332	0.396
Arc Energy	MJ	1.38		

3.3. Test 2-13C – 600 V, 13.5 kA, 2 s duration, main bus top load section

Test 2-13C was performed on August 27, 2019 at 10:19 AM eastern daylight time (EDT). The temperature was approximately 21 °C (70 °F), approximately 68 percent relative humidity and approximately 101.9 kPa of pressure. The weather was cloudy with a 11.3 km/h (7 mi/h) wind out of the east.

The switchgear used in Tests 2-13A and 2-13B was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arc was located near the top of the main bus bar in the load section of the switchgear. A single 10 AWG bare stranded conductors were used to initiate the arc. Due to the previous two experiments not maintaining the arc for the planned arc duration, a shorting plate was added near the top of the vertical main bus bars to allow for arc attachment and reduce the likelihood self-extinguishment. The grounding place was approximately 18 cm (7 in) above the top of the vertical main bus bars. This distance was selected based on available attachment points within the switchgear and discussion with the NRC/RES – EPRI HEAF working group and their review of applicable drawings. The arcing wire installed on the bus, ground plate, and marked up illustrations of the arc wire location is presented in Fig. 40.

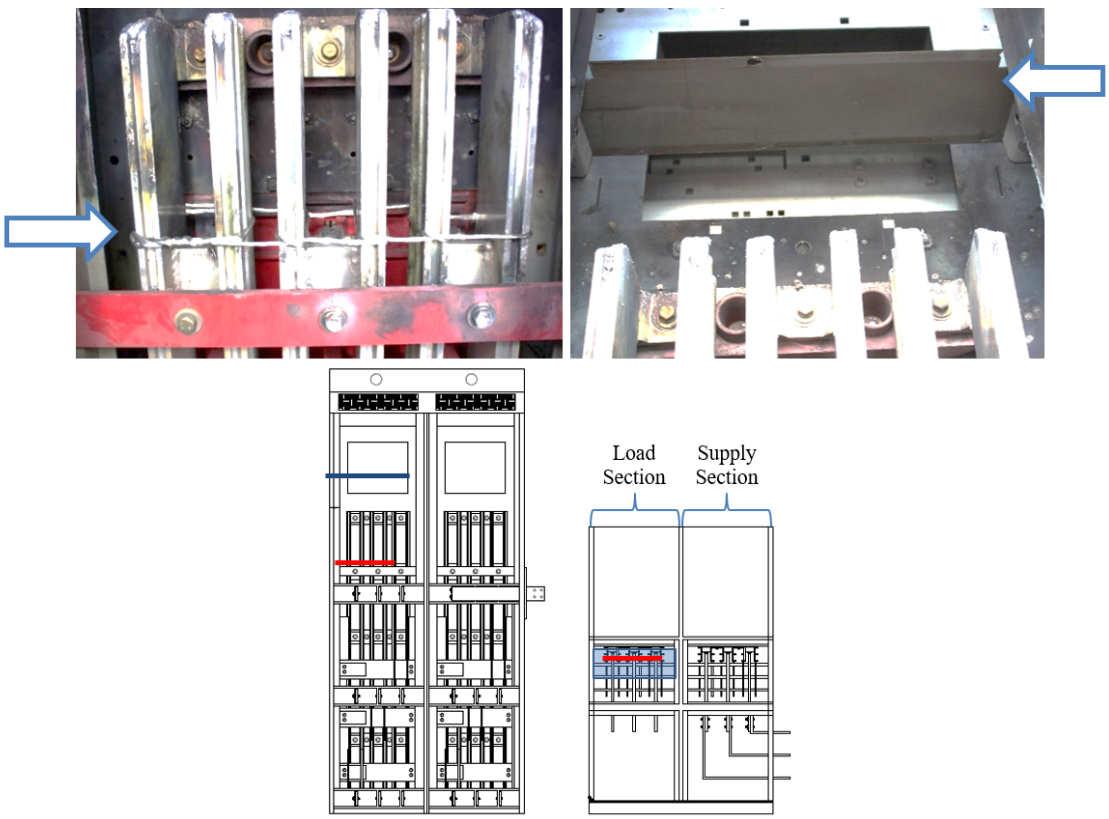


Fig. 40. Shorting Wire Location Test 2-13C (Phases left-to-right: A-B-C) (top left); grounding plate (top right); illustration of shorting wire (red) and grounding plate (blue) locations (bottom left) elevation view and plan view (bottom right).

3.3.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 17 and include an approximate time reference. Corresponding images are provided in Fig. 41.

The experiment did not arc for the planned 2.0 s. Arcing on all three phases was less intermittent than previous experiments but still extinguished at approximately 413 ms. The arcing wire successfully initiated the arc, and the arc moved towards the top of the bars as predicted. There is no apparent evidence of arc damage to the ground plate due to arc root attachment; however, there is some metal splatter and mild soot covering the plate. It is likely that the gap was too large to support arc attachment and sustained ignition. There was minimal degradation to the bars themselves and minimal impact on the enclosure and instrument stands.

Table 17. Observations from Test 2-13C.

Time (ms)	Observation
0	Initial light observed in top rear louver
66	Initial particle ejecta observed
100	Particle ejecta reaches first instrument rack immediately above enclosure
150	Luminescent flash zone reaches first instrument rack immediately above enclosure
250	Luminescent flash zone expands horizontally
350	Particle ejecta reaches second instrument rack above enclosure
400	Luminescent flash zone intensity diminishing
450	Last particle ejecta at arc extinguishment
686 500	NIST data acquisition ends

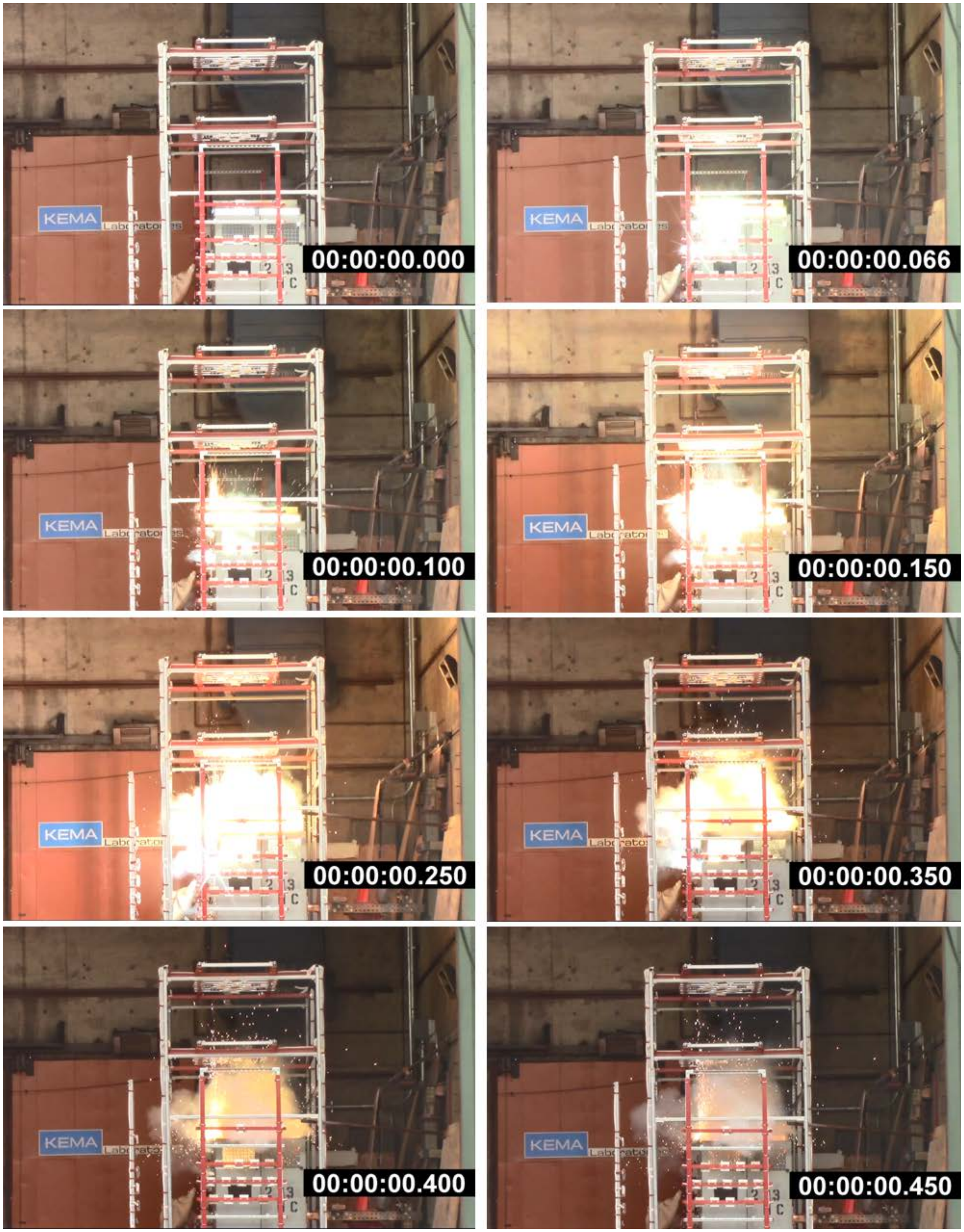


Fig. 41. Sequence of Images from Test 2-13C (image time stamps are in seconds).

Photographs of the enclosure following the experiment is presented in Fig. 42. The enclosure did not experience a breach.

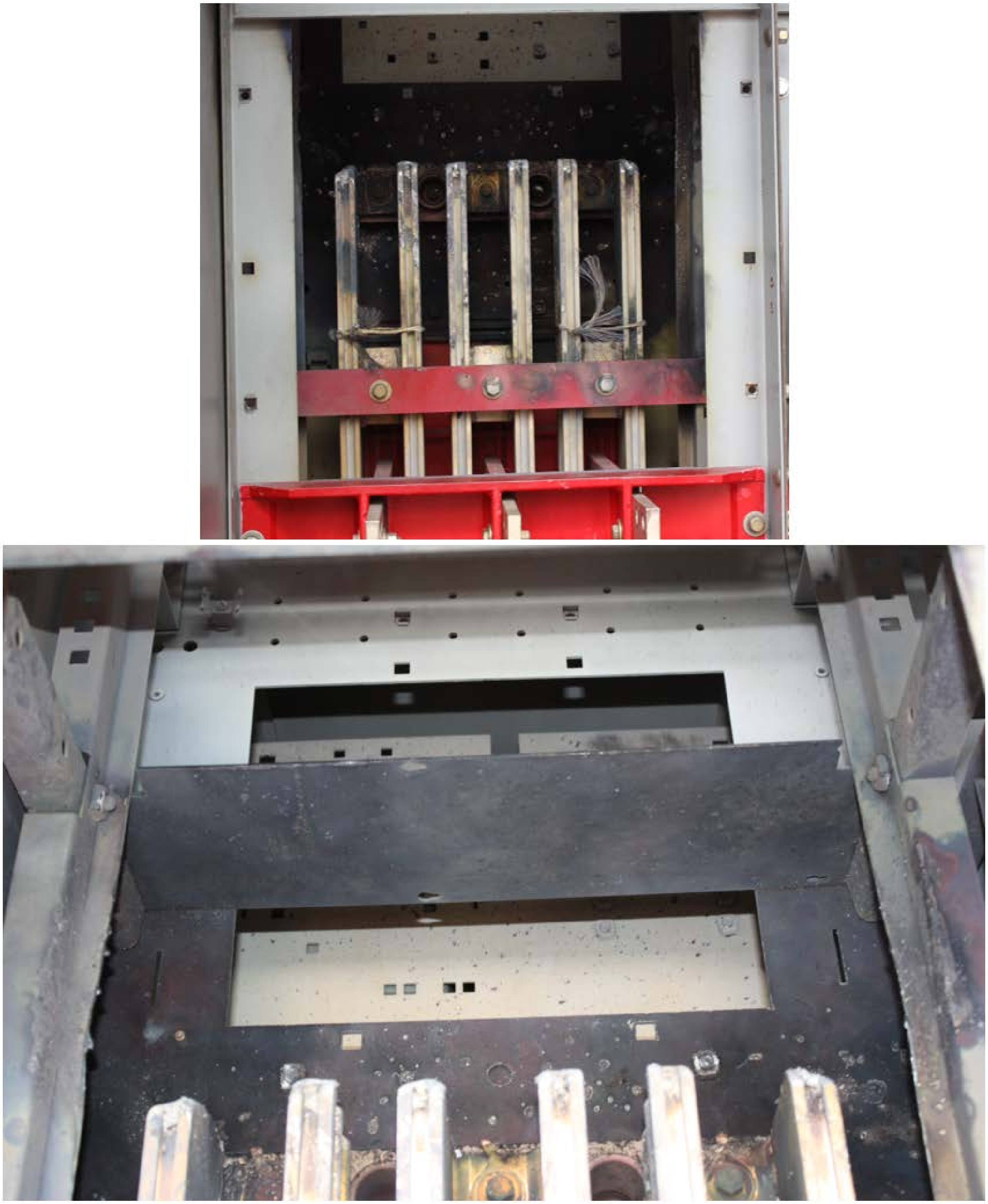


Fig. 42. Enclosure Post-Test 2-13C. Top photo showing top of vertical main buses. Bottom photo.

3.3.1.1. Measurements

Measurements made during Test 2-13C are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.3.1.2. Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 18), ASTM Slug Calorimeter measurements (Table 19), and T_{cap} slug measurements (Table 20). The maximum reading is identified with bold text. For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

Due to the short duration of the arc and no breaching of the exterior skin of the switchgear, the thermal exposures measured outside of the switchgear were very small.

Table 18. Summary of plate thermometer measurements Test 2-13C.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
1	1	Top	3	0	
1	3	Mid-Right	0	0	
1	5	Mid-Center	7	0	
1	7	Mid-Left	1	0	
1	9	Bottom	1	0	
2	10	Top	0	0	
2	12	Mid-Right	0	0	

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
2	14	Mid-Center	0	0	
2	16	Mid-Left	0	0	
2	18	Bottom	0	0	
3	19	Top	3	0	
3	21	Mid-Right	––	0	EMI S/N
3	23	Mid-Center	2	0	
3	25	Mid-Left	1	0	
3	27	Bottom	0	0	
4	28	Front	3	0	
4	30	Center-Right	5	2	
4	32	Center-Mid	**13**	**3**	
4	34	Center-Left	7	1	
4	36	Back	9	2	
5	37	Front	1	0	
5	39	Center-Right	2	1	
5	41	Center-Mid	1	1	
5	43	Center-Left	2	0	
5	45	Back	3	0	

Table 19. Summary of ASTM slug calorimeter measurements, Test 2-13C.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	0	N/A
1	B	Bottom	1	120
2	C	Top	1	123
2	D	Bottom	1	121
3	E	Top	5	122
3	F	Bottom	5	119
4	G	Rear	7	122
4	H	Front	9	96
5	I	Rear	4	108
5	J	Front	4	38

Table 20. Summary of T_{cap} slug measurement, Test 2-13C.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %
1	2	Top	0.2	0.3	19.8
1	4	Mid-Right	0.1	0.0	16.6
1	6	Mid-Left	0.1	0.1	21.9
1	8	Bottom	0.1	0.2	20.9
2	11	Top	0.0	0.0	2.0
2	13	Mid-Right	0.0	0.1	5.1
2	15	Mid-Left	0.1	0.1	1.1
2	17	Bottom	0.2	0.0	5.4
3	20	Top	0.2	0.3	18.2
3	22	Mid-Right	0.2	0.5	23.4
3	24	Mid-Left	0.2	0.2	25.6
3	26	Bottom	0.2	0.2	19.5
4	29	Front	1.6	3.3	5.6
4	31	Center-Right	**2.1**	**4.3**	**29.5**
4	33	Center-Left	1.4	3.0	21.3
4	35	Back	1.8	3.4	15.7
5	38	Front	0.8	0.9	2.6
5	40	Center-Right	0.6	0.8	2.6

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m²) ± 1.5 kW/m² or ± 2.9 %	Incident Energy During Arc Phase (kJ/m²) ± 2.4 kJ/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 2.4 kJ/m² or ± 5 %
5	42	Center-Left	0.6	0.6	3.2
5	44	Back	0.5	0.6	3.5

3.3.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 43. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 5 kPa (0.7 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.4 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

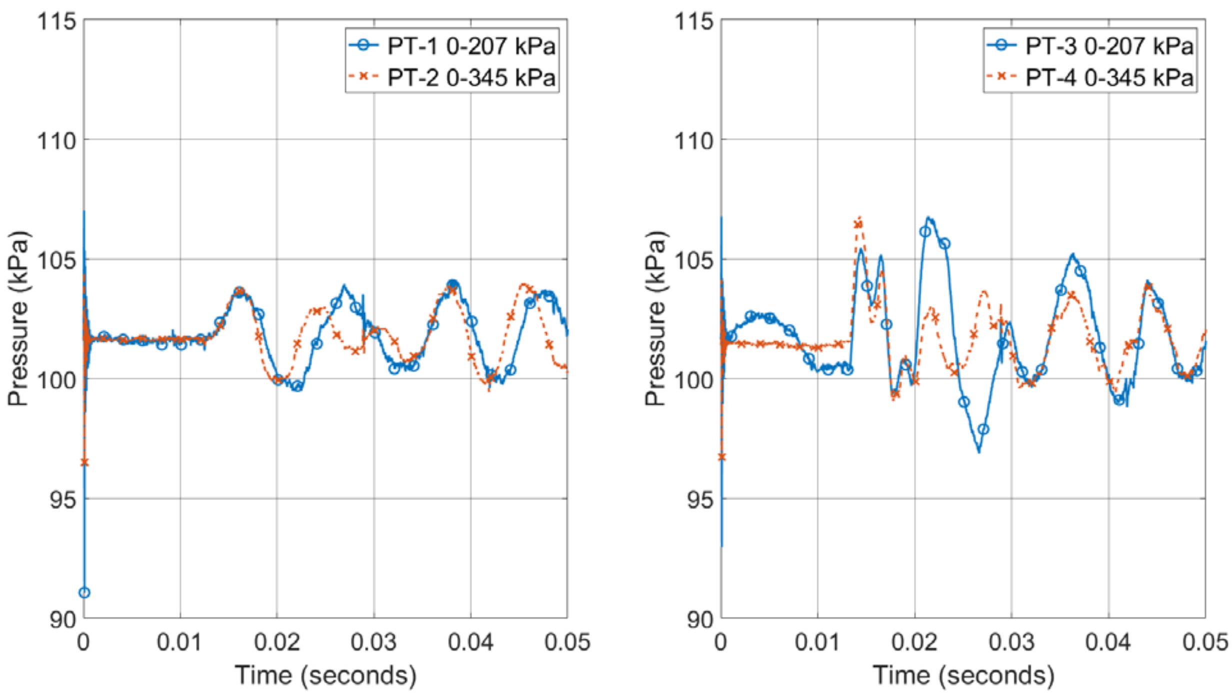


Fig. 43. Pressure measurements from Test 2-13C (breaker compartment (left); Main bus [arcing compartment] (right). Measurement uncertainty ± 3 percent.

3.3.1.4. Electrical measurements

Test 2-13C used KEMA circuit S07 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. Key experimental measurements are presented in Table 21. The KEMA test report identifies this experiment as 190827-7002. Plots of the electrical measurements are presented in Appendix B.

Table 21. Key measurement from Test 2-13C. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	356	356	356
Applied voltage, phase-to-phase	kV_{RMS}	617		
Making current	kA_{peak}	25.0	26.1	-34.4
Current, a.c. component, beginning	kA_{RMS}	13.4	13.2	11.0
Current, a.c. component, middle	kA_{RMS}	8.92	9.14	10.2
Current, a.c. component, end	kA_{RMS}	7.93	4.10	8.05
Current, a.c. component, average	kA_{RMS}	11.5	10.2	9.09
Current, a.c. component, three-phase average	kA_{RMS}	10.3		
Duration	s	0.405	0.405	0.404
Arc Energy	MJ	1.68		

3.4. Test 2-13D – 600 V, 13.5 kA, 2 s duration, breaker stabs (copper) top load section

Test 2-13D was performed on August 27, 2019 at 1:25 PM eastern daylight time (EDT). The temperature was approximately 24 °C (75 °F), approximately 62 percent relative humidity and approximately 101.7 kPa of pressure. The weather was cloudy and raining with an 8 km/h (5 mi/h) wind out of the southeast.

The switchgear used in Tests 2-13A, 2-13B, and 2-13C was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arcing wire was located around the copper breaker stabs in the main bus section at the top load breaker in the load breaker vertical section. All three phases were shorted with the shorting wire. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance. A single 10 AWG bare stranded conductors were used to initiate the arc. The arcing wire installed on the bus and marked up illustrations of the arc wire location is presented in Fig. 44.

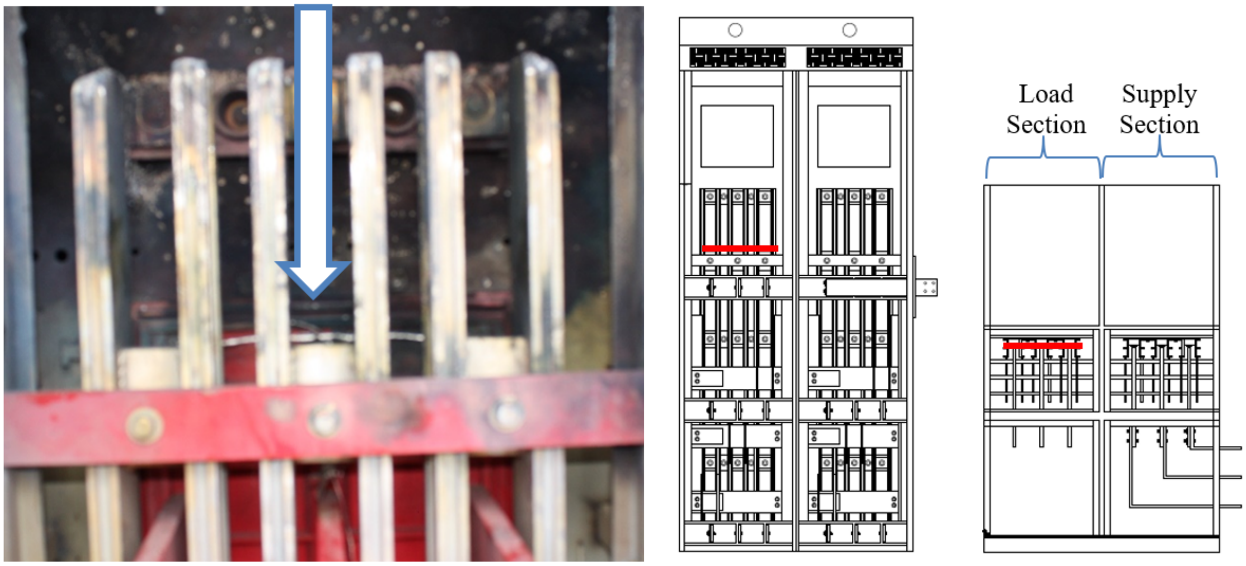


Fig. 44. Shorting Wire Location Test 2-13D (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right). Shorting location shown in red on illustrations.

3.4.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 22 and include an approximate time reference. Corresponding images are provided in Fig. 45.

The experiment did not arc for the planned 2.0 s. Arcing on all three phases was less intermittent than previous experiments but still extinguished at approximately 930 ms. The arc location (on the copper horizontal stabs towards the breaker vs. on the vertical aluminum bus bars) seemed to have no impact on the resultant direction of the arc. The arc still traveled vertically towards the top of the bus bars and established itself on the end of the bus. There was some increased vaporization of the bus bars and thermal impact to the side of the enclosure.

Table 22. Observations from Test 2-13D.

Time (ms)	Observation
0	Initial light observed in top rear louver
66	Initial particle ejecta observed
100	Particle ejecta reaches first instrument rack immediately above enclosure
216	Luminescent flash zone reaches first instrument rack immediately above enclosure
450	Particle ejecta exceeds second instrument rack above enclosure
550	Luminescent flash zone expands
734	Particle ejecta continues and luminescent intensity increases
950	Last particle ejecta at arc extinguishment
503 300	NIST data acquisition ends

Fig. 45. Sequence of Images from Test 2-13D (image time stamps are in seconds).

Photographs of the enclosure following the experiment are presented in Fig. 46 and Fig. 47. The enclosure did not experience a breach.

Fig. 46. Enclosure Post-Test 2-13D.

Fig. 47. Thermal heating on external of load section enclosure adjacent to top of vertical bus bars.

3.4.1.1.Measurements

Measurements made during Test 2-13D are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.4.1.2.Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 23), ASTM Slug Calorimeter measurements (Table 24), and T_{cap} slug measurements (Table 25). The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI."

Due to the short duration of the arc and no breaching of the exterior skin of the switchgear, the thermal exposures measured outside of the switchgear were very small.

Table 23. Summary of plate thermometer measurements Test 2-13D.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m²) ± 1 kW/m² or ± 5 %	Average Heat Flux During Arc (kW/m²) ± 1 kW/m² or ± 5 %	Comment
1	1	Top	8	1	
1	3	Mid-Right	2	0	
1	5	Mid-Center	––	0	EMI
1	7	Mid-Left	2	0	
1	9	Bottom	1	0	
2	10	Top	1	0	
2	12	Mid-Right	1	0	
2	14	Mid-Center	––	0	EMI
2	16	Mid-Left	1	0	
2	18	Bottom	––	0	EMI
3	19	Top	8	1	
3	21	Mid-Right	3	1	
3	23	Mid-Center	4	1	
3	25	Mid-Left	3	1	
3	27	Bottom	1	0	
4	28	Front	15	3	
4	30	Center-Right	19	6	
4	32	Center-Mid	20.	**7**	
4	34	Center-Left	14	6	
4	36	Back	**27**	5	
5	37	Front	10.	3	
5	39	Center-Right	7	2	
5	41	Center-Mid	6	2	
5	43	Center-Left	3	1	
5	45	Back	12	2	

Table 24. Summary of ASTM slug calorimeter measurements, Test 2-13D.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m²) ± 18kJ/m² or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	3	206
1	B	Bottom	2	204
2	C	Top	3	2
2	D	Bottom	0	N/A
3	E	Top	16	201
3	F	Bottom	13	197
4	G	Rear	18	164
4	H	Front	22	207
5	I	Rear	11	140
5	J	Front	7	211

Table 25. Summary of T_{cap} slug measurement, Test 2-13D.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m²) ± 1.5 kW/m² or ± 2.9 %	Incident Energy During Arc Phase (kJ/m²) ± 2.4 kJ/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 2.4 kJ/m² or ± 5 %
1	2	Top	0.4	0.8	5.8
1	4	Mid-Right	0.4	0.5	4.2
1	6	Mid-Left	2.4	0.6	4.1
1	8	Bottom	0.4	0.6	3.8
2	11	Top	1.6	0.0	2.0
2	13	Mid-Right	0.1	0.1	0.3
2	15	Mid-Left	0.3	0.1	0.4
2	17	Bottom	0.0	0.0	0.9
3	20	Top	1.0	1.7	56.1
3	22	Mid-Right	0.7	1.6	58.3
3	24	Mid-Left	0.6	1.2	56.5
3	26	Bottom	0.4	0.7	49.0
4	29	Front	6.7	12.3	**70.8**
4	31	Center-Right	5.2	10.3	60.6
4	33	Center-Left	**7.2**	**12.5**	64.8
4	35	Back	4.7	8.8	66.5
5	38	Front	1.2	2.8	21.6
5	40	Center-Right	1.4	2.8	24.8

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m²) ± 1.5 kW/m² or ± 2.9 %	Incident Energy During Arc Phase (kJ/m²) ± 2.4 kJ/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 2.4 kJ/m² or ± 5 %
5	42	Center-Left	1.2	2.6	16.2
5	44	Back	1.2	1.8	13.6

3.4.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 48. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 7 kPa (0.8 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.4 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

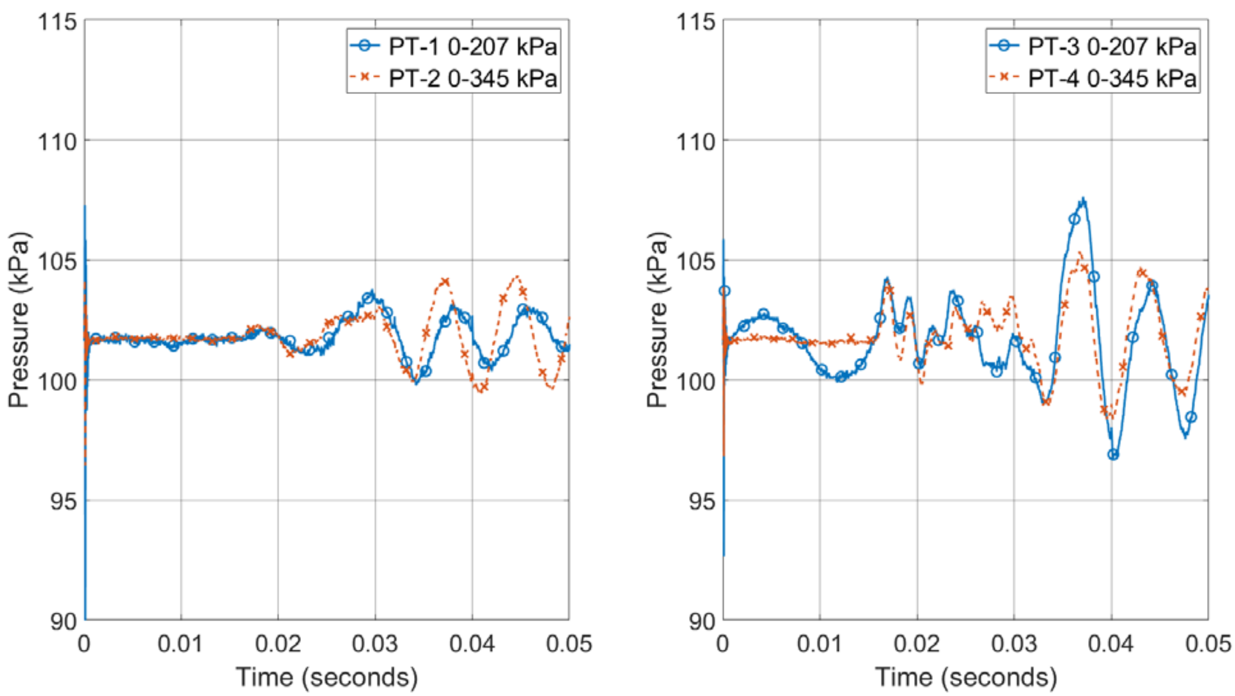


Fig. 48. Pressure measurements from Test 2-13D (breaker compartment (left); Main bus [arcing compartment] (right). Measurement uncertainty ± 3 percent.

3.4.1.4. Electrical measurements

Test 2-13C used KEMA circuit S07 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190827-7003. Key experimental measurements are presented in Table 26. Plots of the electrical measurements are presented in Appendix B.

Table 26. Key measurement from Test 2-13D. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	356	356	356
Applied voltage, phase-to-phase	kV_{RMS}	617		
Making current	kA_{peak}	24.7	28.4	-34.3
Current, a.c. component, beginning	kA_{RMS}	13.4	13.5	12.2
Current, a.c. component, middle	kA_{RMS}	9.05	13.7	11.8
Current, a.c. component, end	kA_{RMS}	10.9	8.03	8.49
Current, a.c. component, average	kA_{RMS}	11.2	10.1	9.88
Current, a.c. component, three-phase average	kA_{RMS}	10.4		
Duration	s	0.924	0.924	0.924
Arc Energy	MJ	4.21		

3.5. Test 2-13E – 600 V, 13.5 kA, 2 s duration, breaker stabs (copper) middle breaker cubicle

Test 2-13E was performed on August 28, 2019 at 9:33 AM eastern daylight time (EDT). The temperature was approximately 26 °C (78 °F), approximately 62 percent relative humidity and approximately 101.2 kPa of pressure. The weather was mostly cloudy with an 8 km/h (5 mi/h) wind out of the east.

The switchgear used in Tests 2-13A, 2-13B, 2-13C and 2-13D was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arcing wire was located around the copper breaker stabs in the second from bottom breaker cubicle in the load breaker vertical section. The arc was initiated on the bus bar stabs (copper) and wrapped through the opening in the stab connections as shown in Fig. 49. This arc was initiated on the breaker cubicle side of the enclosure with the power direction facing the front of the enclosures (rear of KEMA test cell) into the breaker itself. All three phases were shorted with the shorting wire. The current transformers were removed to aid the installation of the arc wire. After installation of the arc wire, the breaker was racked in but not closed. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance. A single 10 AWG bare stranded conductors were used to initiate the arc. The arcing wire installed on stabs and marked up illustrations of the arc wire location is presented in Fig. 49.

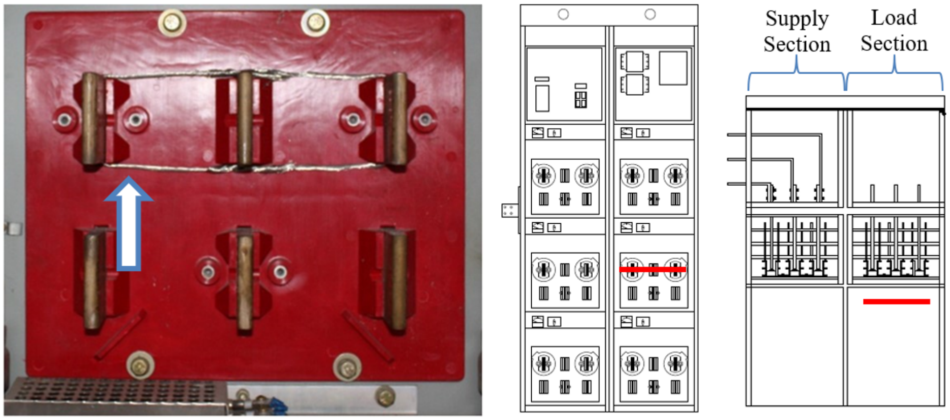


Fig. 49. Shorting Wire Location Test 2-13E (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right).
Shorting location shown in red on illustrations.

3.5.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 27 and include an approximate time reference. Corresponding images are provided in Fig. 50 and Fig. 51.

The experiment did sustain for the planned 2.0 s. The intermittent arcing observed in previous experiments was not observed during this experiment. The arc was consistent and was extinguished by the laboratory at the end of the planned experiment duration. The arc vaporized some of the breaker finger cluster connection pieces as well as some of the breaker structure itself. The breaker caught on fire and required manual suppression. No enclosure doors opened due to pressure challenges; however, two doors were manually opened to find and fight the fire. The arc location and direction of the power supply did not facilitate the involvement of any of the aluminum within the enclosure.

Table 27. Observations from Test 2-13E.

Time (ms)	Observation
0	Start of experiment
100	Initial gasses escaping top of enclosure
250	Gasses reaching first instrument rack above enclosure
316	Initial flames emerge from top of enclosure
1 034	Flames reach first instrument rack above enclosure
1 184	Flame regions expand vertically, and gas region expands horizontally
1 501	Flame region at steady-state
1 901	Flame region 100 ms prior to end of experiment
2 001	Flame region at end of experiment
2 168	Post-arc combustion
648 800	NIST data acquisition ends

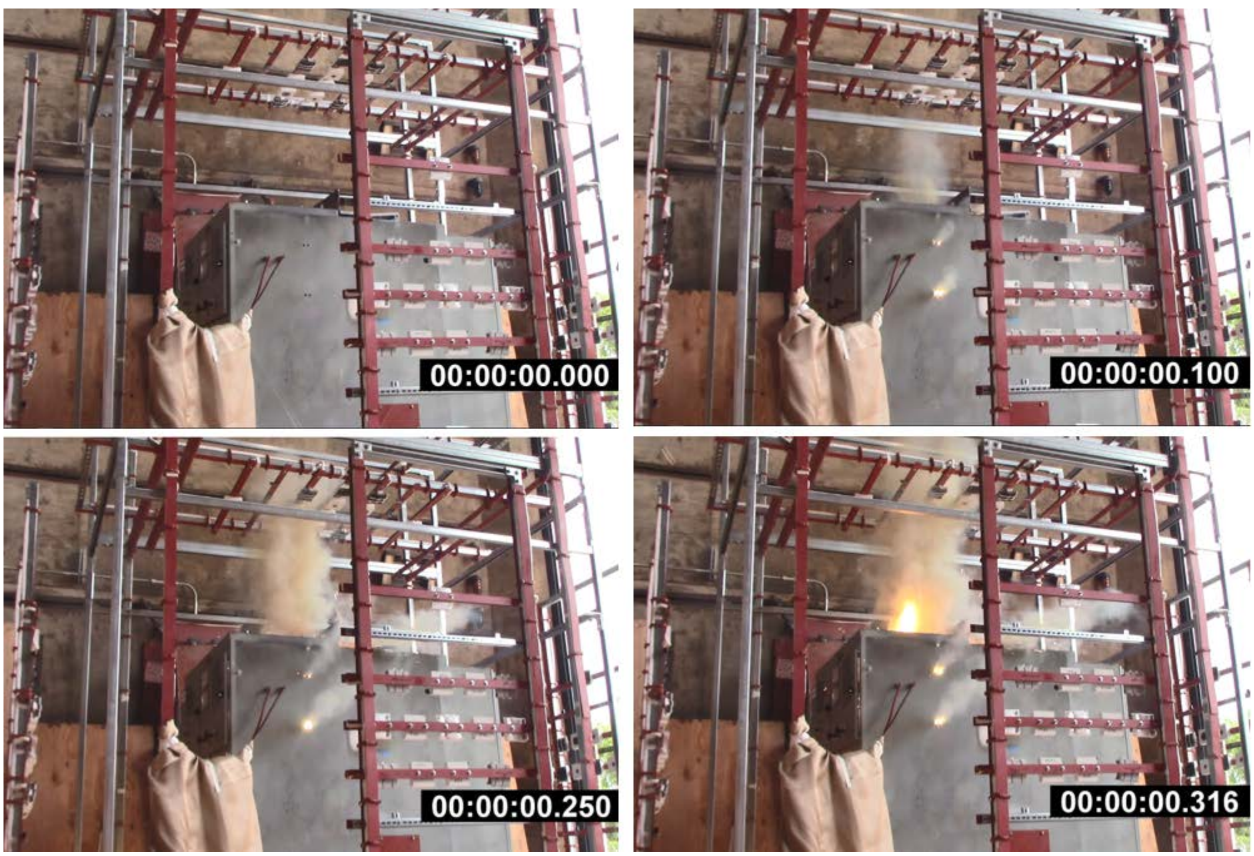


Fig. 50. Sequence of Images from first have of Test 2-13E (image time stamps are in seconds).

Fig. 51. Sequence of Images from second half of Test 2-13E (image time stamps are in seconds).

Photographs of the enclosure following the experiment are presented in Fig. 52, Fig. 53, and Fig. 54. The enclosure did not experience a breach.

Fig. 52. Switchgear stabs post-experiment.

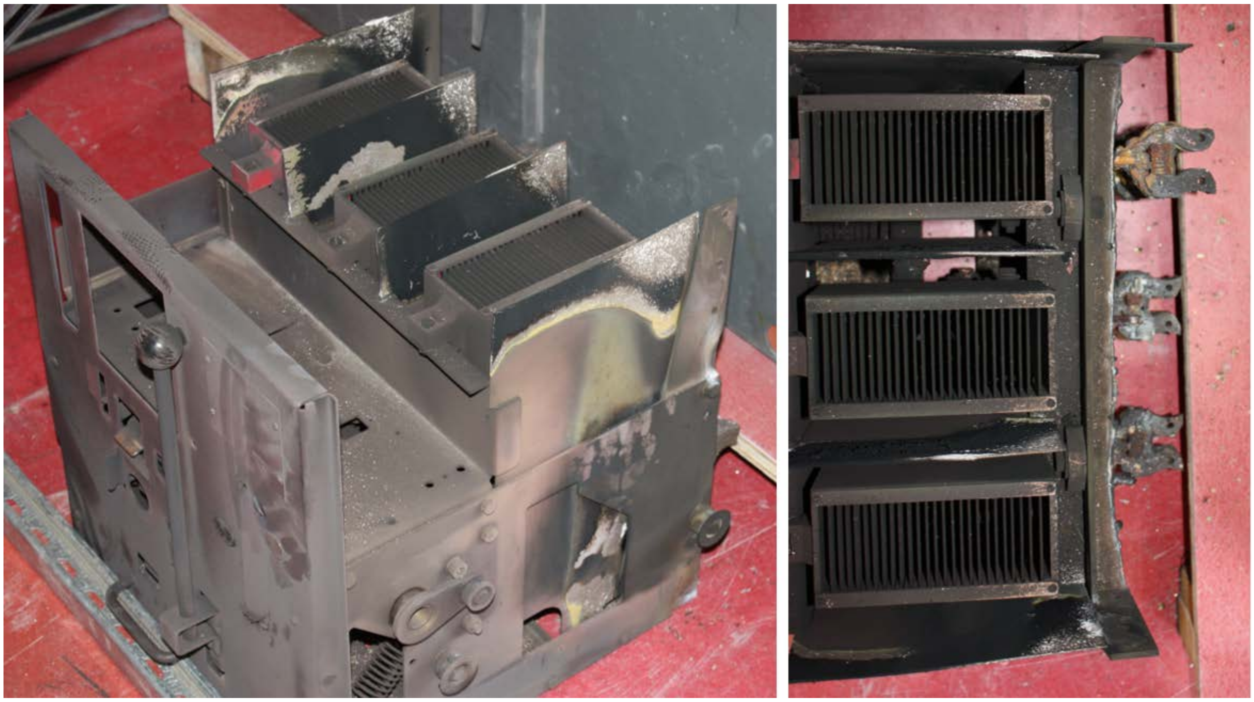


Fig. 53. Breaker post-experiment. (front/side view (left), top/rear view showing breaker contact fingers missing (right)).

Fig. 54. Main bus bar post-experiment.

3.5.1.1. Measurements

Measurements made during Test 2-13E are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.5.1.2. Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 28), ASTM Slug Calorimeter measurements (Table 29), and T_{cap} slug measurements (Table 30). The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI." For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

The thermal exposures measured outside of the switchgear were greater than the proceeding experiments due to the flames issuing from the vents at the top of the electrical enclosure.

Table 28. Summary of plate thermometer measurements Test 2-13E.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
1	1	Top	5	1	
1	3	Mid-Right	2	0	
1	5	Mid-Center	1	0	
1	7	Mid-Left	3	0	
1	9	Bottom	--	0	EMI
2	10	Top	8	3	
2	12	Mid-Right	4	2	
2	14	Mid-Center	16	3	
2	16	Mid-Left	12	2	
2	18	Bottom	18	3	
3	19	Top	8	2	
3	21	Mid-Right	2	1	
3	23	Mid-Center	4	1	
3	25	Mid-Left	3	1	
3	27	Bottom	3	1	
4	28	Front	22	7	
4	30	Center-Right	21	7	
4	32	Center-Mid	**71**	**30.**	
4	34	Center-Left	12	6	
4	36	Back	7	2	
5	37	Front	17	4	

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
5	39	Center-Right	7	3	
5	41	Center-Mid	19	10.	
5	43	Center-Left	10.	4	
5	45	Back	7	1	

Table 29. Summary of ASTM slug calorimeter measurements, Test 2-13E.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	3	606
1	B	Bottom	1	596
2	C	Top	10	542
2	D	Bottom	10	560
3	E	Top	10	630
3	F	Bottom	17	644
4	G	Rear	90	9
4	H	Front	36	142
5	I	Rear	25	13
5	J	Front	19	10

Table 30. Summary of T_{cap} slug measurement, Test 2-13E.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Comment
1	2	Top	––	0.4	14.9	EMI S/N
1	4	Mid-Right	0.0	0.0	0.4	
1	6	Mid-Left	1.1	0.0	6.7	
1	8	Bottom	0.0	-0.1	0.1	
2	11	Top	––	3.2	30.8	EMI S/N
2	13	Mid-Right	2.6	4.2	36.2	
2	15	Mid-Left	1.9	3.1	25.7	
2	17	Bottom	––	3.3	34.7	EMI S/N
3	20	Top	1.1	1.6	29.9	
3	22	Mid-Right	1.0	1.1	30.7	
3	24	Mid-Left	1.0	1.9	44.9	
3	26	Bottom	0.6	0.5	39.8	
4	29	Front	**64.1**	**87.4**	**262.6**	
4	31	Center-Right	15.4	19.7	117.1	
4	33	Center-Left	21.0	30.0	164.9	
4	35	Back	––	9.0	90.2	EMI S/N
5	38	Front	12.4	16.6	57.3	
5	40	Center-Right	5.2	5.8	29.9	
5	42	Center-Left	8.3	10.7	42.5	
5	44	Back	––	2.1	26.9	EMI S/N

3.5.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 55. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 6 kPa (0.8 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.4 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

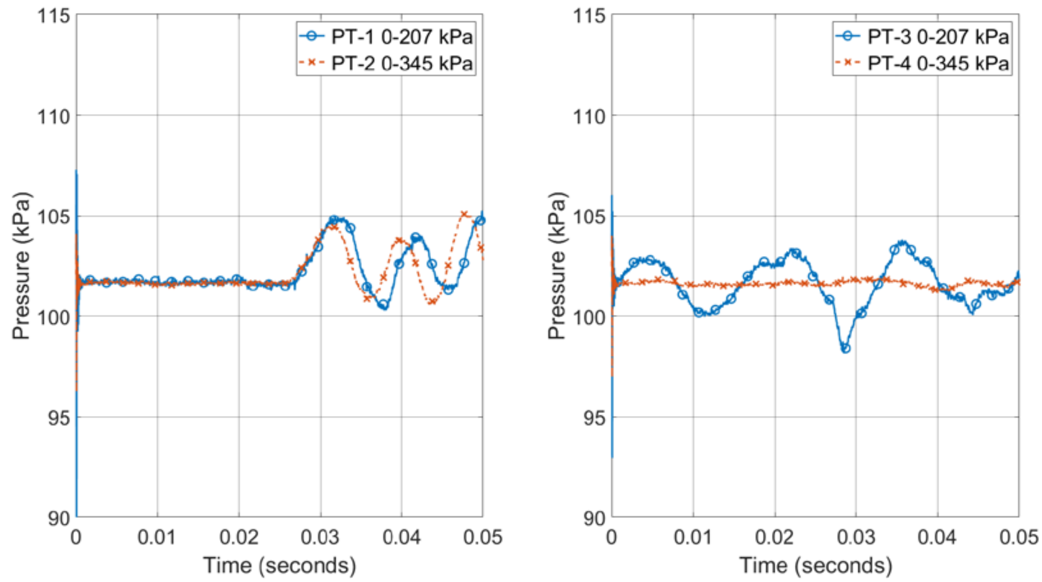


Fig. 55. Pressure measurements from Test 2-13E (breaker compartment (left); Main bus [arcing compartment] (right). Measurement uncertainty ± 3 percent.

3.5.1.4. Electrical measurements

Test 2-13E used KEMA circuit S07 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190827-7004. Key experimental measurements are presented in Table 31. Plots of the electrical measurements are presented in Appendix B.

Table 31. Key measurement from Test 2-13E. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	356	356	356
Applied voltage, phase-to-phase	kV_{RMS}		617	
Making current	kA_{peak}	24.9	28.4	-34.3
Current, a.c. component, beginning	kA_{RMS}	12.6	13.5	11.6
Current, a.c. component, middle	kA_{RMS}	10.4	10.5	9.79
Current, a.c. component, end	kA_{RMS}	10.2	9.35	9.26
Current, a.c. component, average	kA_{RMS}	11.1	10.8	10.0
Current, a.c. component, three-phase average	kA_{RMS}		10.6	
Duration	s	2.06	2.06	2.06
Arc Energy	MJ		9.64	

3.6. Test 2-13F – 480 V, 13.5 kA, 2 s duration, main bus, load section

Test 2-13E was performed on August 28, 2019 at 9:33 AM eastern daylight time (EDT). The temperature was approximately 26 °C (78 °F), approximately 62 percent relative humidity and approximately 100.9 kPa of pressure. The weather was mostly cloudy with an 8 km/h (5 mi/h) wind out of the east.

The switchgear used in Tests 2-13A, 2-13B, 2-13C, 2-13D and 2-13E was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arcing wire was located around the vertical main bus work at the bottom of the load breaker vertical section. All three phases were shorted with the shorting wire. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance. The zero-sequence voltage was removed from all three voltage phases in the plot above. The arcing wire installed on the main bus and marked up illustrations of the arc wire location is presented in Fig. 56.

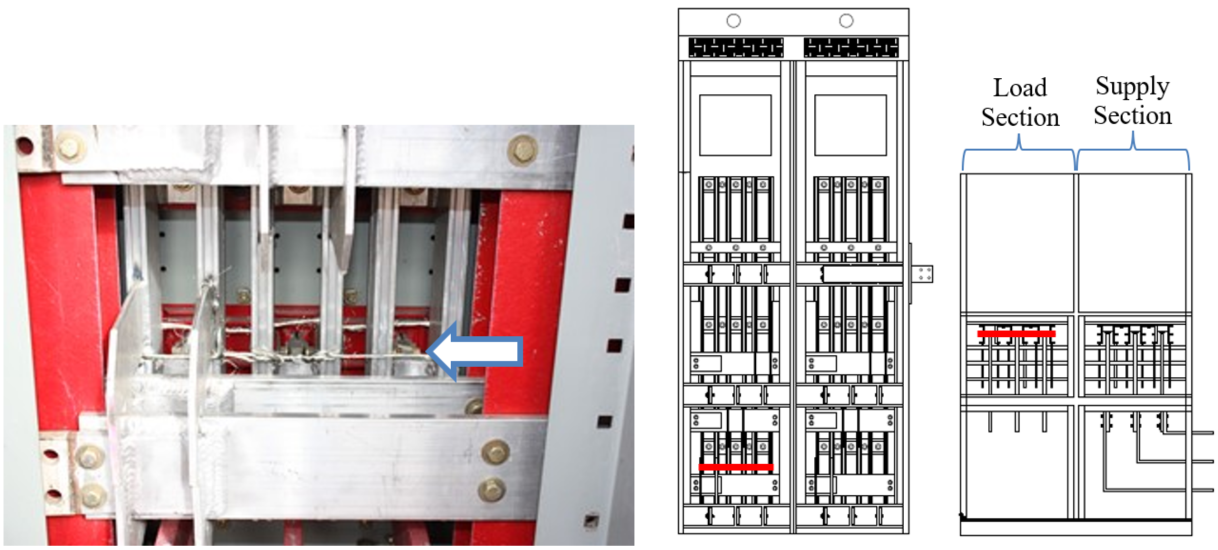


Fig. 56. Shorting Wire Location Test 2-13F (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right). Shorting location shown in red on illustrations.

3.6.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 32 and include an approximate time reference. Corresponding images are provided in Fig. 57.

The arc did not sustain for the expected 2.0 s duration. The final arc extinguished at 1 550 ms. Intermittent arcing was observed but not as severe as in previous experiments on the main bus. There were a number of extinguishments and weak re-strikes, but none lasted longer than ½ a cycle up until phase B and C concurrently extinguished at 1 320 ms. Phase A remained arcing current until final arc extinguishment at 1 550 ms. The arc was initiated in the bottom of the left side of the enclosure and held for 1 300 ms. It appears from looking at the high-speed thermal imaging camera that the arc held for roughly 900 ms on the left bus bar run then the arc migrated over to the right hand side of the enclosure where the arc extinguished. The A phase held in the arc for approximately 200 ms after the migration until the grounding cable disconnected from the cabinet as seen in Fig. 59.

Table 32. Observations from Test 2-13F.

Time (ms)	Observation
0	Initial light observed in bottom rear louver
150	Initial gasses exiting bottom rear louver
350	Particle ejecta reaching rear instrumentation rack
500	Gasses expanding and encompassing rear instrumentation rack
750	Gas and flame regions expanding
1 000	Gasses reach first instrumentation rack above enclosure
1 518	Final arc flash observed externally in load section (lower left)
1 634	Post arc gasses and particle ejecta exceeding instrumentation rack to side of load vertical section (left)
319 900	NIST data acquisition ends

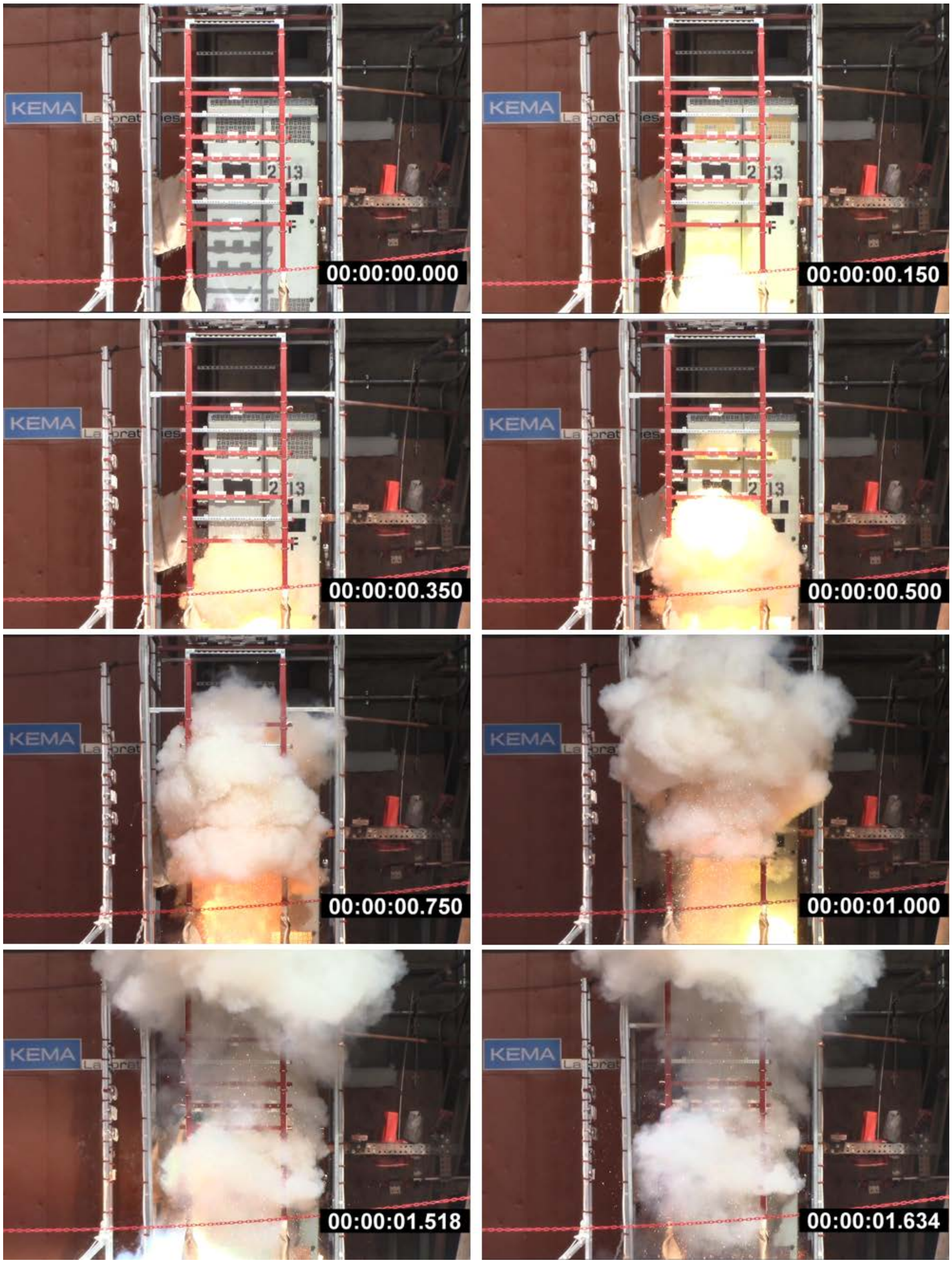


Fig. 57. Sequence of Images from Test 2-13F (image time stamps are in seconds).

Photographs of the enclosure following the experiment are presented in Fig. 58 and Fig. 59. The enclosure did not experience a breach.

Fig. 58. Enclosure Post-Test 2-13F.

Fig. 59. Post-experiment image of enclosure grounding cable disconnected from enclosure due to current flow through ground circuit.

3.6.1.1.Measurements

Measurements made during Test 2-13F are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.6.1.2. Thermal Measurements

Thermal measurements from the active instruments are reported below in Table 33 through Table 35. These include PT measurements, ASTM Slug Calorimeter measurements, and T_{cap} slug measurements. The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI." For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

Table 33. Summary of plate thermometer measurements Test 2-13F.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ±1 kW/m^2 or ± 5 %	Comment
1	1	Top	56	15	
1	3	Mid-Right	53	13	
1	5	Mid-Center	115	24	
1	7	Mid-Left	91	15	
1	9	Bottom	**155**	**48**	
2	10	Top	1	0	
2	12	Mid-Right	1	0	
2	14	Mid-Center	--	0	EMI
2	16	Mid-Left	1	0	
2	18	Bottom	--	0	EMI
3	19	Top	6	1	
3	21	Mid-Right	7	2	
3	23	Mid-Center	7	1	
3	25	Mid-Left	4	1	
3	27	Bottom	6	2	
4	28	Front	5	1	
4	30	Center-Right	4	1	
4	32	Center-Mid	6	1	
4	34	Center-Left	5	1	
4	36	Back	5	2	
5	37	Front	--	0	EMI

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ±1 kW/m^2 or ± 5 %	Comment
5	39	Center-Right	3	1	
5	41	Center-Mid	2	1	
5	43	Center-Left	2	1	
5	45	Back	6	1	

Table 34. Summary of ASTM slug calorimeter measurements, Test 2-13F.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	37	5
1	B	Bottom	61	2
2	C	Top	4	287
2	D	Bottom	3	280
3	E	Top	6	181
3	F	Bottom	9	275
4	G	Rear	8	183
4	H	Front	9	259
5	I	Rear	5	186
5	J	Front	6	259

Table 35. Summary of T_{cap} slug measurement, Test 2-13F.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Comment
1	2	Top	--	45.3	67.1	EMI
1	4	Mid-Right	--	40.9	68.2	EMI
1	6	Mid-Left	--	44.0	70.3	EMI
1	8	Bottom	**34.2**	**60.9**	**87.3**	
2	11	Top	--	0.1	8.0	EMI S/N
2	13	Mid-Right	0.2	0.2	7.3	
2	15	Mid-Left	0.9	0.1	7.3	

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Comment
2	17	Bottom	1.6	0.1	9.2	
3	20	Top	1.4	1.8	12.1	
3	22	Mid-Right	2.3	3.2	19.8	
3	24	Mid-Left	1.1	1.7	8.9	
3	26	Bottom	1.8	2.0	23.0	
4	29	Front	1.4	1.5	17.3	
4	31	Center-Right	––	1.1	21.0	EMI S/N
4	33	Center-Left	0.8	1.1	14.4	
4	35	Back	0.4	1.4	22.0	
5	38	Front	0.9	0.4	12.3	
5	40	Center-Right	0.4	0.6	8.1	
5	42	Center-Left	0.8	0.8	9.1	
5	44	Back	––	0.5	10.9	EMI S/N

3.6.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 60. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 4 kPa (0.6 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 2 kPa (0.3 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

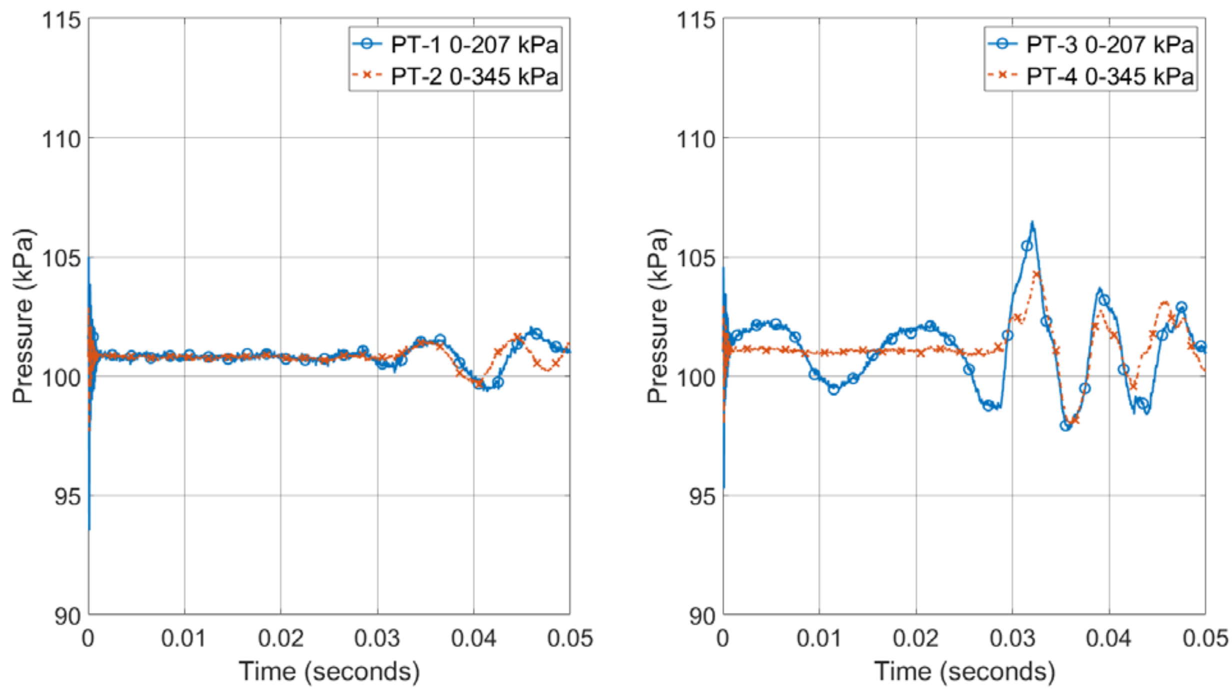


Fig. 60. Pressure measurements from Test 2-13F (breaker compartment (left); Main bus [arcing compartment] – (right)). Measurement uncertainty ± 3 percent.

3.6.1.4. Electrical measurements

Test 2-13F used KEMA circuit S06 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190828-7001. Key experimental measurements are presented in Table 36. Plots of the electrical measurements are presented in Appendix B.

Table 36. Key measurement from Test 2-13F. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	282	282	282
Applied voltage, phase-to-phase	kV_{RMS}	488		
Making current	kA_{peak}	24.7	28.4	-34.2
Current, a.c. component, beginning	kA_{RMS}	13.1	13.6	12.8
Current, a.c. component, middle	kA_{RMS}	8.32	9.92	7.61
Current, a.c. component, end	kA_{RMS}	9.46	10.4	8.55
Current, a.c. component, average	kA_{RMS}	10.3	9.95	9.26
Current, a.c. component, three-phase average	kA_{RMS}	9.84		
Duration	s	1.55	1.32	1.32
Arc Energy	MJ	5.44		

3.7. Test 2-13G – 600 V, 13.5 kA, 2 s duration, main bus, Supply section

Test 2-13E was performed on August 28, 2019 at 3:36 PM eastern daylight time (EDT). The temperature was approximately 28 °C (82 °F), approximately 84 percent relative humidity and approximately 100.7 kPa of pressure. The weather was cloudy with a 13 km/h (8 mi/h) wind out of the west.

The switchgear used in Tests 2-13A, 2-13B, 2-13C, 2-13D, 2-13E and 2-13F was used again in this experiment. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arcing wire was located around the vertical main bus work at the bottom of the supply breaker vertical section as shown in Fig. 61. All three phases were shorted with the shorting wire. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance.

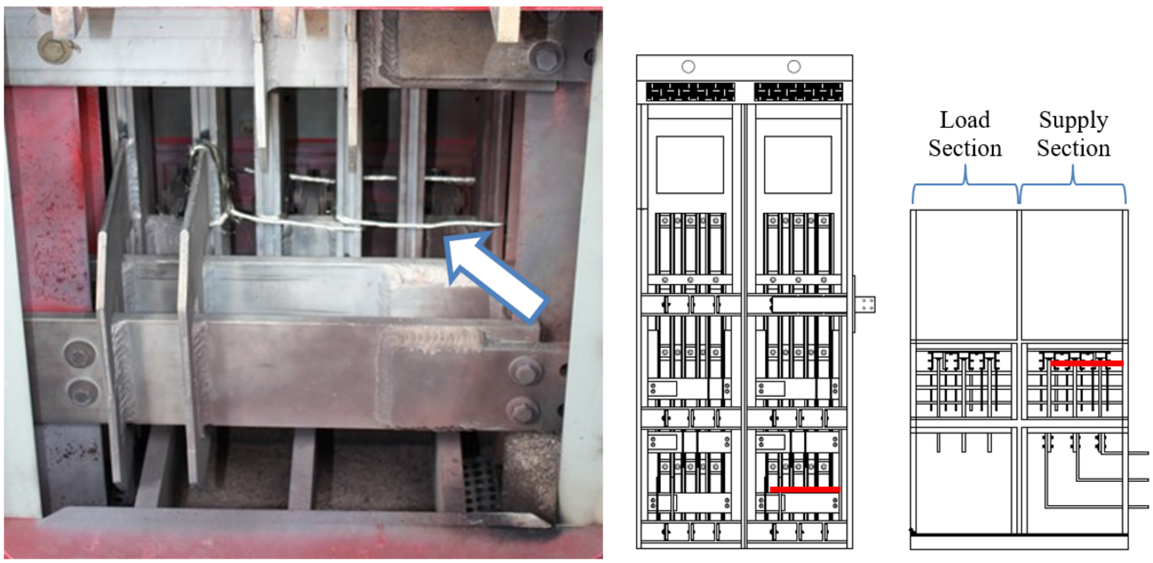


Fig. 61. Shorting Wire Location Test 2-13G (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right). Shorting location shown in red on illustrations.

3.7.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 37 and include an approximate time reference. Corresponding images are provided in Fig. 62.

The arc did sustain for the expected 2.0 s duration. The final arc extinguished at 2 050 ms. There was no arc extinguishment on any phase; however, phase B demonstrated a slow re-strike around 229 ms. There was arc migration between the load and supply vertical sections, first from the supply to the load and then back to the supply. The post-experiment inspection looks like the aluminum became involved in the event and white powder as well as particulate deposition towards the instrumentation rack were observed.

Table 37. Observations from Test 2-13G.

Time (ms)	Observation
0	Initial light observed in bottom rear louver
183	Particle ejecta observed from bottom louvers
500	Particle ejecta observed in top louvers and reach back instrumentation rack
750	Gasses expand and exceed back instrumentation rack
1 016	Gasses expand to top instrumentation rack
1 501	Rear instrumentation rack fully enveloped in hot gasses
2 001	Flame sheet observed exiting lower louvers
2 185	Post-experiment final particle ejecta and combustion
641 000	NIST data acquisition ends

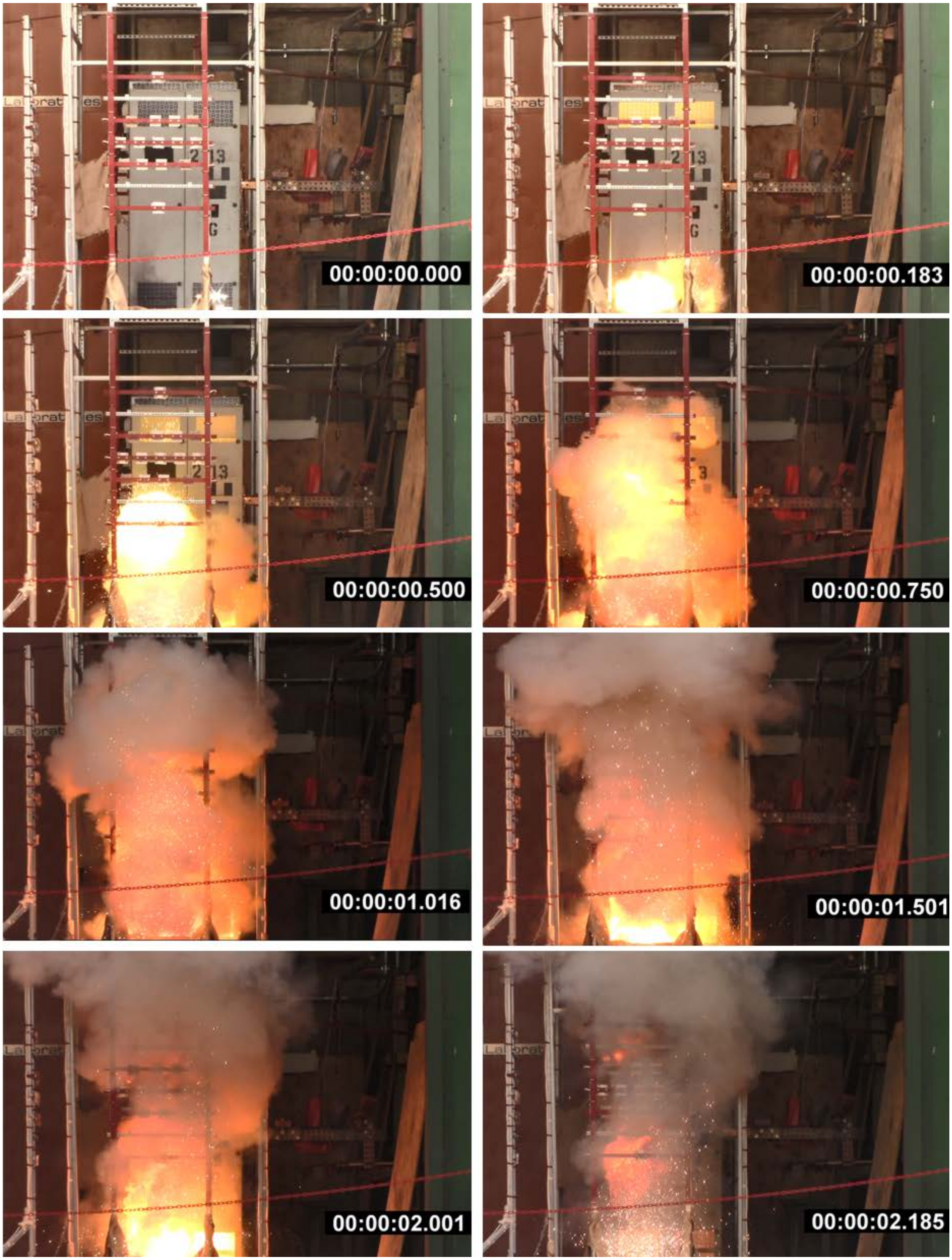


Fig. 62. Sequence of Images from Test 2-13G (image time stamps are in seconds).

Photographs of the enclosure following the experiment is presented in Fig. 63. The enclosure did not experience a breach.

Fig. 63. Enclosure Post-Test 2-13G.

3.7.1.1.Measurements

Measurements made during Test 2-13G are presented below. These measurements include:

- Thermal
    - Heat flux – Plate Thermometers
    - Incident energy – ASTM Slug Calorimeter
    - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
    - Internal pressure
- Electrical

3.7.1.2. Thermal Measurements

Thermal measurements from the active instruments are reported below in Table 38 through Table 40. These include PT measurements, ASTM Slug Calorimeter measurements, and T_{cap} slug measurements. The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI." For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

Table 38. Summary of plate thermometer measurements Test 2-13G.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
1	1	Top	53	25	
1	3	Mid-Right	78	29	
1	5	Mid-Center	117	45	
1	7	Mid-Left	166	28	
1	9	Bottom	**176**	**70.**	
2	10	Top	2	0	
2	12	Mid-Right	2	1	
2	14	Mid-Center	--	0	EMI
2	16	Mid-Left	2	0	
2	18	Bottom	2	0	
3	19	Top	9	3	
3	21	Mid-Right	16	5	
3	23	Mid-Center	15	3	
3	25	Mid-Left	8	2	
3	27	Bottom	15	4	
4	28	Front	3	1	
4	30	Center-Right	13	2	
4	32	Center-Mid	12	2	
4	34	Center-Left	6	2	
4	36	Back	28	4	
5	37	Front	5	1	
5	39	Center-Right	14	1	
5	41	Center-Mid	6	1	
5	43	Center-Left	4	1	
5	45	Back	12	2	

Table 39. Summary of ASTM slug calorimeter measurements, Test 2-13G.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	75	5
1	B	Bottom	110	3
2	C	Top	1	5
2	D	Bottom	1	6
3	E	Top	10	9
3	F	Bottom	10	281
4	G	Rear	17	50
4	H	Front	30	7
5	I	Rear	10	51
5	J	Front	11	9

Table 40. Summary of Tcap slug measurement, Test 2-13G.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Comment
1	2	Top	––	81.0	106.6	EMI
1	4	Mid-Right	57.0	83.1	118.5	
1	6	Mid-Left	**57.6**	81.3	111.8	
1	8	Bottom	56.6	**101.1**	**141.1**	
2	11	Top	1.8	0.3	3.7	
2	13	Mid-Right	0.1	0.2	0.6	
2	15	Mid-Left	0.2	0.1	0.5	
2	17	Bottom	2.4	0.3	3.1	
3	20	Top	3.0	3.5	23.9	
3	22	Mid-Right	4.3	6.7	34.4	
3	24	Mid-Left	2.3	3.7	29.1	
3	26	Bottom	––	3.5	36.4	EMI S/N
4	29	Front	––	2.8	35.0	EMI S/N
4	31	Center-Right	1.0	1.6	77.2	
4	33	Center-Left	––	2.8	44.0	EMI S/N
4	35	Back	2.4	2.8	107.0	
5	38	Front	0.7	1.5	18.5	

5	40	Center-Right	--	1.4	27.9	EMI S/N
5	42	Center-Left	--	1.7	16.5	EMI S/N
5	44	Back	0.8	1.2	32.4	

3.7.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 64. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 7 kPa (1.0 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.5 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

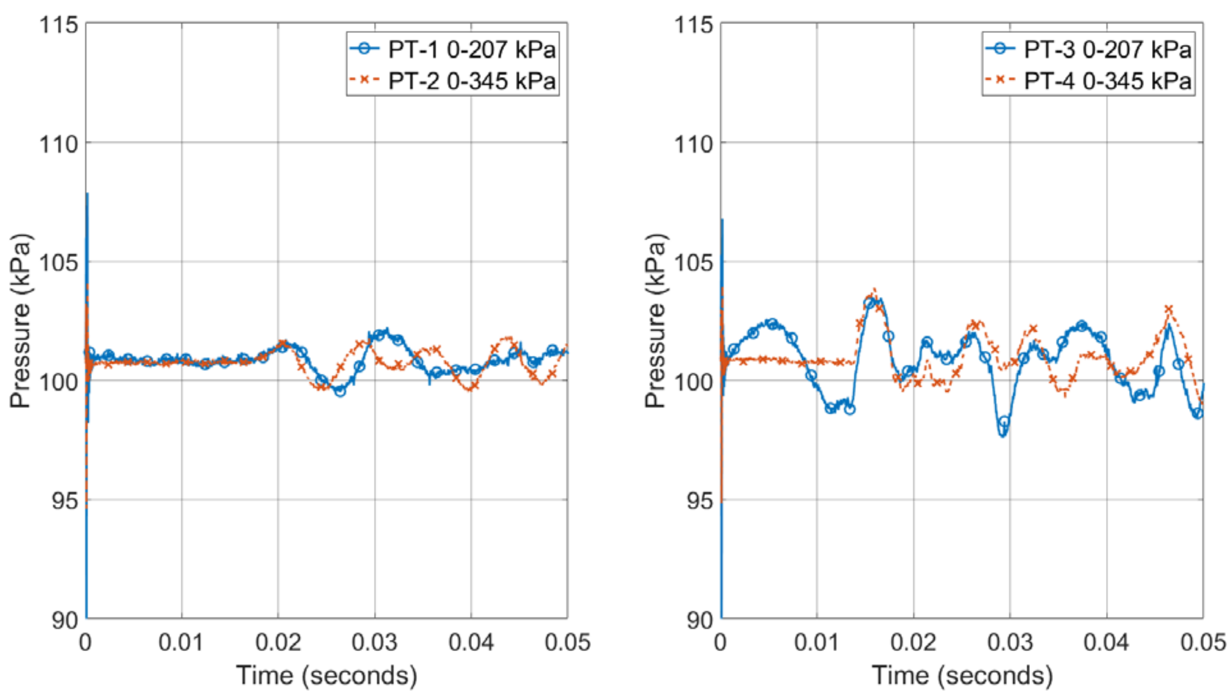


Fig. 64. Pressure measurements from Test 2-13G (breaker compartment (left); Main bus [arcing compartment] – (right)). Measurement uncertainty ± 3 percent.

3.7.1.4. Electrical measurements

Test 2-13G used KEMA circuit S07 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to

0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190828-7002. Key experimental measurements are presented in Table 41. Plots of the electrical measurements are presented in Appendix B.

Table 41. Key measurement from Test 2-13G. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	356	356	356
Applied voltage, phase-to-phase	kV_{RMS}	617		
Making current	kA_{peak}	25.1	26.6	-33.8
Current, a.c. component, beginning	kA_{RMS}	14.0	13.1	13.0
Current, a.c. component, middle	kA_{RMS}	9.62	12.1	9.18
Current, a.c. component, end	kA_{RMS}	12.1	8.87	11.1
Current, a.c. component, average	kA_{RMS}	12.3	10.8	11.0
Current, a.c. component, three-phase average	kA_{RMS}	11.4		
Duration	s	2.04	2.04	2.04
Arc Energy	MJ	10.40		

3.8. Test 2-18A – 480 V, 25 kA, 8 s duration, main bus, load section

Test 2-18A was performed on August 29, 2019 at 11:22 AM eastern daylight time (EDT). The temperature was approximately 26 °C (79 °F), approximately 40 percent relative humidity and approximately 101.1 kPa of pressure. The weather was fair with a 19 km/h (12 mi/h) wind out of the north.

The arcing wire was located around the vertical main bus work at the bottom of the load breaker vertical section as shown in Fig. 65. All three phases were shorted with the shorting wire. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance.

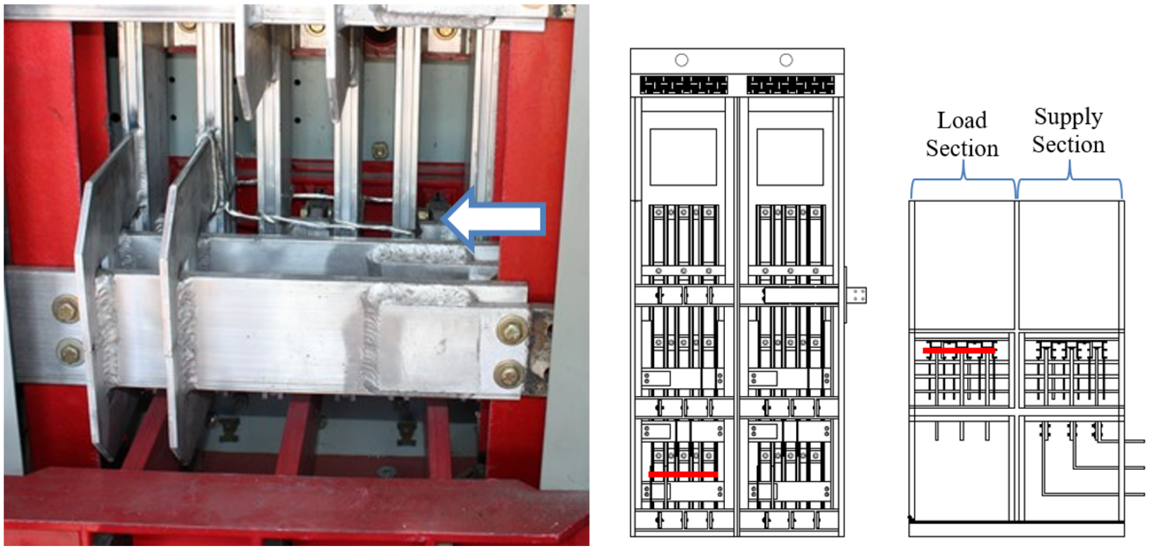


Fig. 65. Shorting Wire Location Test 2-18A (Phases left-to-right: A-B-C), photo of arc initiation point (left), elevation view (center), plan view (right). Shorting location shown in red on illustrations.

3.8.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 42 and include an approximate time reference. Corresponding images are provided in Fig. 66 and Fig. 67.

The arc did not sustain for the expected 8.0 s duration. The final arc extinguished at 2 020 ms. There were arc extinguishment on Phase B and C near 633 ms and was concurrent for 22 ms.

Table 42. Observations from Test 2-18A.

Time (ms)	Observation
0	Initial light observed in bottom rear louver
166	Particle ejecta observed exiting bottom of supply vertical section, hot gasses exiting rear of enclosure and exceeding the rear instrumentation rack location
316	Particle eject exiting top louvers
417	Arc location observed in top of supply vertical section (distinct relocation from initial location = bottom of supply vertical section)
517	Arc location moves briefly to load vertical section (left)
617	Gasses reach first instrumentation rack above enclosure and rack to left of load vertical section. Particle ejecta reaches top instrumentation rack above enclosure
834	Arc location move to bottom of switchgear
1 016	Arc moves to lower portion of supply section. Gasses and particle ejecta observed exceeding all instrumentation rack locations
1 718	Arc moves to upper portion of load section
2 102	Final particle ejecta post-experiment
443 800	NIST data acquisition ends

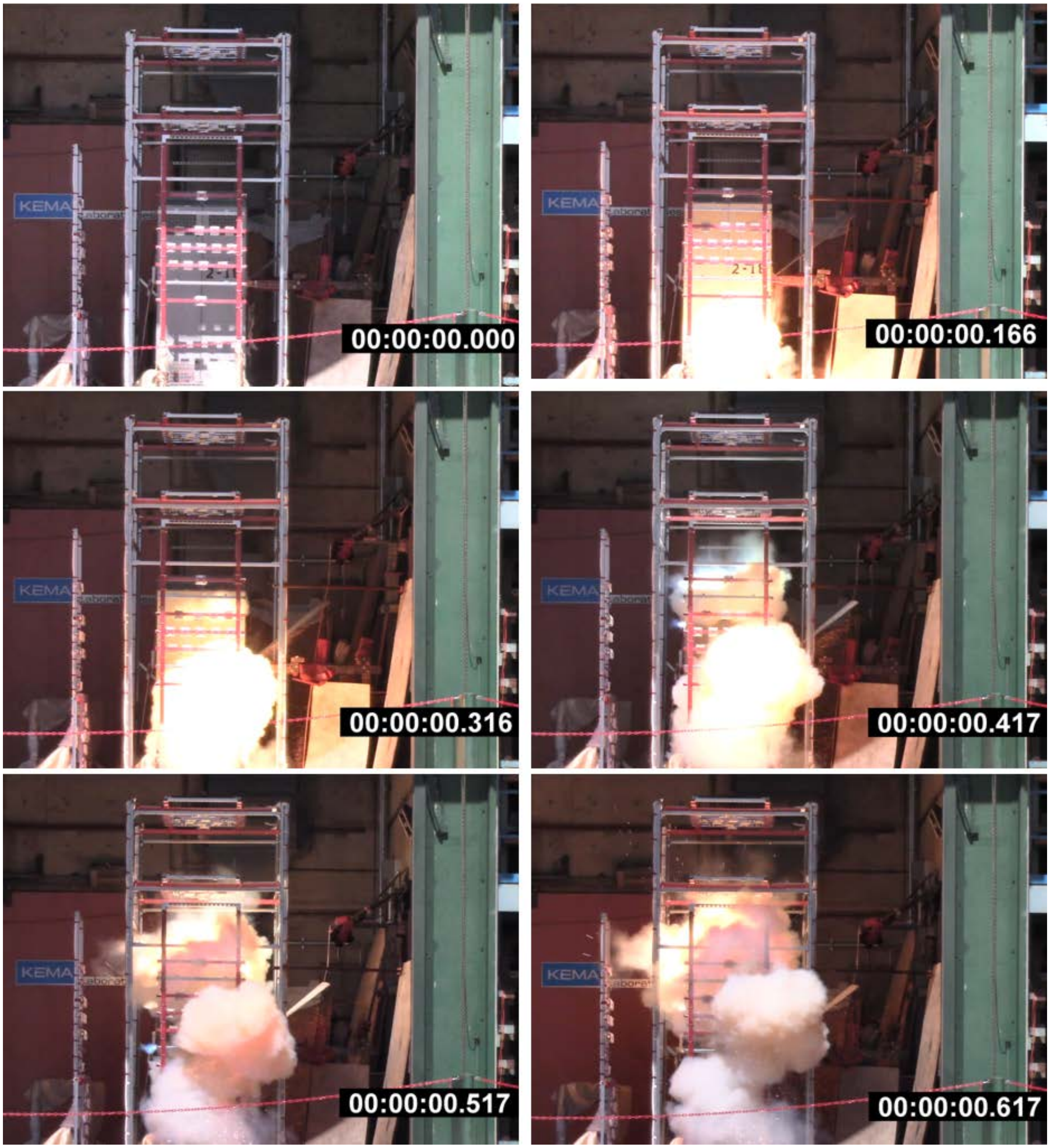


Fig. 66. Sequence of Images from Test 2-18A up to 0.617 s (image time stamps are in seconds).

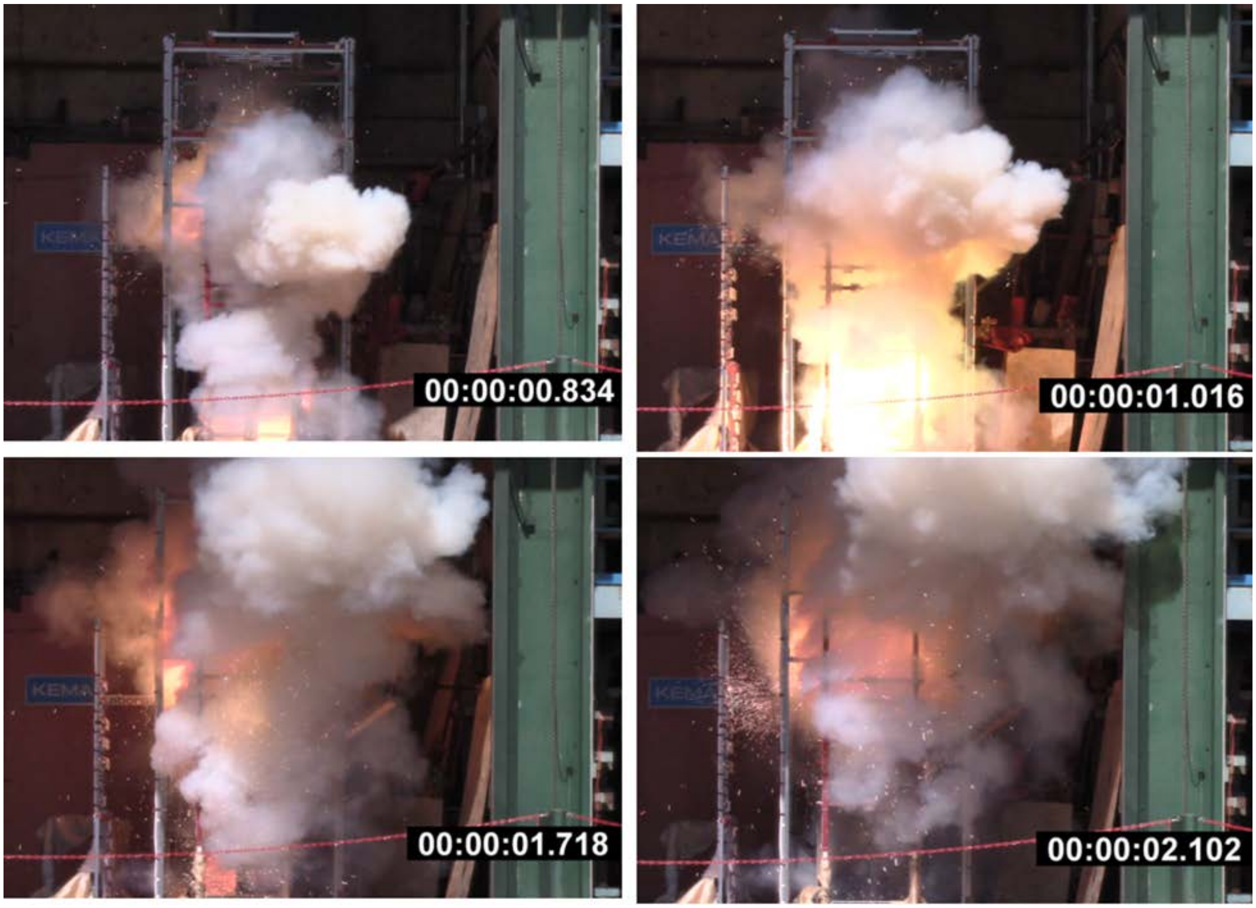


Fig. 67. Sequence of Images from Test 2-18A from 0.617 s to end of experiment (image time stamps are in seconds).

Photographs of the enclosure following the experiment are presented in Fig. 68 and Fig. 69. The enclosure did not experience a breach.

Fig. 68. Enclosure Post-Test 2-18A. Top of main bus, Load side (left), supply side (right).

Fig. 69. Post-experiment image of enclosure breach and thermal effects on supply side of gear.

3.8.1.1.Measurements

Measurements made during Test 2-18A are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.8.1.2. Thermal Measurements

Thermal measurements from the active instruments are reported below in Table 43 through Table 45. These include PT measurements, ASTM Slug Calorimeter measurements, and T_{cap} slug measurements. The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI." For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

Table 43. Summary of plate thermometer measurements Test 2-18A.

Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
1	Top	84	6	
3	Mid-Right	62	7	
5	Mid-Center	93	9	
7	Mid-Left	133	8	
9	Bottom	**152**	**17**	
10	Top	11	1	
12	Mid-Right	3	0	
14	Mid-Center	9	0	
16	Mid-Left	3	0	
18	Bottom	––	0	EMI
19	Top	35	3	
21	Mid-Right	18	2	
23	Mid-Center	15	2	
25	Mid-Left	21	1	

Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %	Comment
27	Bottom	10.	1	
28	Top	29	3	
30	Mid-Right	118	9	
32	Mid-Center	129	10.	
34	Mid-Left	143	11	
36	Bottom	135	9	
37	Front	27	2	
39	Center-Right	30.	3	
41	Center-Mid	23	4	
43	Center-Left	20.	3	
45	Back	20.	4	
46	Front	23	2	
48	Center-Bottom	8	1	
50	Center-Mid	6	1	
52	Center-Top	7	1	
54	Back	5	0	

Table 44. Summary of ASTM slug calorimeter measurements, Test 2-18A.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	58	4
1	B	Bottom	83	3
2	C	Top	5	434
2	D	Bottom	4	430
3	E	Top	27	335
3	F	Bottom	24	436
4	G	Rear	65	179
4	H	Front	92	8
5	I	Rear	27	250
5	J	Front	29	4
6	K	Rear	15	277
6	L	Front	16	422

Table 45. Summary of T_{cap} slug measurement, Test 2-18A.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m^2) ± 1.5 kW/m^2 or ± 2.9 %	Incident Energy During Arc Phase (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Total Incident Energy (kJ/m^2) ± 2.4 kJ/m^2 or ± 5 %	Comment
1	2	Top	35.1	53.7	116.8	
1	4	Mid-Right	35.8	65.1	129.6	
1	6	Mid-Left	37.4	57.3	129.5	
1	8	Bottom	**48.4**	**93.9**	146.2	
2	11	Top	1.6	1.0	16.6	
2	13	Mid-Right	0.4	0.8	15.6	
2	15	Mid-Left	1.5	0.7	15.7	
2	17	Bottom	––	0.3	14.2	EMI S/N
3	20	Top	4.5	8.3	96.8	
3	22	Mid-Right	5.1	9.2	96.3	
3	24	Mid-Left	3.6	6.8	93.7	
3	26	Bottom	––	4.3	94.5	EMI S/N
4	29	Top	19.4	44.7	259.2	
4	31	Mid-Right	19.0	39.0	261.4	
4	33	Mid-Left	35.6	67.6	**275.9**	
4	35	Bottom	40.4	48.2	224.2	
5	38	Front	11.0	17.2	92.6	
5	40	Center-Right	5.1	11.4	79.5	
5	42	Center-Left	––	16.3	84.0	EMI
5	44	Back	9.0	9.1	78.2	
6	47	Front	2.6	4.5	58.9	
6	49	Center-Bottom	0.6	2.7	55.2	
6	51	Center-Top	––	2.7	63.1	EMI S/N
6	53	Back	––	1.6	46.2	EMI S/N

3.8.1.3. Pressure Measurements

The pressure profiles for the first two tenths of a second are shown in Fig. 70. After the initial pressure spike, the pressure rapidly decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 5 kPa (0.7 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 2 kPa (0.3 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

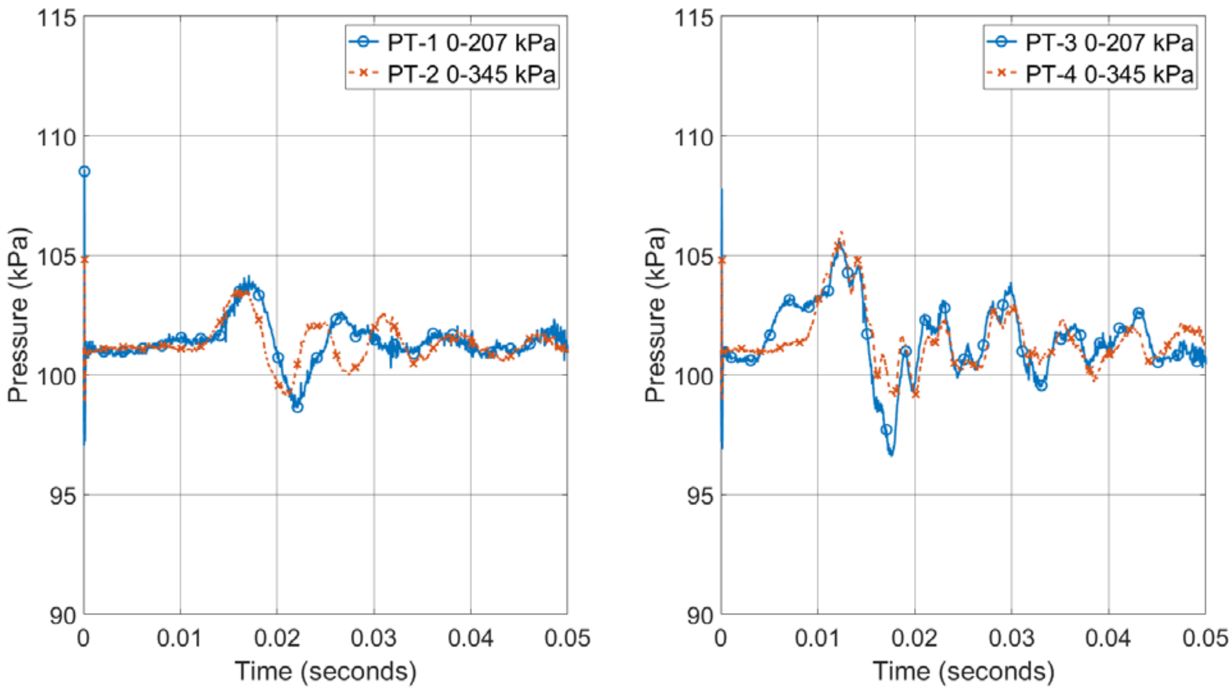


Fig. 70. Pressure measurements from Test 2-18A (breaker compartment (left); Main bus [arcing compartment] – (right)). Measurement uncertainty ± 3 percent.

3.8.1.4.Electrical measurements

Test 2-18A used KEMA circuit S09 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 13.5 kA symmetrical, and 35.6 kA peak. The KEMA report identifies this experiment as 190829-7005. Key experimental measurements are presented in Table 46. Plots of the electrical measurements are presented in Appendix B.

Table 46. Key measurement from Test 2-18A. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	277	277	277
Applied voltage, phase-to-phase	kV_{RMS}	480		
Making current	kA_{peak}	-41.4	-38.5	46.2
Current, a.c. component, beginning	kA_{RMS}	23.5	21.0	22.4
Current, a.c. component, middle	kA_{RMS}	20.7	23.5	16.6
Current, a.c. component, end	kA_{RMS}	15.9	18.2	12.5
Current, a.c. component, average	kA_{RMS}	19.8	17.3	17.9
Current, a.c. component, three-phase average	kA_{RMS}	18.3		
Duration	s	2.02	2.02	2.02
Arc Energy	MJ	17.23		

3.9. Test 2-18B – 600 V, 25 kA, 8 s duration, main bus, supply section

Test 2-18A was performed on August 29, 2019 at 3:07 PM eastern daylight time (EDT). The temperature was approximately 28 °C (82 °F), approximately 34 percent relative humidity and approximately 101.3 kPa of pressure. The weather was fair with a 21 km/h (13 mi/h) wind out of the west.

The switchgear used in Tests 2-18A was used again in this experiment. The enclosure breach opening that occurred in Test 2-18A was covered by a piece of sheet metal. The gear was tested for sufficient insulation resistance between phases and found to be functional. The arcing wire was located around the vertical main bus work at the bottom of the supply breaker vertical section as shown in Fig. 71. All three phases were shorted with the shorting wire. Ground plates were installed near the top of the vertical main bus. The plate was approximately 6.4 cm (2.5 in) above the top of the vertical main bus. Switchgear enclosure was connected to neutral. Generator neutral was tied to ground via impedance.

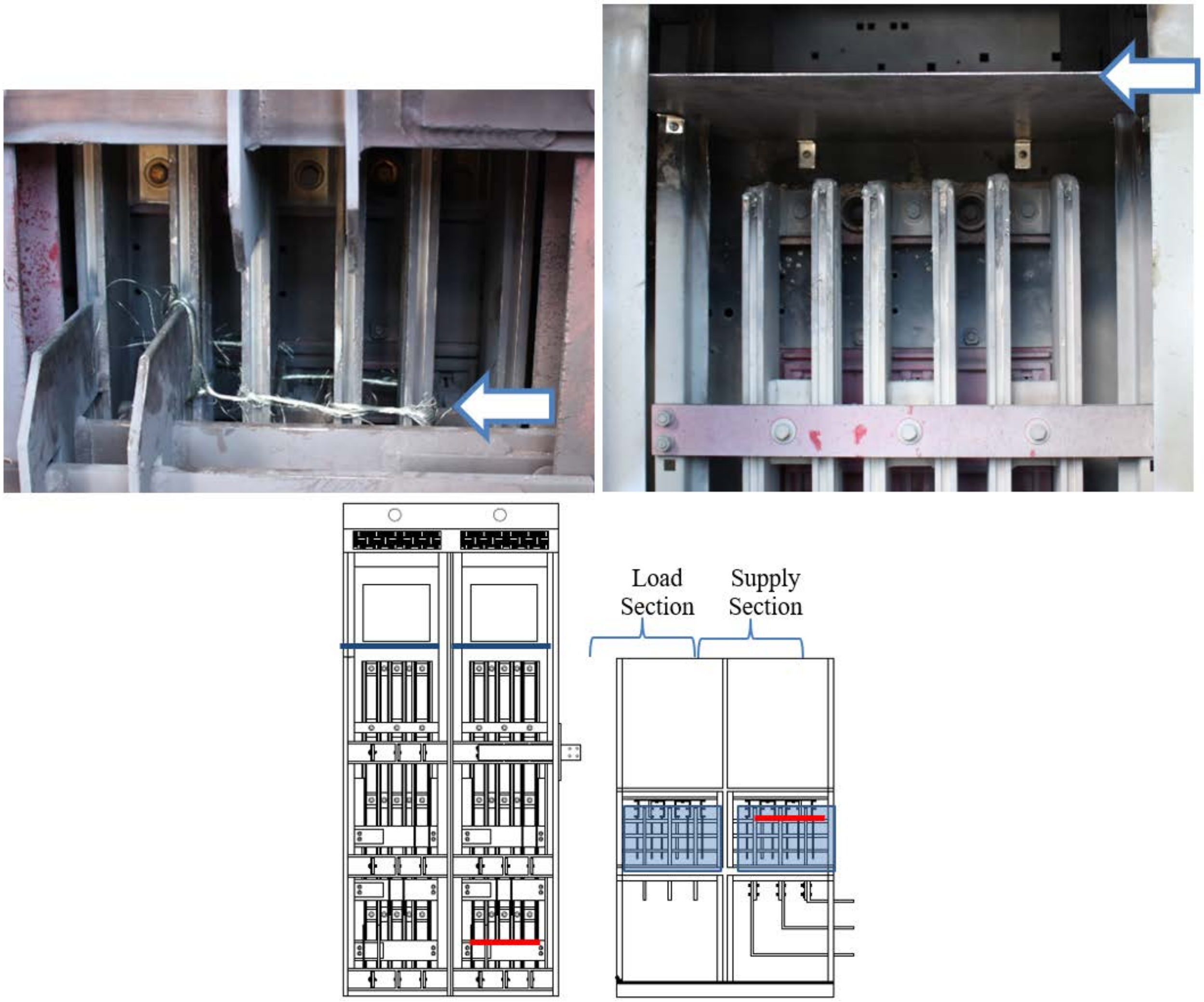


Fig. 71. Shorting Wire Location Test 2-18B (Phases left-to-right: A-B-C) (top left); grounding plate (top right); illustration of shorting wire (red) and grounding plate (blue) locations elevation view (bottom left) and plan view (bottom right).

3.9.1. Observations

Observations documented below are based on review of video and thermal imaging that was taken during the experiment. The observations are provided in Table 47 and include an approximate time reference. Corresponding images are provided in Fig. 72 and Fig. 73.

The arc did not sustain for the expected 8.0 s duration. The final arc extinguished at 8 310 ms.

Table 47. Observations from Test 2-18B.

Time (ms)	Observation
0	Initial light observed in bottom rear louver
200	Particle ejecta reaches rear instrumentation rack and observed in upper portion of switchgear
500	Arcing observed in upper portion of switchgear. Particle ejecta reaches first instrumentation rack above enclosure
750	Particle ejecta reaches second instrumentation rack above enclosure
900	Arcing observed in lower portion of switchgear
1 568	Particle ejecta exceeds instrumentation rack to left side of load vertical section
4 003	Arcing observed in upper portion of switchgear
4 671	Arcing observed in lower portion of switchgear
5 105	Particle eject from lower portion and larger hot gases (combustion) occurring in upper region
5 488	Arcing occurring in lower region of enclosure and color change indicating arc is occurring near enclosure breach
8 341	Post-experiment particle ejecta and combustion
39 739	Fire continues to burn in lower portion of cabinet
732 700	NIST data acquisition ends

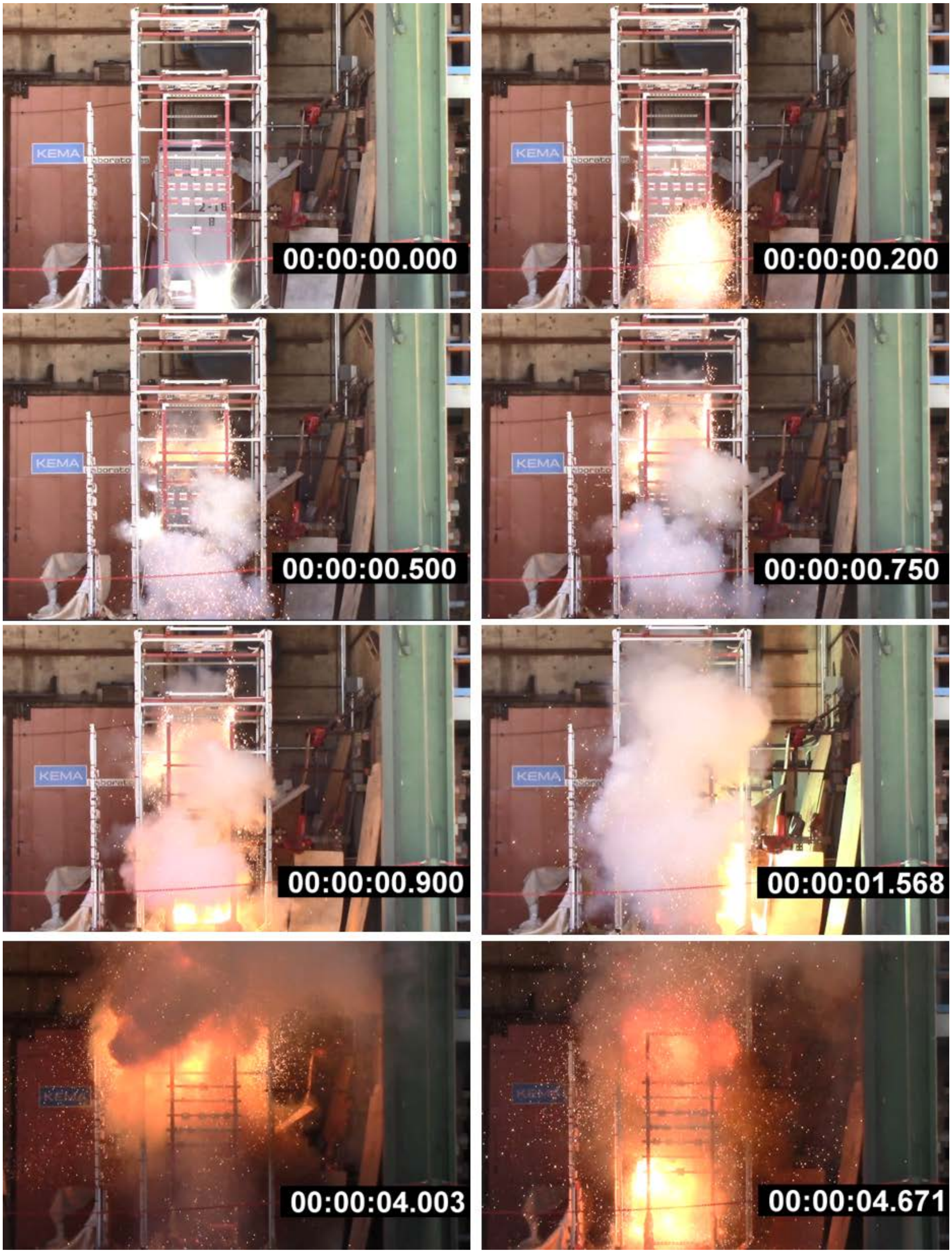


Fig. 72. Sequence of Images from Test 2-18B up to 4.671 s (image time stamps are in seconds).

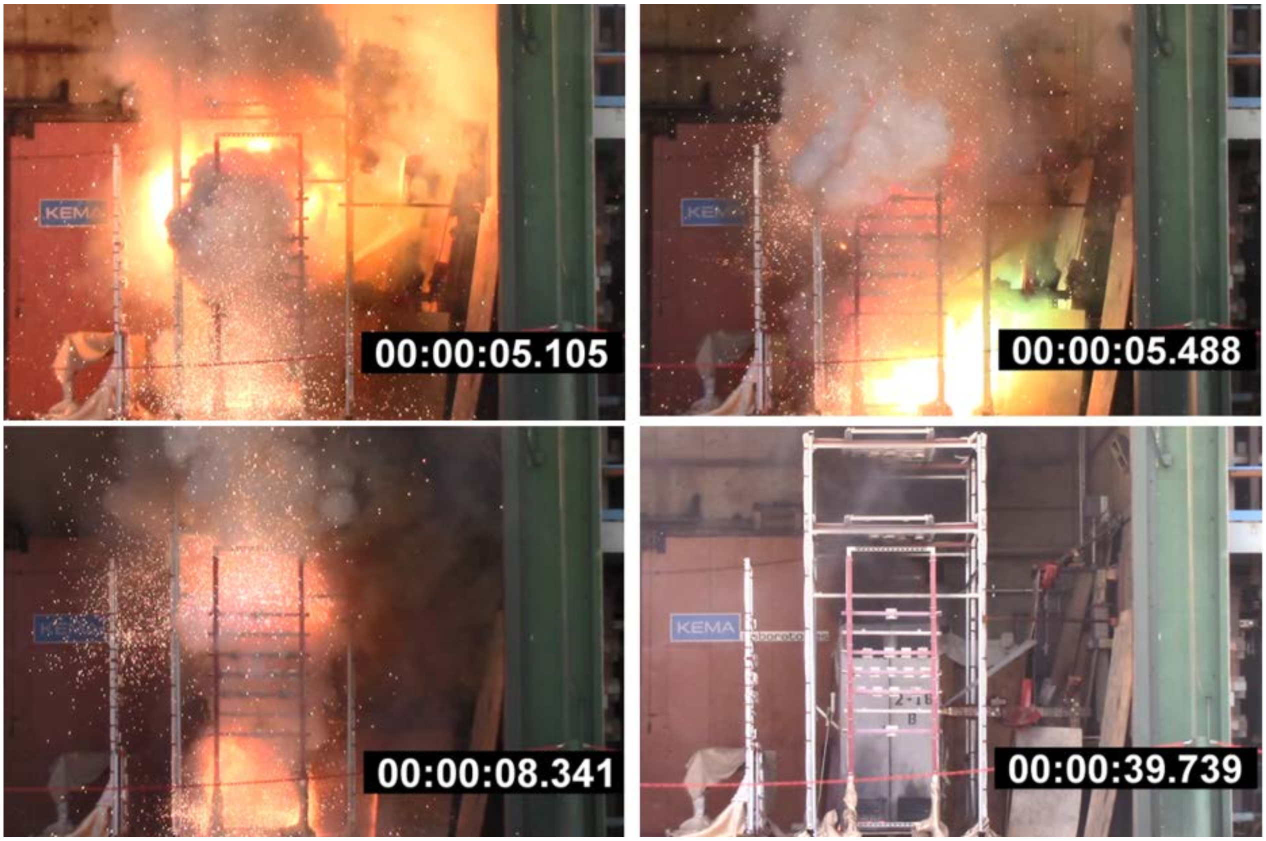


Fig. 73. Sequence of images from Test 2-18B from 4.671 s (image time stamps are in seconds).

Photographs of the enclosure following the experiment are presented in Fig. 74 and Fig. 75. The enclosure did experience small breaches on the incoming (supply) side of the switchgear. There were no instruments located in this area due to the limited room and required separation distances by the incoming laboratory power conductors.

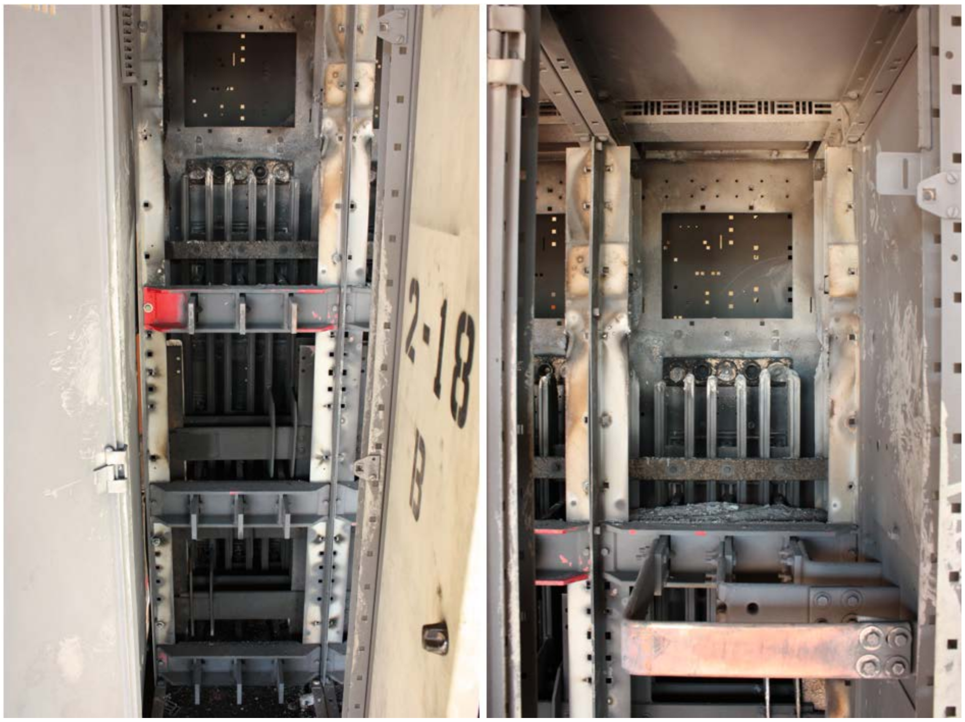


Fig. 74. Enclosure Post-Test 2-18B. load section (left), supply section (right)).

Fig. 75. Post-experiment image of enclosure. (load side (left), supply side (right)).

Fig. 76. Failure of KEMA cable connection observed as arcing occurring in Cell 8 (non-test cell).

3.9.1.1. Measurements

Measurements made during Test 2-18B are presented below. These measurements include:

- Thermal
  - Heat flux – Plate Thermometers
  - Incident energy – ASTM Slug Calorimeter
  - Heat flux, incident energy – T_{cap} Slug Calorimeter
- Pressure
  - Internal pressure
- Electrical

3.9.1.2.Thermal Measurements

Thermal measurements from the active instruments are reported below. These include PT measurements (Table 48), ASTM Slug Calorimeter measurements (Table 49), and T_{cap} slug measurements (Table 50). The maximum reading is identified with bold text. For some sensors, the EMI interfered with the thermal measurement. These are listed as "--" and noted with "EMI." For some measurements, the EMI magnitude was of the same order as the signal. These are listed as "--" and noted with "EMI S/N."

The thermal exposures measured over the top of the switchgear (Instrument Rack 4) were greater than the preceding experiments in this report. This was due to the arc duration (approximately 2 s) and the heat and combustion products exiting from the vents at the top of the electrical enclosure from an ensuing fire in the enclosure.

Table 48. Summary of plate thermometer measurements Test 2-18B.

Rack No.	Plate No.	Location	Max Heat Flux (kW/m^2) ± 1 kW/m^2 or ± 5 %	Average Heat Flux During Arc (kW/m^2) ± 1 kW/m^2 or ± 5 %
1	1	Top	175	56
1	3	Mid-Right	128	31
1	5	Mid-Center	261	52
1	7	Mid-Left	286	51
1	9	Bottom	305	61
2	10	Top	46	7
2	12	Mid-Right	14	3
2	14	Mid-Center	13	2
2	16	Mid-Left	14	3
2	18	Bottom	27	1
3	19	Top	153	26
3	21	Mid-Right	54	16
3	23	Mid-Center	67	12
3	25	Mid-Left	38	9
3	27	Bottom	29	7
4	28	Top	185	34
4	30	Mid-Right	280.	81
4	32	Mid-Center	320.	**91**
4	34	Mid-Left	**390.**	81
4	36	Bottom	357	89
5	37	Front	68	17
5	39	Center-Right	99	23
5	41	Center-Mid	195	29
5	43	Center-Left	150.	23
5	45	Back	208.	36
6	46	Front	83	13
6	48	Center-Bottom	23	5
6	50	Center-Mid	36	6
6	52	Center-Top	55	6
6	54	Back	23	3

Table 49. Summary of ASTM slug calorimeter measurements, Test 2-18B.

Rack No.	ASTM No.	Location	Incident Energy (kJ/m^2) ± 18kJ/m^2 or ± 4 %	Time to Max Temperature (s) ± 3%
1	A	Top	366	10
1	B	Bottom	453	9
2	C	Top	32	14
2	D	Bottom	24	1040
3	E	Top	187	512
3	F	Bottom	200	611
4	G	Rear	670	13
4	H	Front	962	12
5	I	Rear	245	16
5	J	Front	290	13
6	K	Rear	178	322
6	L	Front	177	522

Table 50. Summary of Tcap slug measurement, Test 2-18B.

Rack No.	T_{cap} No.	Location	Heat Flux During Arc (kW/m²) ± 1.5 kW/m² or ± 2.9 %	Incident Energy During Arc Phase (kJ/m²) ± 2.4 kJ/m² or ± 5 %	Total Incident Energy (kJ/m²) ± 2.4 kJ/m² or ± 5 %	Comment
1	2	Top	78.7	429.8	584.0	
1	4	Mid-Right	60.9	372.9	527.1	
1	6	Mid-Left	86.7	450.1	604.1	
1	8	Bottom	73.9	429.9	577.8	
2	11	Top	4.8	26.0	133.1	
2	13	Mid-Right	3.2	17.6	110.6	
2	15	Mid-Left	2.0	16.3	114.8	
2	17	Bottom	1.8	10.3	100.5	
3	20	Top	19.9	115.9	806.1	
3	22	Mid-Right	18.4	110.8	859.2	
3	24	Mid-Left	14.7	88.4	811.7	
3	26	Bottom	12.3	65.2	856.7	
4	29	Top	97.5	535.8	1648.0	
4	31	Mid-Right	118.9	625.7	1576.6	
4	33	Mid-Left	123.8	683.7	**1788.7**	
4	35	Bottom	**125.9**	**754.2**	1513.1	
5	38	Front	36.8	191.4	807.4	
5	40	Center-Right	34.7	193.8	675.5	
5	42	Center-Left	41.8	205.6	708.9	
5	44	Back	45.7	201.1	648.3	
6	47	Front	––	50.9	750.5	EMI S/N
6	49	Center-Bottom	––	40.1	773.9	EMI S/N
6	51	Center-Top	5.2	39.8	805.9	
6	53	Back	––	28.7	726.5	EMI S/N

3.9.1.3.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 decays to a relative steady state. The peak pressure is higher in the primary cable connection compartment as would be expected since this is the compartment where the arc is initiated. The maximum change in pressure in the main bus compartment is approximately 7 kPa (1.0 psi) above ambient at its peak. The maximum change in pressure in the breaker compartment is approximately 3 kPa (0.4 psi) above ambient. The 0 kPa to 207 kPa (0 psia to 30 psia) and 0 kPa to 345 kPa (0 psia to 50 psia) transducer recordings at a specific location were consistent.

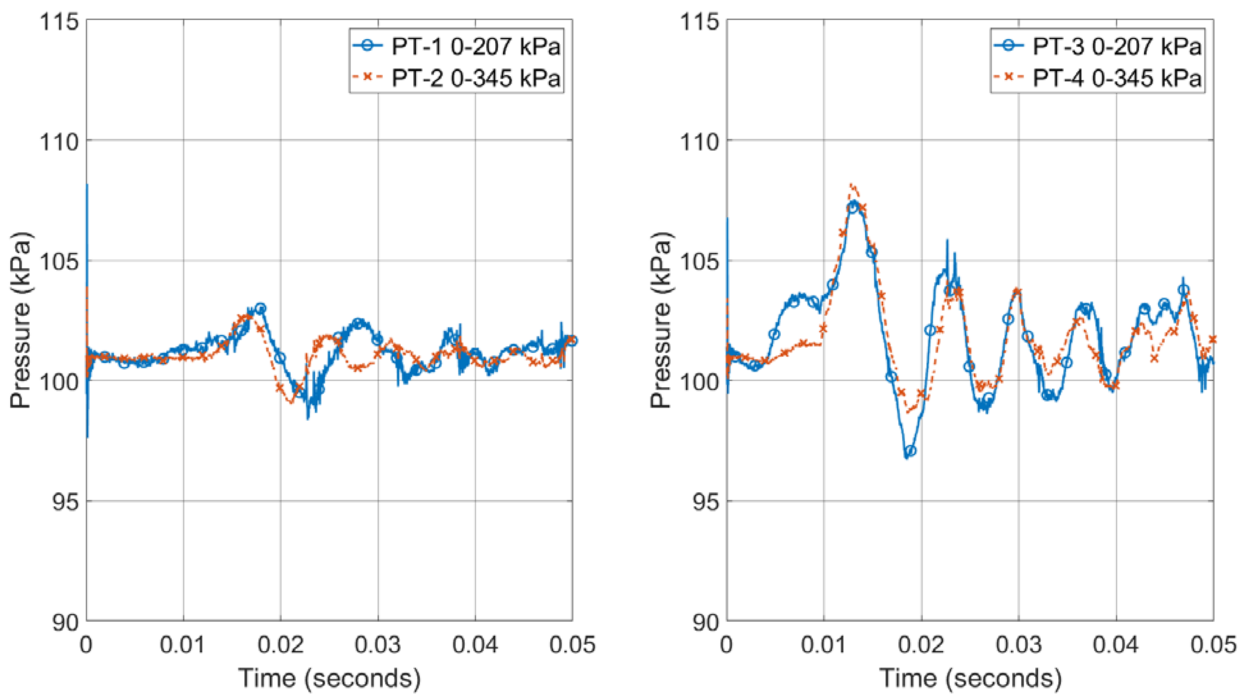


Fig. 77. Pressure measurements from Test 2-18B (breaker compartment (left); Main bus [arcing compartment] – (right)). Measurement uncertainty ± 3 percent.

3.9.1.4. Electrical measurements

Test 2-18B used KEMA circuit S08 presented in Appendix C. Full-level circuit checks (calibration tests) were performed prior to the experiment to verify the experimental parameters were acceptable. For this experiment the calibration tests configured the power system to 0.616 kV, 25 kA symmetrical, and 63.3 kA peak. The KEMA report identifies this experiment as 190829-7006. Key experimental measurements are presented in Table 51. Plots of the electrical measurements are presented in Appendix B.

Table 51. Key measurement from Test 2-18B. Measurement uncertainty ± 3 percent.

Phase	Units	A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	357	357	357
Applied voltage, phase-to-phase	kV_{RMS}	618		
Making current	kA_{peak}	35.4	-38.8	-32.4
Current, a.c. component, beginning	kA_{RMS}	22.6	20.9	22.0
Current, a.c. component, middle	kA_{RMS}	25.8	23.6	21.9
Current, a.c. component, end	kA_{RMS}	15.6	22.2	24.3
Current, a.c. component, average	kA_{RMS}	21.1	20.0	19.6
Current, a.c. component, three-phase average	kA_{RMS}	20.2		
Duration	s	8.3	8.3	8.3
Arc Energy	MJ	72.76		

4. Summary and Conclusion

This section provides a brief summary and conclusions made from the series of experiments documented in this report.

4.1. Summary

A series of nine (9) individual arcing fault experiments on two separate switchgear units were performed. Each experiment consisted of a three-phase arcing fault initiated and sustained on aluminum or copper electrodes within the low-voltage metal enclosed switchgear. Two experiments were initiated on the copper bus stabs; one experiment in the main bus compartment (Test 2-13D) and the other in the breaker cubicle (Test 2-13E). Post-experiment evaluation of Test 2-13D indicated that the arc migrated to the aluminum portion of the main bus. In Test 2-13E the arc was sustained on the copper portion of the gear without involving aluminum components. All other experiments were initiated on the aluminum main bus. The magnitude of the arc current and duration was varied at a nominal system voltage of either 480 V or 600 V. Electrical parameters are summarized in Table 52. Numerous measurements were made to characterize the environment surrounding the switchgear, including external heat flux, external incident energy, electric field strength, air conductivity, optical emission spectrum, and internal pressure. A summary of the thermal measurements is provided in Table 53. Photometric equipment was deployed to capture the event using a combination of devices to characterize the thermal environment and event timing.

Table 52. Experiment Summary.

Test No.	Nominal Voltage (kV) ± 3 %	Current (kA) ± 3 %	Arc Duration (sec) ± 3 %	Energy (MJ) ± 3 %	Arc Location
2-13A	0.480	9 800	0.950	1.44	Main bus – upper
2-13B	0.600	9 973	0.399	1.38	Main bus – upper
2-13C	0.600	11 650	0.413	1.67	Main bus – upper
2-13D	0.600	9 266	0.926	4.21	Main bus – upper
2-13E	0.600	10 388	2.060	9.64	Breaker cubicle (copper)
2-13F	0.480	9 733	1.550	5.44	Main bus – lower
2-13G	0.600	10 707	2.020	10.40	Main bus – lower
2-18A	0.480	19 146	2.020	17.23	Main bus – lower
2-18B	0.600	19 349	8.310	72.76	Main bus – lower

Table 53. Summary of maximum incident energy measurements.

Experiment #	Bar Material		Electrical Energy	Rack Location	Distance (m)	ASTM (Copper) Slug	T_{cap} (Tungsten) Slug
	Al	Cu	(MJ) ± 3 %			Max. Total Incident Energy (MJ/m^2) ± 0.018 MJ/m^2 or ± 4 %	Max. Total Incident Energy (MJ/m^2) ± 0.002 MJ/m^2 or ± 5 %
2-13A	X		1.44	Sides	0.91	No Data	0.013
				Above	0.91	No Data	0.018
				Above	1.82	No Data	0.007
2-13B	X		1.38	Sides	0.91	0.001	0.013
				Above	0.91	0.006	0.020
				Above	1.82	0.004	0.005
2-13C	X		1.67	Sides	0.91	0.005	0.026
				Above	0.91	0.009	0.030
				Above	1.82	0.004	0.004
2-13D		X	4.21	Sides	0.91	0.016	0.058
				Above	0.91	0.022	0.071
				Above	1.82	0.011	0.025
2-13E		X	9.64	Sides	0.91	0.017	0.045
				Above	0.91	0.090	0.263
				Above	1.82	0.025	0.057
2-13F	X		5.44	Sides	0.91	0.061	0.087
				Above	0.91	0.009	0.022
				Above	1.82	0.006	0.012
2-13G	X		10.40	Sides	0.91	0.110	0.141
				Above	0.91	0.030	0.107
				Above	1.82	0.011	0.032
2-18A	X		17.23	Sides	0.91	0.083	0.146
				Above	0.91	0.092	0.276
				Above	1.82	0.029	0.093
2-18B	X		72.76	Sides	0.91	0.453	0.859
				Above	0.91	0.962	1.789
				Above	1.82	0.290	0.807

4.2. Conclusions

This series of experiments provides valuable information related to the characteristics of the electrical arc and potential hazards, including:

- Low-voltage arc faults were difficult to sustain in the configuration studied.
- Arc migration from initiation point was evident in several of the experiments and consistent with observations from Phase 1 Testing [2]. The inability to sustain the arc in one location reduces the possibility of breaching the enclosure and exposing external targets to HEAF-generated incident energy.
- Sustaining an arc on copper was easier even with larger phase-to-phase separation than experiments performed on the aluminum bus. Location of the arc and internal combustible materials resulted in an ensuing fire which required manual intervention to extinguish.
- Pressure increases within the enclosure appeared to be minimal and didn't cause in the enclosure panels to deform or doors to open.

Acknowledgments

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References

[1] OECD Fire Project – Topical Report No. 1, Analysis of High Energy Arcing Faults (HEAF) Fire Events, Nuclear Energy Agency Committee on the Safety of Nuclear Installations, Organization for Economic Cooperation and Development, June 2013.
[2] NEA HEAF Project – TOPICAL REPORT No. 1, Experimental Results from the International High Energy Arcing Fault (HEAF) Research Program – Phase 1 Testing 2014 to 2016, Nuclear Energy Agency Committee on The Safety of Nuclear Installations, 2017
[3] NRC Information Notice 2017-04: High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components, US NRC, Washington, DC, August 2017.
[4] EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology. Electric Power Research Institute (EPRI), Palo Alto, CA, and U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research (RES), Rockville, MD: 2005, EPRI TR-1011989 and NUREG/CR-6850.
[5] Fire Probabilistic Risk Assessment Methods Enhancements: Supplement 1 to NUREG/CR-6850 and EPRI 1011989, EPRI, Palo Alto, CA, and NRC, Washington, DC.: December 2009.
[6] Memorandum from Mark Henry Salley, to Thomas H. Boyce, Regarding submittal of possible generic issue concerning the damage caused by high energy arc faults in electrical equipment containing aluminum components, ADAMS Accession No. ML16126A096, May 2016.
[7] Memorandum from Joseph Giitter to Michael F. Weber, regarding Results of Generic Issue Review Panel Screening Evaluation for Proposed Generic Issue PRE-GI-018, 'High Energy Arcing Faults involving Aluminum,' ADAMS Accession No. ML16349A027, July 15, 2017.
[8] Memorandum from Michael Franovich and Michael Cheok to Raymond V. Furstenau, regarding Assessment Plan for Pre-GI-018, Proposed Generic Issue on High Energy Arc Faults Involving Aluminum, ADAMS Accession No. ML18172A189, August 22, 2018.
[9] An International Phenomena Identification and Ranking Table (PIRT) Expert Elicitation Exercise for High Energy Arcing Faults (HEAFs), US NRC, Washington, DC, NUREG-2218, January 2018.
[10] NRC RIL 2021-10, NIST TN 2188, SNL SAND2021-12049 R, Report on High Energy Arcing Fault Experiments, Experimental Results from Medium Voltage Electrical Enclosures, U.S. Nuclear Regulatory Commission, Washington, DC, National Institute of Standards and Technology, Gaithersburg, MD, Sandia National Laboratories, Albuquerque, NM, November 2021.
[11] Tambakuchi, A., et. al., *NRC HEAF Tests, Imaging and Measurement Methodology Report*, SAND2021-12086 R, Sandia National Laboratories, September 2018.
[12] Lafarge, T. and Possolo, A, "The NIST Uncertainty Machine," NCLSI Measure J. Meas. Sci., Vol. 10, No. 3, pp.20-27, September 2015.
[13] Putorti, A., Melly, M., Bareham, S., and Praydis Jr., J., "Characterizing the Thermal Effects of High Energy Arc Faults." 23rd International Conference on Structural Mechanics in Reactor Technology (SMiRT 23) – 14th International Post-Conference Seminar on "FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS," Salford, UK, August 17-18, 2015, http://www.grs.de/en/publications/grs-a-3845.

[14] Ingason, H. and Wickstrom, U., "Measuring incident radiant heat flux using the plate thermometer," *Fire Safety Journal*, Vol. 42, No. 2, 2007, pp. 161-166.
[15] Taylor, B.N. and Kuyatt, C.E., "Guidelines for evaluating and expressing the uncertainty of NIST measurement results," NIST Technical Note 1297, National Institute of Standards and Technology, Gaithersburg, MD, USA, 1994.
[16] Joint Committee for Guides in Metrology. Evaluation of measurement data – Guide to the expression of uncertainty in measurement, Sèvres, France: International Bureau of Weights and Measures (BIPM), URL www.bipm.org/en/publications/guides/gum.html, BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, JCGM 100:2008, GUM 1995 with minor corrections (2008).
[17] Joint Committee for Guides in Metrology. International vocabulary of metrology – Basic and general concepts and associated terms (VIM), Sèvres, France: International Bureau of Weights and Measures (BIPM), 3rd ed., URL www.bipm.org/en/publications/guides/vim.html, BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, JCGM 200:2012 (2008 version with minor corrections) (2012).
[18] ASTM (1993), *Manual on the Use of Thermocouples in Temperature Measurement*, ASTM Manual Series: MNL12, Revision of Special Publication (STP) 470B, 4th ed., ASTM International, West Conshohocken, PA, 1993, United States.
[19] McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., Overholt, K., Fire Dynamics Simulator, Technical Reference Guide. National Institute of Standards and Technology, Gaithersburg, MD, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013. Vol. 1: Mathematical Model; Vol. 2: Verification Guide; Vol. 3: Validation Guide; Vol. 4: Configuration Management Plan.
[20] ASTM Standard F1959 / F1959M-14, 2014, "Standard Test Method for Determining the Arc Rating of Materials for Clothing," ASTM International, West Conshohocken, PA, 2014.
[21] ASTM Standard E457-08, "Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter," ASTM International, West Conshohocken, PA, 2008.
[22] Tektronix Mixed Domain Oscilloscopes, MDO4000C Series Datasheet, Tektronix, Beaverton, OR, https://www.tek.com site accessed November 2021.
[23] NRC RIL 2021-18, NIST TN 2198, SAND2021-16075 R, Report on High Energy Arcing Fault Experiments, Experimental Results from Open Box Enclosures, U.S. Nuclear Regulatory Commission, Washington, DC, National Institute of Standards and Technology, Gaithersburg, MD, Sandia National Laboratories, Albuquerque, NM, December 2021.
[24] Taylor, G., et. al., NUREG/CP-0311, Proceedings of the Information Sharing Workshop on High Energy Arcing Fault (HEAF), U.S. Nuclear Regulatory Commission, Rockville, MD, July 2019.
[25] NUREG/CR-6931, SAND2007-600/V2, Vol. 2, Nowlen, S.P., Wyant, F.J., *Cable Response to Live Fire (CAROLFIRE), Vol 2.: Cable Fire Response Data for Fire Model Improvement*, U.S. Nuclear Regulatory Commission, Washington, DC, Sandia National Laboratories, Albuquerque, NM, 2008.

Appendix A: Engineering Drawings

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

A.1 Experimental Facility

Drawings of the testing facility are presented in Fig. 78 through Fig. 80.

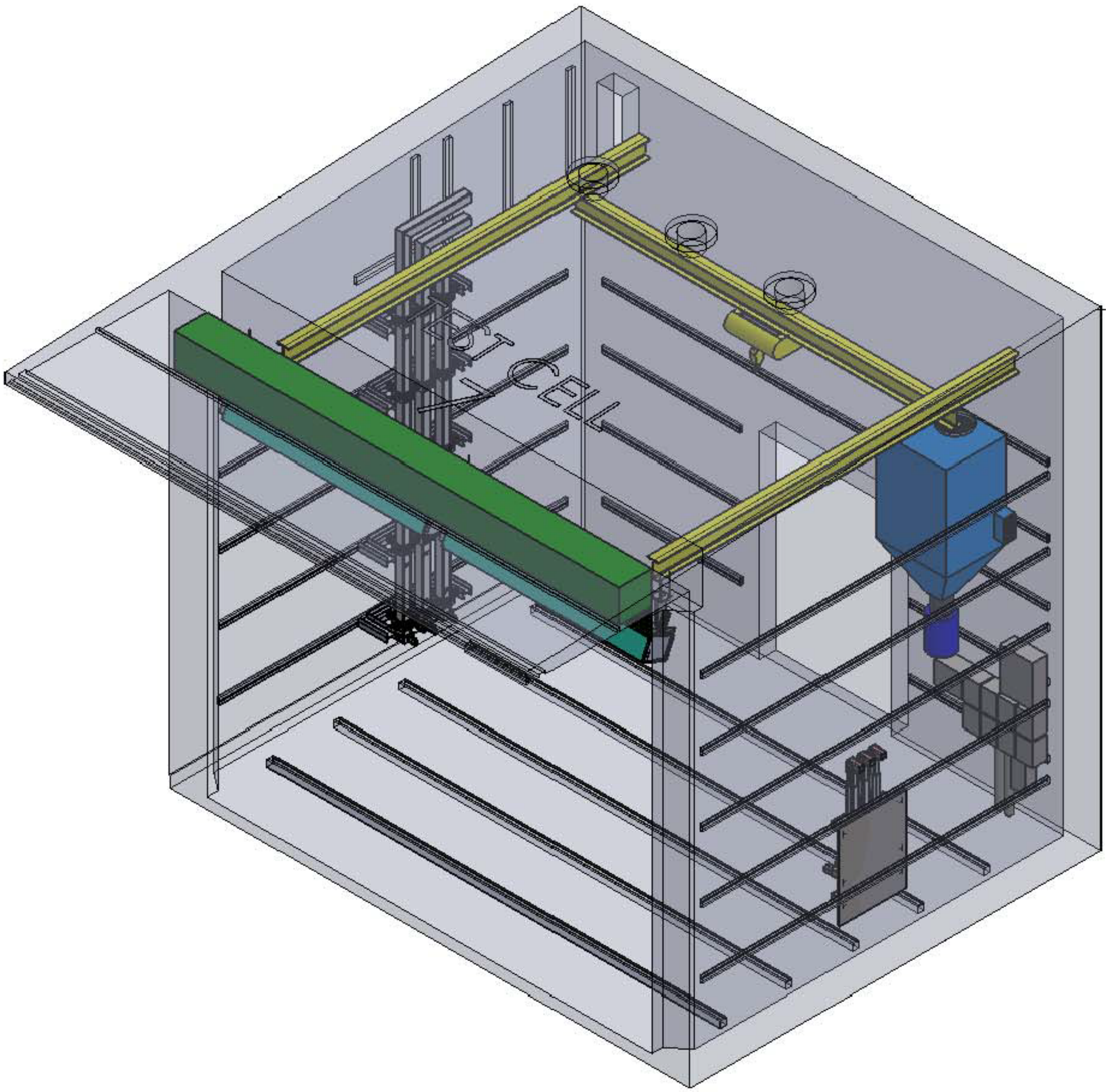


Fig. 78. Isometric drawing of Test Cell #7.

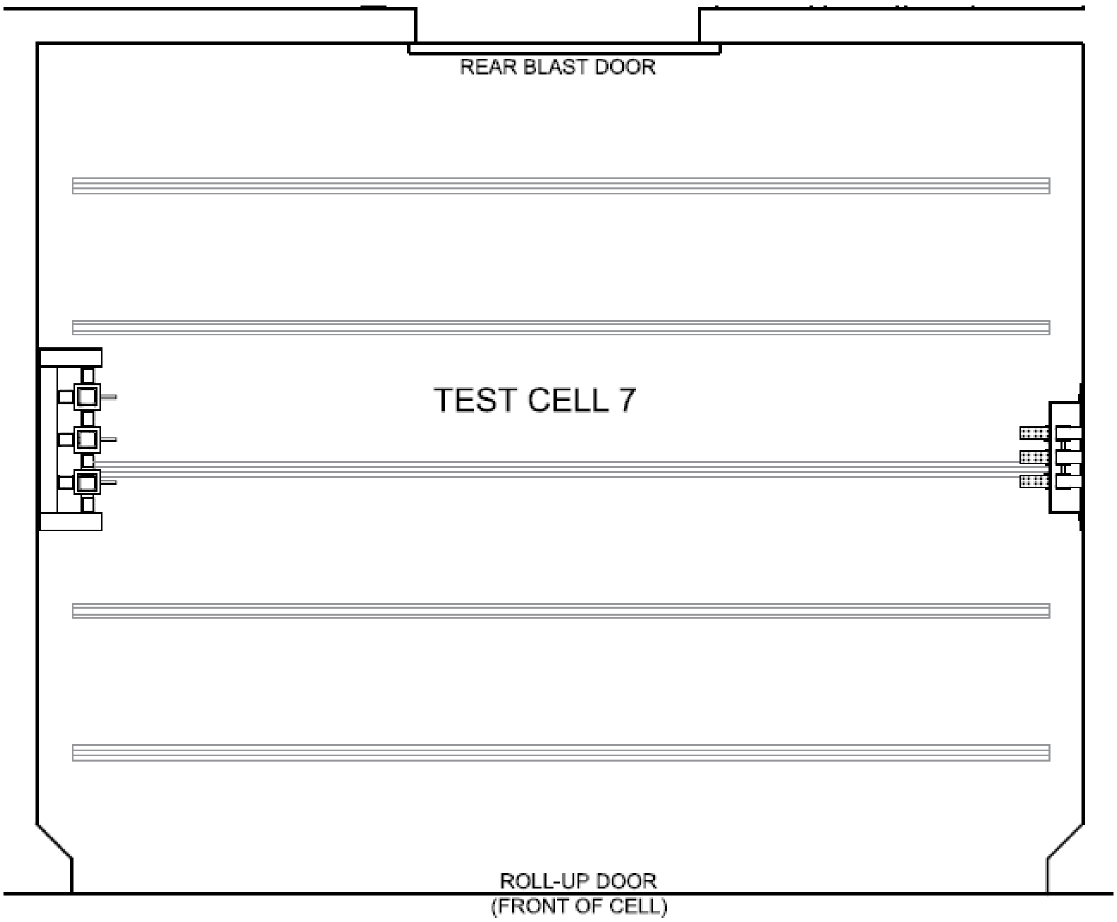


Fig. 79. Plan view of Test Cell #7. Low-voltage power connections located on right side of drawing.

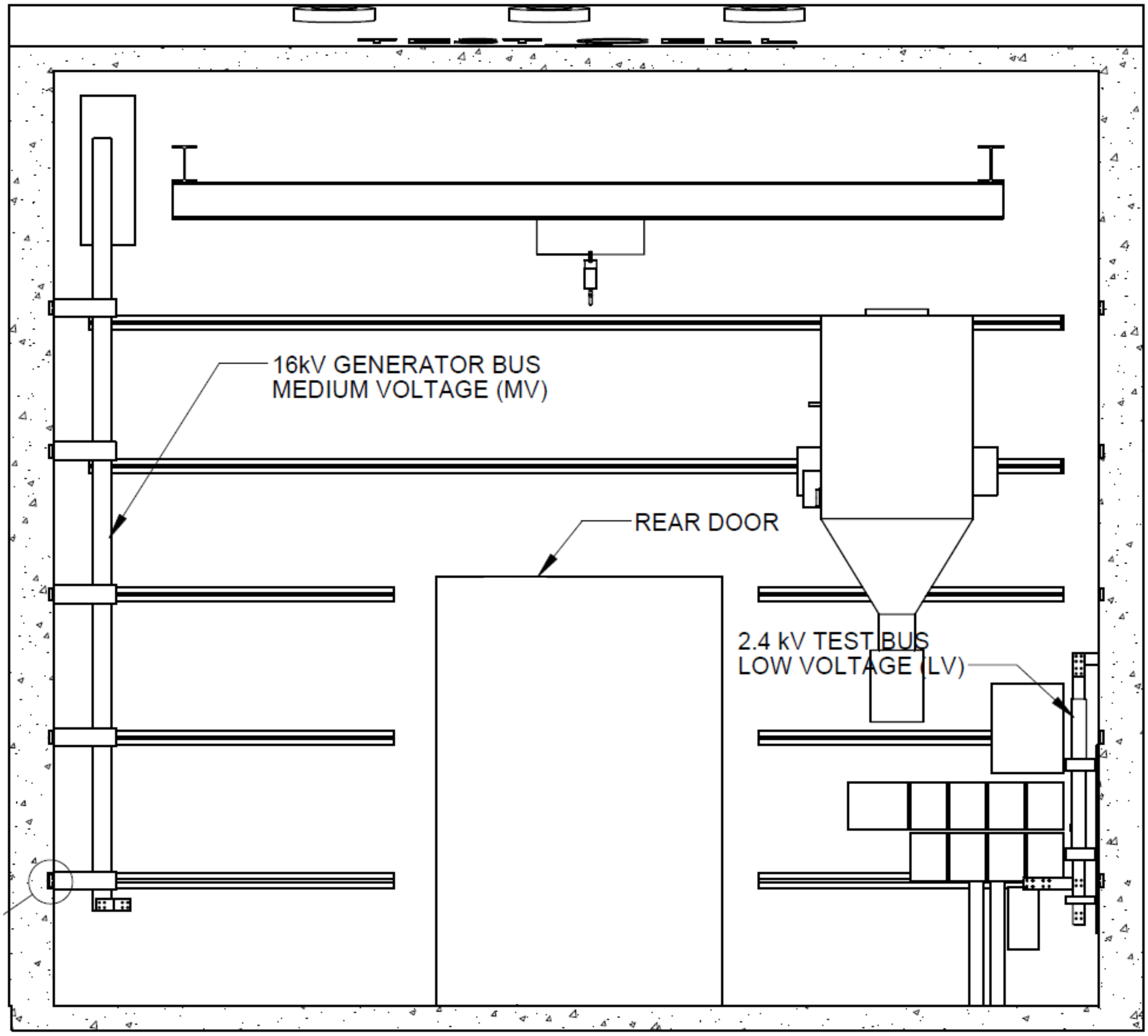


Fig. 80. Elevation view of Test Cell #7. Low-voltage power connections located on right side of drawing.

A.2 Support Drawings

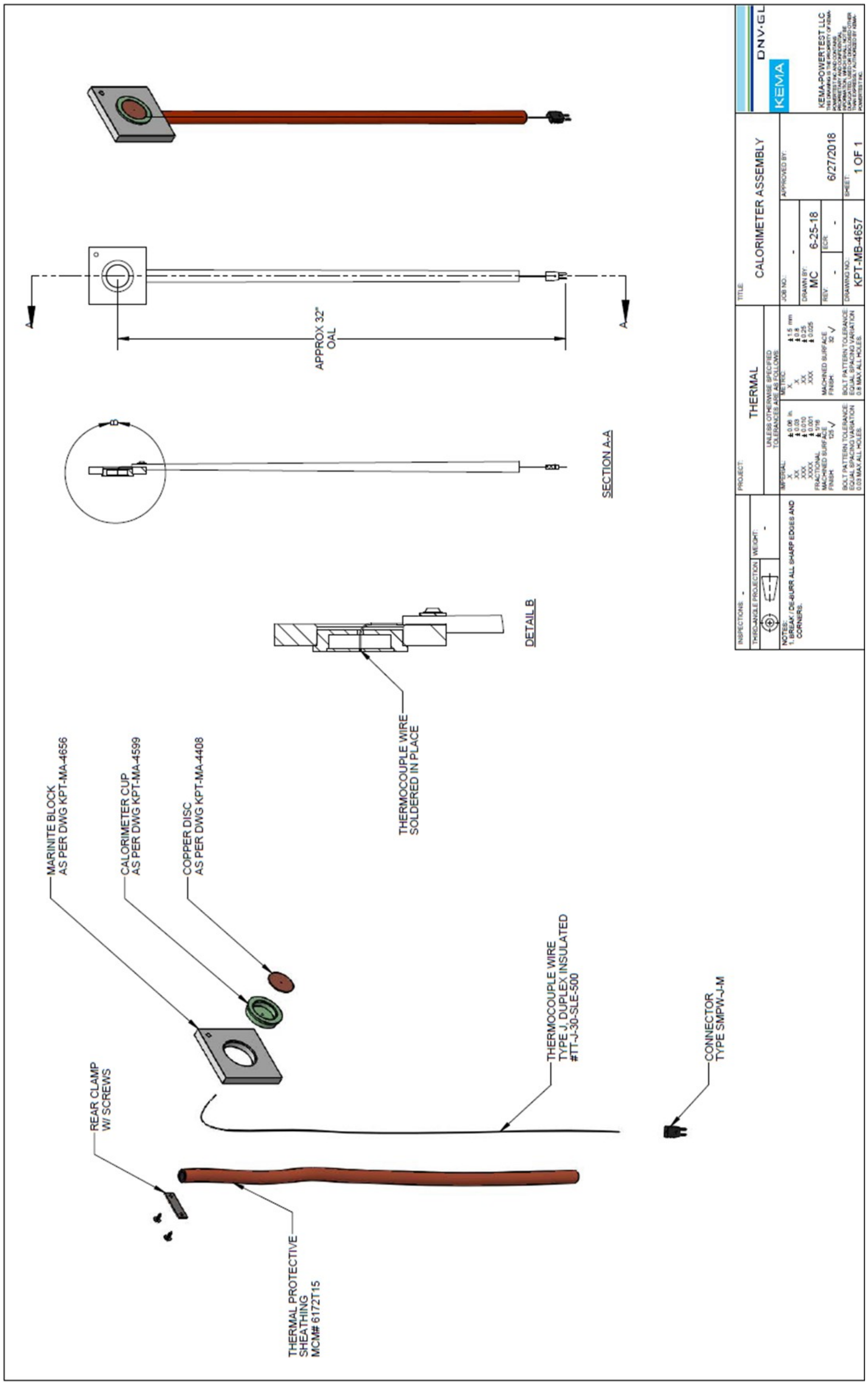


Fig. 81. Drawing KPT-MB-4657, ASTM Calorimeter Assembly.

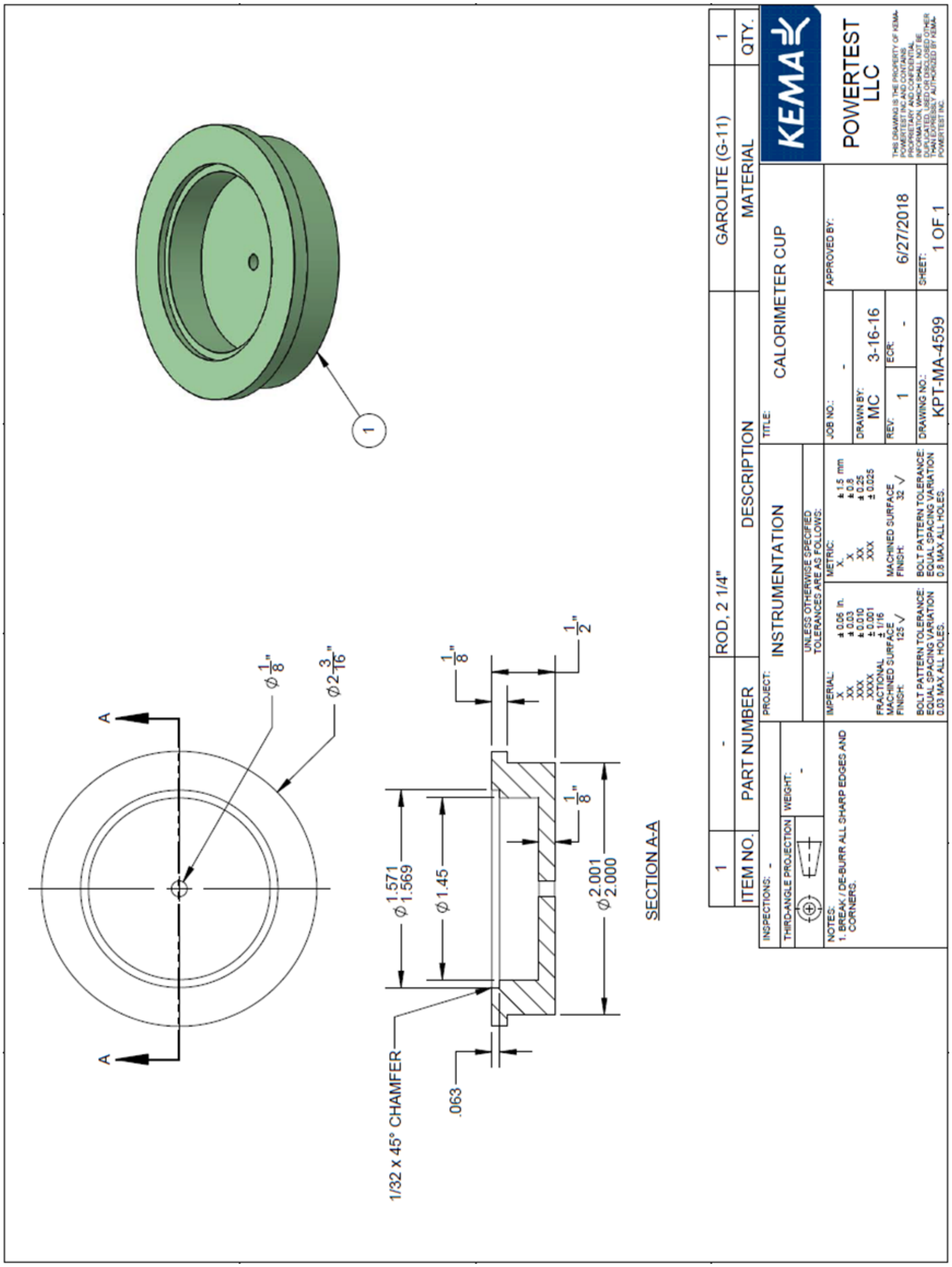


Fig. 82. Drawing KPT-MA-4599, ASTM Calorimeter Cup.

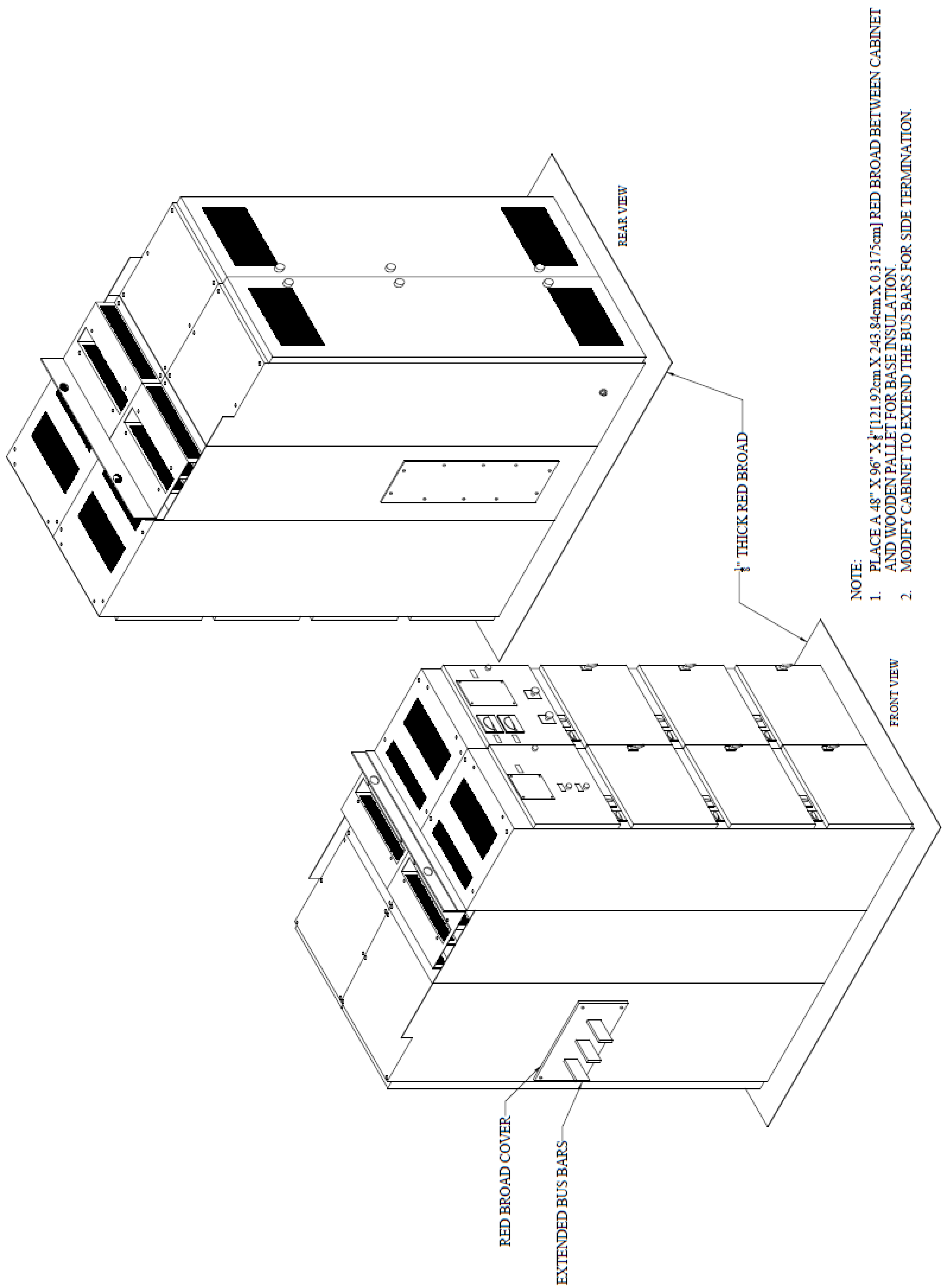


Fig. 83. Isometric drawings of LV metal enclosed indoor switchgear.

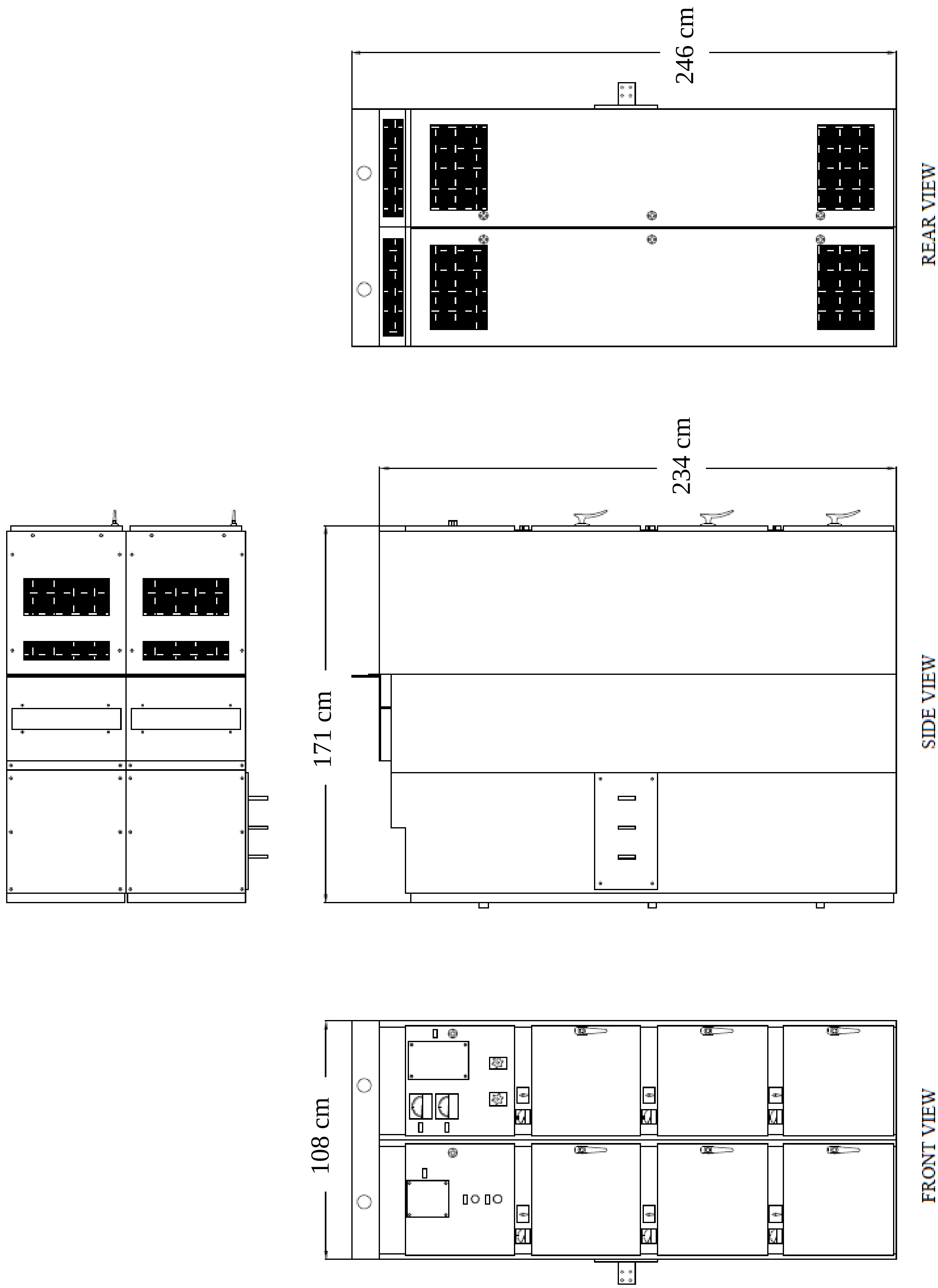


Fig. 84. Plan and elevation drawings of LV metal enclosed indoor switchgear.

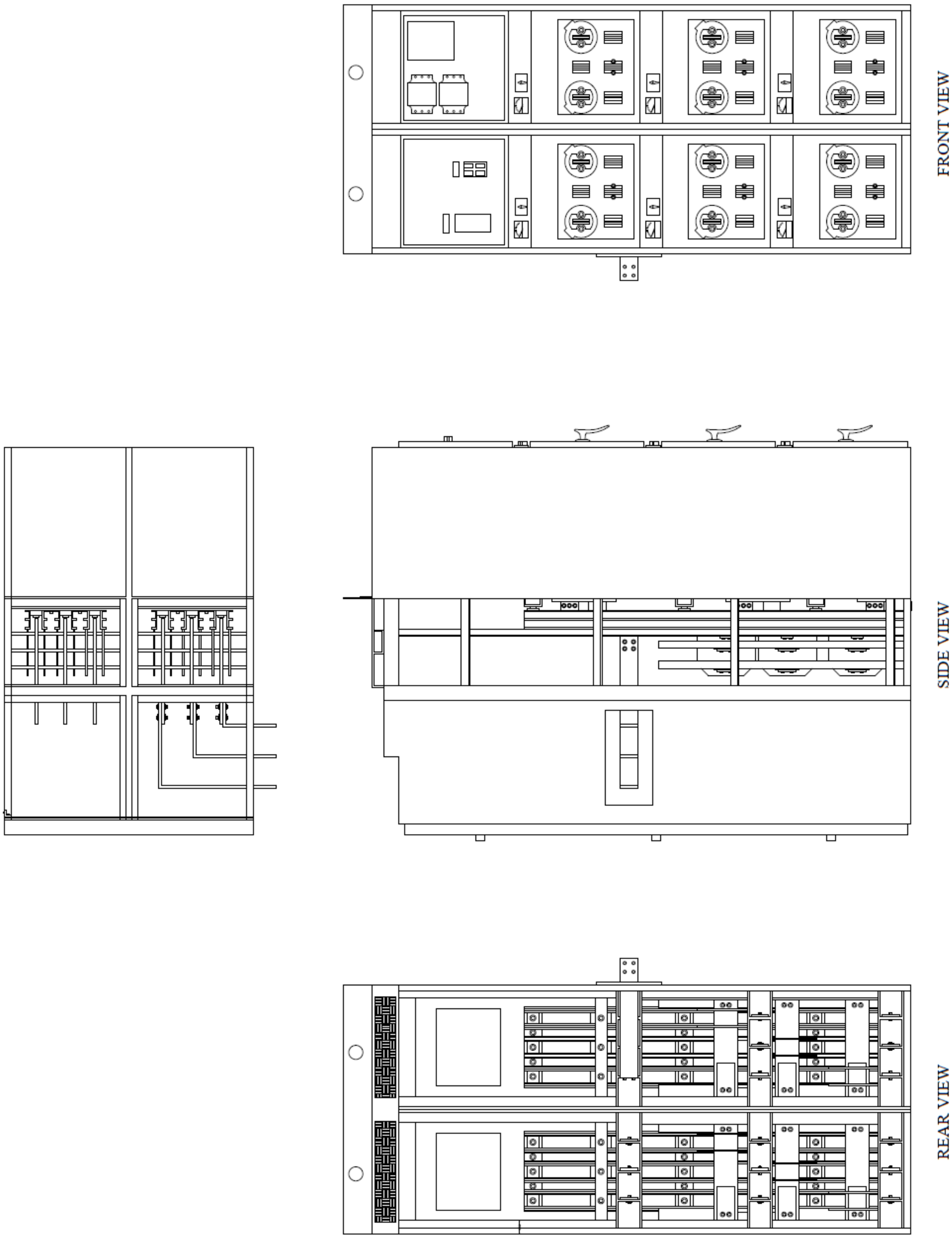


Fig. 85. Drawing of interior layout of LV metal enclosed indoor switchgear.

Appendix B: Electrical Measurement

This appendix presents plots of the electrical measurements made during each experiment.

Experiment 2-13A, 480 V, 13.5 kA, 2 s, main bus top, load section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 86. The transient region for current phases is presented in Fig. 87. Energy and power profiles are presented in Fig. 88.

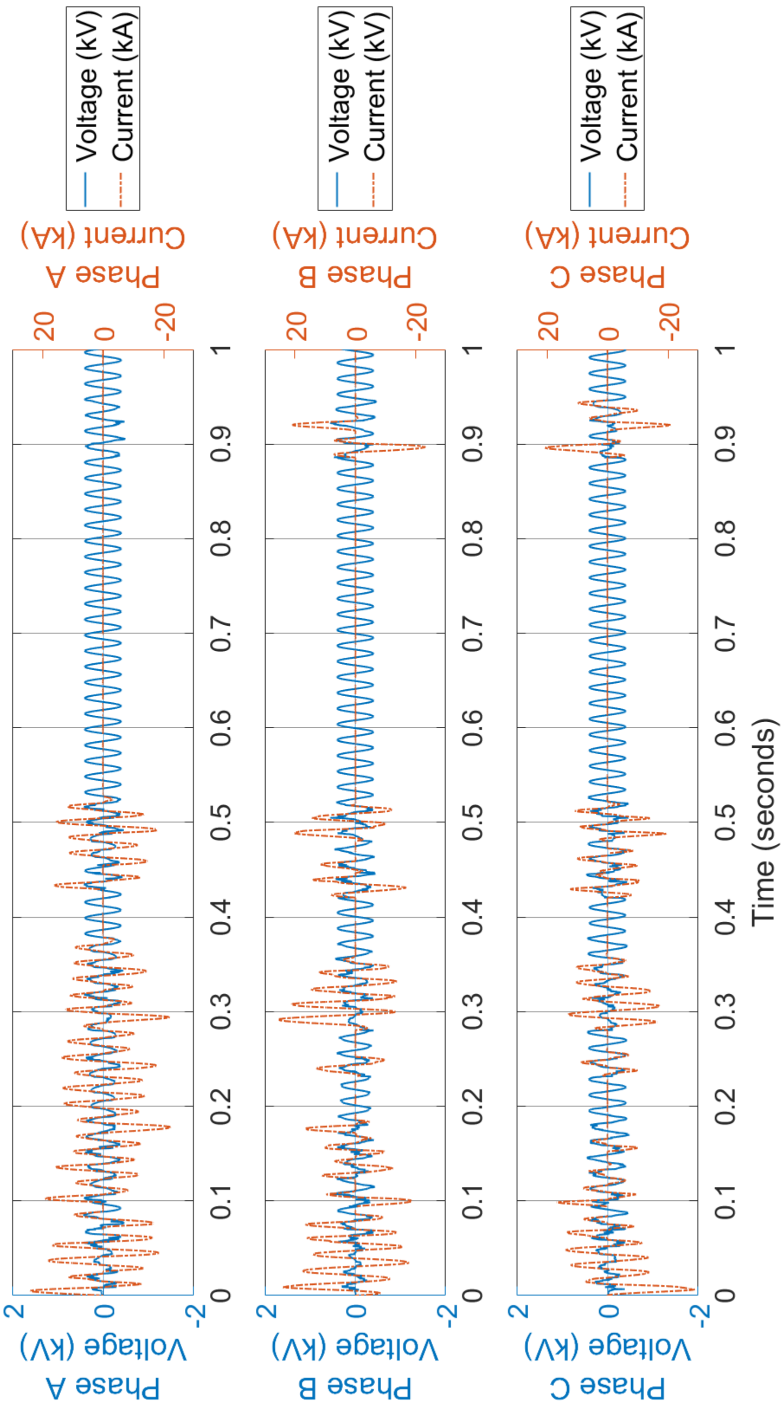


Fig. 86. Voltage and Current Profile during Test 2-13A. Measurement uncertainty ± 3 percent.

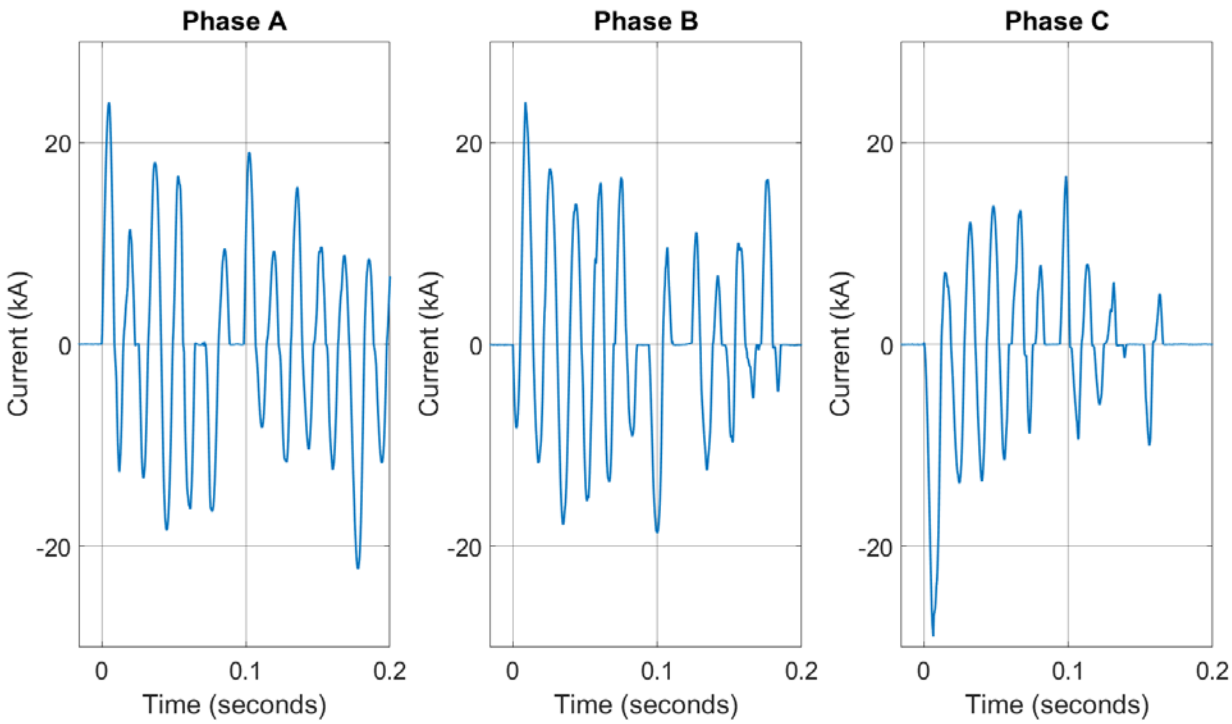


Fig. 87. Transient current profiles for Test 2-13A. Measurement uncertainty ± 3 percent.

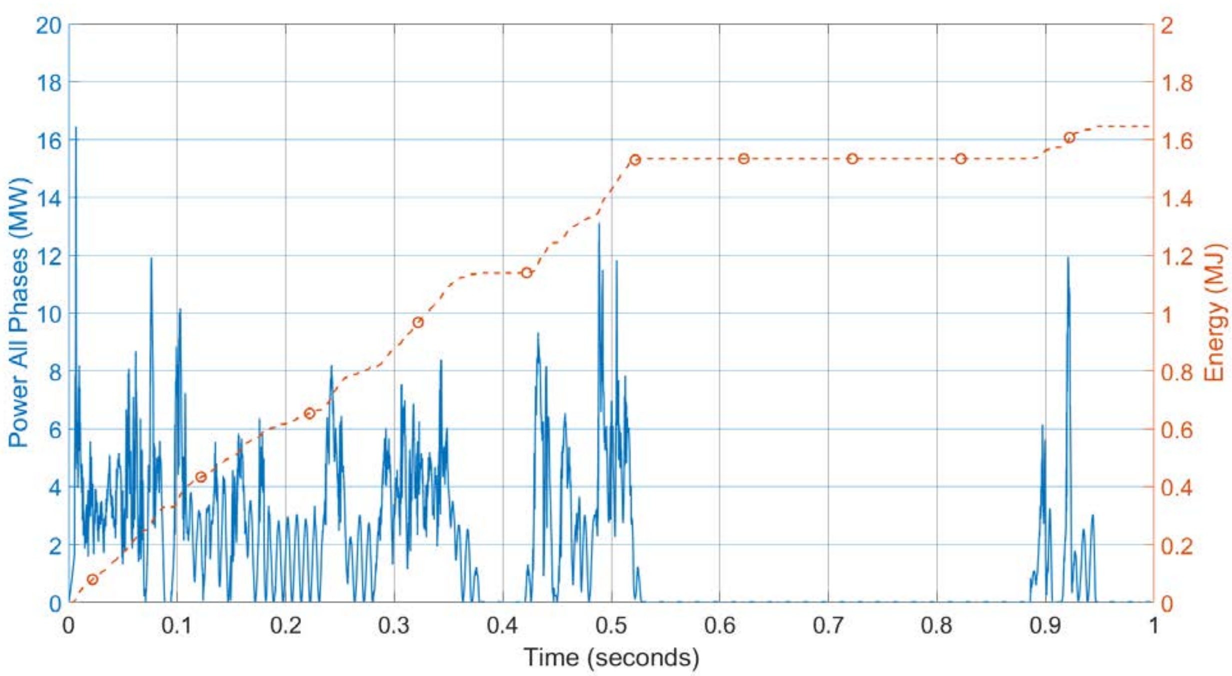


Fig. 88. Power and Energy for Test 2-13A. Measurement uncertainty ± 3 percent.

<u>Experiment 2-13B, 600 V, 13.5 kA, 2 s, main bus top, load section</u>

The voltage and current profile for the entire duration of the experiment is shown in Fig. 89. The transient region for current phases is presented in Fig. 90. Energy and power profiles are presented in Fig. 91.

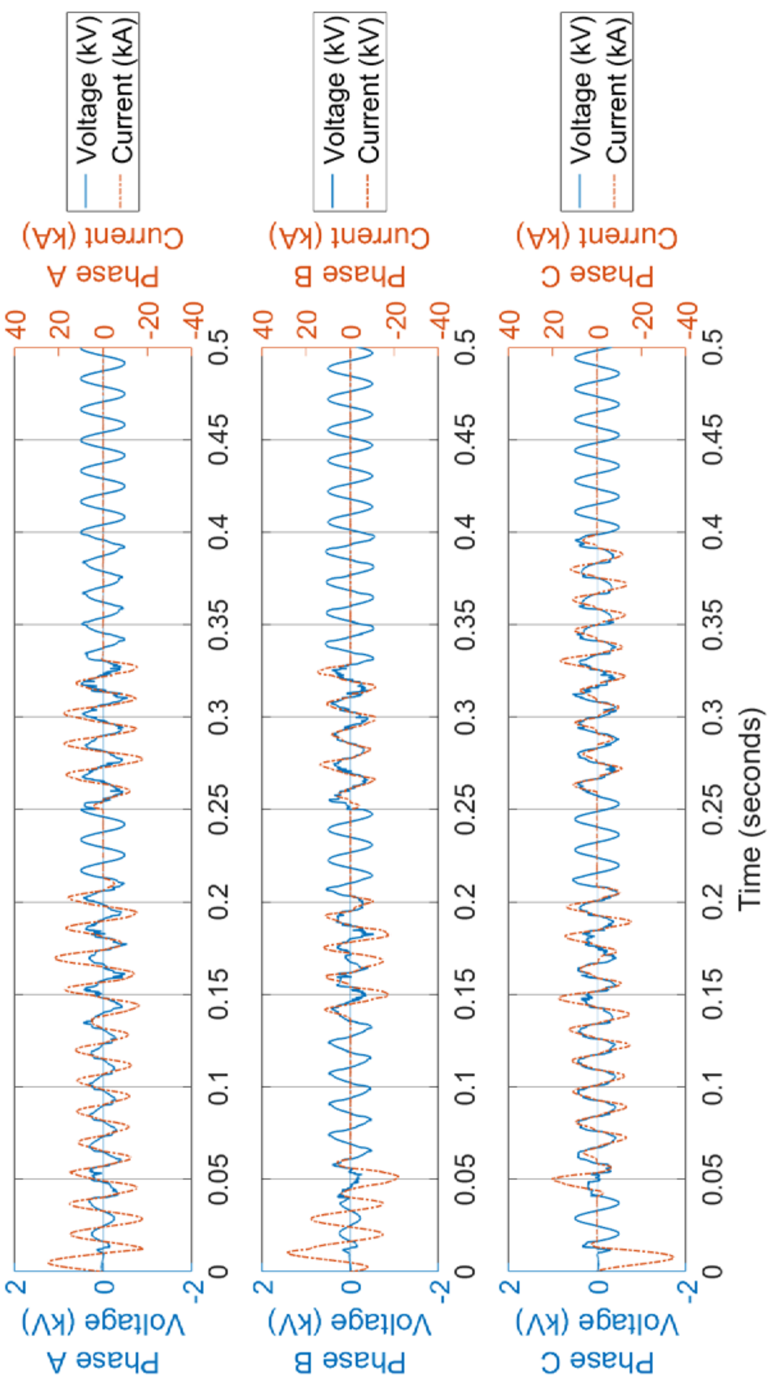


Fig. 89. Voltage and Current Profile during Test 2-13B. Measurement uncertainty ± 3 percent.

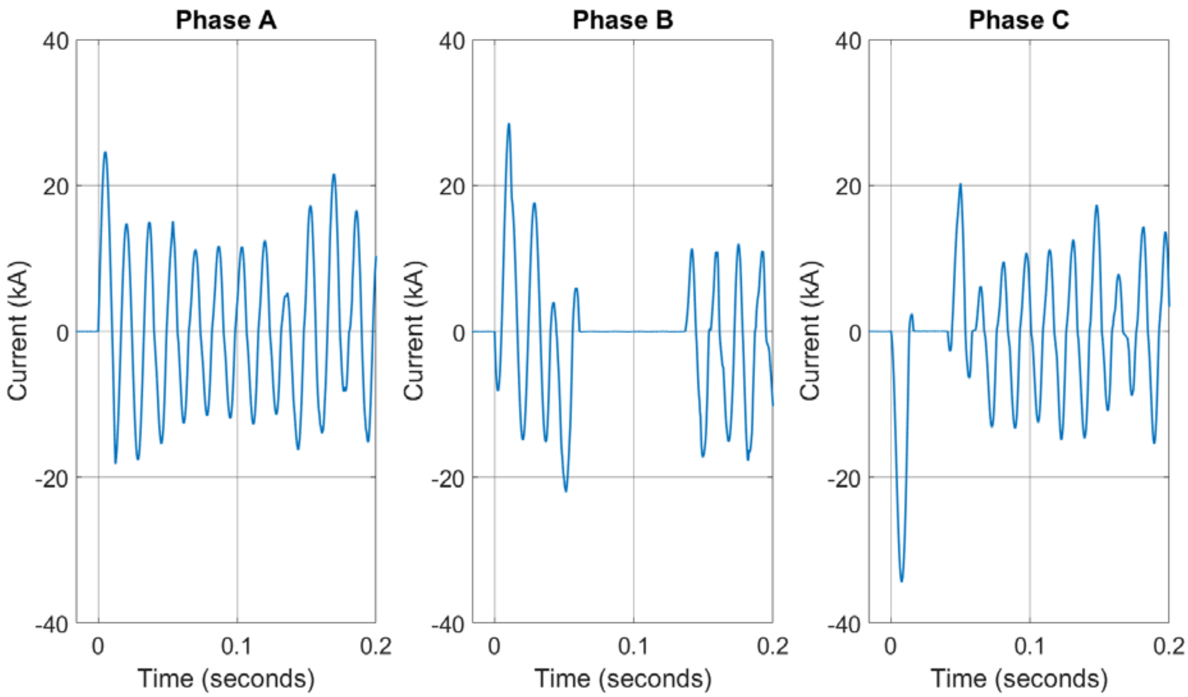


Fig. 90. Transient current profiles for Test 2-13B. Measurement uncertainty ± 3 percent.

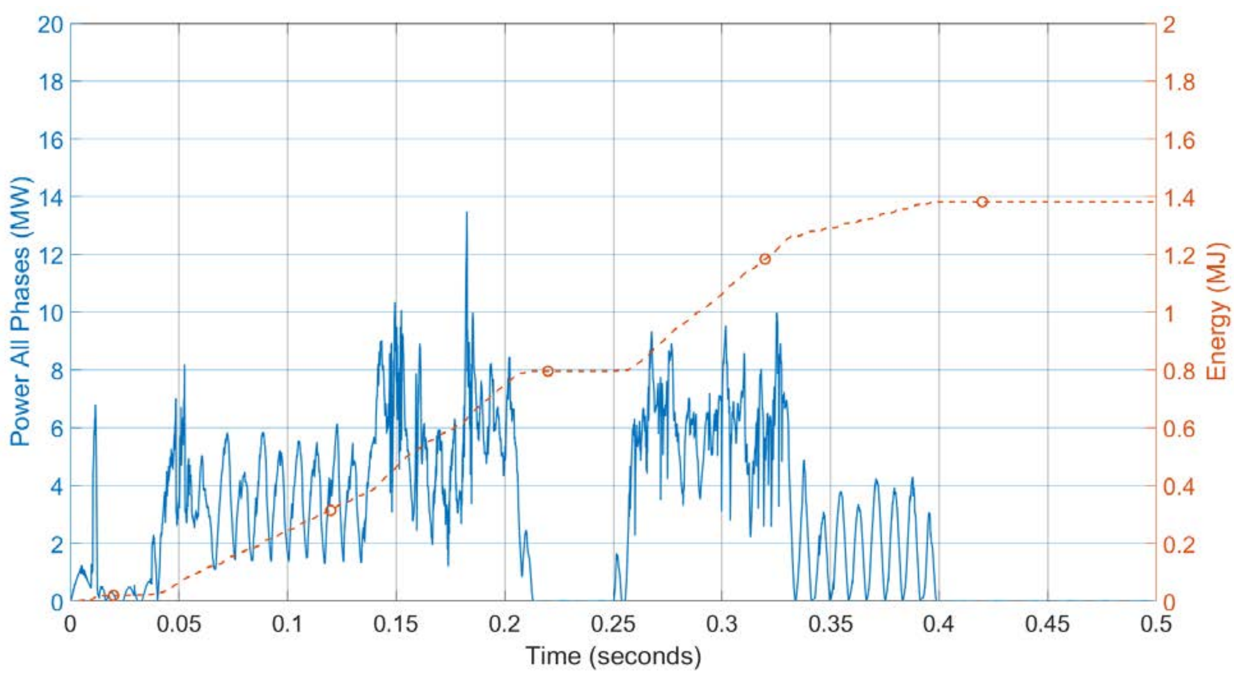


Fig. 91. Power and Energy for Test 2-13B. Measurement uncertainty ± 3 percent.

Experiment 2-13C, 600 V, 13.5 kA, 2 s, main bus top load section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 92. The transient region for current phases is presented in Fig. 93. Energy and power profiles are presented in Fig. 94.

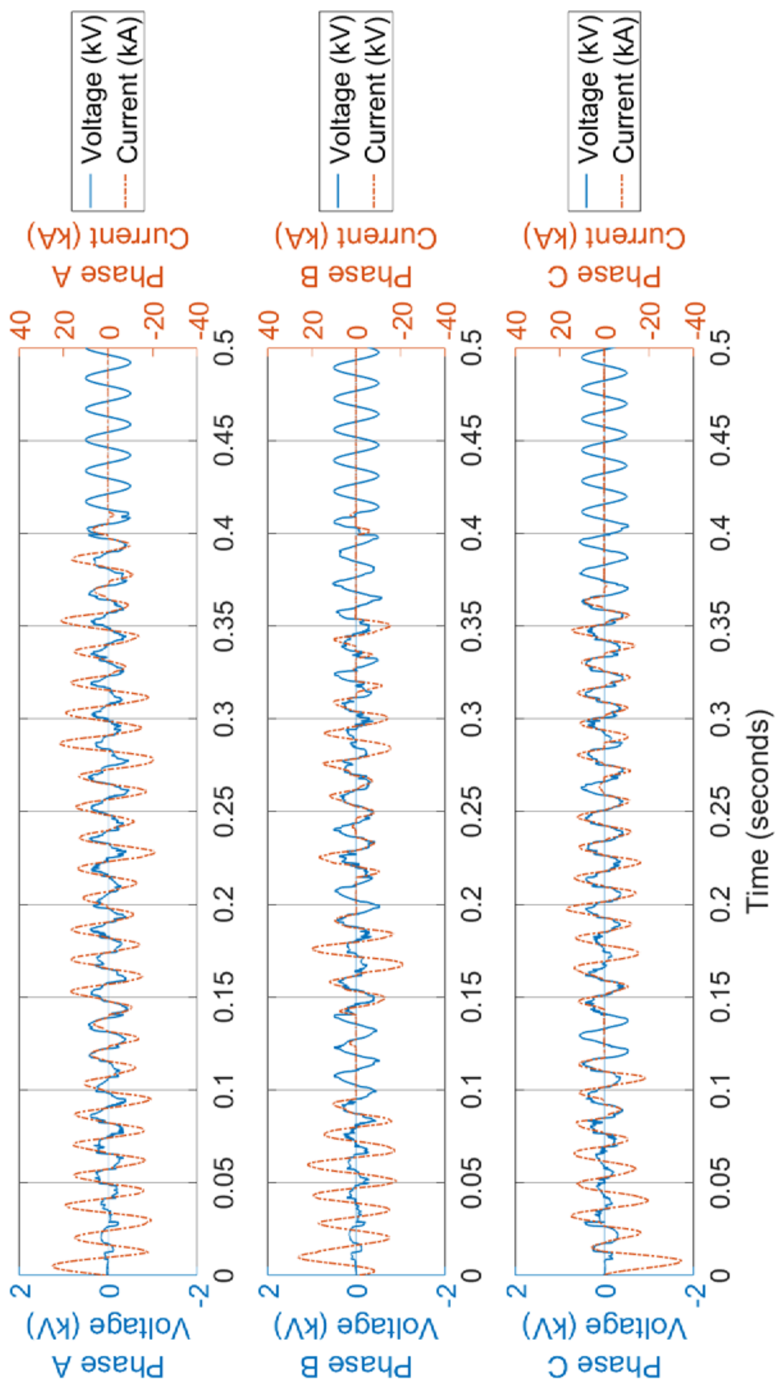


Fig. 92. Voltage and Current Profile during Test 2-13C. Measurement uncertainty ± 3 percent.

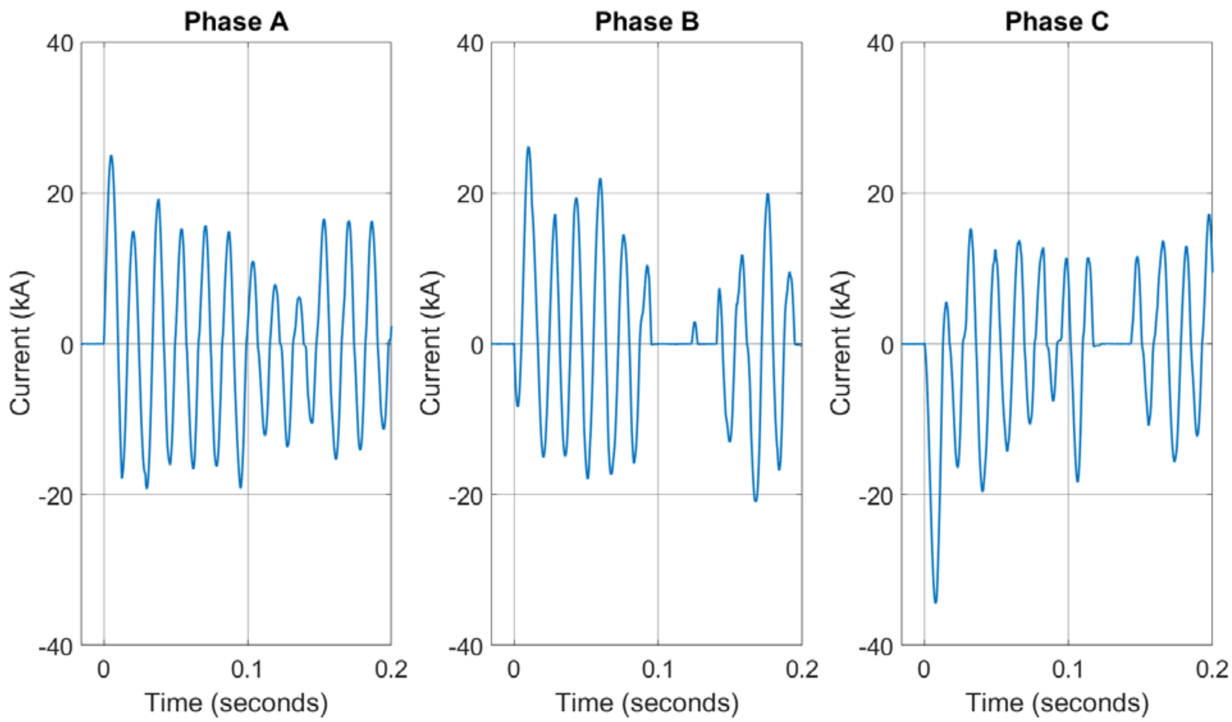


Fig. 93. Transient current profiles for Test 2-13C. Measurement uncertainty ± 3 percent.

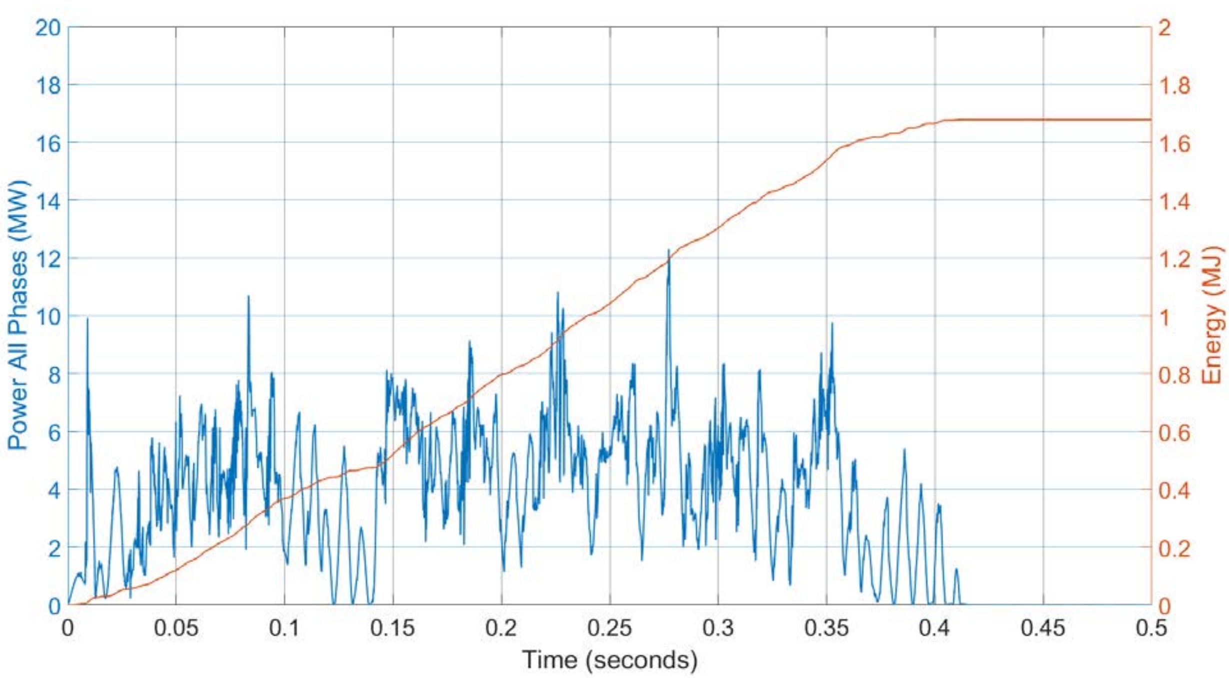


Fig. 94. Power and Energy for Test 2-13C. Measurement uncertainty ± 3 percent.

<u>Experiment 2-13D, 600 V, 13.5 kA, 2 s, breaker stabs (copper), top load section</u>

The voltage and current profile for the entire duration of the experiment is shown in Fig. 95. The transient region for current phases is presented in Fig. 96. Energy and power profiles are presented in Fig. 97.

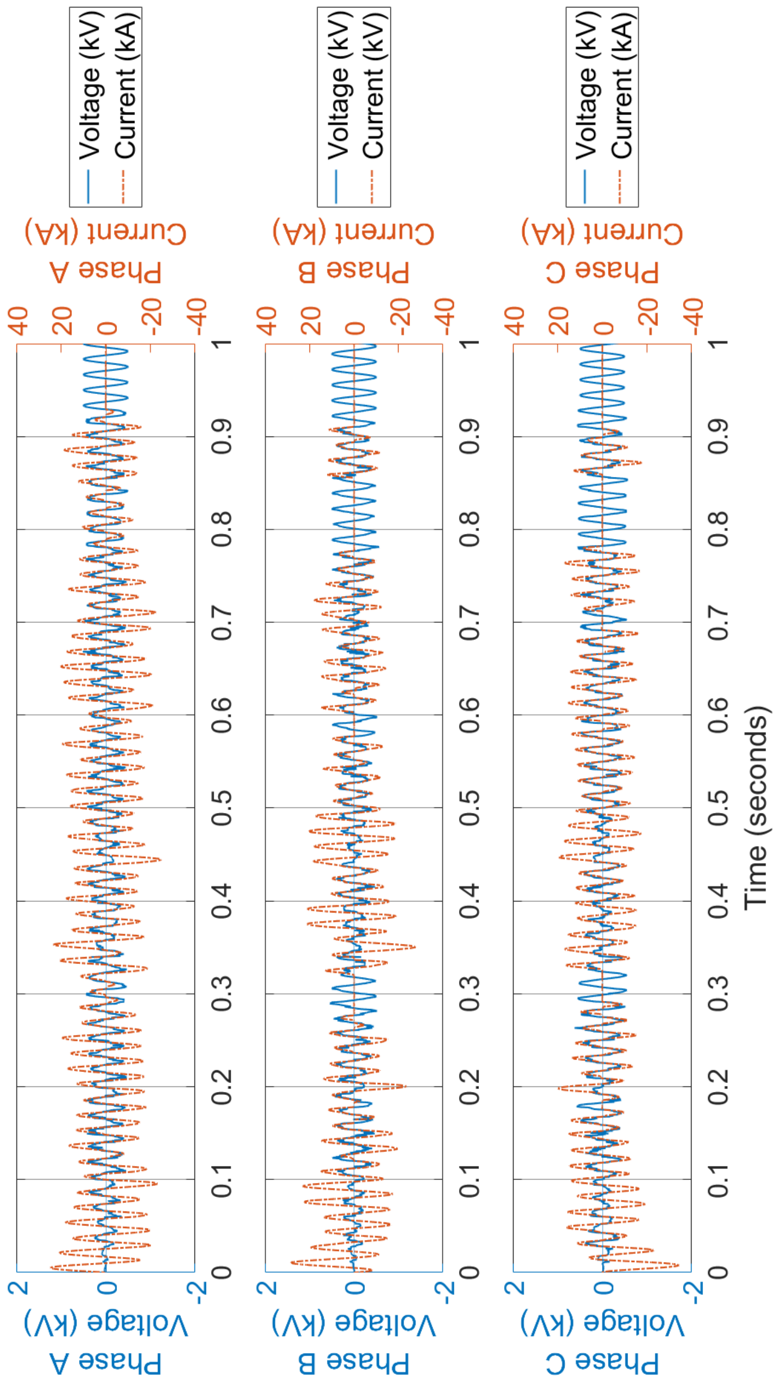


Fig. 95. Voltage and Current Profile during Test 2-13D. Measurement uncertainty ± 3 percent.

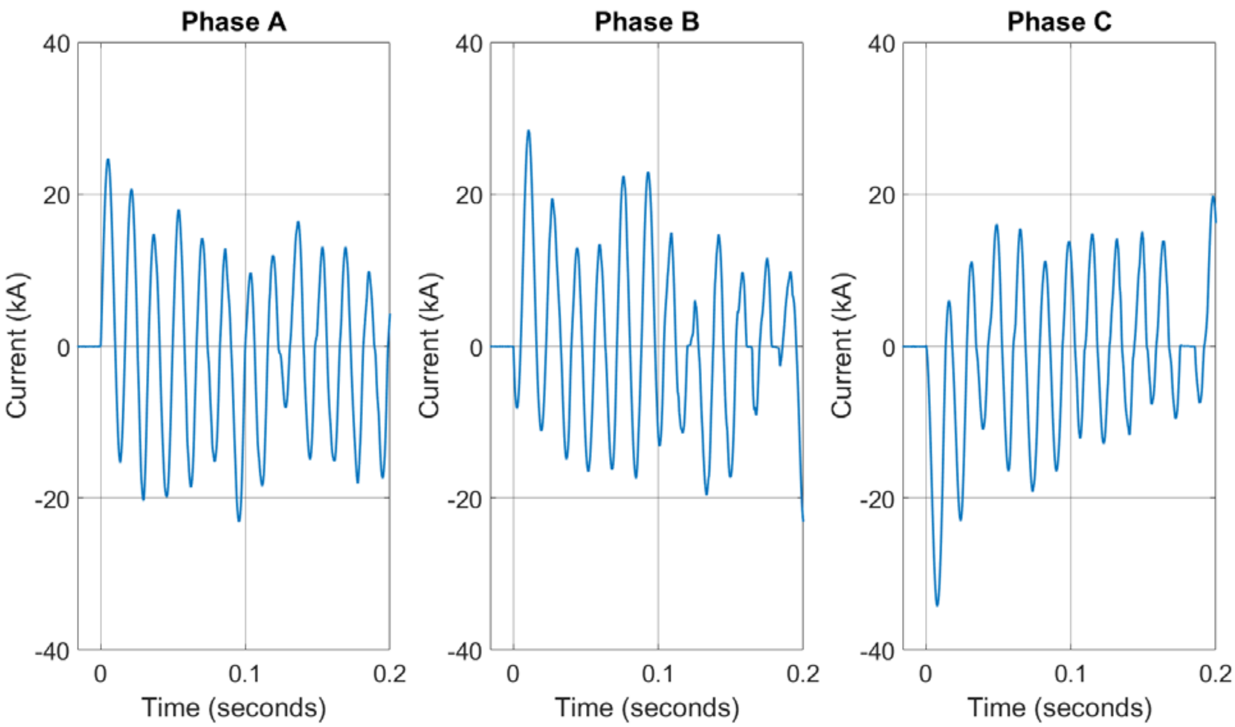


Fig. 96. Transient current profiles for Test 2-13D. Measurement uncertainty ± 3 percent.

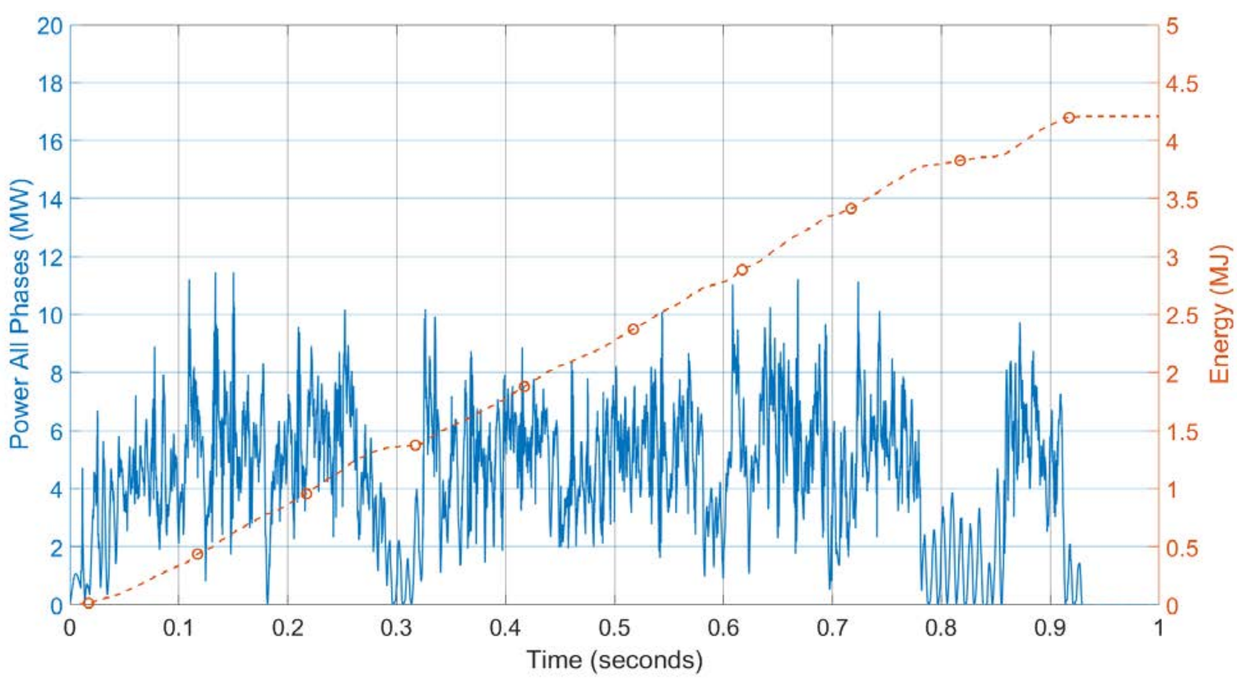


Fig. 97. Power and Energy for Test 2-13D. Measurement uncertainty ± 3 percent.

<u>Experiment 2-13E, 600 V, 13.5 kA, 2 s, breaker stabs (copper) middle breaker cubicle</u>

The voltage and current profile for the entire duration of the experiment is shown in Fig. 98. The transient region for current phases is presented in Fig. 99. Energy and power profiles are presented in Fig. 100.

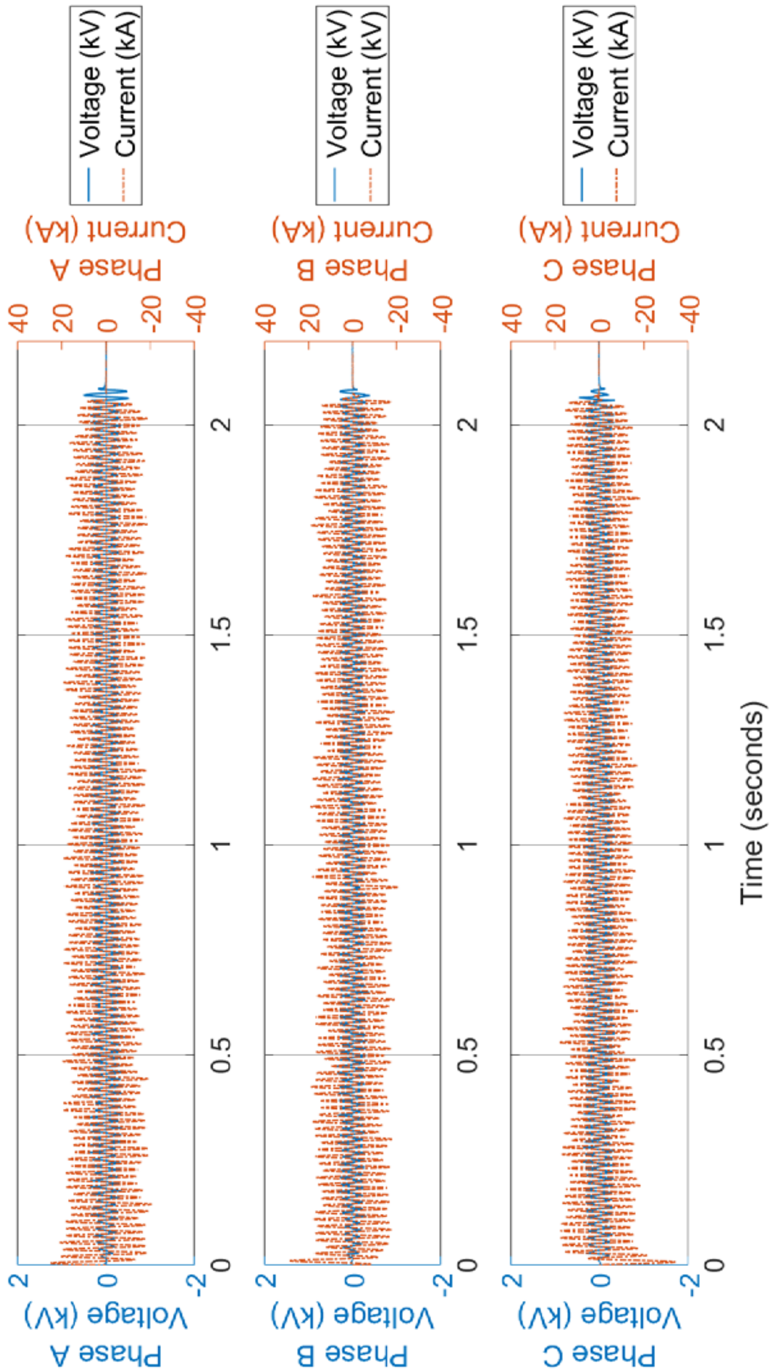


Fig. 98. Voltage and Current Profile during Test 2-13E. Measurement uncertainty ± 3 percent.

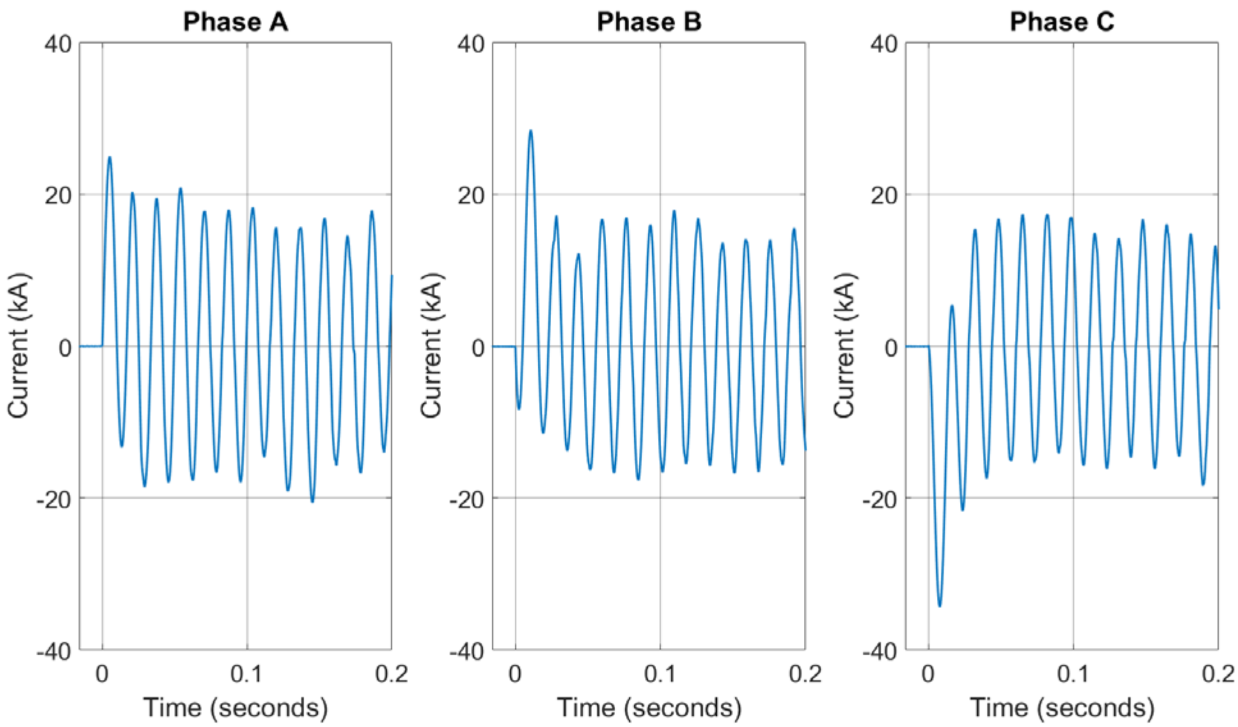


Fig. 99. Transient current profiles for Test 2-13E. Measurement uncertainty ± 3 percent.

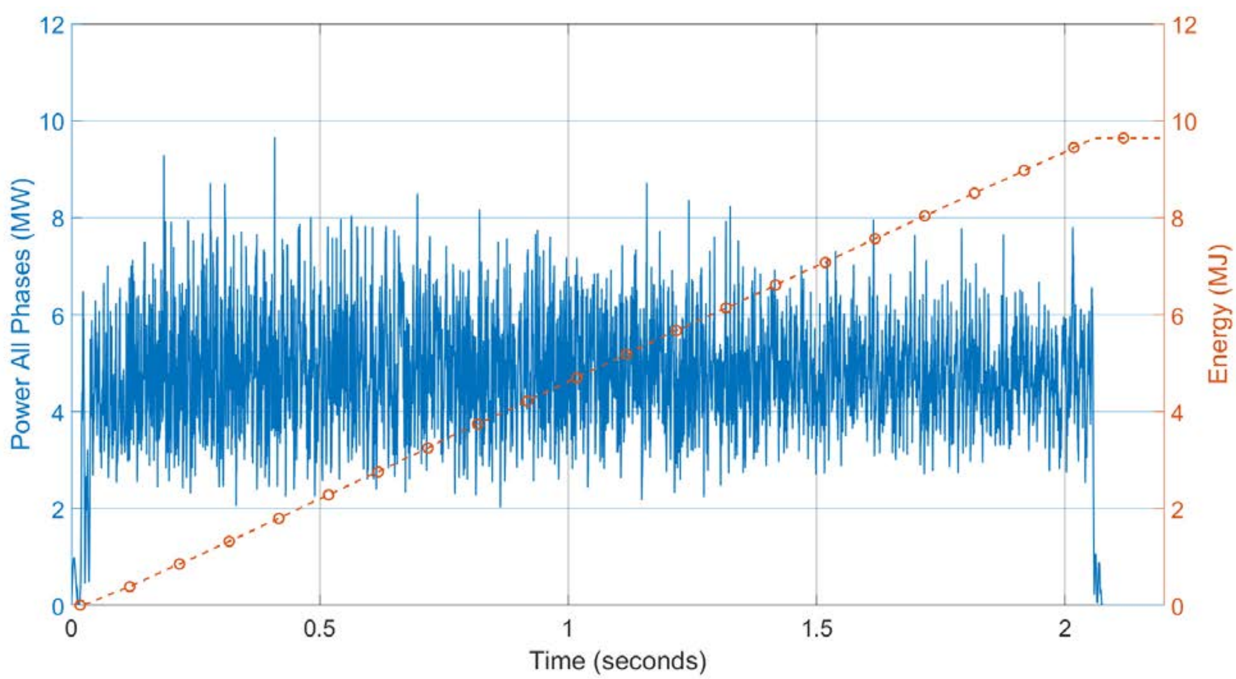


Fig. 100. Power and Energy for Test 2-13E. Measurement uncertainty ± 3 percent.

Experiment 2-13F, 480 V, 13.5 kA, 2 s main bus, load section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 101. The transient region for current phases is presented in Fig. 102. Energy and power profiles are presented in Fig. 103.

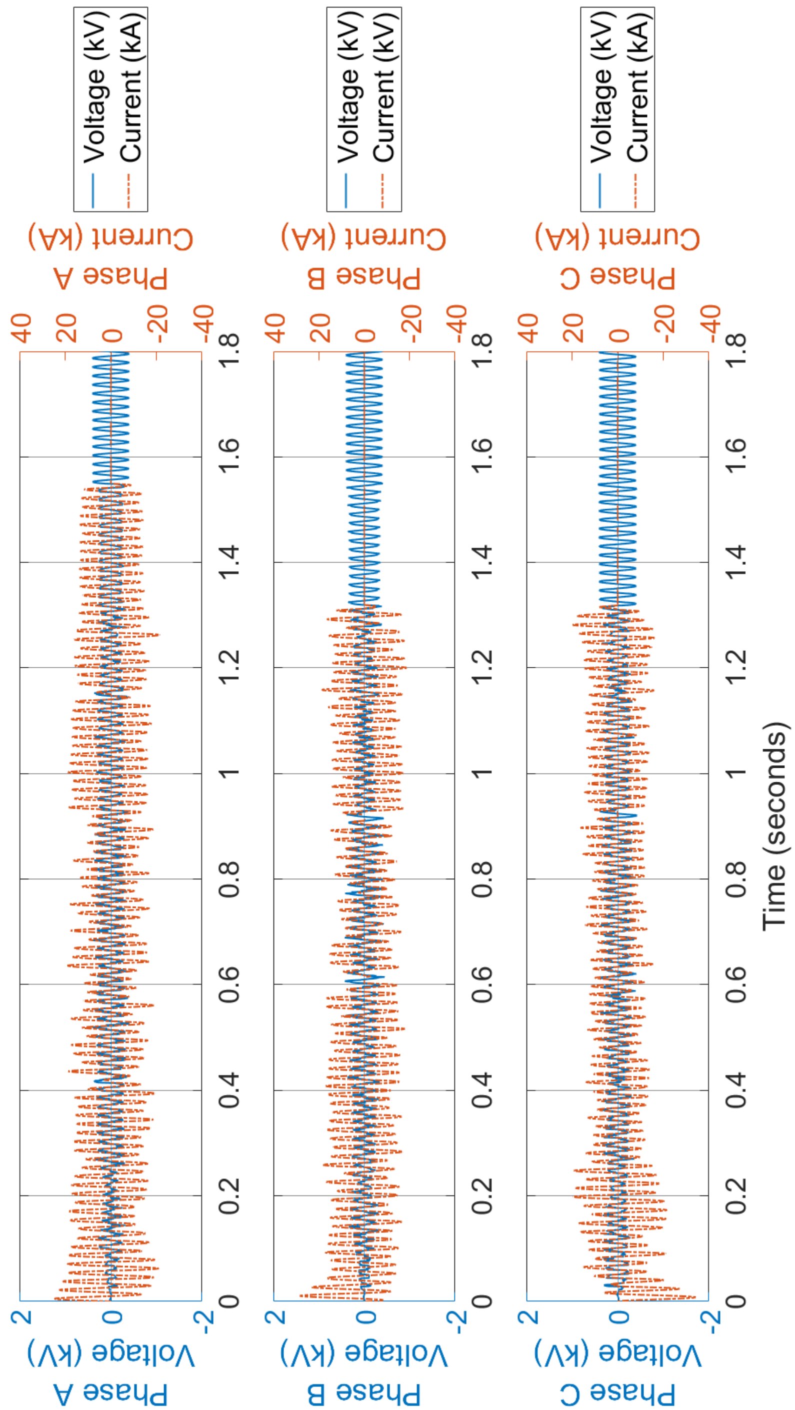


Fig. 101. Voltage and Current Profile during Test 2-13F. Measurement uncertainty ± 3 percent.

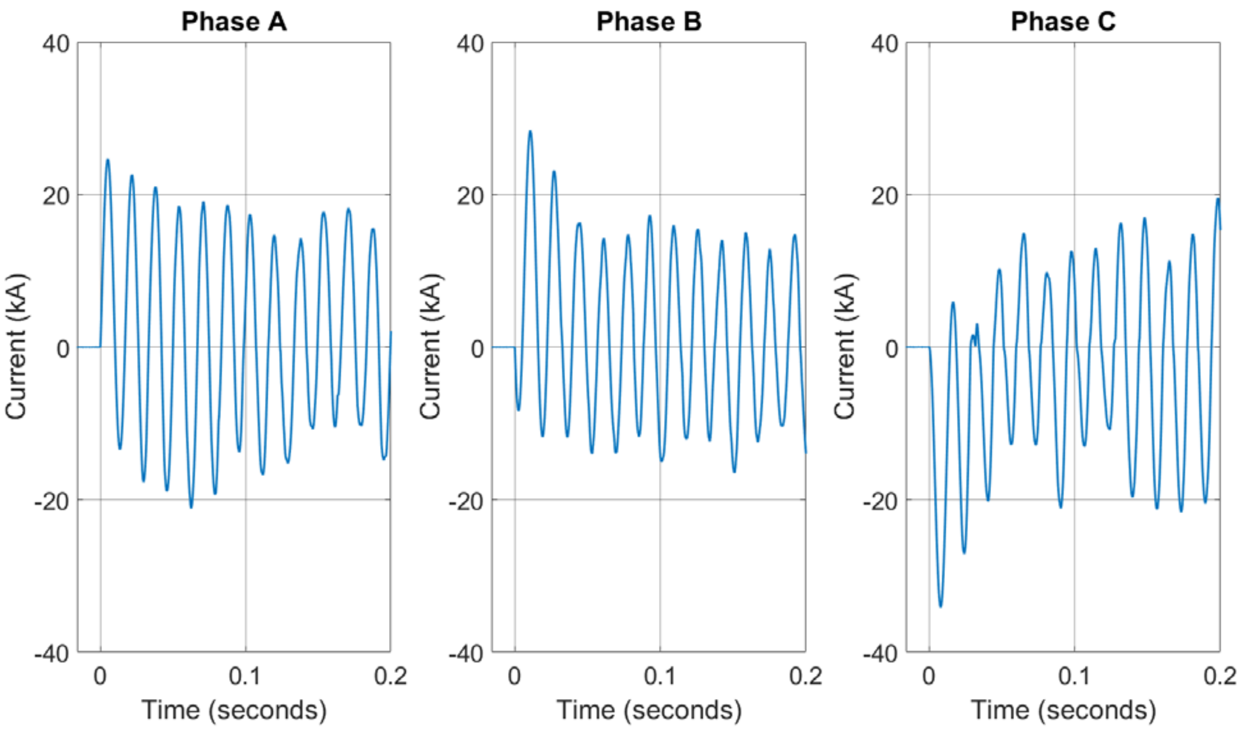


Fig. 102. Transient current profiles for Test 2-13F. Measurement uncertainty ± 3 percent.

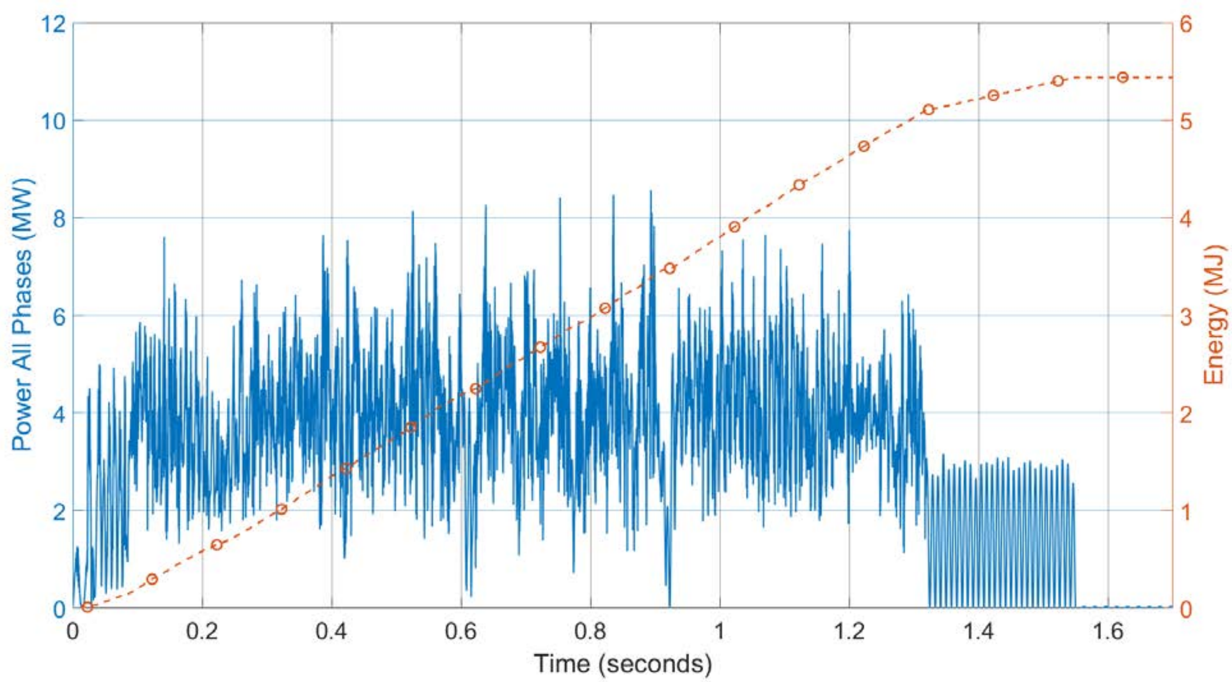


Fig. 103. Power and Energy for Test 2-13F. Measurement uncertainty ± 3 percent.

Experiment 2-13G, 600 V, 13.5 kA, 2 s, main bus, supply section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 104. The transient region for current phases is presented in Fig. 105. Energy and power profiles are presented in Fig. 106.

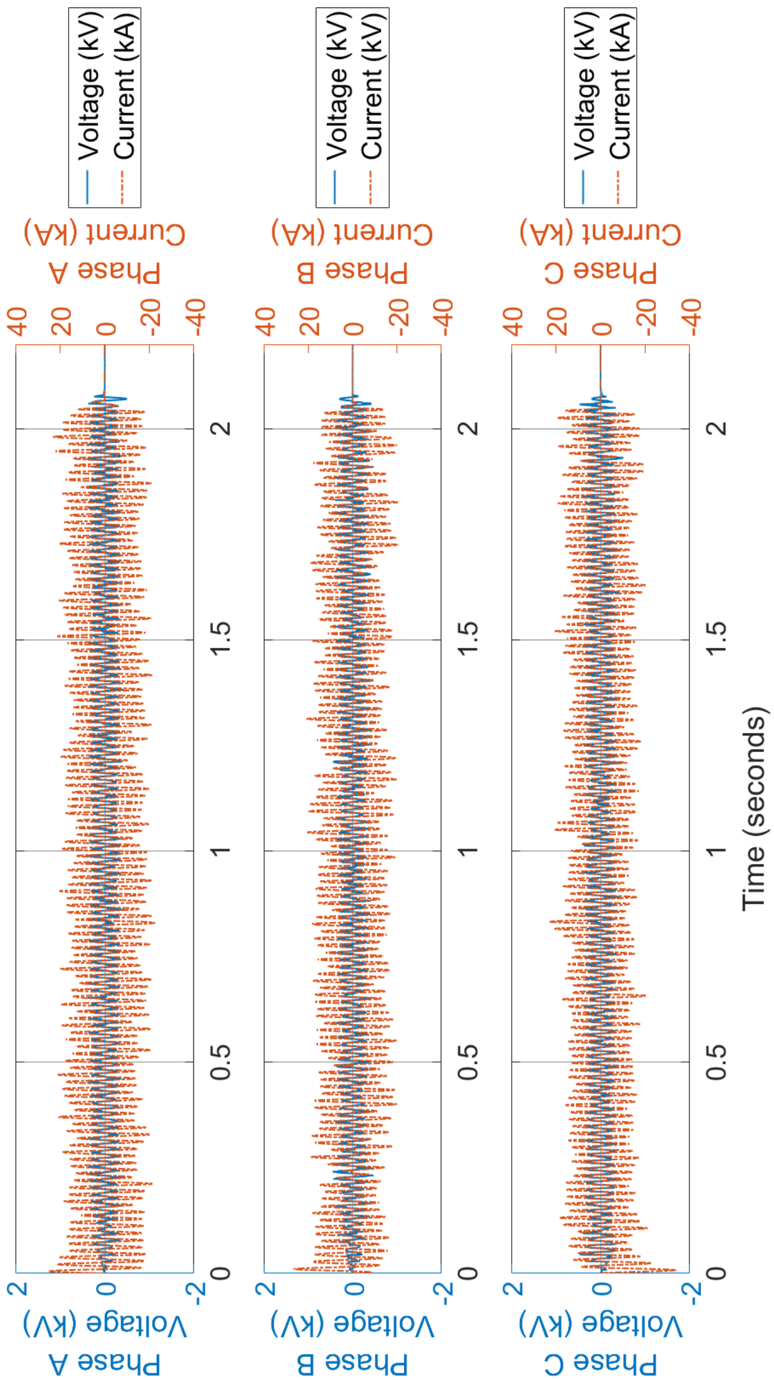


Fig. 104. Voltage and Current Profile during Test 2-13G. Measurement uncertainty ± 3 percent.

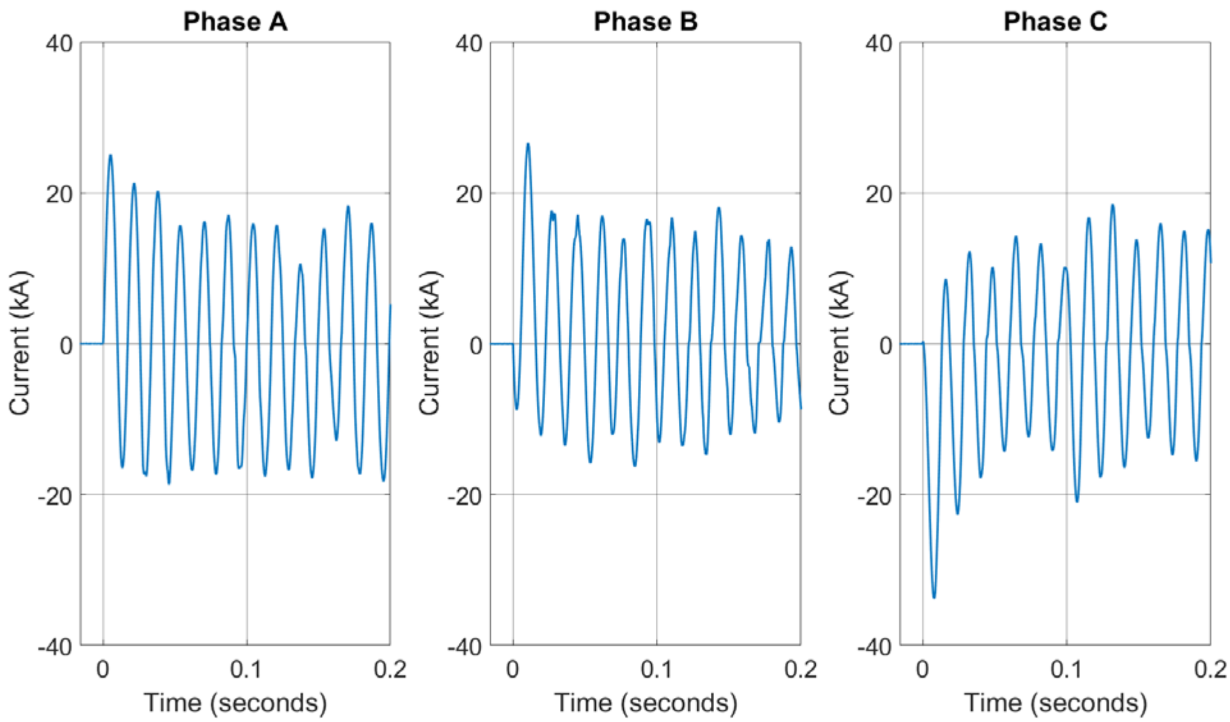


Fig. 105. Transient current profiles for Test 2-13G. Measurement uncertainty ± 3 percent.

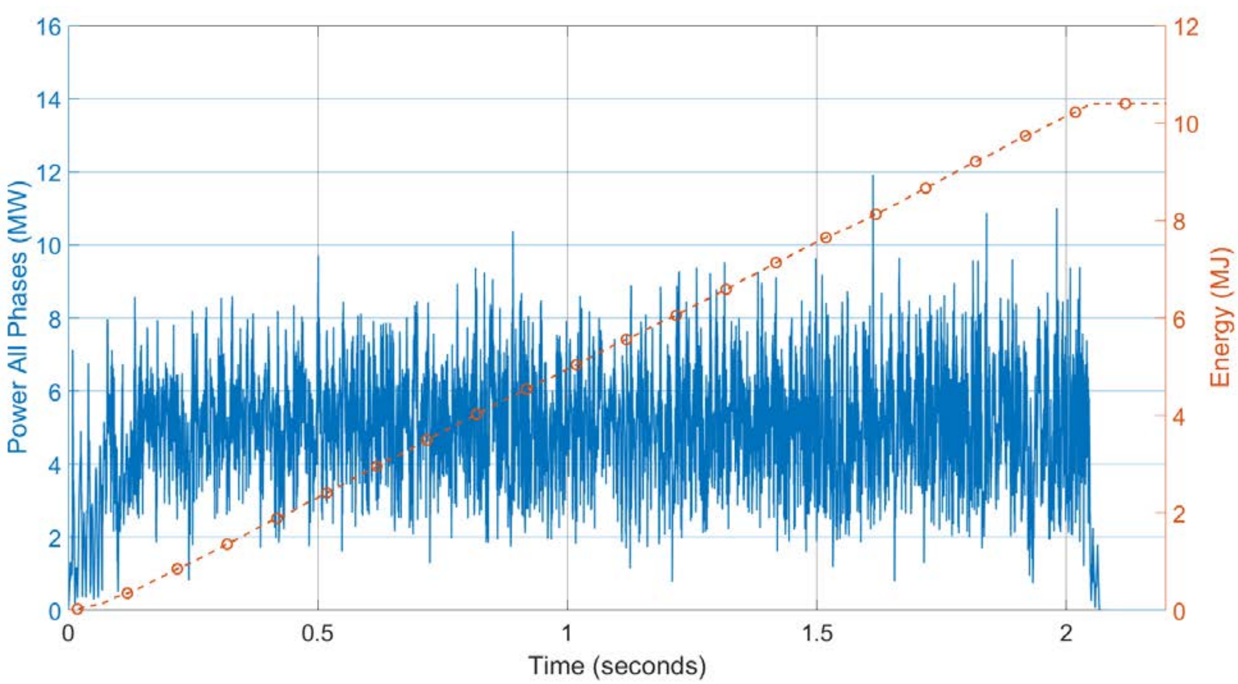


Fig. 106. Power and Energy for Test 2-13G. Measurement uncertainty ± 3 percent.

Experiment 2-18A, 480 V, 25 kA, 8 s, main bus, load section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 107. The transient region for current phases is presented in Fig. 108. Energy and power profiles are presented in Fig. 109.

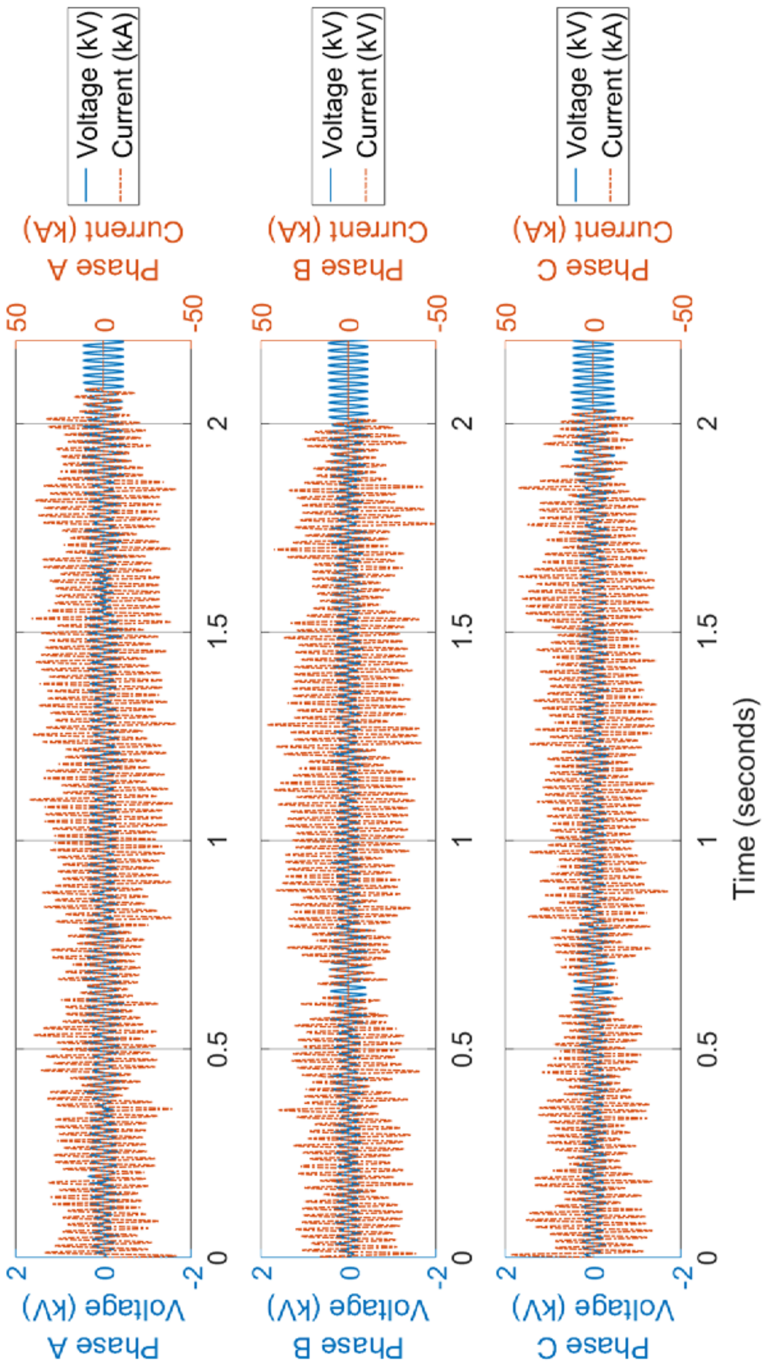


Fig. 107. Voltage and Current Profile during Test 2-18A. Measurement uncertainty ± 3 percent.

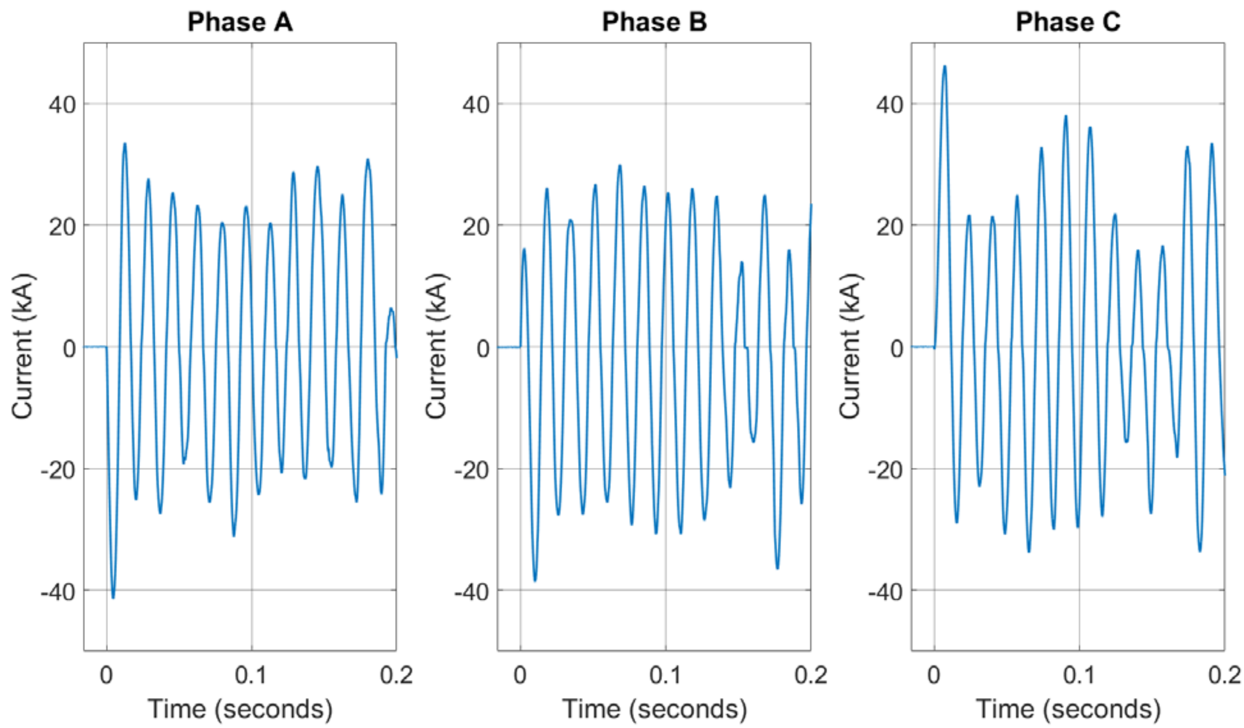


Fig. 108. Transient current profiles for Test 2-18A. Measurement uncertainty ± 3 percent.

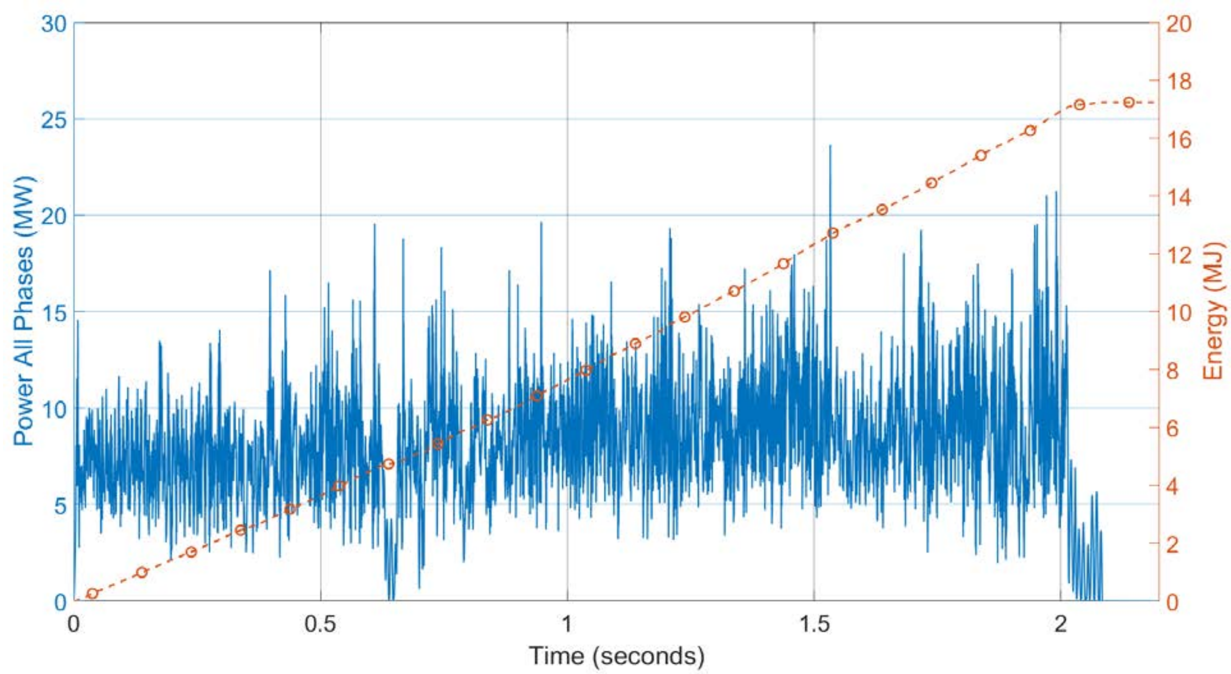


Fig. 109. Power and Energy for Test 2-18A. Measurement uncertainty ± 3 percent.

Experiment 2-18B, 600 V, 25 kA, 8 s, main bus, supply section

The voltage and current profile for the entire duration of the experiment is shown in Fig. 110. The transient region for current phases is presented in Fig. 111. Energy and power profiles are presented in Fig. 112.

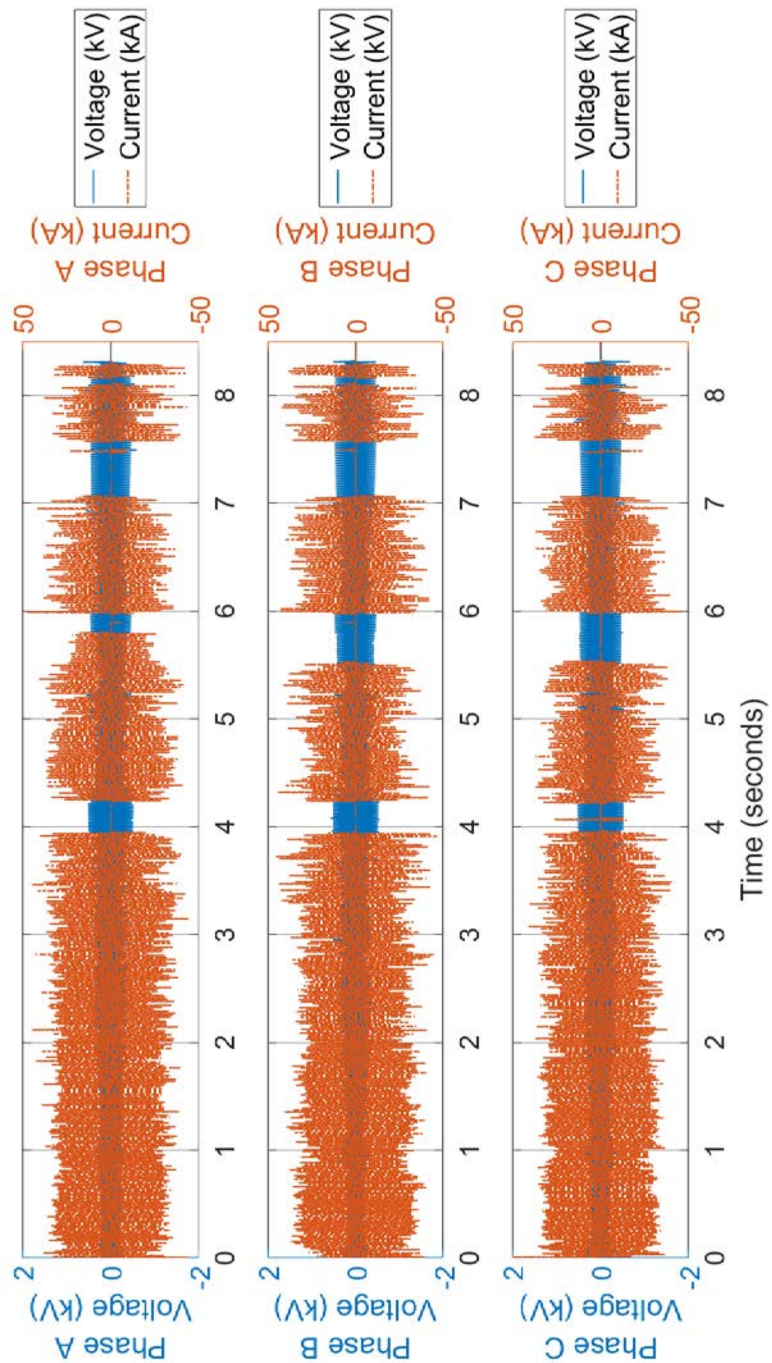


Fig. 110. Voltage and Current Profile during Test 2-18B. Measurement uncertainty ± 3 percent.

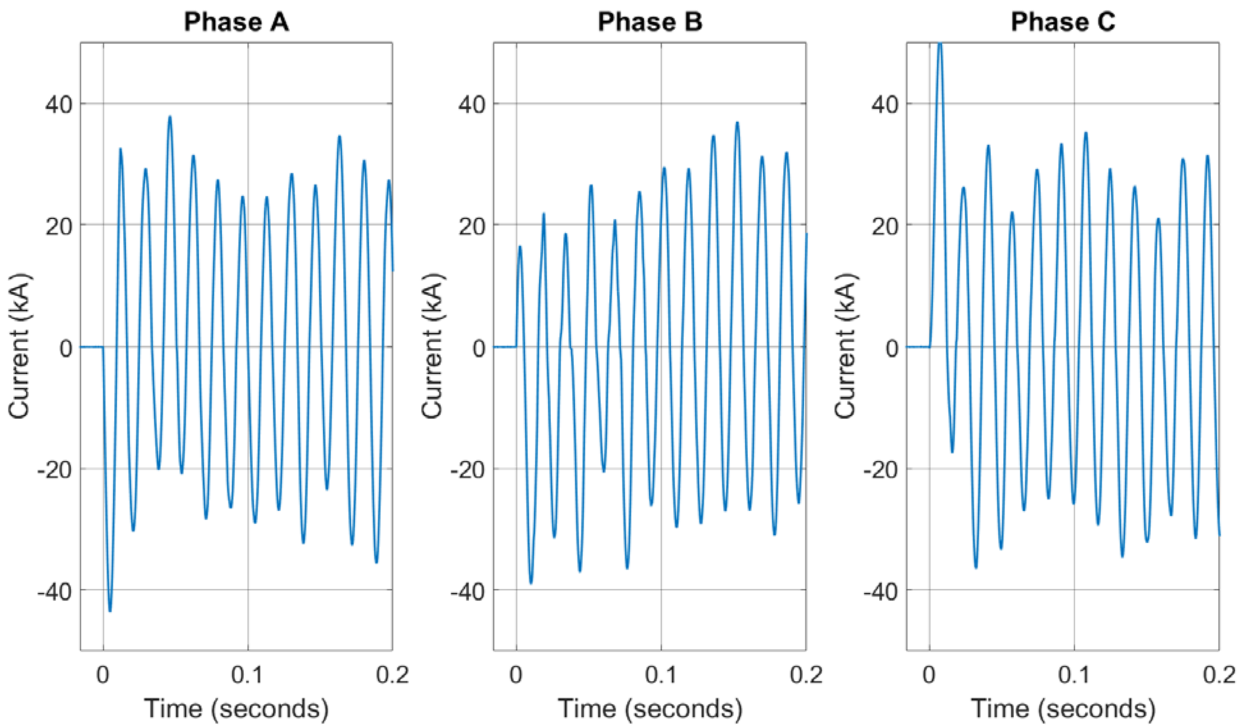


Fig. 111. Transient current profiles for Test 2-18B. Measurement uncertainty ± 3 percent.

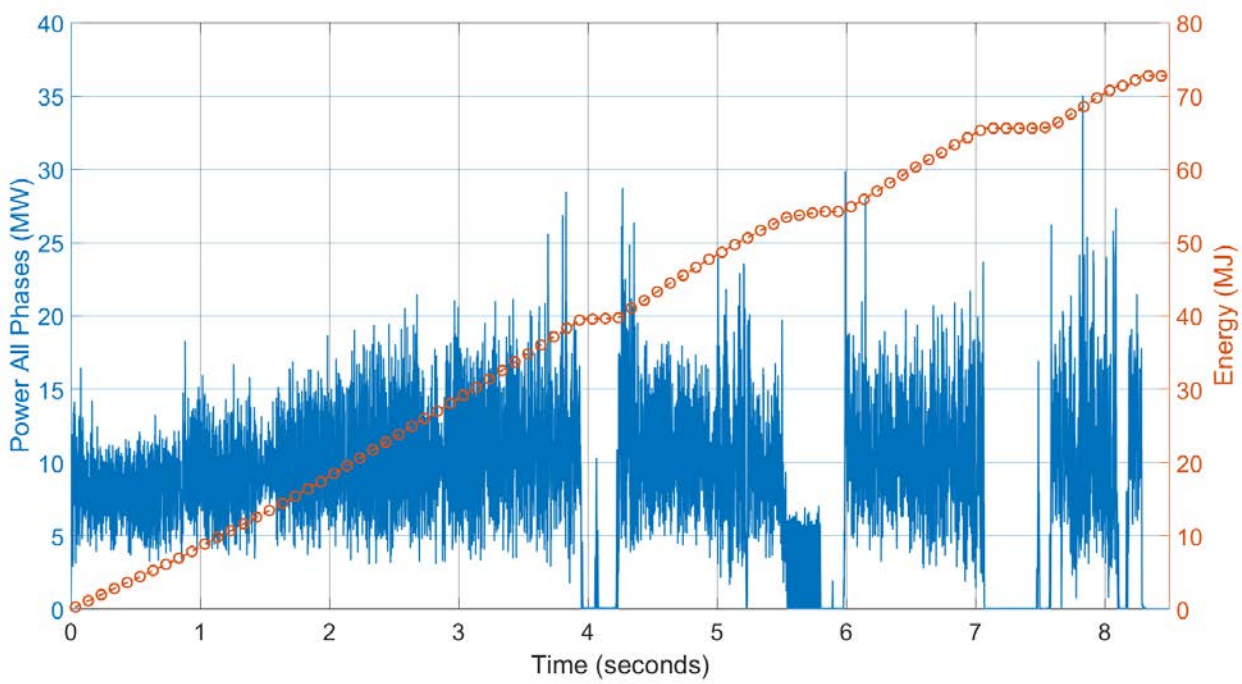


Fig. 112. Power and Energy for Test 2-18B. Measurement uncertainty ± 3 percent.

Appendix C: KEMA Test Report

This appendix provides a copy of KEMA test report.

DNV·GL

KEMA TEST REPORT

24512323

Object	Medium & Low Voltage Switchgear		
Type	High Energy Arc Fault (HEAF)	**Serial No.**	N/A
	Various V, rms – Various kA, rms – 60 Hz		
Client	U.S. Nuclear Regulatory Commission Washington, DC, USA		
Tested by	KEMA-Powertest LLC, 4379 County Line Road Chalfont, PA 18914, USA		
Date of tests	22, 23, 26, 27, 28, 29 and 30 August 2019 and 16, 17 and 18 September 2019		
Test specification	The arc fault tests have been carried out in accordance with client's instructions.		

This report applies only to the object tested. The responsibility for conformity of any object having the same type references as that tested rests with the Manufacturer.

This report consists of 356 pages in total.

KEMA Powertest, LLC

Frank Cielo
Head of Department, Operations
KEMA Laboratories

Chalfont, February 11, 2020
DATE

KEMA Laboratories

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 DNV GL. 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. DNV GL 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 DNV GL's Certification procedure applicable to KEMA Laboratories.

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. Reasons for issuing a KEMA Test Report could be:

- Tests were performed according to the client's instructions.
- Tests were performed only partially according to the standard.
- No technical drawings were submitted for verification and/or no assessment of the condition of the object after the tests was performed.
- The object failed one or more of the performed tests.

The KEMA Test Report can be identified by the grey-embossed lettering on the cover and grey seal on its front sheet.
In case the number of tests, the test procedure and the test parameters are based on a recognized standard and related to the ratings assigned by the manufacturer, the following sentence will appear on the front sheet. The tests have been carried out in accordance with the client's instructions. Test procedure and test parameters were based on ..... If the object does not pass the tests such behaviour will be mentioned on the front sheet. Verification of the drawings (if submitted) and assessment of the condition after the tests is only done on client's request.
When the tests, test procedure and/or test parameters are not in accordance with a recognized standard, the front sheet will state the tests have been carried out in accordance with client's instructions.

4 Official and uncontrolled test documents

The official test documents of DNV GL 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 Laboratories

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

TABLE OF CONTENTS

1 IDENTIFICATION OF THE OBJECT TESTED

1.1 Ratings/characteristics of the object tested

Voltage	Various V
Number of phases	3
Frequency	60 Hz
Short-circuit current	Various kA

1.2 Description of the object tested

Low and Medium Voltage Box Tests, High Energy Arcing Faults
Low Voltage Switchgear, High Energy Arcing Faults

2 GENERAL INFORMATION

2.1 The tests were witnessed by

Name	Company
Christopher Brown	National Institute of Standards and Technology (NIST)
Michael Selepak	
Anthony Putorti	
Scott Bareham	
Andre Thompson	
Philip Deardorff	
Benny Lee	BSI Electrical Contractors
John Jones	Montgomeryville, PA, USA
Robert Taylor	
Jeff McKnight	
Byron Demostehnous	Sandia National Laboratories
Kenneth Armijo	Albuquerque, NM, USA
James Taylor	
Alvaro Augusto Cruz-Cabrera	
Chris Lafleur	
Raina Weaver	
Scott Sanborn	
Austin Glover	
Paul Clem	
Ray Martinez	
Caroline Winters	
Nick Melly	U.S. Nuclear Regulatory Commission
Kenneth Hamburger	Washington, DC, USA
Kenn Miller	
Gabriel Taylor	
Thomas Koshy	
Ken Fleischer	Electric Power Research Institue
Marko Randelovic	

2.2 The tests were carried out under responsibility of

Name	Company
Joe Duffy	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

-

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
Ineut	Neutral current
PT # 1	Pressure transducer # 1
PT # 2	Pressure transducer # 2
PT # 3	Pressure transducer # 3
PT # 4	Pressure transducer # 4
TRIG	Trigger signal transient recorder
U1TO	Voltage across test object
U2TO	Voltage across test object
U3TO	Voltage across test object

4 CHECKING THE PROSPECTIVE CURRENT

Standard and date

Standard	Client's instructions
Test date	22 August 2019

4.1 Condition before test

Shorting bar connected at station terminals directly prior to test device.

4.2 Test results and oscillograms

Overview of test numbers

190822-7001, 7002

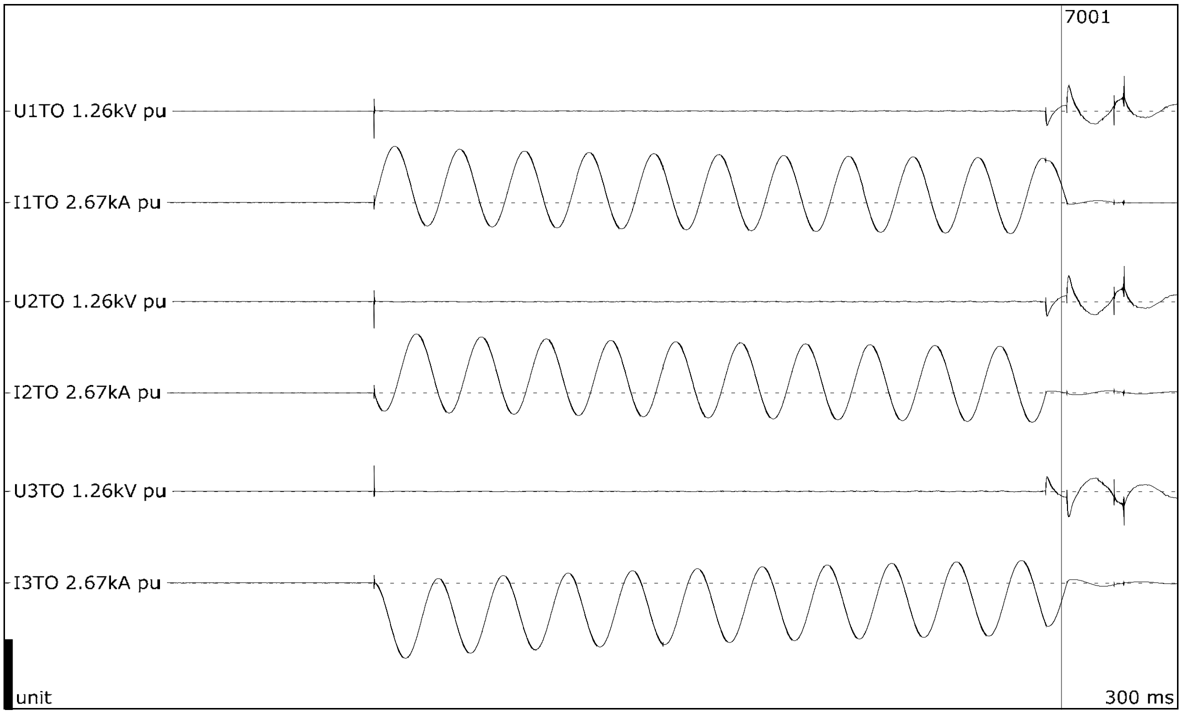
Remarks

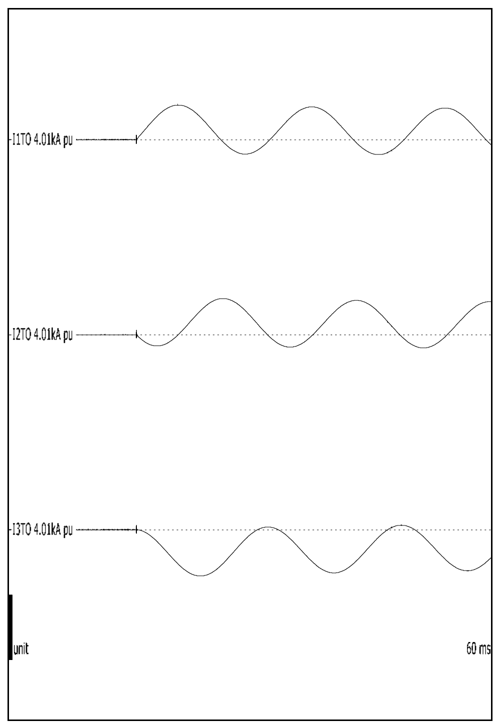
Prospective circuit parameters calibrated in this test duty:

190822-7001: 1000 V, 1040 A, 2860 A peak.

190822-7002: 1000 V, 5053 A, 14.9 kA peak.

Checking the prospective current



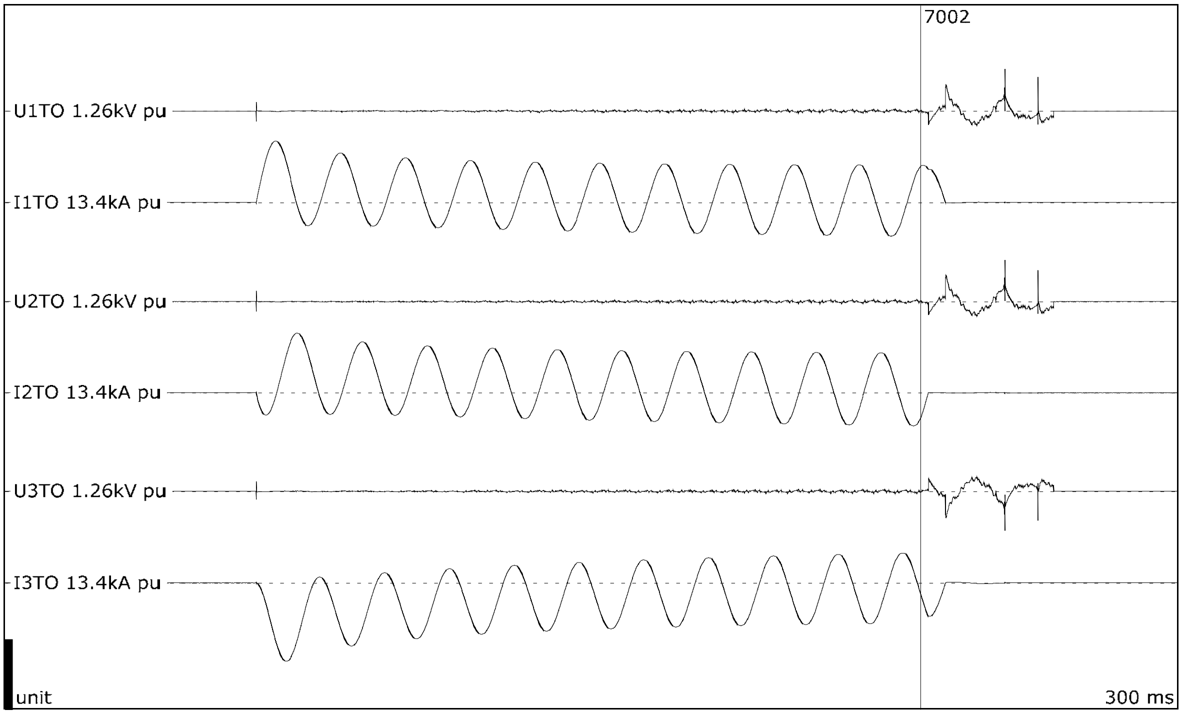


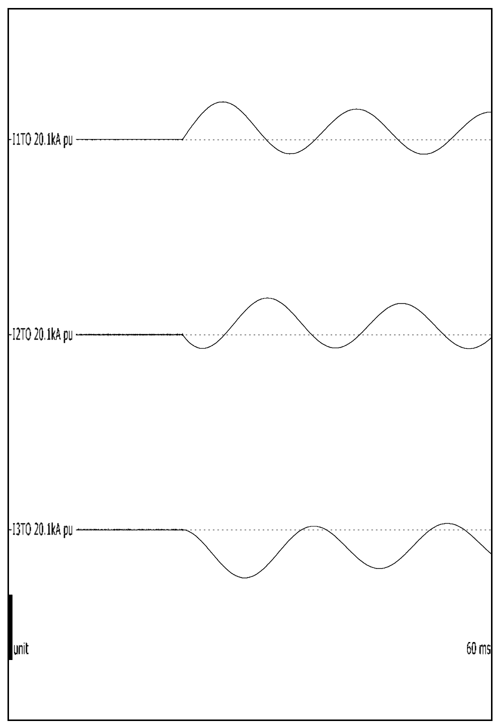
Test number: 190822-7001

Phase		A	B	C
Current	kA_{peak}	2.13	2.23	-2.86
Current, a.c. component	kA_{RMS}	1.04	1.04	1.04
Current, a.c. component, three-phase average	kA_{RMS}	1.04		
Duration, current	s	0.176	0.176	0.175

Observations: No visible disturbance.

Checking the prospective current





Test number: 190822-7002

Phase		A	B	C
Current	kA_{peak}	11.6	11.3	-14.9
Current, a.c. component	kA_{RMS}	4.89	5.15	5.12
Current, a.c. component, three-phase average	kA_{RMS}	5.05		
Duration, current	s	0.170	0.170	0.169

Observations: No visible disturbance.

5 OPEN BOX TEST # 1 (OB01(A)) - 1000 V, 1 KA

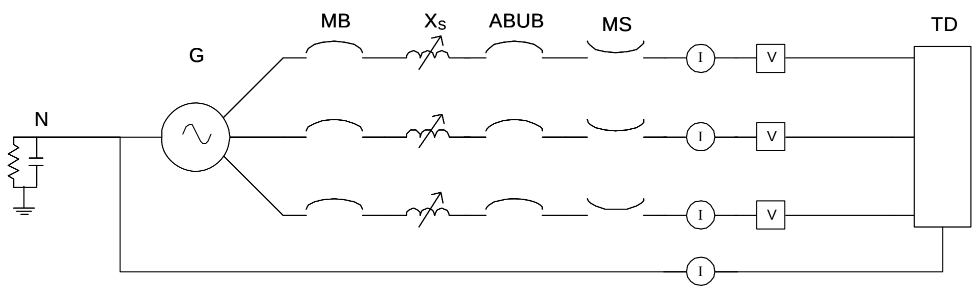
Standard and date

Standard	Client’s instructions
Test date	22 August 2019

5.1 Condition before test

Test device new. Arc to be initiated by #10 AWG stranded wire. Arc wire connected to 1/2" diameter copper rods. Test duration is 2 seconds.

5.2 Test circuit S01



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

Supply		
Power	MVA	1.801
Frequency	Hz	60
Phase(s)		3
Voltage	V	1000
Sym. Current	kA	1.040
Peak current	kA	2.86
Impedance	Ω	0.5551

Remarks: -

5.3 Test results and oscillograms

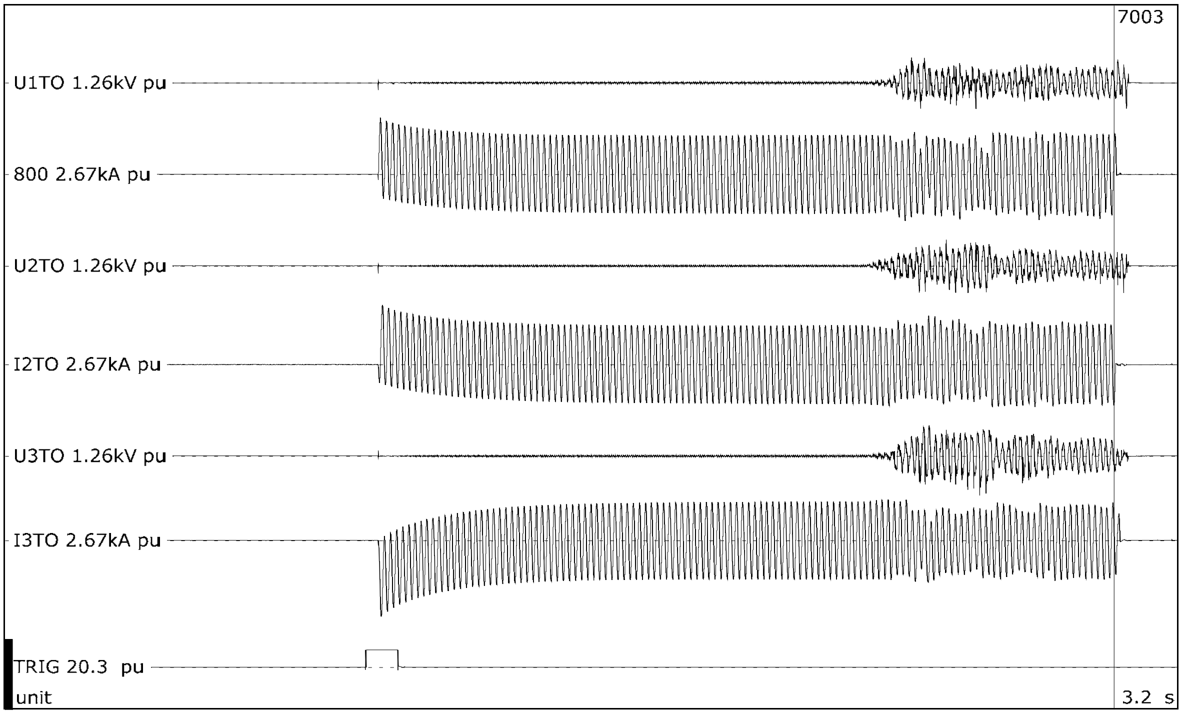
Overview of test numbers

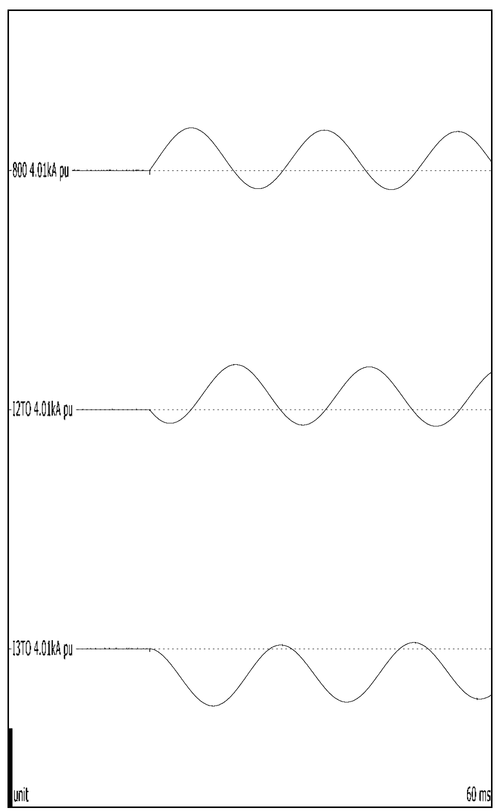
190822-7003

Remarks

-

Open Box Test # 1 (OB01) - 1000 V, 1 kA





Test number: **190822-7003**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	577	577	577
Applied voltage, phase-to-phase	V_{RMS}	999		
Making current	kA_{peak}	2.14	2.26	-2.89
Current, a.c. component, beginning	A_{RMS}	1064	1061	1050
Current, a.c. component, middle	A_{RMS}	1052	1049	1039
Current, a.c. component, end	A_{RMS}	1119	1006	985
Current, a.c. component, average	A_{RMS}	1042	1048	1009
Current, a.c. component, three-phase average	A_{RMS}	1033		
Duration	s	2.01	2.01	2.01
Arc energy	kJ	66.7	106	27.9

Observations: Emission of flames and gas observed. Arc wire took approximately 1.35 seconds to melt and initiate the arc.

5.4 Condition / inspection after test

Box lightly damaged, another arc test can be performed with this sample.

6 OPEN BOX TEST # 2 (OB01(B)) - 1000 V, 1 KA

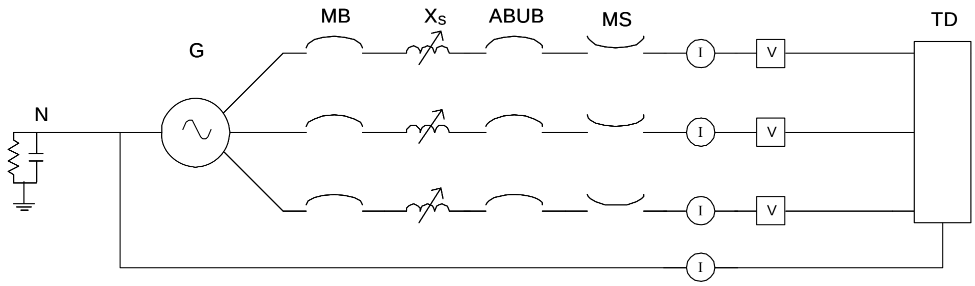
Standard and date

Standard	Client’s instructions
Test date	22 August 2019

6.1 Condition before test

Test device previously subjected to arc test at 1000 V, 1 kA. Arc to be initiated by #24 AWG wire. Arc wire connected to 1/2" diameter copper rods. Test duration is 2 seconds.

6.2 Test circuit S01



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

Supply		
Power	MVA	1.801
Frequency	Hz	60
Phase(s)		3
Voltage	V	1000
Sym. Current	kA	1.040
Peak current	kA	2.86
Impedance	Ω	0.5551

Remarks: -

6.3 Test results and oscillograms

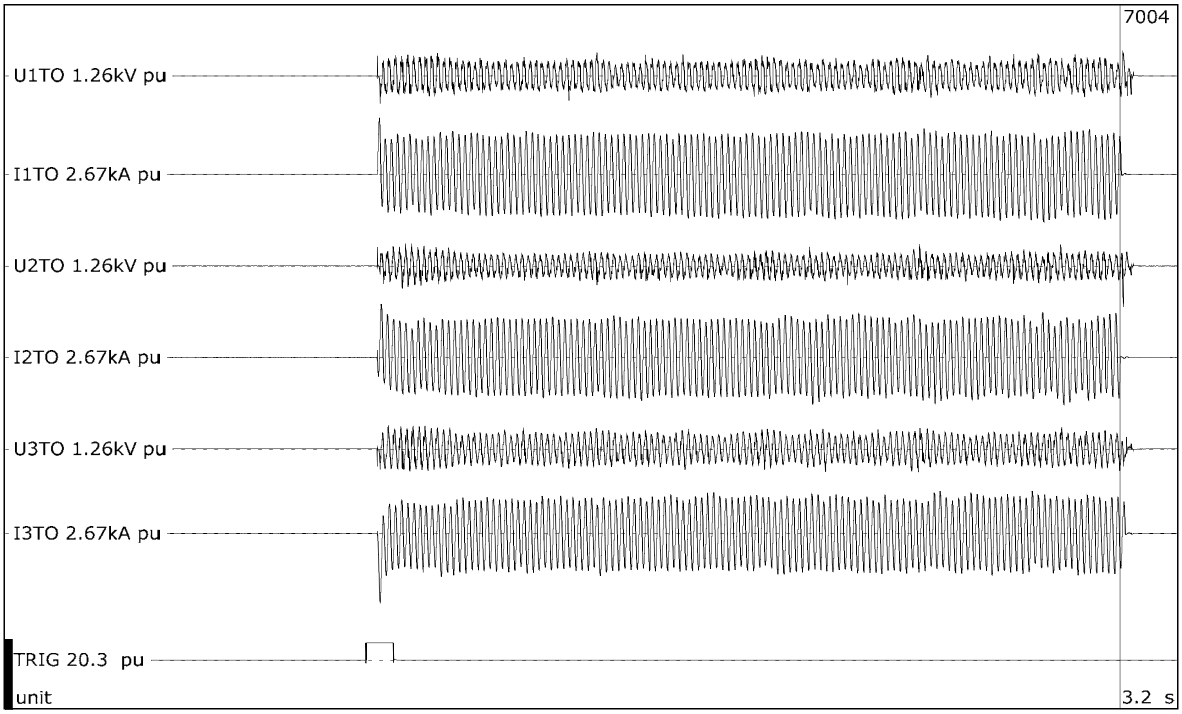
Overview of test numbers

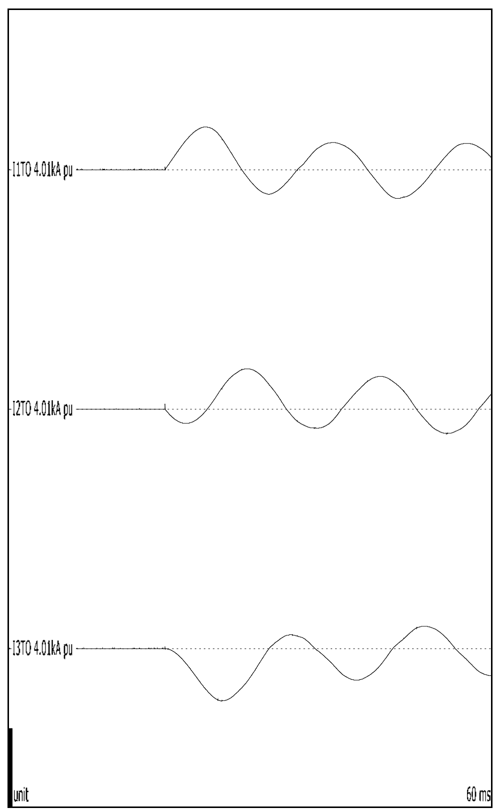
190822-7004

Remarks

-

Open Box Test # 2 (OB01, re-test) - 1000 V, 1 kA





Test number: **190822-7004**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	577	577	577
Applied voltage, phase-to-phase	V_{RMS}	999		
Making current	kA_{peak}	2.14	2.02	-2.63
Current, a.c. component, beginning	A_{RMS}	1056	1009	985
Current, a.c. component, middle	A_{RMS}	1124	1035	1015
Current, a.c. component, end	A_{RMS}	1128	1011	974
Current, a.c. component, average	A_{RMS}	1083	1030	985
Current, a.c. component, three-phase average	A_{RMS}	1033		
Duration	s	2.02	2.02	2.02
Arc energy	kJ	248	289	199

Observations: Emission of flames and gas observed.

6.4 Condition / inspection after test

Box slightly more damaged than previous arc test. End of copper conductors melted slightly.

7 OPEN BOX TEST # 3 (OB05) - 1000 V, 1 KA

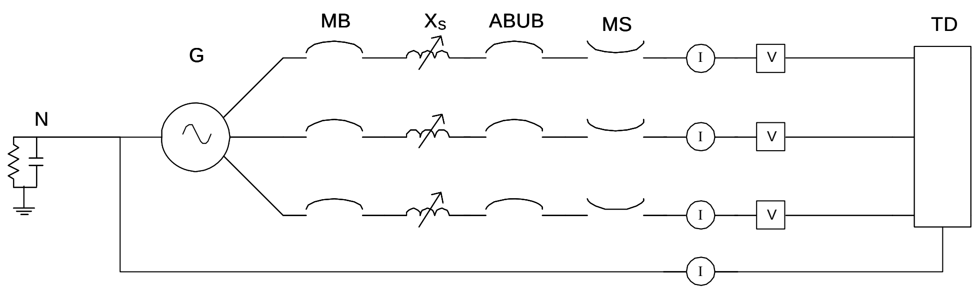
Standard and date

Standard	Client’s instructions
Test date	22 August 2019

7.1 Condition before test

Test device previously subjected to two arc tests at 1000 V, 1 kA. Arc to be initiated by #24 AWG wire. Arc wire connected to 1/2" diameter aluminum rods. Test duration is 2 seconds.

7.2 Test circuit S01



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

Supply		
Power	MVA	1.801
Frequency	Hz	60
Phase(s)		3
Voltage	V	1000
Sym. Current	kA	1.040
Peak current	kA	2.86
Impedance	Ω	0.5551

Remarks: -

7.3 Test results and oscillograms

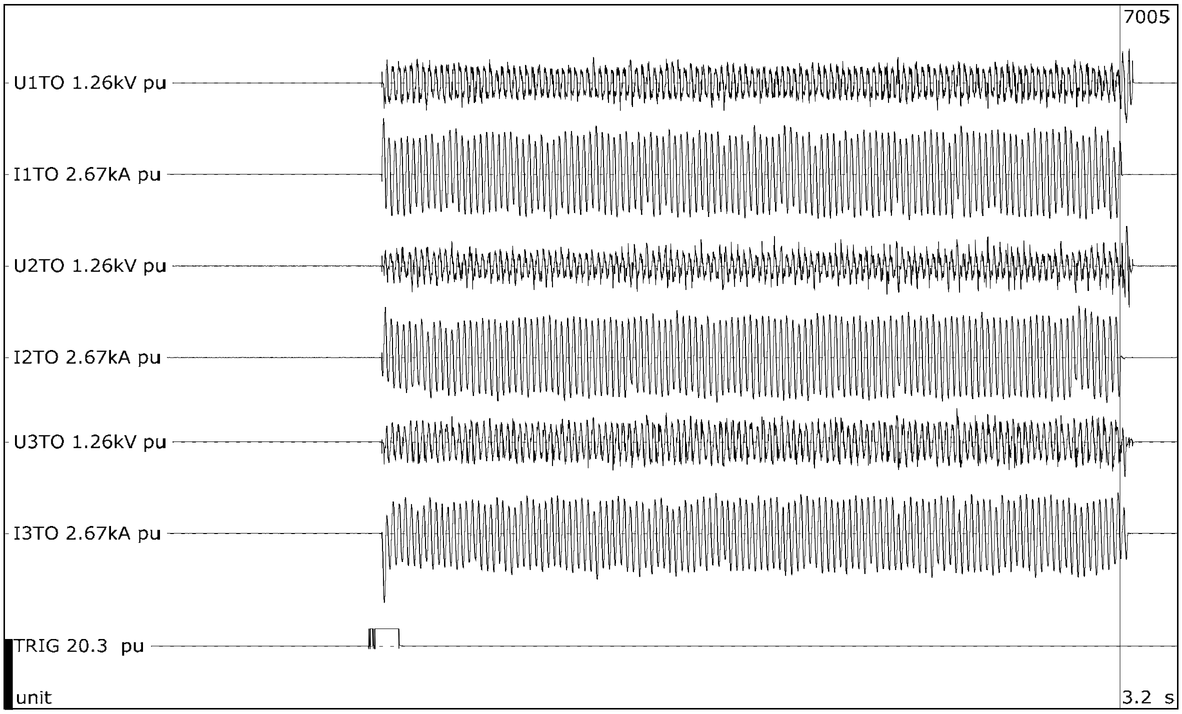
Overview of test numbers

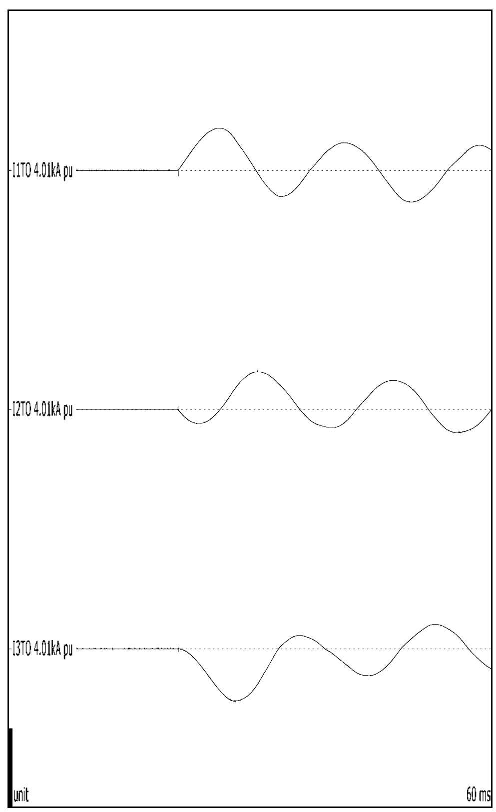
190822-7005

Remarks

-

Open Box Test # 3 (OB05) - 1000 V, 1 kA





Test number: 190822-7005

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	577	577	577
Applied voltage, phase-to-phase	V_{RMS}		999	
Making current	kA_{peak}	2.12	1.91	-2.63
Current, a.c. component, beginning	A_{RMS}	1088	958	949
Current, a.c. component, middle	A_{RMS}	1173	1064	963
Current, a.c. component, end	A_{RMS}	1000	1075	943
Current, a.c. component, average	A_{RMS}	1080	1031	942
Current, a.c. component, three-phase average	A_{RMS}		1018	
Duration	s	2.01	2.01	2.01
Arc energy	kJ	262	329	205

Observations: Emission of flames and gas observed.

7.4 Condition / inspection after test

Box covered in ash, but still able to withstand another arc test. Aluminum rods discolored to a slightly white color.

8 OPEN BOX TEST # 4 (OB10) - 1000 V, 5 KA

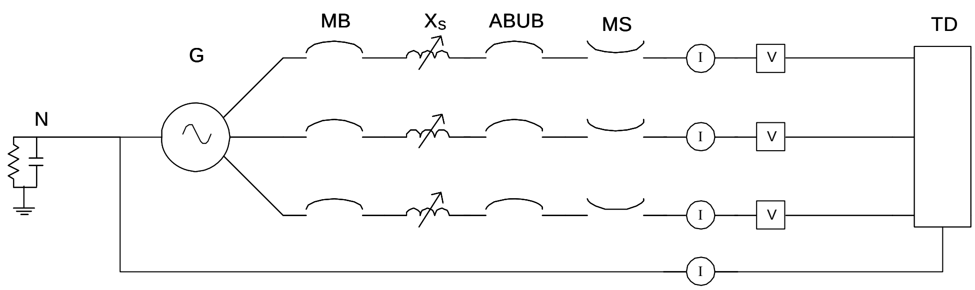
Standard and date

Standard	Client's instructions
Test date	22 August 2019

8.1 Condition before test

Test device previously subjected to three arc tests at 1000 V, 1 kA. Arc to be initiated by #24 AWG wire. Arc wire connected to 1/2" diameter aluminum rods. Test duration is 2 seconds.

8.2 Test circuit S02



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

Supply		
Power	MVA	8.75
Frequency	Hz	60
Phase(s)		3
Voltage	V	1000
Sym. Current	kA	5.053
Peak current	kA	14.9
Impedance	Ω	0.114

Remarks: -

8.3 Test results and oscillograms

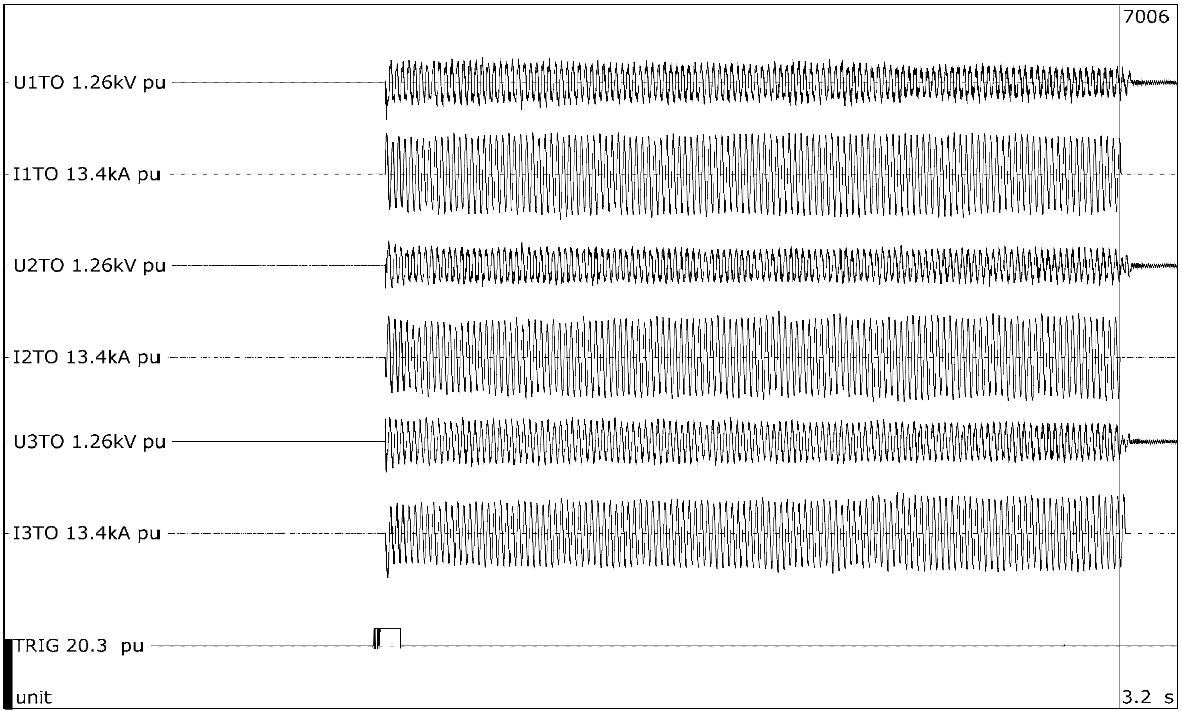
Overview of test numbers

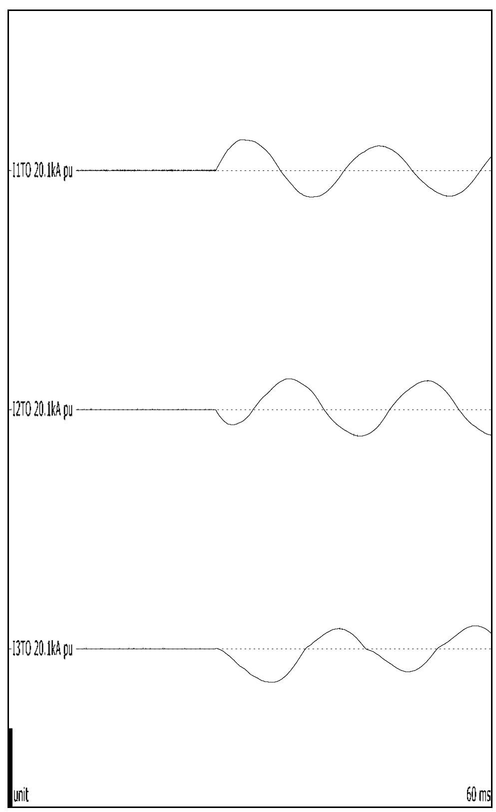
190822-7006

Remarks

-

Open Box Test # 4 (OB10) - 1000 V, 5 kA





Test number: 190822-7006

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	577	577	577
Applied voltage, phase-to-phase	V_{RMS}	999		
Making current	kA_{peak}	7.73	7.76	-8.47
Current, a.c. component, beginning	A_{RMS}	4812	4548	4309
Current, a.c. component, middle	A_{RMS}	5190	5297	4487
Current, a.c. component, end	A_{RMS}	5041	5559	4936
Current, a.c. component, average	A_{RMS}	5193	5081	4499
Current, a.c. component, three-phase average	A_{RMS}	4924		
Duration	s	2.00	2.00	2.00
Arc energy	kJ	1190	1960	968

Observations: Emission of flames and gas observed.

8.4 Condition / inspection after test

Interior and sides of the exterior of the box were heavily burned. Box will be replaced for next test.

9 OPEN BOX TEST # 5 (OB09) - 1000 V, 5 KA

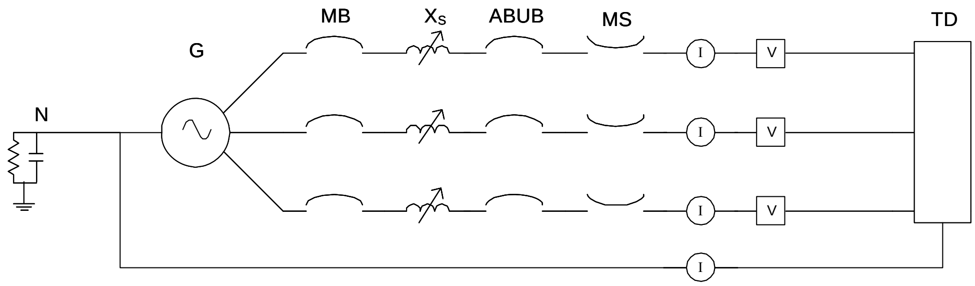
Standard and date

Standard	Client’s instructions
Test date	22 August 2019

9.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1/2" diameter copper rods. Test duration is 2 seconds.

9.2 Test circuit S02



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

Supply		
Power	MVA	8.75
Frequency	Hz	60
Phase(s)		3
Voltage	V	1000
Sym. Current	kA	5.053
Peak current	kA	14.9
Impedance	Ω	0.114

Remarks: -

9.3 Test results and oscillograms

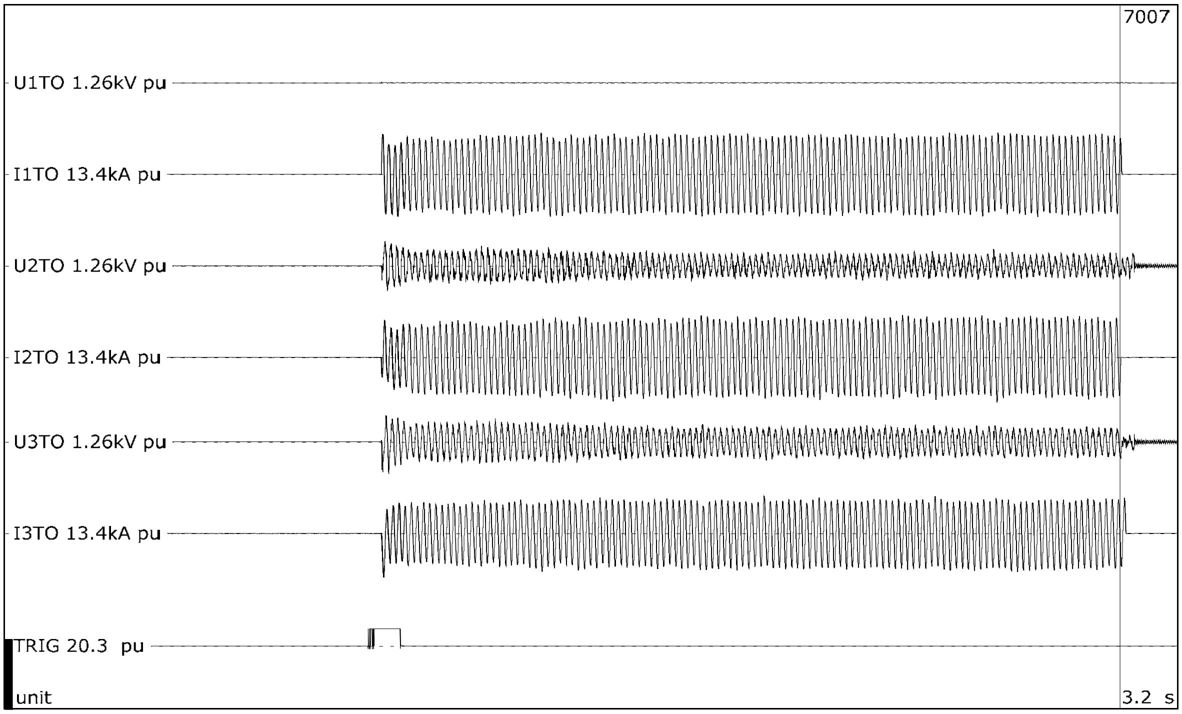
Overview of test numbers

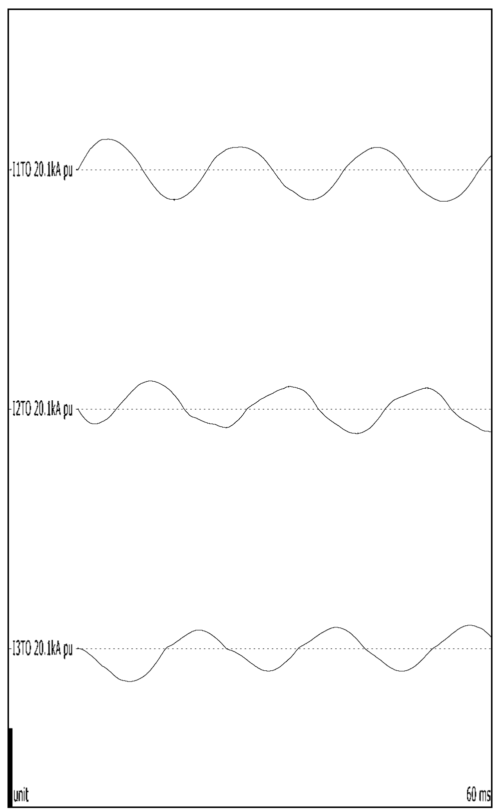
190822-7007

Remarks

-

Open Box Test # 5 (OB09) - 1000 V, 5 kA





Test number: **190822-7007**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	577	577	577
Applied voltage, phase-to-phase	V_{RMS}	999		
Making current	kA_{peak}	7.64	7.07	-8.32
Current, a.c. component, beginning	A_{RMS}	5011	3955	4100
Current, a.c. component, middle	A_{RMS}	5140	5170	4313
Current, a.c. component, end	A_{RMS}	5296	5113	4494
Current, a.c. component, average	A_{RMS}	5179	4869	4370
Current, a.c. component, three-phase average	A_{RMS}	4806		
Duration	s	2.01	2.01	2.01
Arc energy	kJ	21.7	1401	819

Observations: Emission of flames and gas observed.

9.4 Condition / inspection after test

Interior and sides of the exterior of the box were heavily burned. Box will be replaced for next test.

10 CHECKING THE PROSPECTIVE CURRENT

Standard and date

Standard	Client’s instructions
Test date	23 August 2019

10.1 Condition before test

Shorting bar connected at station terminals directly prior to test device.

10.2 Test results and oscillograms

Overview of test numbers

190823-7001, 7002

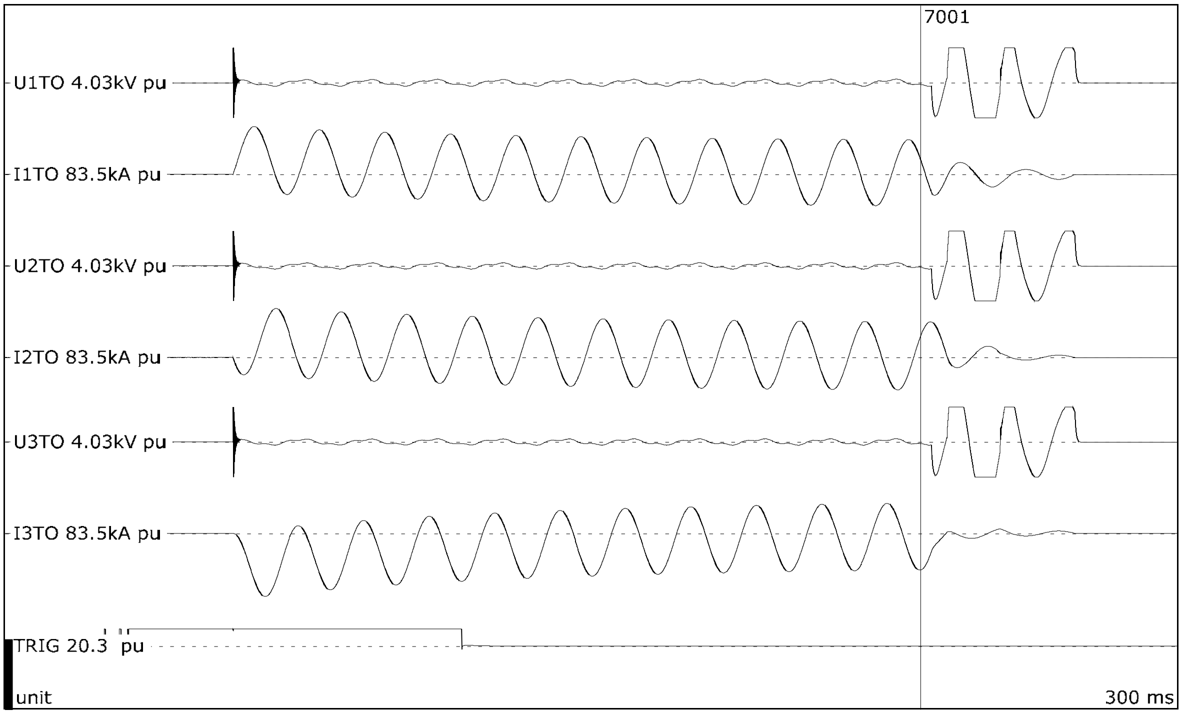
Remarks

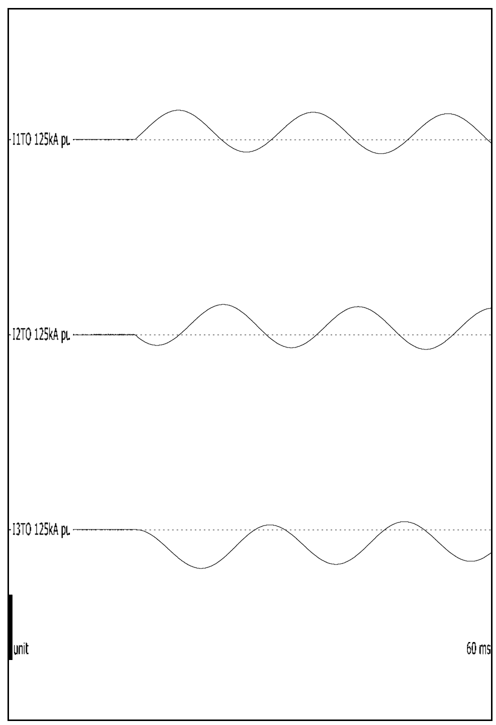
Prospective circuit parameters calibrated in this test duty:

190823-7001: 1064 V, 30 kA, 79.1 kA peak.

190823-7002: 1009 V, 15 kA, 40.4 kA peak.

Checking the prospective current



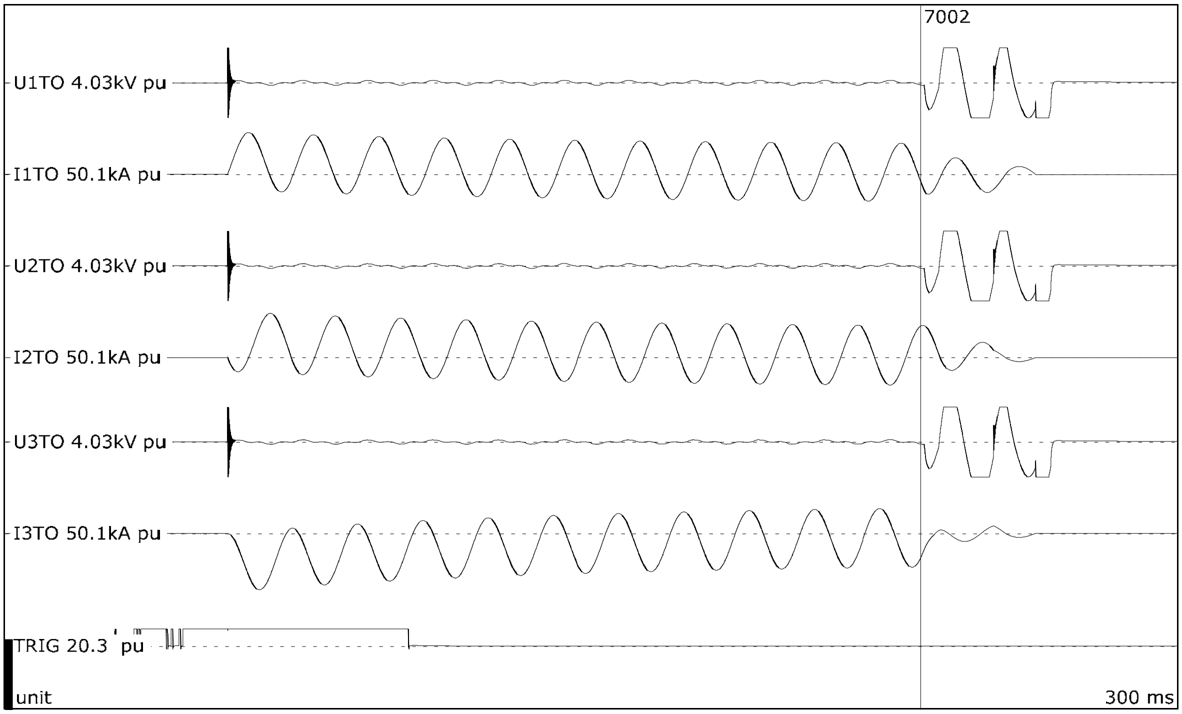


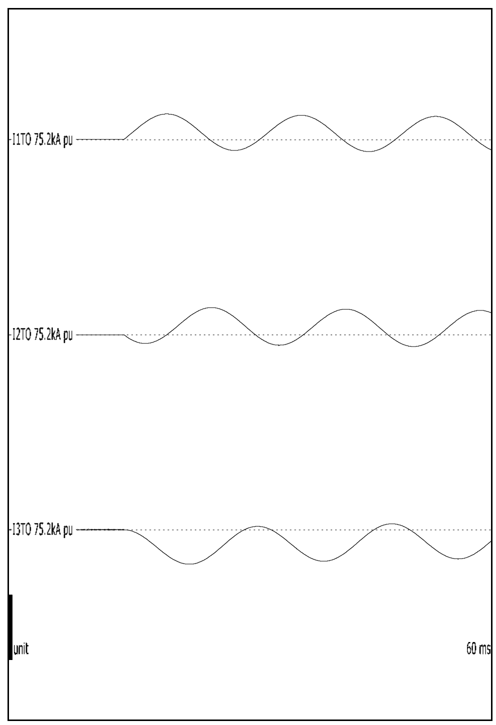
Test number: 190823-7001

Phase		A	B	C
Current	kA$_{peak}$	56.6	58.1	-74.6
Current, a.c. component	kA$_{RMS}$	27.8	28.7	28.1
Current, a.c. component, three-phase average	kA$_{RMS}$	28.2		
Duration, current	s	0.176	0.176	0.175

Observations: No visible disturbance.

Checking the prospective current





Test number: 190823-7002

Phase		A	B	C
Current	kApeak	29.7	31.3	-40.0
Current, a.c. component	kARMS	14.6	15.1	14.9
Current, a.c. component, three-phase average	kARMS		14.9	
Duration, current	s	0.177	0.177	0.176

Observations: No visible disturbance.

11 OPEN BOX TEST # 6 (OB06) - 1000 V, 15 KA

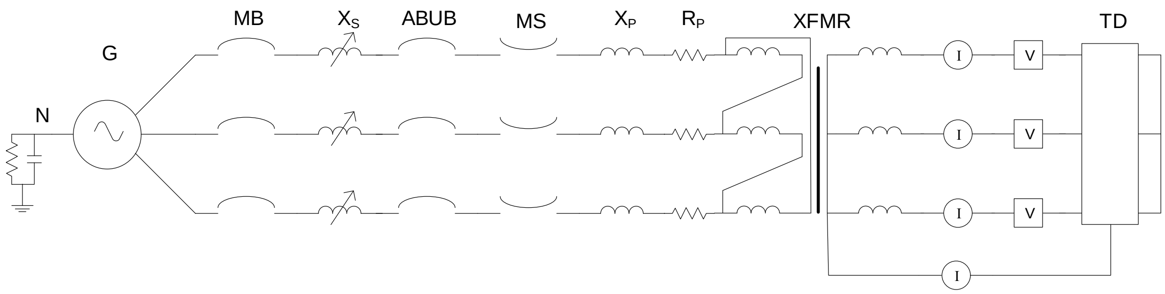
Standard and date

Standard	Client’s instructions
Test date	23 August 2019

11.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rods. Test duration is 2 seconds.

11.2 Test circuit S03



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks: -

11.3 Test results and oscillograms

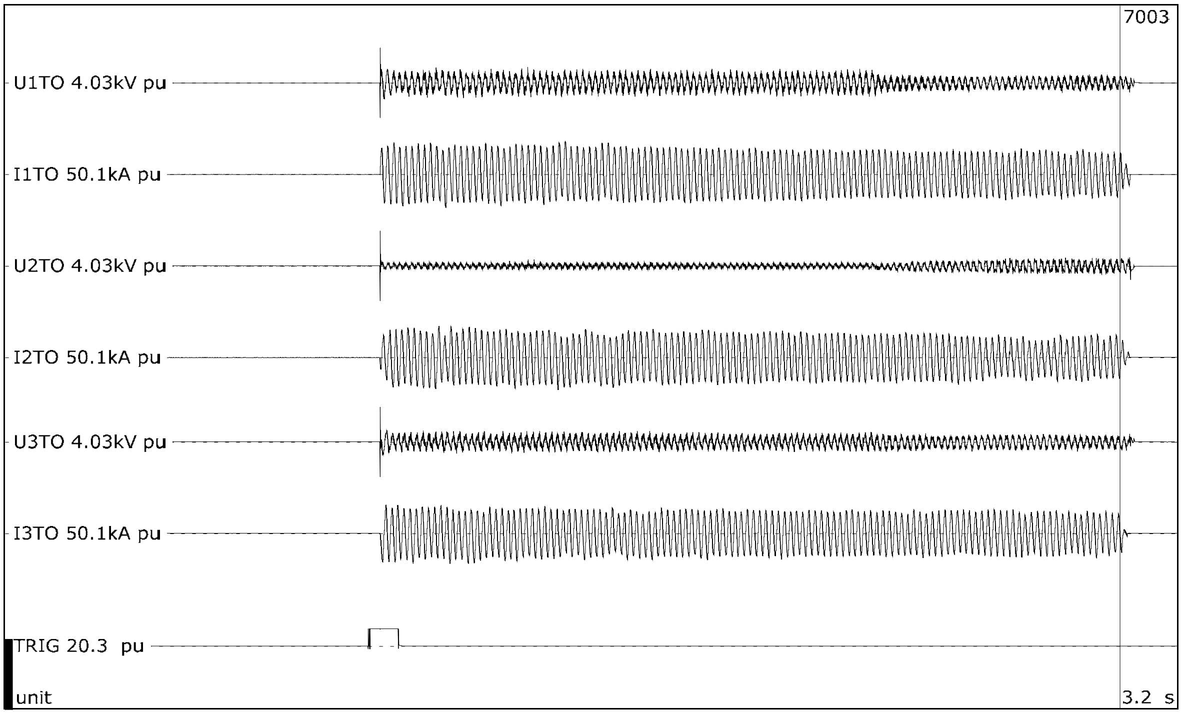
Overview of test numbers

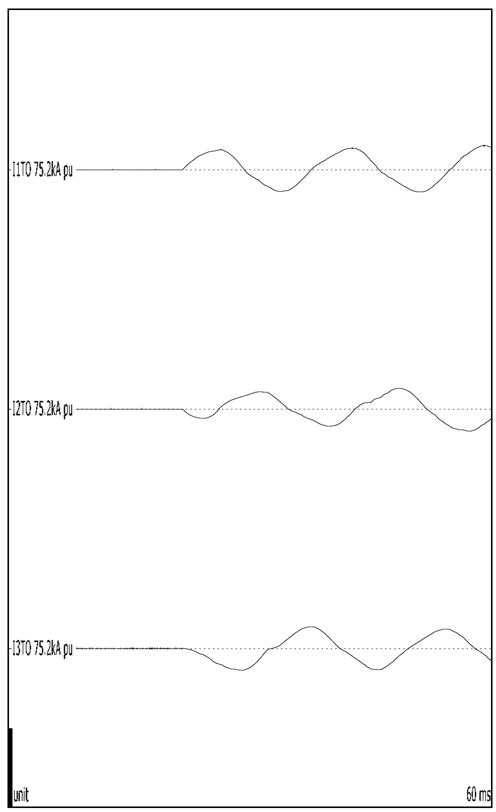
190823-7003

Remarks

-

Open Box Test # 6 (OB06) - 1000 V, 15 kA





Test number: 190823-7003

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}		1010	
Making current	kA_{peak}	-21.1	19.6	20.6
Current, a.c. component, beginning	kA_{RMS}	14.1	9.95	14.5
Current, a.c. component, middle	kA_{RMS}	12.8	12.6	11.4
Current, a.c. component, end	kA_{RMS}	11.3	9.74	10.1
Current, a.c. component, average	kA_{RMS}	13.1	12.1	12.1
Current, a.c. component, three-phase average	kA_{RMS}		12.4	
Duration	s	2.02	2.02	2.02
Arc energy	kJ	7434	483	4674

Observations: Emission of flames and gas observed.

11.4 Condition / inspection after test

Bottom of box burned completely through. Sides of box heavily burned, but not burned through completely.

12 OPEN BOX TEST # 7 (OB07) - 1000 V, 15 KA

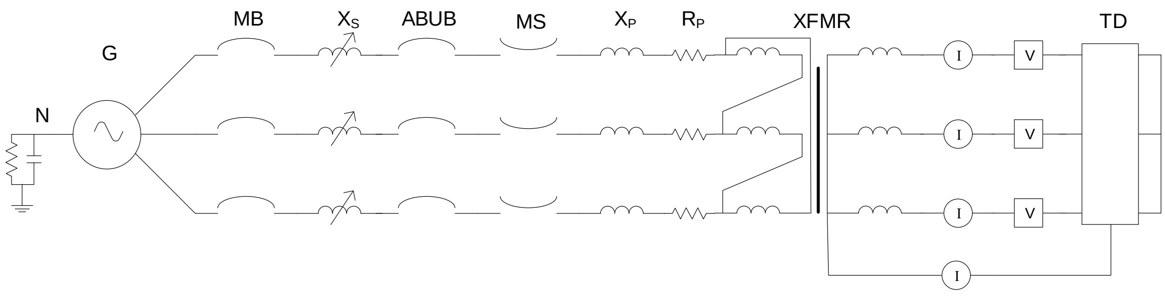
Standard and date

Standard	Client’s instructions
Test date	23 August 2019

12.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rods. Test duration is 1.5 seconds.

12.2 Test circuit S03



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks: -

12.3 Test results and oscillograms

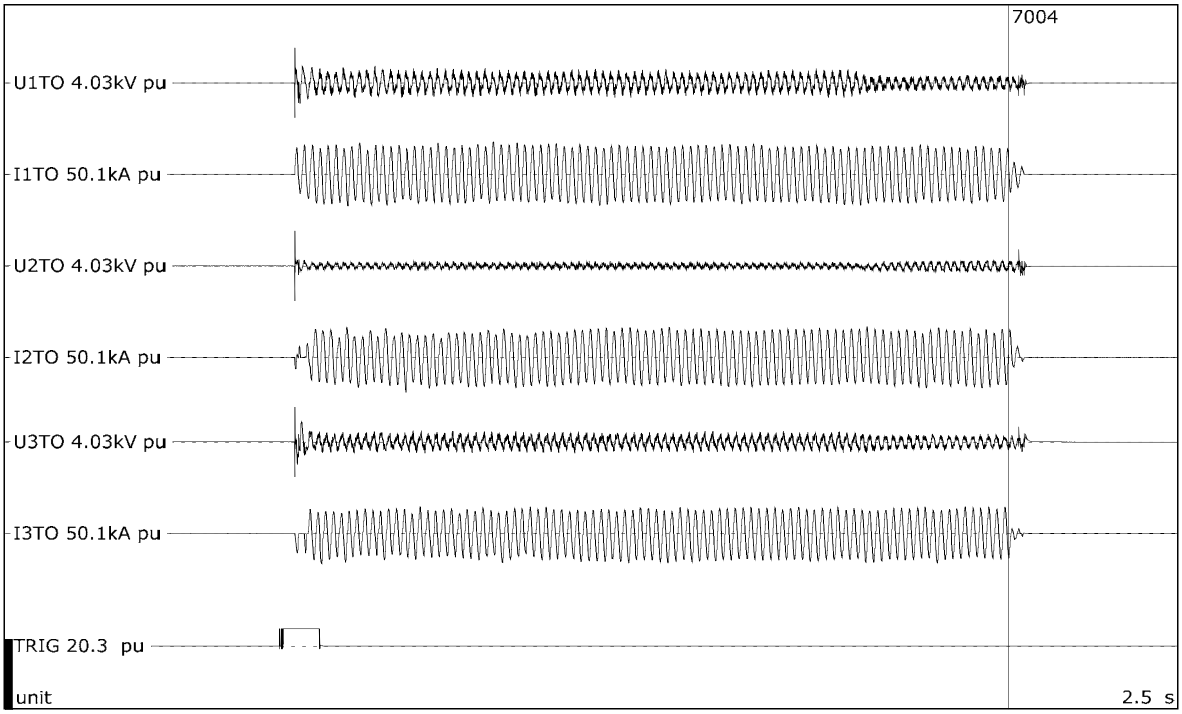
Overview of test numbers

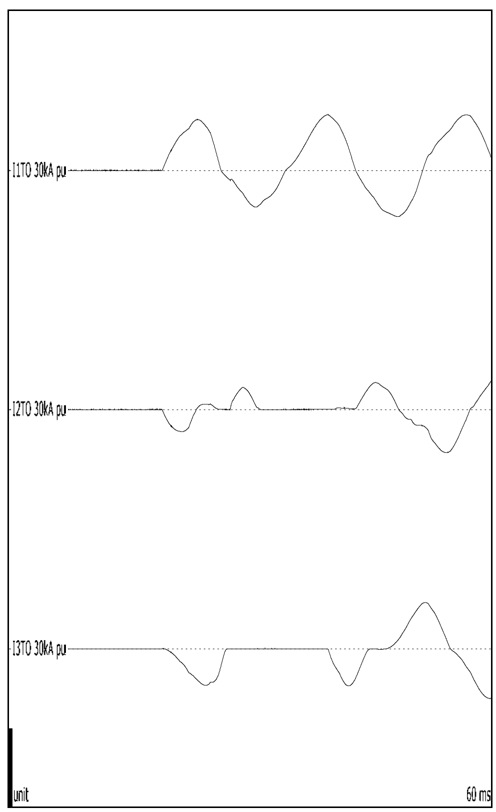
190823-7004

Remarks

-

Open Box Test # 7 - 1000 V, 15 kA





Test number: 190823-7004

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	20.9	10.2	17.4
Current, a.c. component, beginning	kA_{RMS}	14.5	13.0	12.6
Current, a.c. component, middle	kA_{RMS}	13.9	14.0	13.0
Current, a.c. component, end	kA_{RMS}	13.6	14.6	12.7
Current, a.c. component, average	kA_{RMS}	13.9	12.3	11.8
Current, a.c. component, three-phase average	kA_{RMS}	12.6		
Duration	s	1.52	1.52	1.52
Arc energy	kJ	6460	118	3655

Observations: Emission of flames and gas observed. Arc extinguished for approximately 12 ms on B & C phases before re-igniting. After this period, the arc was sustained on B & C phases for the remainder of the test.

12.4 Condition / inspection after test

Bottom of box burned completely through. Sides of box heavily burned, but not burned through completely. There were two small holes on the side of the box towards the bottom of the box.

13 OPEN BOX TEST # 8 (OB08) - 1000 V, 30 KA

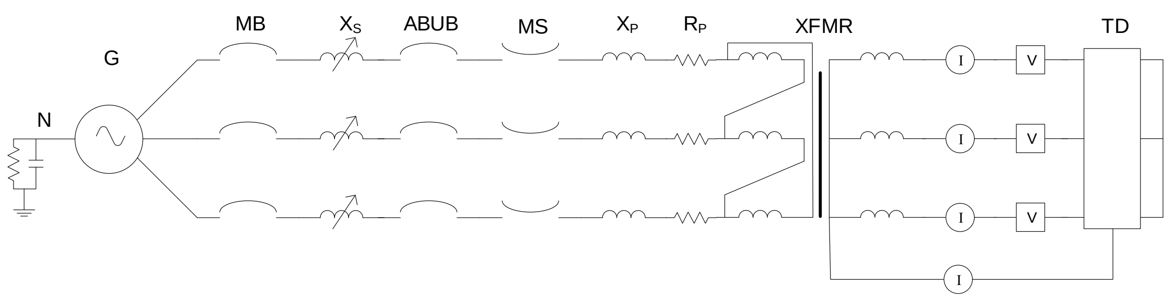
Standard and date

Standard	Client’s instructions
Test date	23 August 2019

13.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rods. Test duration is 1 second.

13.2 Test circuit S04



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

Supply		
Power	MVA	55.3
Frequency	Hz	60
Phase(s)		3
Voltage	V	1064
Sym. Current	kA	30
Peak current	kA	79.1
Impedance	Ω	0.020

Remarks: -

13.3 Test results and oscillograms

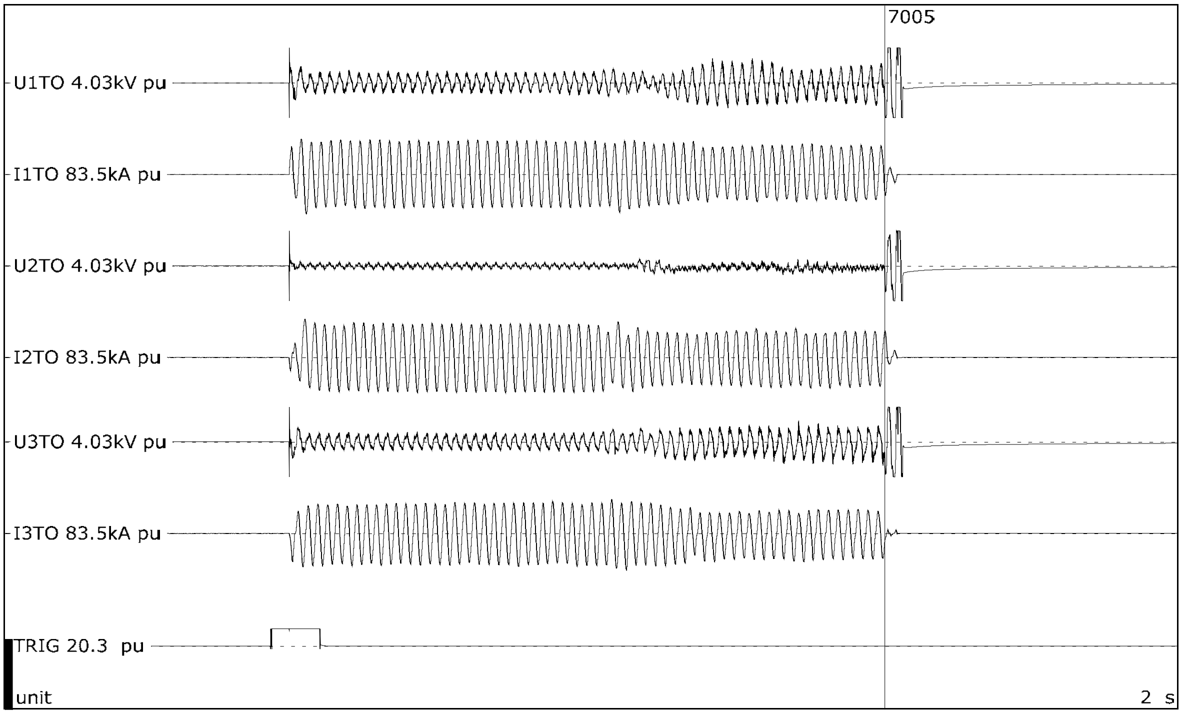
Overview of test numbers

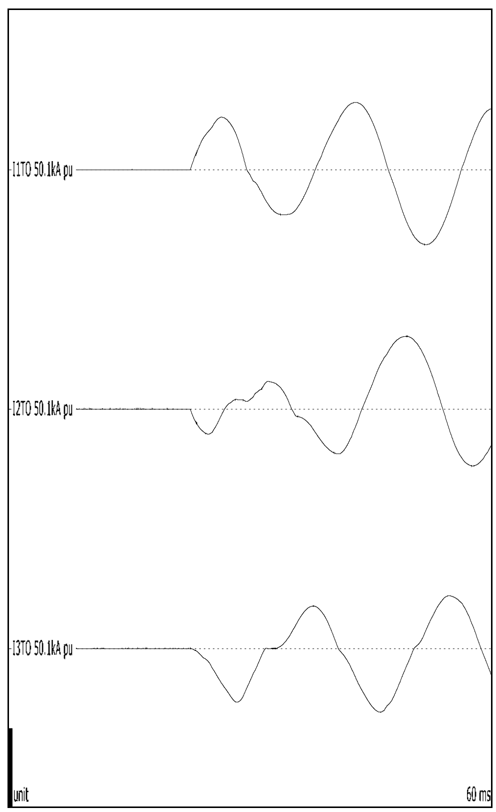
190823-7005

Remarks

-

Open Box Test # 8 - 1000 V, 30 kA





Test number: 190823-7005

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	614	614	614
Applied voltage, phase-to-phase	V_{RMS}	1063		
Making current	kA_{peak}	-47.0	45.7	-40.1
Current, a.c. component, beginning	kA_{RMS}	28.8	28.0	26.0
Current, a.c. component, middle	kA_{RMS}	27.7	28.1	26.2
Current, a.c. component, end	kA_{RMS}	23.5	23.3	20.6
Current, a.c. component, average	kA_{RMS}	26.1	24.8	23.9
Current, a.c. component, three-phase average	kA_{RMS}	24.9		
Duration	s	1.01	1.01	1.01
Arc energy	MJ	10.5	1.17	7.90

Observations: Emission of flames and gas observed.

13.4 Condition / inspection after test

Small hole burned through bottom of box. Sides of box burned, but not completely through. B-phase aluminum rod ejected from the box. A and C phase rods were bent away from one another. Aluminum rods broke apart.

14 OPEN BOX TEST # 9 (OB11) - SINGLE PHASE INVESTIGATION

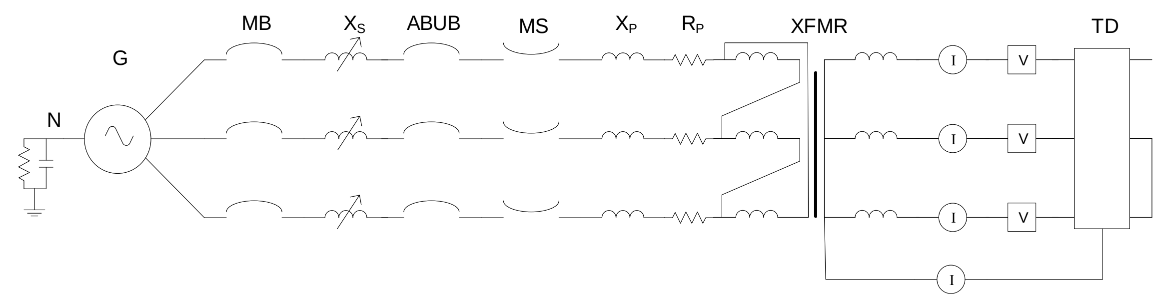
Standard and date

Standard	Client's instructions
Test date	23 August 2019

14.1 Condition before test

Test box previously subject to arc tests on 8/23. Aluminum rods new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rods on B & C phase only. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to third phase.

14.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks:	Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

14.3 Test results and oscillograms

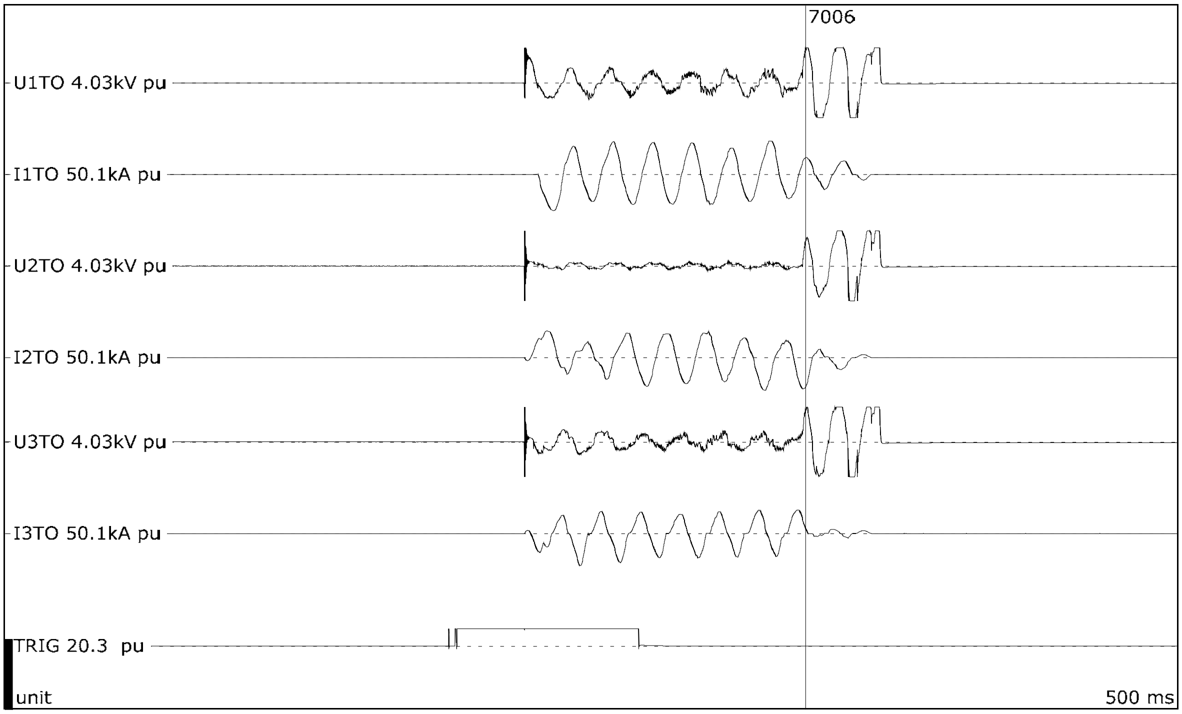
Overview of test numbers

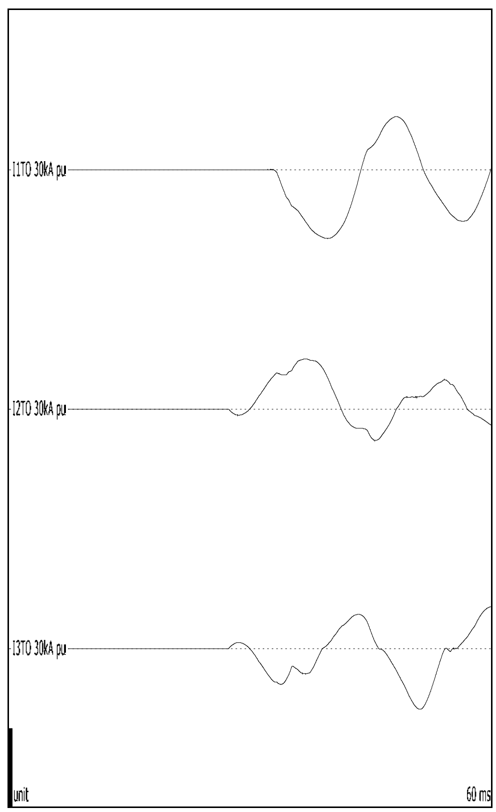
190823-7006

Remarks

-

Open Box Test # 9 - Single Phase Investigation





Test number: 190823-7006

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	-25.9	18.8	-22.9
Current, a.c. component, beginning	kA_{RMS}	15.1	9.44	11.2
Current, a.c. component, middle	kA_{RMS}	15.4	12.7	11.2
Current, a.c. component, end	kA_{RMS}	15.4	2.82	11.2
Current, a.c. component, average	kA_{RMS}	15.2	11.7	11.9
Current, a.c. component, three-phase average	kA_{RMS}	12.9		
Duration	s	0.114	0.120	0.117
Arc energy	kJ	758	73.0	334

Observations:	Emission of flames and gas observed. Arc propigated to A-phase rod in approximately 6 ms.

14.4 Condition / inspection after test

Minimal damage to test box observed.

15 CHECKING THE PROSPECTIVE CURRENT

Standard and date

Standard	Client’s instructions
Test date	26 August 2019

15.1 Condition before test

Shorting bar connected at station terminals directly prior to test device.

15.2 Test results and oscillograms

Overview of test numbers

190826-7001, 7002

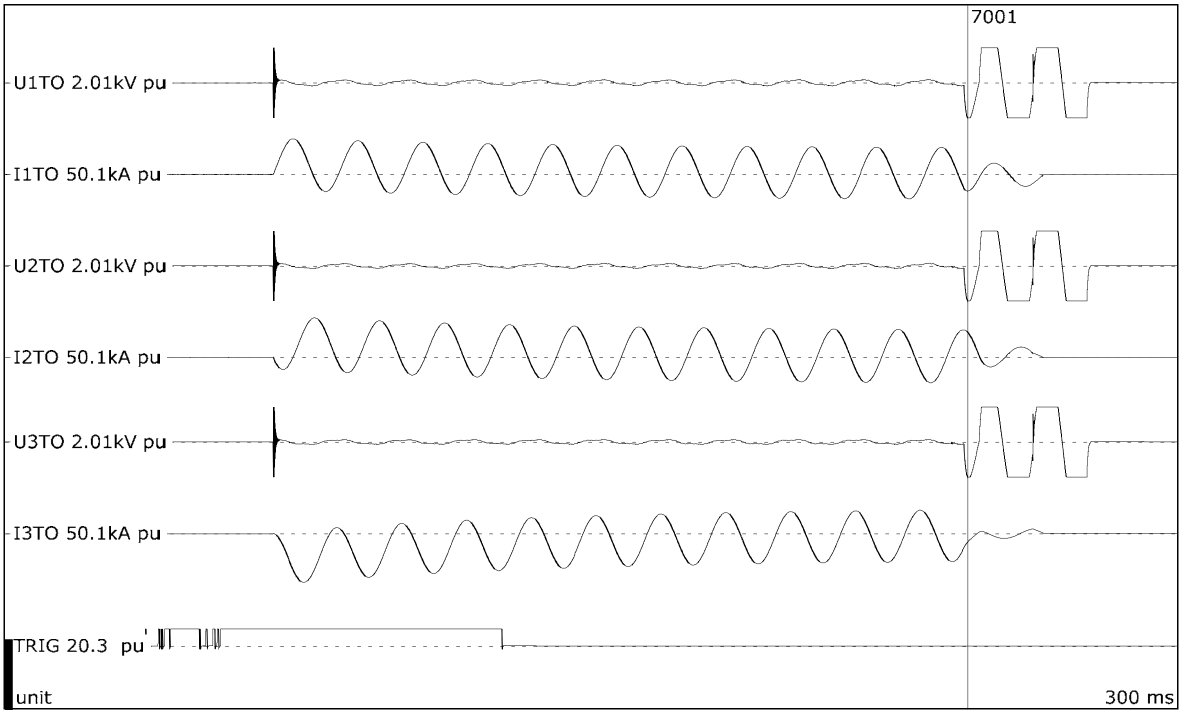
Remarks

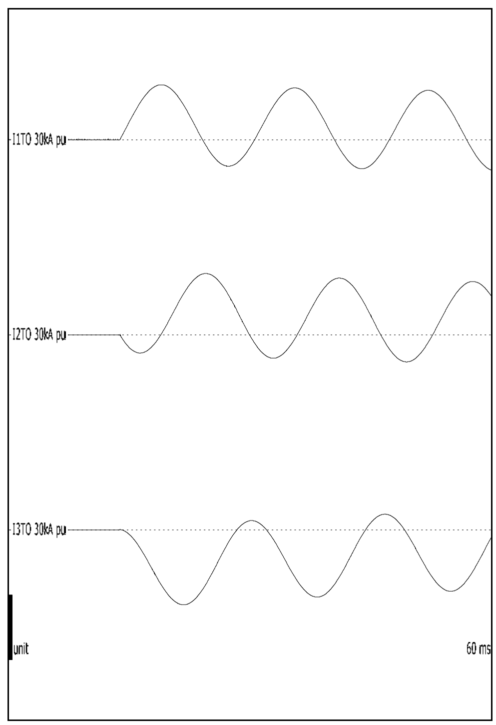
Prospective circuit parameters calibrated in this test duty:

190826-7001: 616 V, 13.5 kA, 35.6 kA peak.

190826-7002: 489 V, 13.5 kA, 35.5 kA peak.

Checking the prospective current



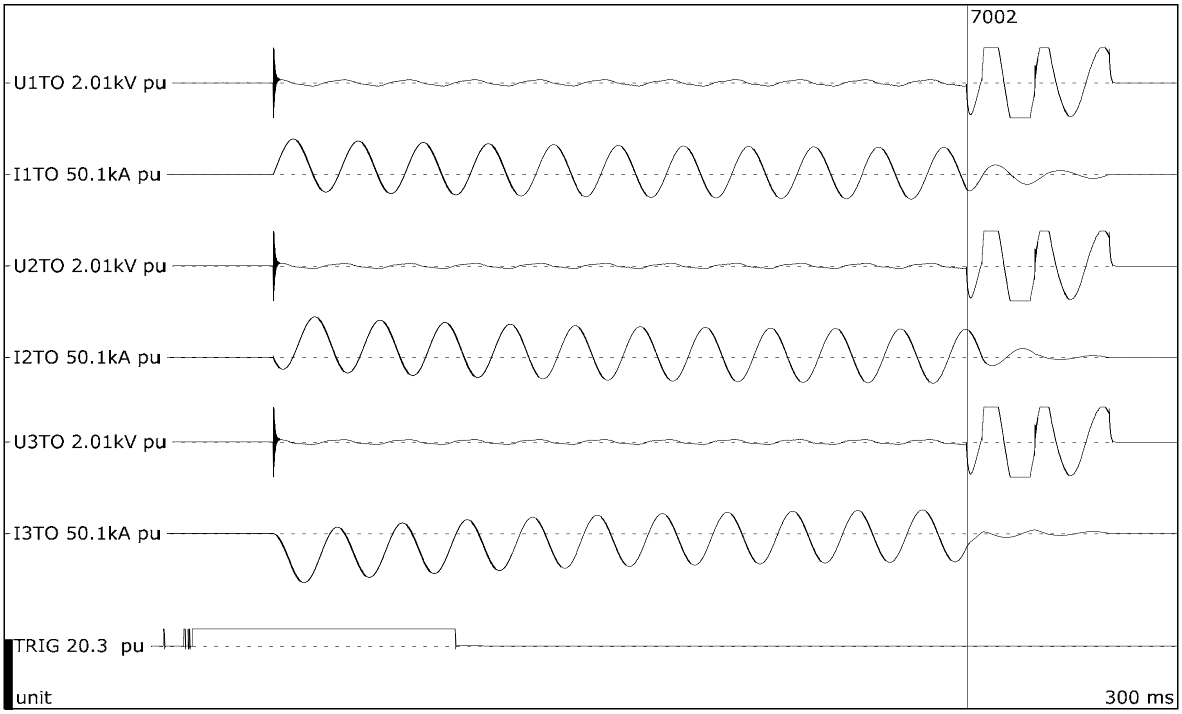


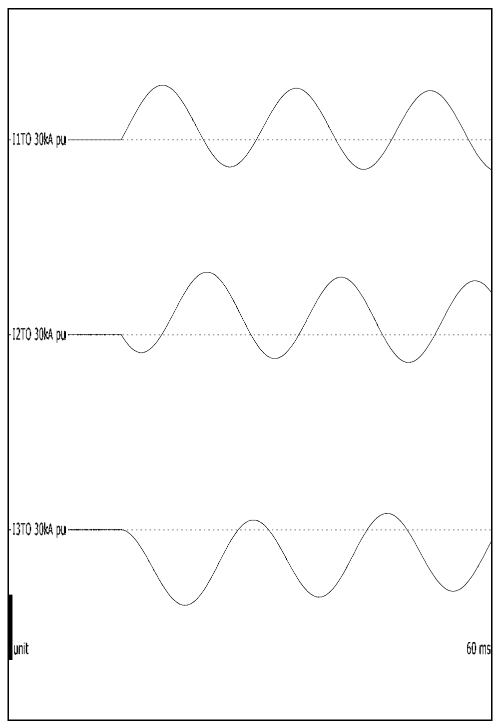
Test number: 190826-7001

Phase		A	B	C
Current	kA$_{peak}$	25.3	28.2	-34.7
Current, a.c. component	kA$_{RMS}$	13.0	13.4	13.0
Current, a.c. component, three-phase average	kA$_{RMS}$	13.1		
Duration, current	s	0.177	0.177	0.177

Observations: No visible disturbance.

Checking the prospective current





Test number: 190826-7002

Phase		A	B	C
Current	kA$_{peak}$	25.1	28.9	-34.9
Current, a.c. component	kA$_{RMS}$	13.0	13.6	13.2
Current, a.c. component, three-phase average	kA$_{RMS}$	13.3		
Duration, current	s	0.177	0.177	0.176

Observations: No visible disturbance.

16 SAMPLE 2-13 (A) - 480 V, 13.5 KA

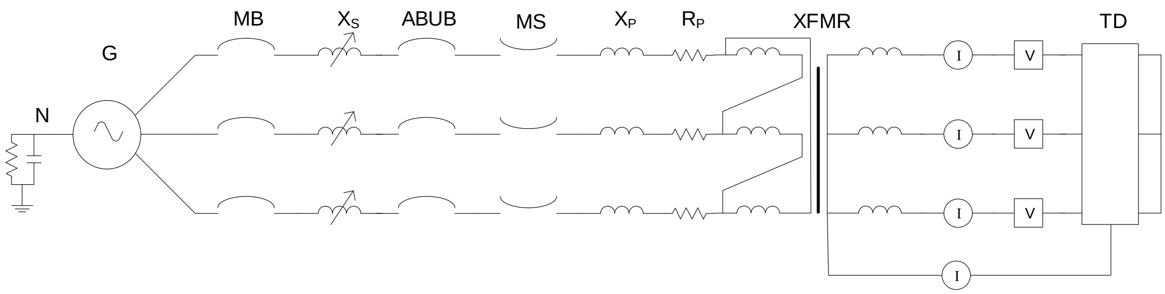
Standard and date

Standard	Client's instructions
Test date	26 August 2019

16.1 Condition before test

Switchgear new. Arc to be initiated by #10 AWG stranded wire.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

16.2 Test circuit S06



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

Supply		
Power	MVA	11.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	489
Sym. Current	kA	13.5
Peak current	kA	35.5
Impedance	Ω	0.021

Remarks: -

16.3 Test results and oscillograms

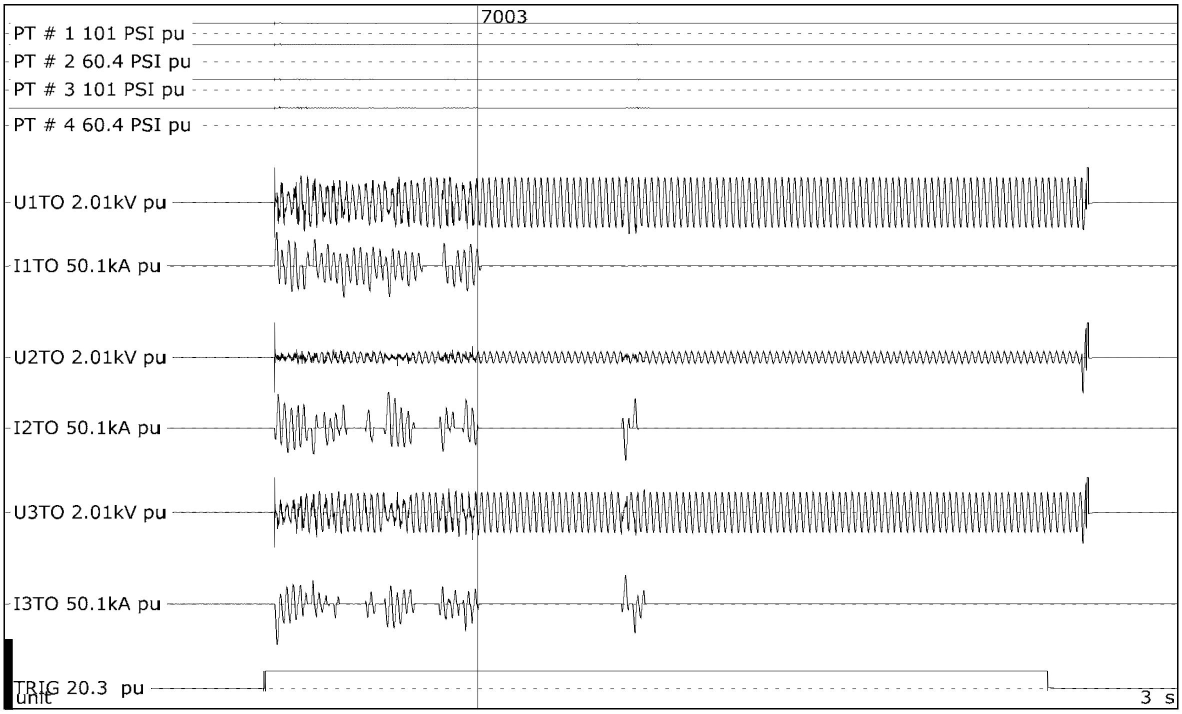
Overview of test numbers

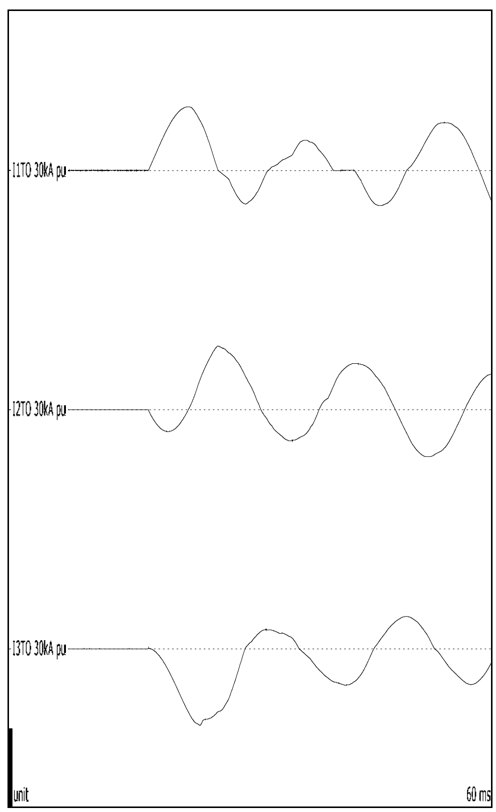
190826-7003

Remarks

Voltage traces for this test duty appear uneven on the oscillographs. This is due to the fact that station voltage dividers are referenced to ground. The test was conducted with the neutral of the wye transformer floating, so the station voltage dividers do not have a solid reference.

Sample 2-13 (A) - 480 V, 13.5 kA





Test number: 190826-7003

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	282	282	282
Applied voltage, phase-to-phase	V_{RMS}		488	
Making current	kA_{peak}	24.0	23.8	-28.7
Current, a.c. component, beginning	kA_{RMS}	10.7	11.9	10.2
Current, a.c. component, middle	kA_{RMS}	7.52	9.15	5.89
Current, a.c. component, end	kA_{RMS}	7.98	4.04	5.44
Current, a.c. component, average	kA_{RMS}	8.78	9.35	7.71
Current, a.c. component, three-phase average	kA_{RMS}		8.61	
Duration	s	0.519	0.519	0.519
Arc energy	kJ	1122	28.9	554

Observations: Emission of flames and gas observed.

16.4 Condition / inspection after test

Switchgear sustained minimal damage. Arc self-extinguished.

17 SAMPLE 2-13 (B) - 600 V, 13.5 KA

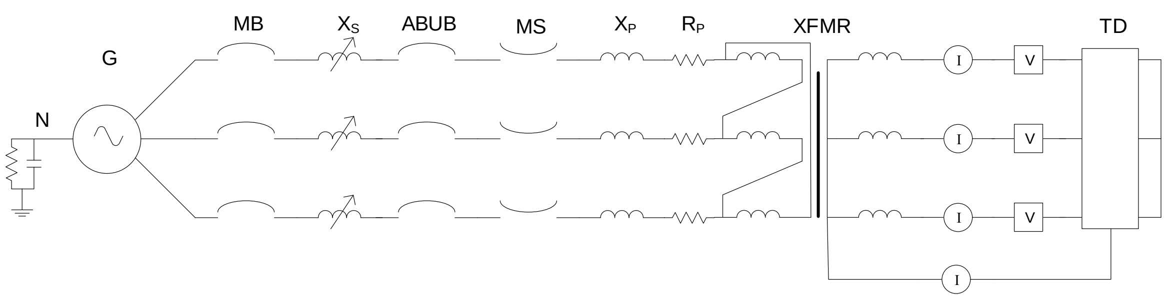
Standard and date

Standard	Client's instructions
Test date	27 August 2019

17.1 Condition before test

Switchgear previously subjected to arc test at 480 V, 13.5 kA. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

17.2 Test circuit S07



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

Supply		
Power	MVA	14.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	616
Sym. Current	kA	13.5
Peak current	kA	35.6
Impedance	Ω	0.026

Remarks: -

17.3 Test results and oscillograms

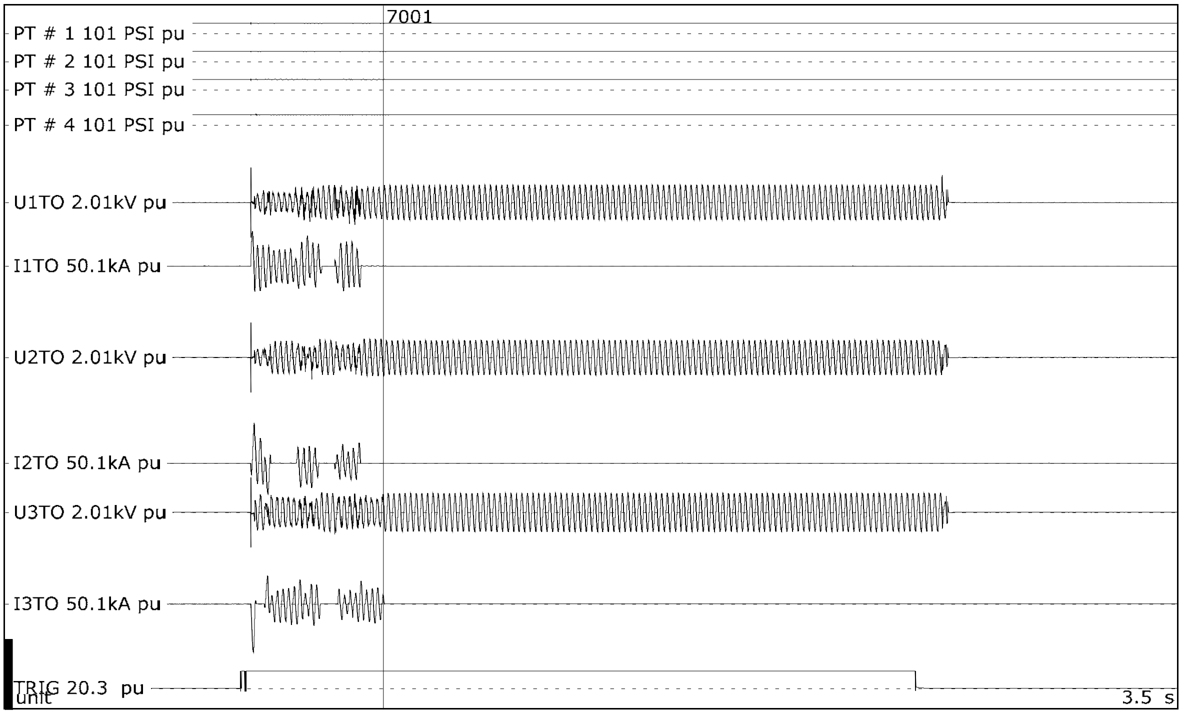
Overview of test numbers

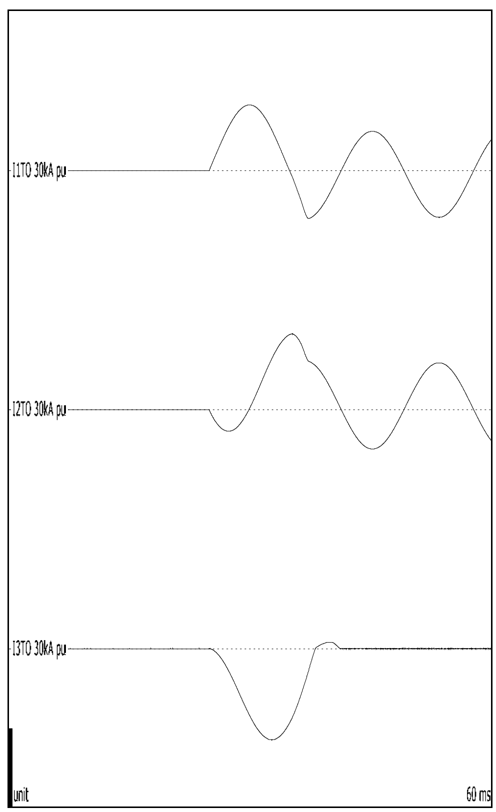
190827-7001

Remarks

-

Sample 2-13 (B) - 600 V, 13.5 kA





Test number: 190827-7001

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	356	356	356
Applied voltage, phase-to-phase	V_{RMS}		617	
Making current	kA_{peak}	24.7	28.5	-34.3
Current, a.c. component, beginning	kA_{RMS}	13.4	14.0	2.05
Current, a.c. component, middle	kA_{RMS}	8.76	7.33	6.74
Current, a.c. component, end	kA_{RMS}	0.000	0.000	7.95
Current, a.c. component, average	kA_{RMS}	9.91	9.46	8.27
Current, a.c. component, three-phase average	kA_{RMS}		9.22	
Duration	s	0.332	0.332	0.396
Arc energy	kJ	562	216	596

Observations: Emission of flames and gas observed.

17.4 Condition / inspection after test

Switchgear sustained minimal damage. Arc self-extinguished.

18 SAMPLE 2-13 (C) - 600 V, 13.5 KA

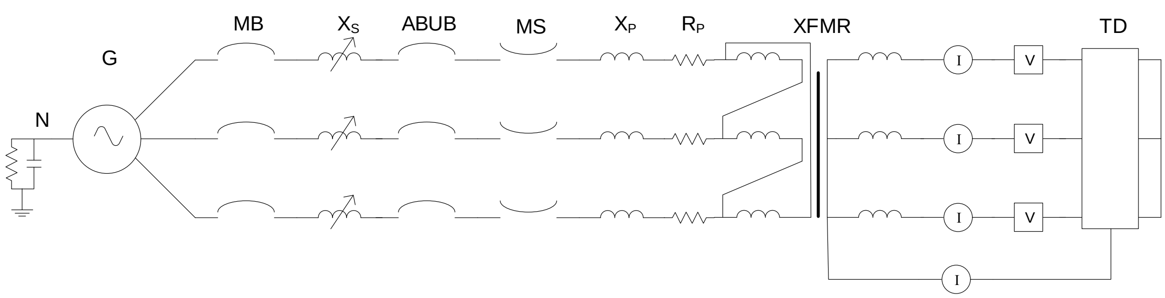
Standard and date

Standard	Client's instructions
Test date	27 August 2019

18.1 Condition before test

Switchgear in same condition as after trial 190827-7001. Arc to be initiated by two #10 AWG stranded wires. Additional grounding plate added to gear to attempt to sustain the arc.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

18.2 Test circuit S07



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

Supply		
Power	MVA	14.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	616
Sym. Current	kA	13.5
Peak current	kA	35.6
Impedance	Ω	0.026

Remarks: -

18.3 Test results and oscillograms

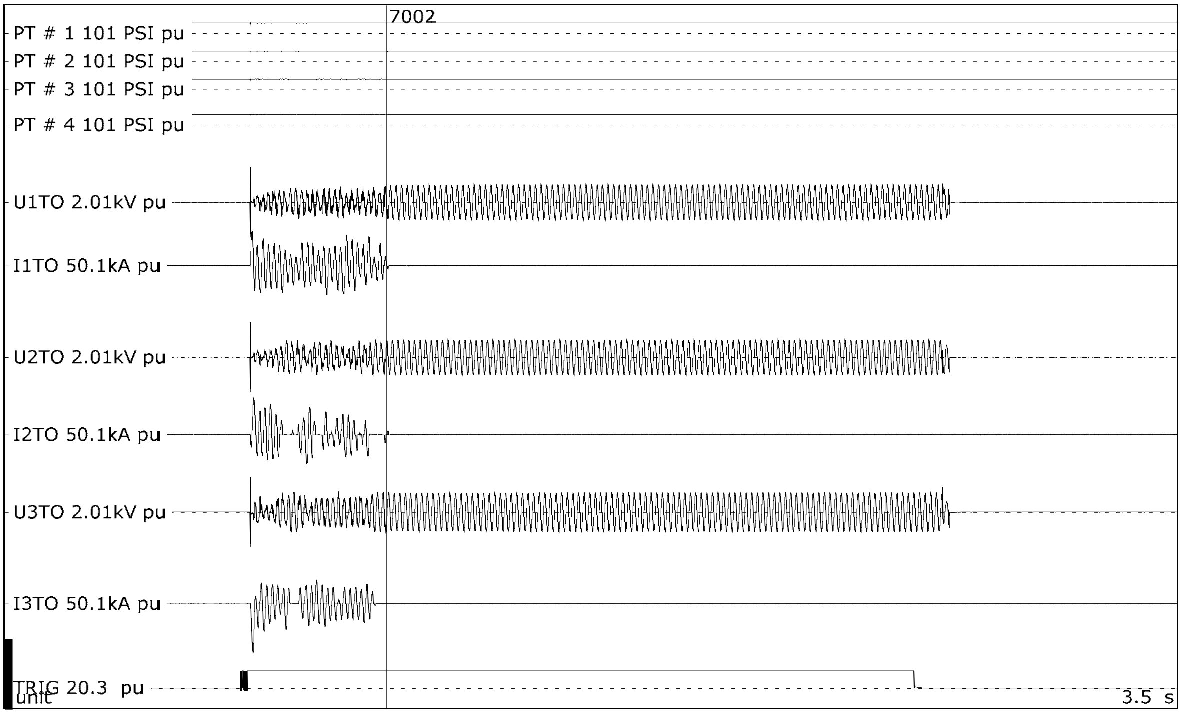
Overview of test numbers

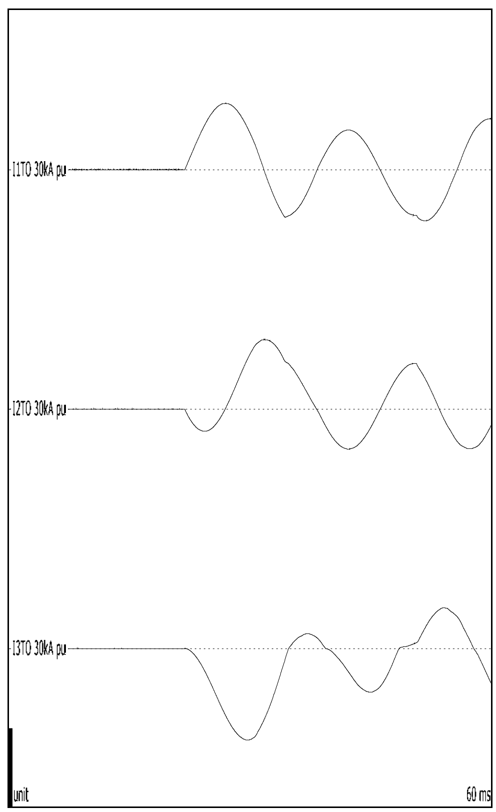
190827-7002

Remarks

-

Sample 2-13 (C) - 600 V, 13.5 kA





Test number: 190827-7002

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	356	356	356
Applied voltage, phase-to-phase	V_{RMS}	617		
Making current	kA_{peak}	25.0	26.1	-34.4
Current, a.c. component, beginning	kA_{RMS}	13.4	13.2	11.0
Current, a.c. component, middle	kA_{RMS}	8.92	9.14	10.2
Current, a.c. component, end	kA_{RMS}	7.93	4.10	8.05
Current, a.c. component, average	kA_{RMS}	11.5	10.2	9.09
Current, a.c. component, three-phase average	kA_{RMS}	10.3		
Duration	s	0.405	0.405	0.404
Arc energy	kJ	705	342	601

Observations: Emission of flames and gas observed.

18.4 Condition / inspection after test

Switchgear sustained minimal damage. Arc self-extinguished.

19 SAMPLE 2-13 (D) - 600 V, 13.5 KA

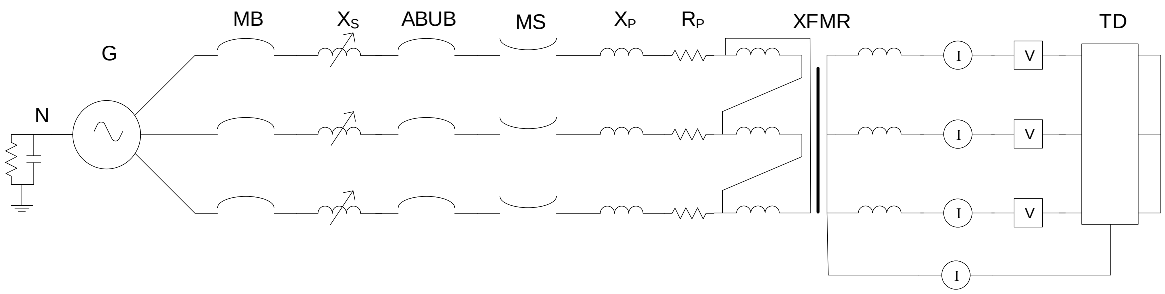
Standard and date

Standard	Client's instructions
Test date	27 August 2019

19.1 Condition before test

Switchgear in same condition as after trial 190827-7002. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

19.2 Test circuit S07



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

Supply		
Power	MVA	14.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	616
Sym. Current	kA	13.5
Peak current	kA	35.6
Impedance	Ω	0.026

Remarks: -

19.3 Test results and oscillograms

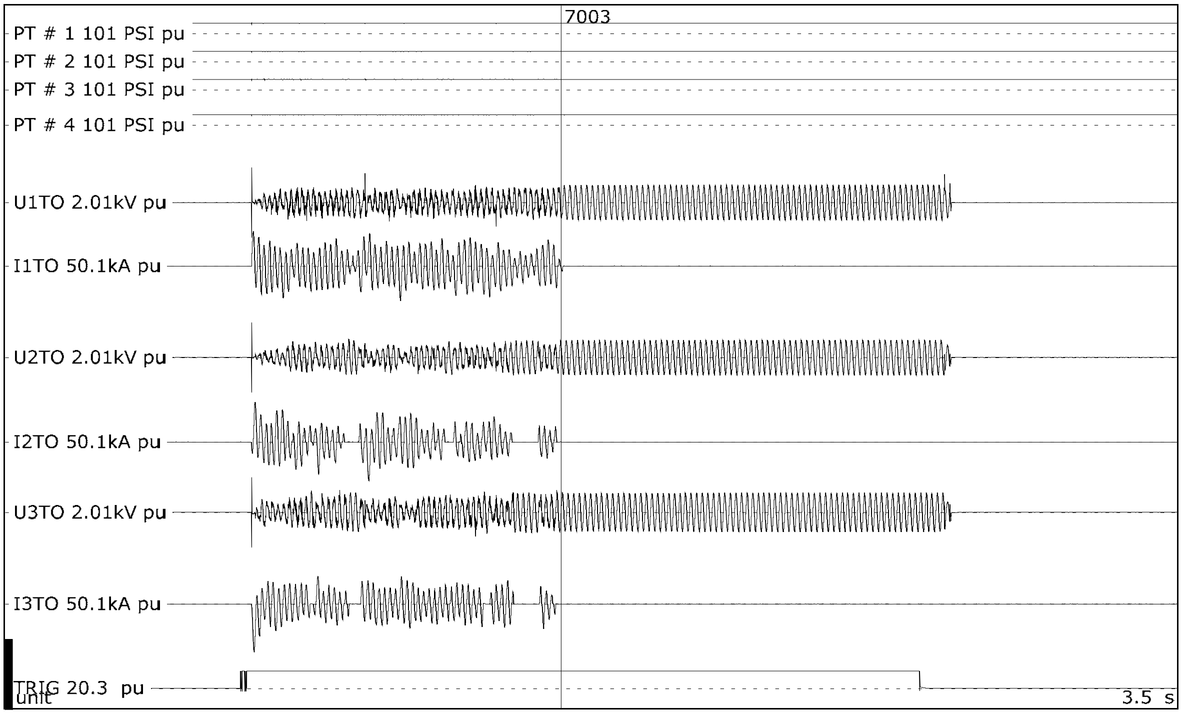
Overview of test numbers

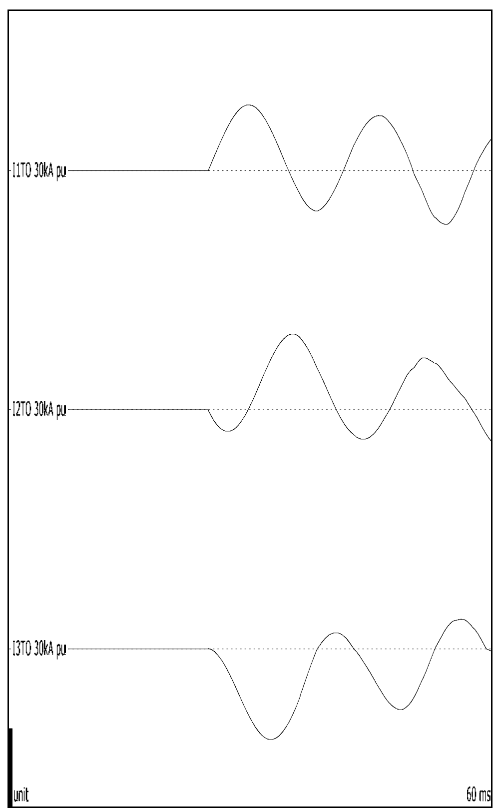
190827-7003

Remarks

-

Sample 2-13 (D) - 600 V, 13.5 kA





Test number: 190827-7003

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	356	356	356
Applied voltage, phase-to-phase	V_{RMS}	617		
Making current	kA_{peak}	24.7	28.4	-34.3
Current, a.c. component, beginning	kA_{RMS}	13.4	13.5	12.2
Current, a.c. component, middle	kA_{RMS}	9.05	13.7	11.8
Current, a.c. component, end	kA_{RMS}	10.9	8.03	8.49
Current, a.c. component, average	kA_{RMS}	11.2	10.1	9.88
Current, a.c. component, three-phase average	kA_{RMS}	10.4		
Duration	s	0.924	0.924	0.924
Arc energy	kJ	1754	1031	1356

Observations: Emission of flames and gas observed.

19.4 Condition / inspection after test

Switchgear sustained minimal damage. Arc self-extinguished.

20 SAMPLE 2-13 (E) - 600 V, 13.5 KA

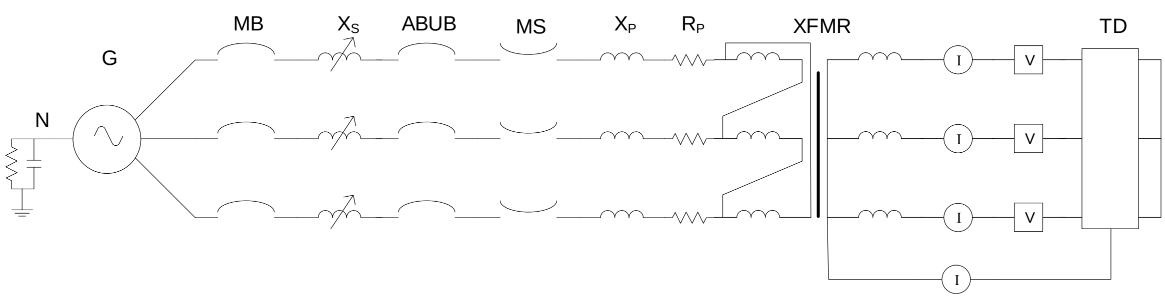
Standard and date

Standard	Client's instructions
Test date	27 August 2019

20.1 Condition before test

Switchgear in same condition as after trial 190827-7003. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

20.2 Test circuit S07



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

Supply		
Power	MVA	14.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	616
Sym. Current	kA	13.5
Peak current	kA	35.6
Impedance	Ω	0.026

Remarks: -

20.3 Test results and oscillograms

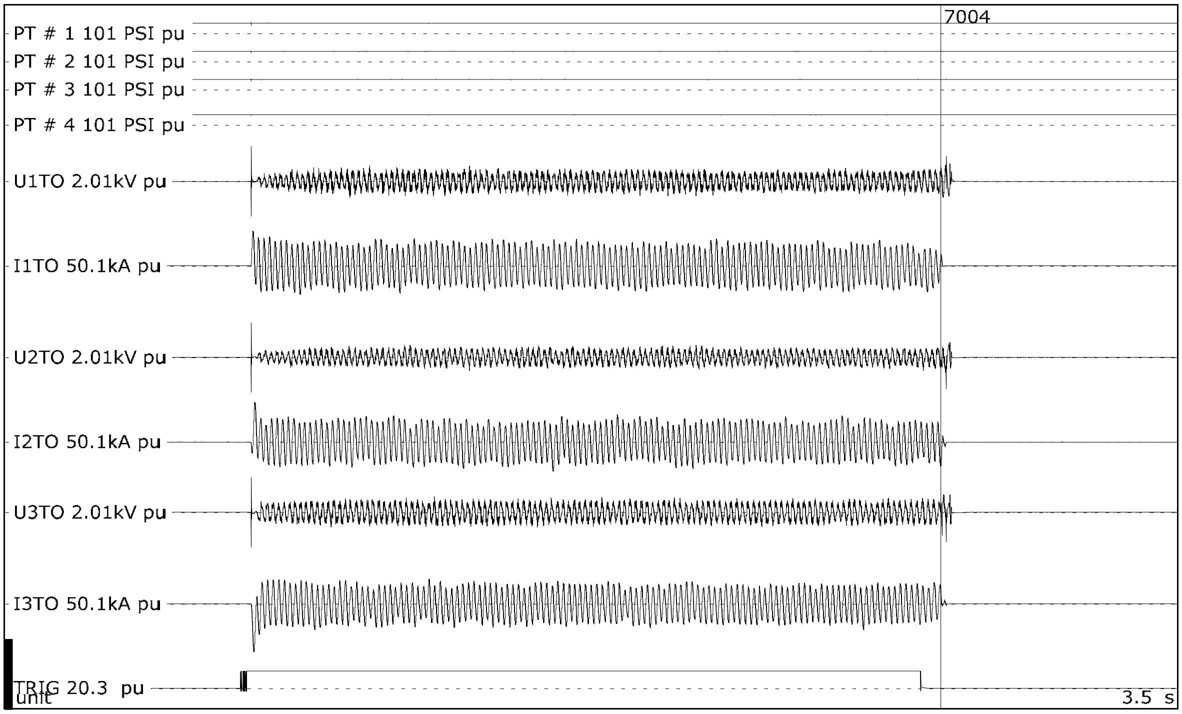
Overview of test numbers

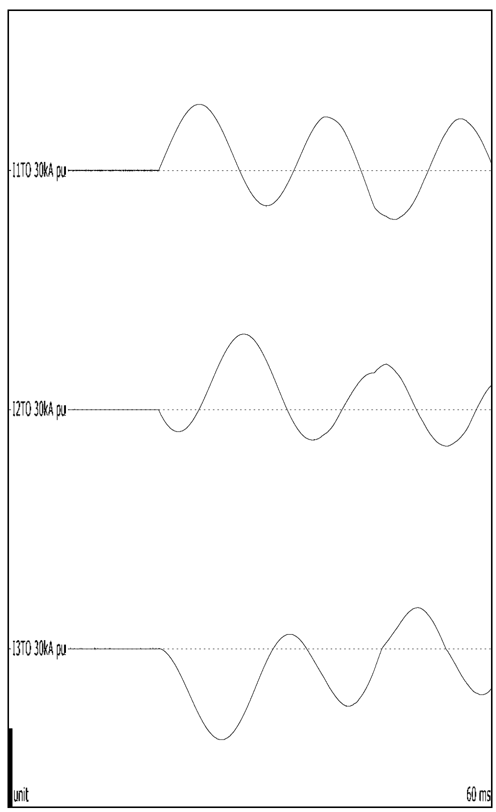
190827-7004

Remarks

-

Sample 2-13 (E) - 600 V, 13.5 kA





Test number: **190827-7004**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	356	356	356
Applied voltage, phase-to-phase	V_{RMS}		617	
Making current	kA_{peak}	24.9	28.4	-34.3
Current, a.c. component, beginning	kA_{RMS}	12.6	13.5	11.6
Current, a.c. component, middle	kA_{RMS}	10.4	10.5	9.79
Current, a.c. component, end	kA_{RMS}	10.2	9.35	9.26
Current, a.c. component, average	kA_{RMS}	11.1	10.8	10.00
Current, a.c. component, three-phase average	kA_{RMS}		10.6	
Duration	s	2.06	2.06	2.06
Arc energy	kJ	3497	2815	3289

Observations: Emission of flames and gas observed.

20.4 Condition / inspection after test

Evidence of arcing found around the outside of the switchgear (burning and charring). No complete burn-throughs. Two of the breaker doors opened.

21 SAMPLE 2-13 (F) - 480 V, 13.5 KA

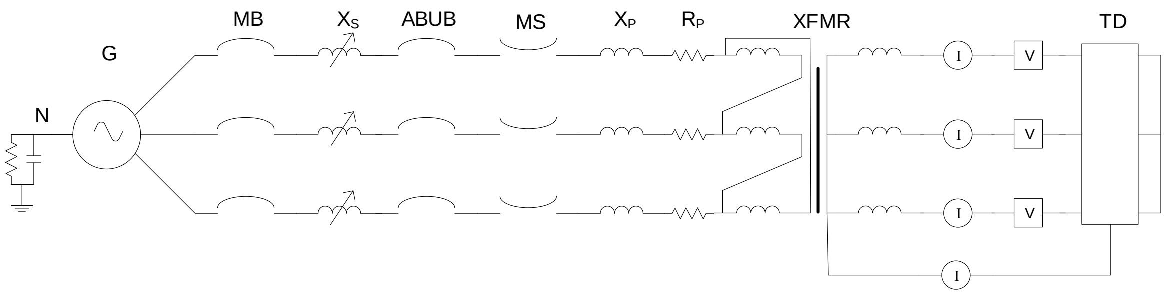
Standard and date

Standard	Client's instructions
Test date	28 August 2019

21.1 Condition before test

Switchgear in same condition as after trial 190827-7004. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

21.2 Test circuit S06



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

Supply		
Power	MVA	11.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	489
Sym. Current	kA	13.5
Peak current	kA	35.5
Impedance	Ω	0.021

Remarks: -

21.3 Test results and oscillograms

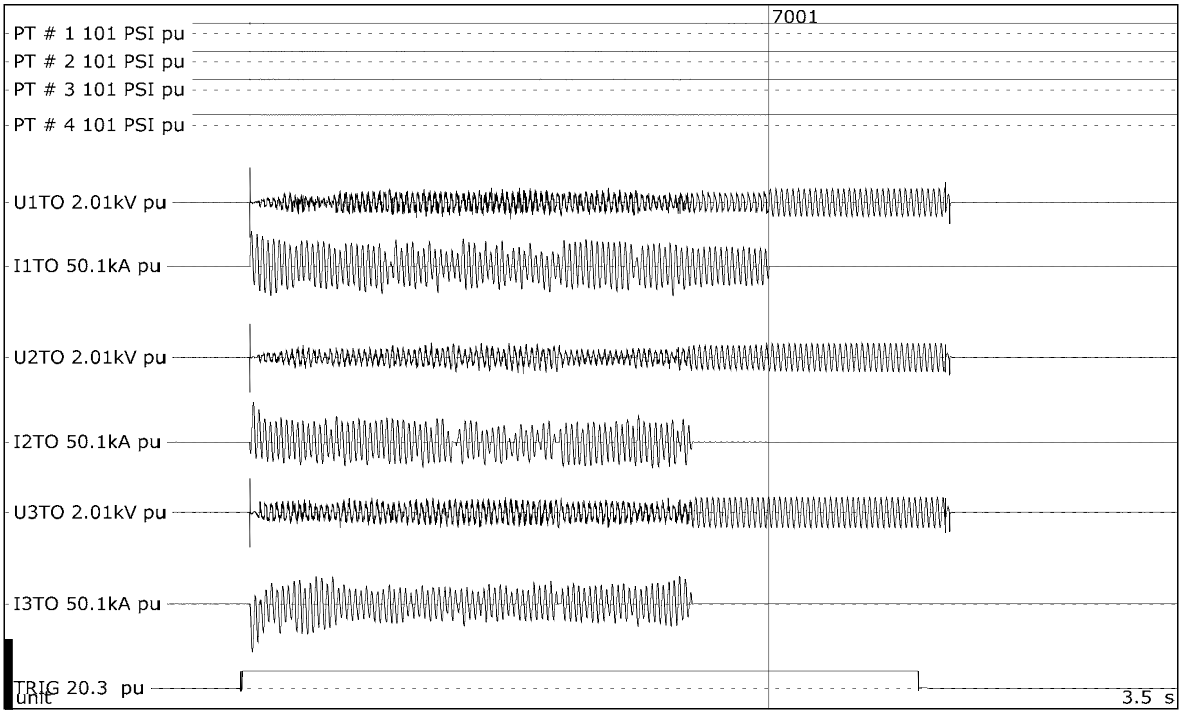
Overview of test numbers

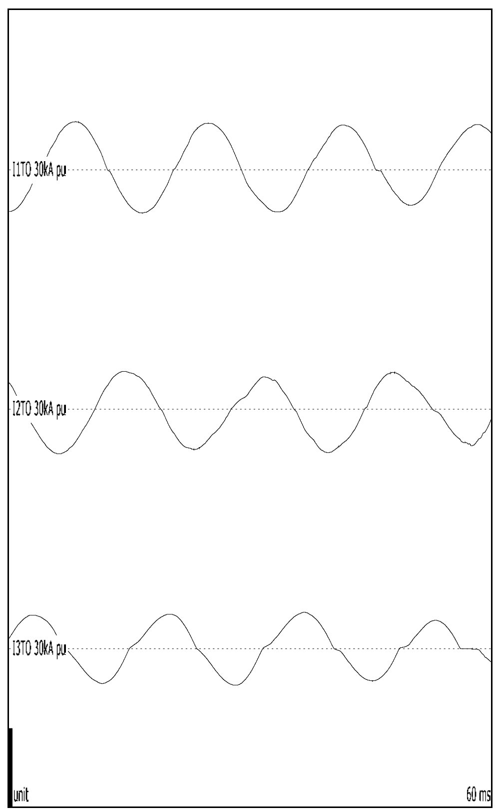
190828-7001

Remarks

-

Sample 2-13 (F) - 480 V, 13.5 kA





Test number: 190828-7001

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	282	282	282
Applied voltage, phase-to-phase	V_{RMS}	488		
Making current	kA_{peak}	24.7	28.4	-34.2
Current, a.c. component, beginning	kA_{RMS}	13.1	13.6	12.8
Current, a.c. component, middle	kA_{RMS}	8.32	9.92	7.61
Current, a.c. component, end	kA_{RMS}	9.46	10.4	8.55
Current, a.c. component, average	kA_{RMS}	10.3	9.95	9.26
Current, a.c. component, three-phase average	kA_{RMS}	9.84		
Duration	s	1.55	1.32	1.32
Arc energy	kJ	2119	1518	1732

Observations: Emission of flames and gas observed.

21.4 Condition / inspection after test

Cable connected from enclosure of switchgear to neutral of supply transformer was ejected during test.

22 SAMPLE 2-13 (G) - 600 V, 13.5 KA

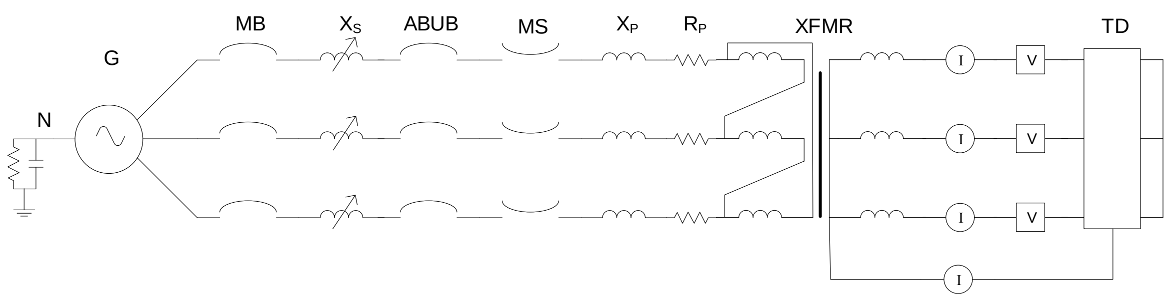
Standard and date

Standard	Client’s instructions
Test date	28 August 2019

22.1 Condition before test

Switchgear in same condition as after trial 190828-7001. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

22.2 Test circuit S07



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

Supply		
Power	MVA	14.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	616
Sym. Current	kA	13.5
Peak current	kA	35.6
Impedance	Ω	0.026

Remarks: -

22.3 Test results and oscillograms

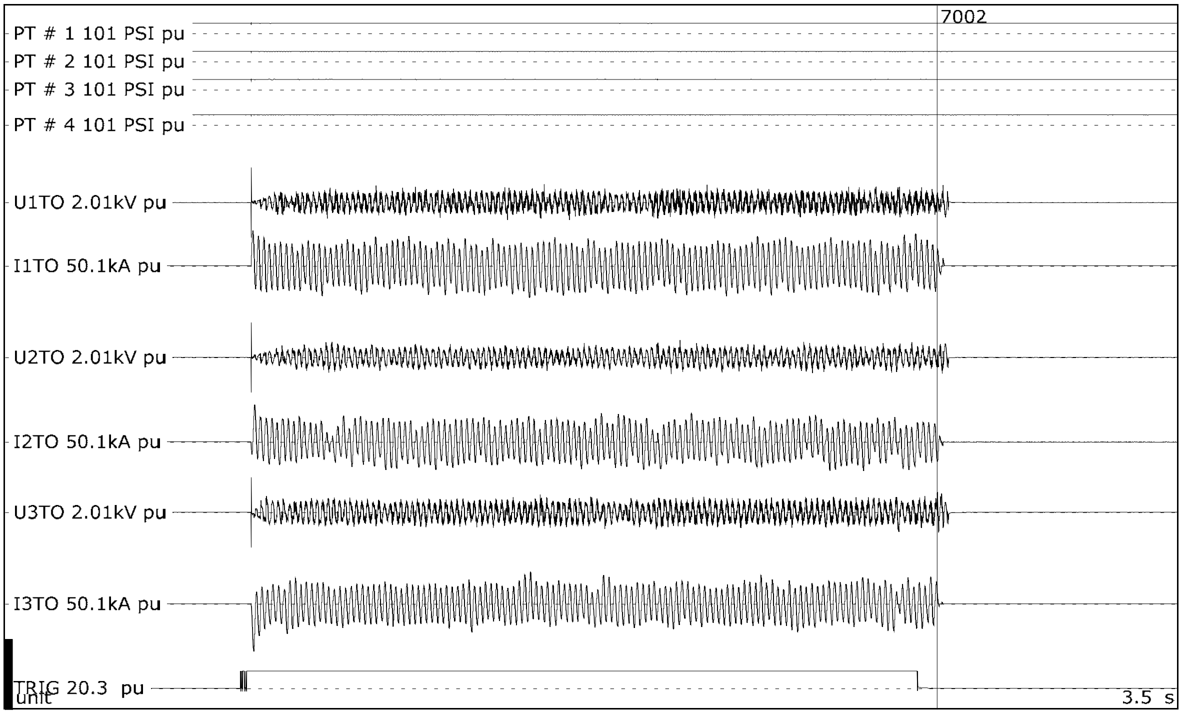
Overview of test numbers

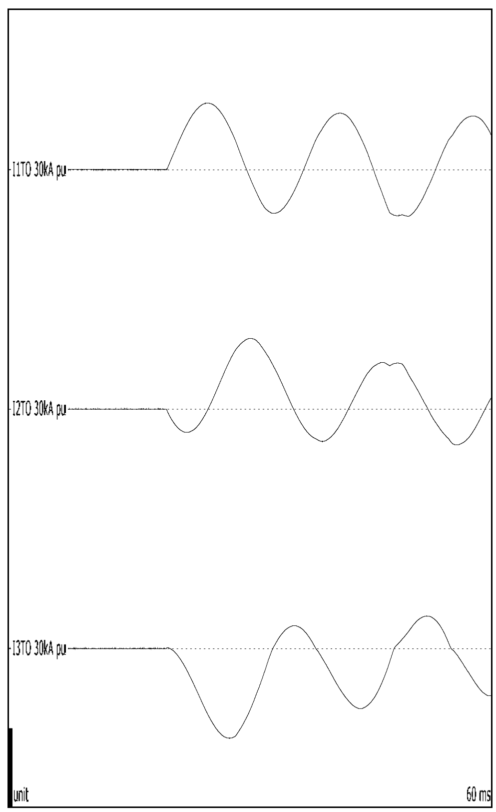
190828-7002

Remarks

-

Sample 2-13 (G) - 600 V, 13.5 kA





Test number: 190828-7002

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	356	356	356
Applied voltage, phase-to-phase	V_{RMS}		617	
Making current	kA_{peak}	25.1	26.6	-33.8
Current, a.c. component, beginning	kA_{RMS}	14.0	13.1	13.0
Current, a.c. component, middle	kA_{RMS}	9.62	12.1	9.18
Current, a.c. component, end	kA_{RMS}	12.1	8.87	11.1
Current, a.c. component, average	kA_{RMS}	12.3	10.8	11.0
Current, a.c. component, three-phase average	kA_{RMS}		11.4	
Duration	s	2.04	2.04	2.04
Arc energy	kJ	3525	3106	3646

Observations: Emission of flames and gas observed.

22.4 Condition / inspection after test

Switchgear burned, but otherwise structurally intact.

23 CHECKING THE PROSPECTIVE CURRENT

Standard and date

Standard	Client’s instructions
Test date	29 August 2019

23.1 Condition before test

Shorting bar connected at station terminals directly prior to test device.

23.2 Test results and oscillograms

Overview of test numbers

190829-7001 to 7004

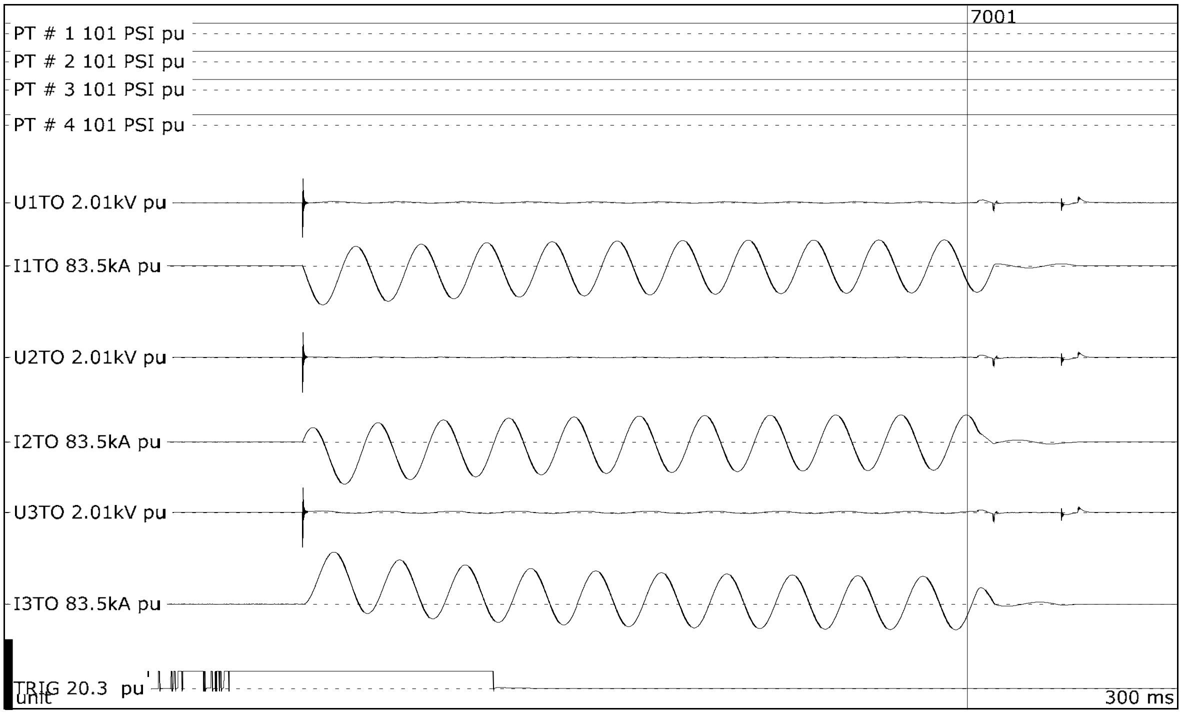
Remarks

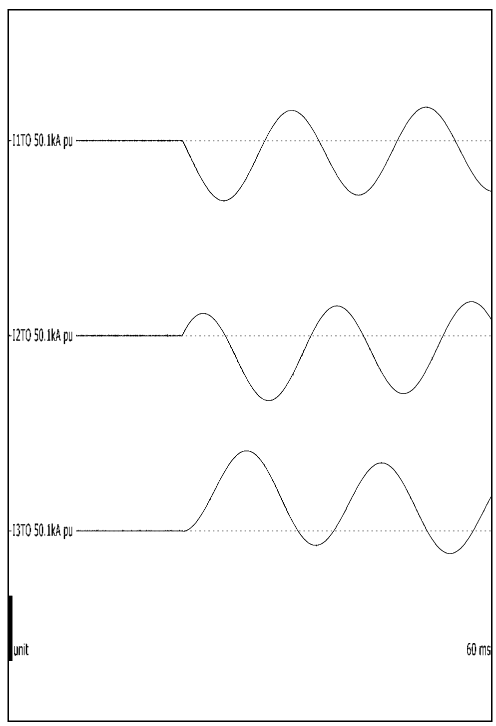
Prospective circuit parameters calibrated in this test duty:

190829-7001 and 190829-7002: 619 V, 25.0 kA, 63.3 kA peak.

190829-7003 and 190829-7004: 480 V, 25.6 kA, 64.5 kA peak.

Checking the prospective current



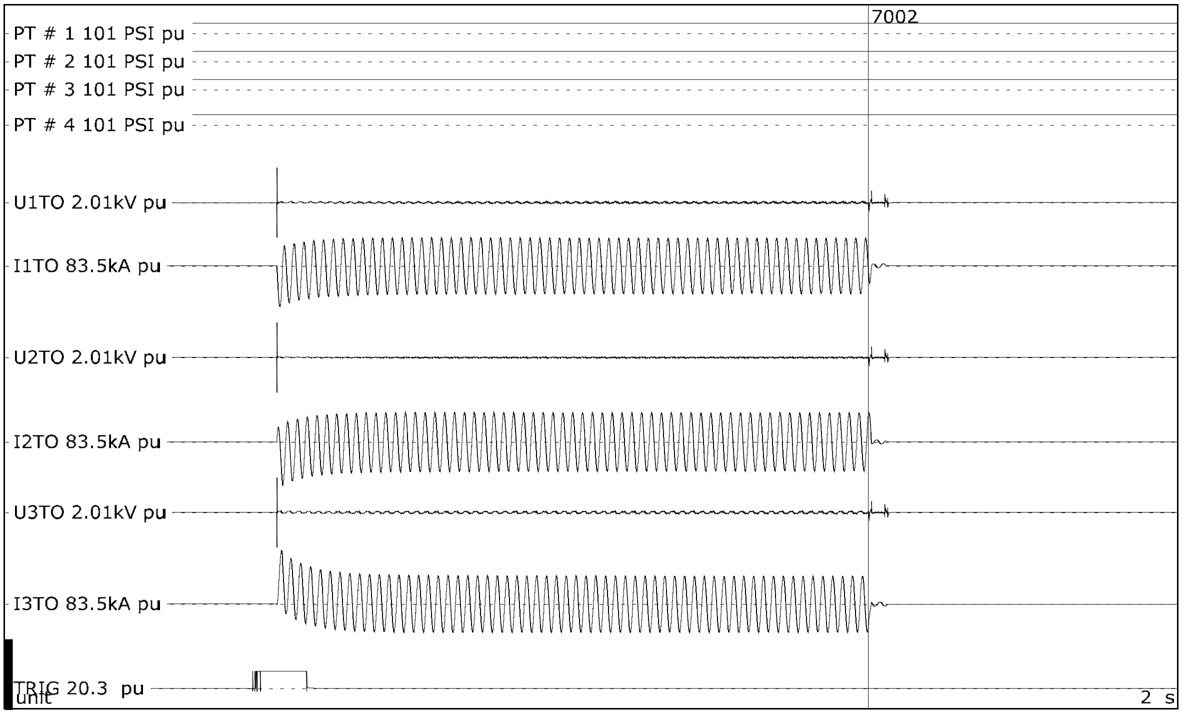


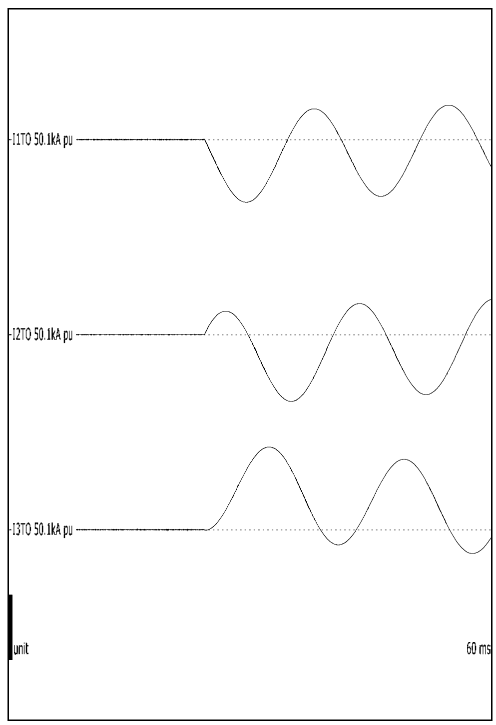
Test number: 190829-7001

Phase		A	B	C
Current	kApeak	-46.4	-50.1	61.5
Current, a.c. component	kARMS	23.8	24.8	24.1
Current, a.c. component, three-phase average	kARMS	24.2		
Duration, current	s	0.170	0.170	0.169

Observations: No visible disturbance.

Checking the prospective current



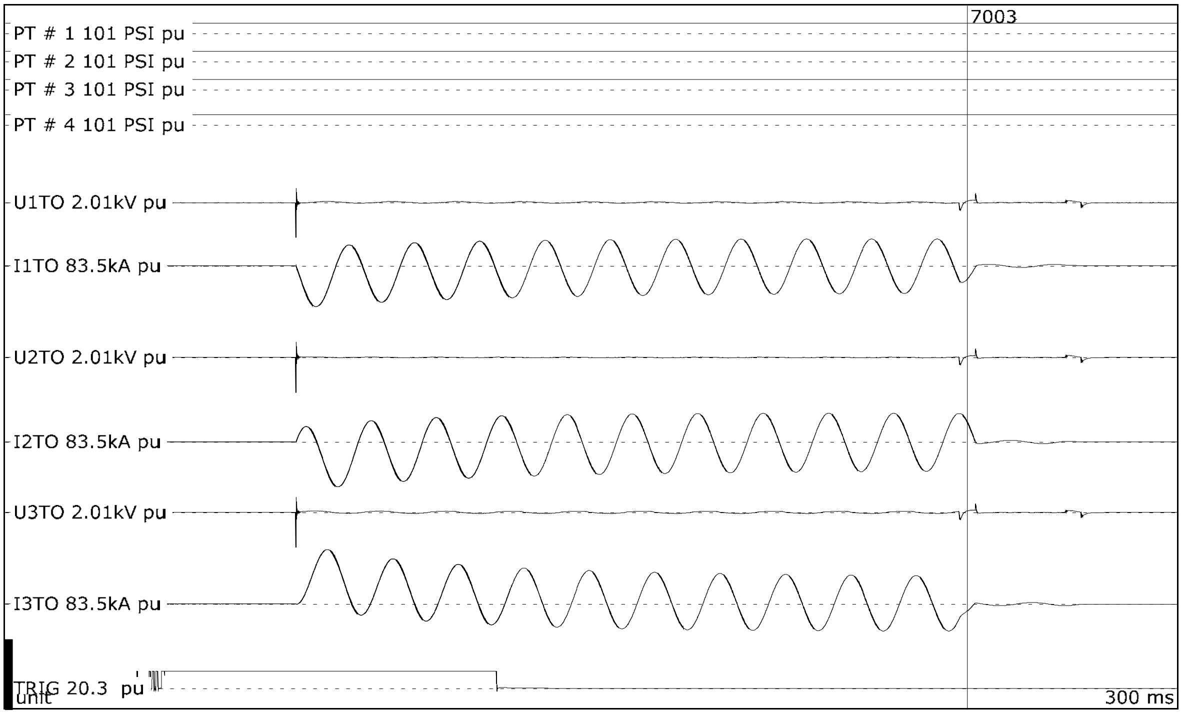


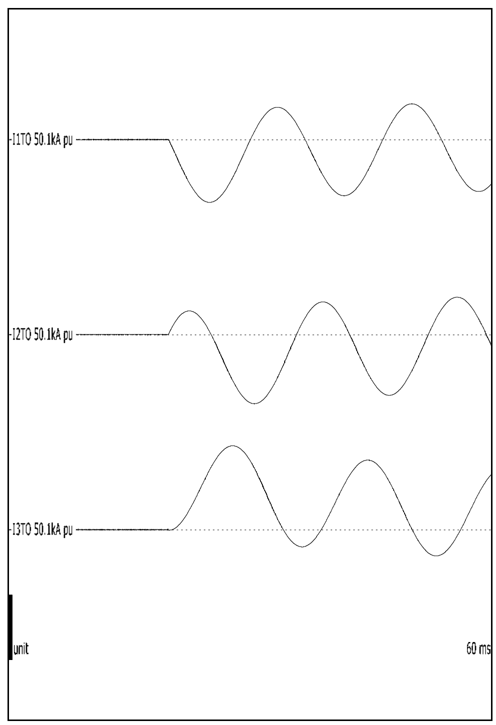
Test number: 190829-7002

Phase		A	B	C
Current	kA_{peak}	33.3	34.9	-33.7
Current, a.c. component	kA_{RMS}	24.6	25.6	25.0
Current, a.c. component, three-phase average	kA_{RMS}		25.1	
Duration, current	s	1.01	1.01	1.01

Observations: No visible disturbance. One second calibration to test super excitation.

Checking the prospective current



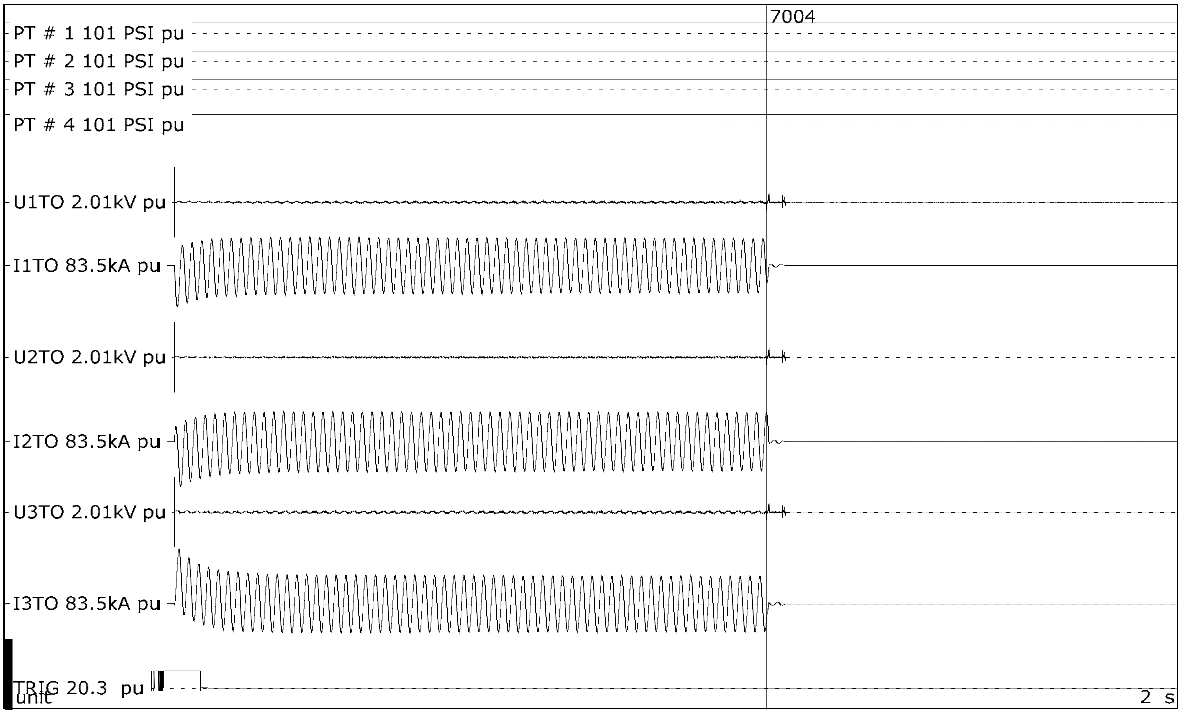


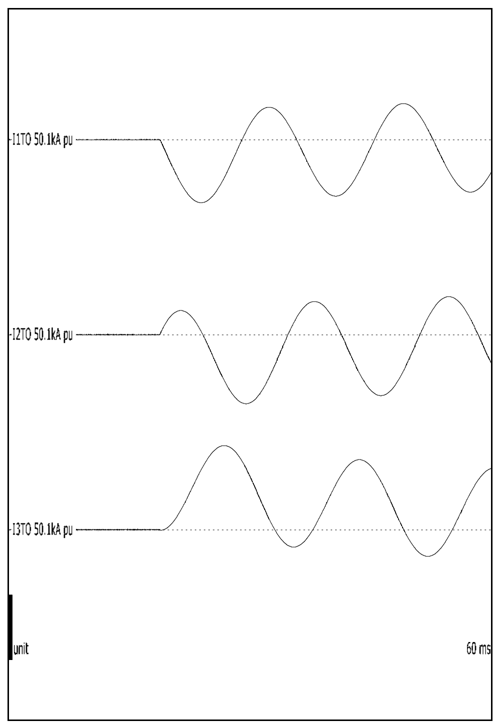
Test number: 190829-7003

Phase		A	B	C
Current	kA$_{peak}$	-48.4	-53.2	64.6
Current, a.c. component	kA$_{RMS}$	25.0	26.5	25.5
Current, a.c. component, three-phase average	kA$_{RMS}$	25.7		
Duration, current	s	0.171	0.172	0.170

Observations: No visible disturbance.

Checking the prospective current





Test number: 190829-7004

Phase		A	B	C
Current	kA_{peak}	33.0	-35.3	-33.7
Current, a.c. component	kA_{RMS}	24.7	26.2	25.0
Current, a.c. component, three-phase average	kA_{RMS}		25.3	
Duration, current	s	1.01	1.01	1.01

Observations: No visible disturbance. One second calibration to check super excitation.

24 SAMPLE 2-18 (A) - 480 V, 25 KA

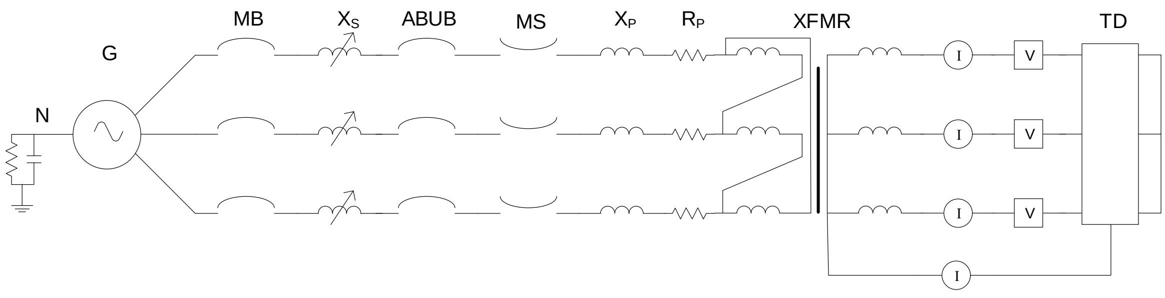
Standard and date

Standard	Client's instructions
Test date	29 August 2019

24.1 Condition before test

Switchgear new. Arc to be initiated by #10 AWG stranded wire.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

24.2 Test circuit S09



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

Supply		
Power	MVA	21.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	480
Sym. Current	kA	25.6
Peak current	kA	64.5
Impedance	Ω	0.011

Remarks: -

24.3 Test results and oscillograms

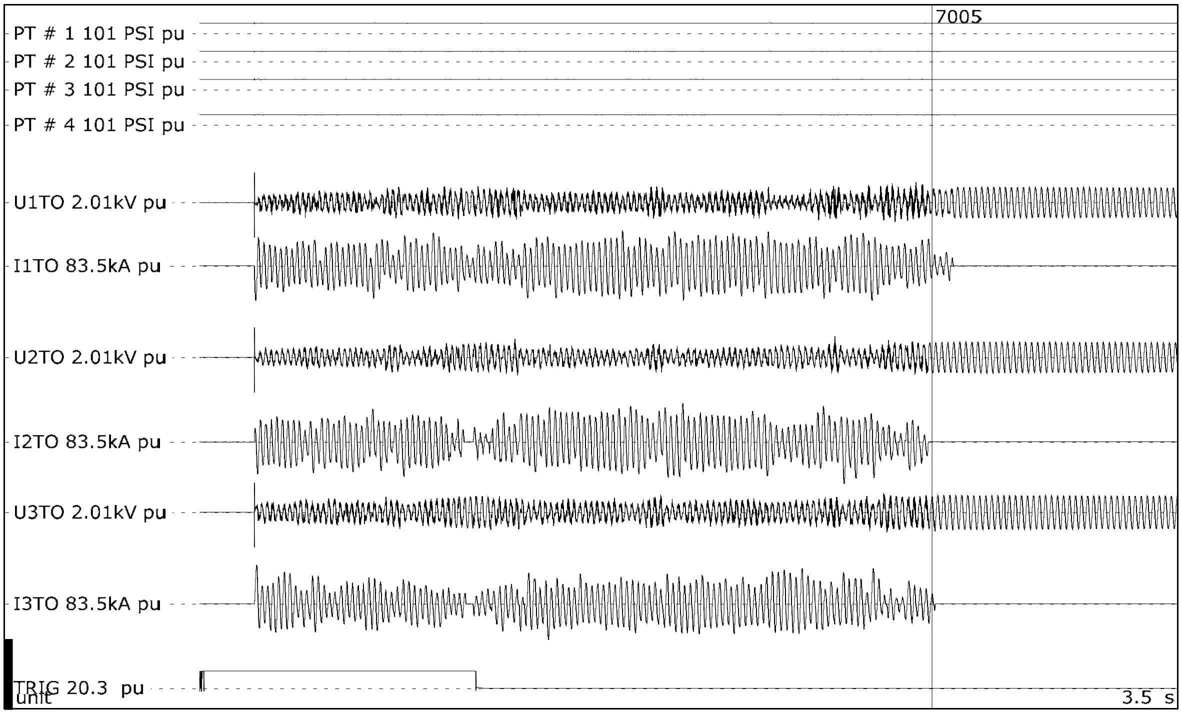
Overview of test numbers

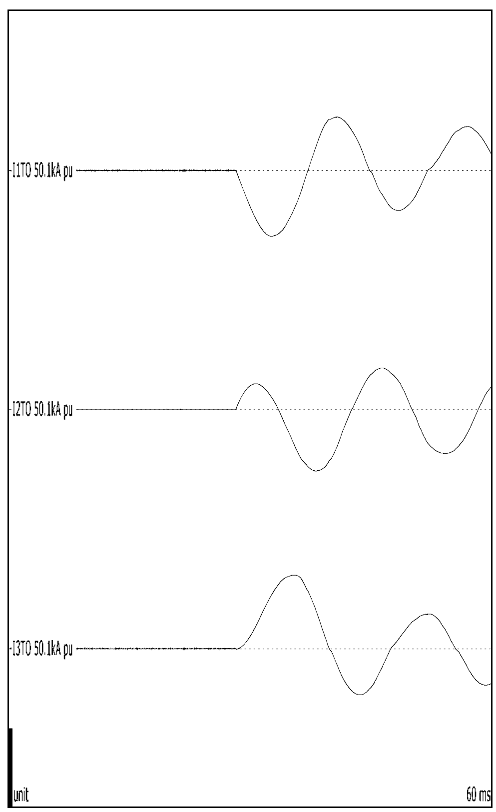
190829-7005

Remarks

-

Sample 2-18 (A) - 480 V, 25 kA





Test number: 190829-7005

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	277	277	277
Applied voltage, phase-to-phase	V_{RMS}	480		
Making current	kA_{peak}	-41.4	-38.5	46.2
Current, a.c. component, beginning	kA_{RMS}	23.5	21.0	22.4
Current, a.c. component, middle	kA_{RMS}	20.7	23.5	16.6
Current, a.c. component, end	kA_{RMS}	15.9	18.2	12.5
Current, a.c. component, average	kA_{RMS}	19.8	17.3	17.9
Current, a.c. component, three-phase average	kA_{RMS}	18.3		
Duration	s	2.02	2.02	2.02
Arc energy	kJ	5925	5509	5597

Observations: Emission of flames and gas observed.

24.4 Condition / inspection after test

Evidence of arcing and burning found within the switchgear. Exterior of switchgear mostly intact.

25 SAMPLE 2-18 (B) - 600 V, 25 KA

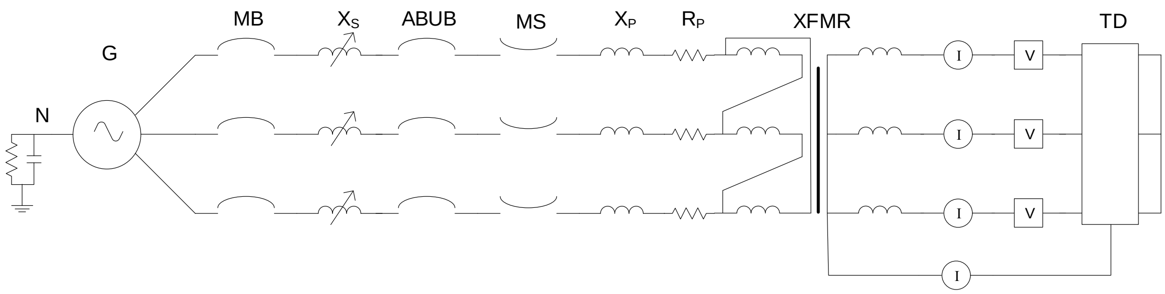
Standard and date

Standard	Client's instructions
Test date	29 August 2019

25.1 Condition before test

Switchgear in same condition as after trial 190829-7005. Arc to be initiated by two #10 AWG stranded wires.
Pressure transducers # 1 & 2 located on right side of switchgear (when facing the front of the gear).
Pressure transducers # 3 & 4 located on left side of switchgear (when facing the front of the gear).
Pressure transducers # 1 & 3 are 0-50 PSI transducers.
Pressure transducers # 2 & 4 are 0-30 PSI transducers.

25.2 Test circuit S08



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

Supply		
Power	MVA	26.8
Frequency	Hz	60
Phase(s)		3
Voltage	V	619
Sym. Current	kA	25.0
Peak current	kA	63.3
Impedance	Ω	0.014

Remarks: -

25.3 Test results and oscillograms

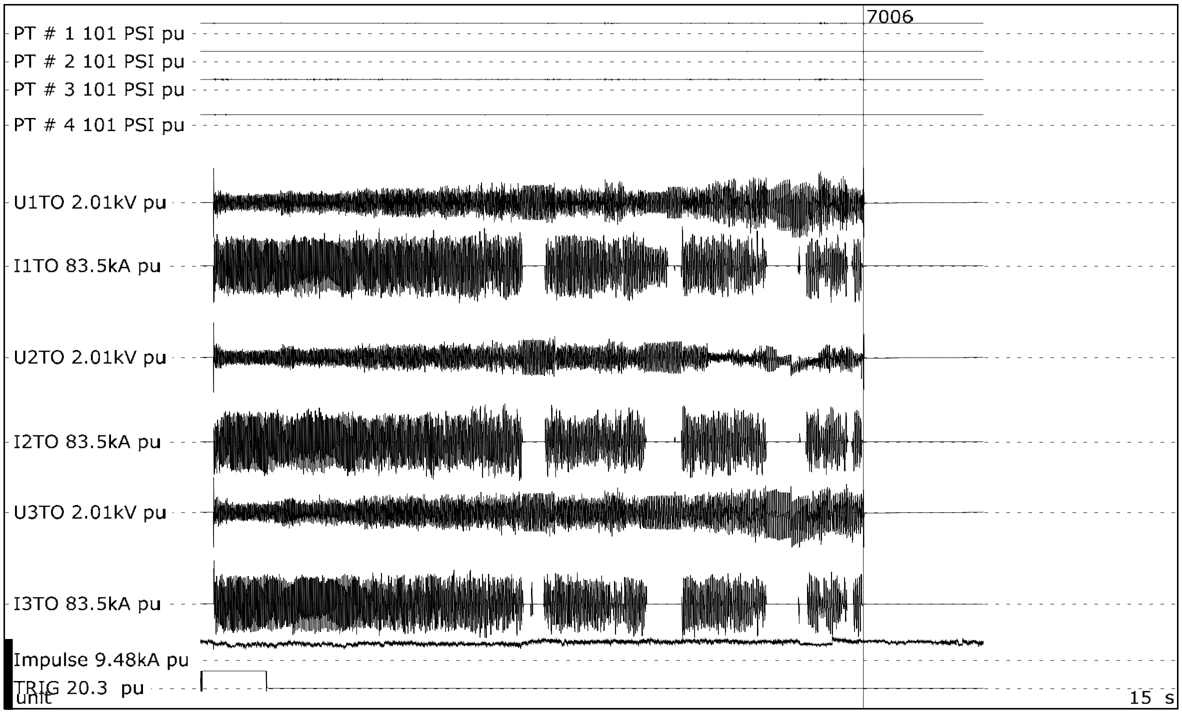
Overview of test numbers

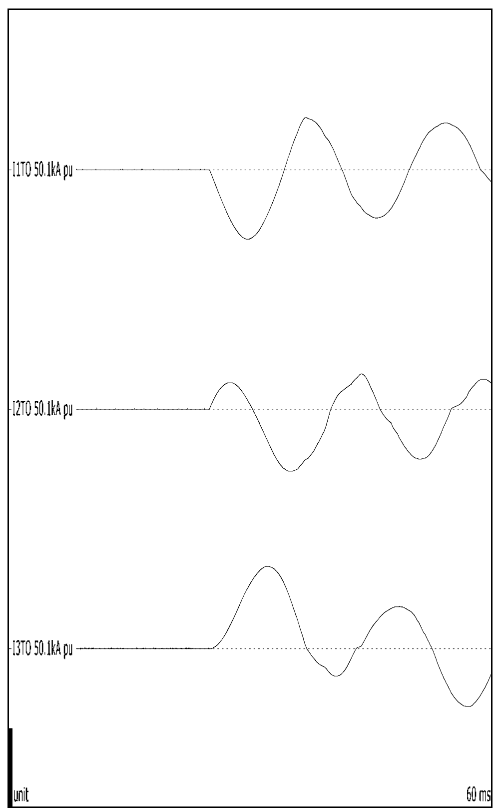
190829-7006

Remarks

-

Sample 2-18 (B) - 600 V, 25 kA





Test number: 190829-7006

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	357	357	357
Applied voltage, phase-to-phase	V_{RMS}	618		
Making current	kA_{peak}	35.4	-38.8	-32.4
Current, a.c. component, beginning	kA_{RMS}	22.6	20.9	22.0
Current, a.c. component, middle	kA_{RMS}	25.8	23.6	21.9
Current, a.c. component, end	kA_{RMS}	15.6	22.2	24.3
Current, a.c. component, average	kA_{RMS}	21.1	20.0	19.6
Current, a.c. component, three-phase average	kA_{RMS}	20.2		
Duration	s	8.30	8.30	8.30
Arc energy	MJ	26.1	19.3	27.1

Observations: Emission of flames and gas observed.

25.4 Condition / inspection after test

Switchgear heavily damaged.

26 OPEN BOX TEST # 10 (OB02) - 1000 V, 15 KA

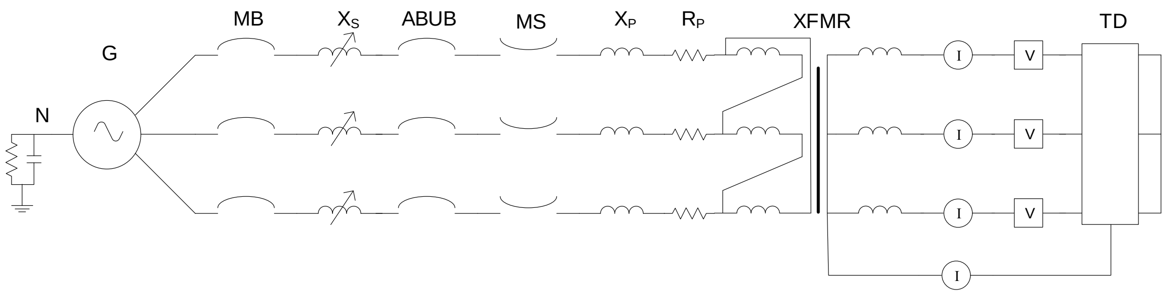
Standard and date

Standard	Client’s instructions
Test date	30 August 2019

26.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rods. Test duration is 2 seconds.

26.2 Test circuit S03



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks: -

26.3 Test results and oscillograms

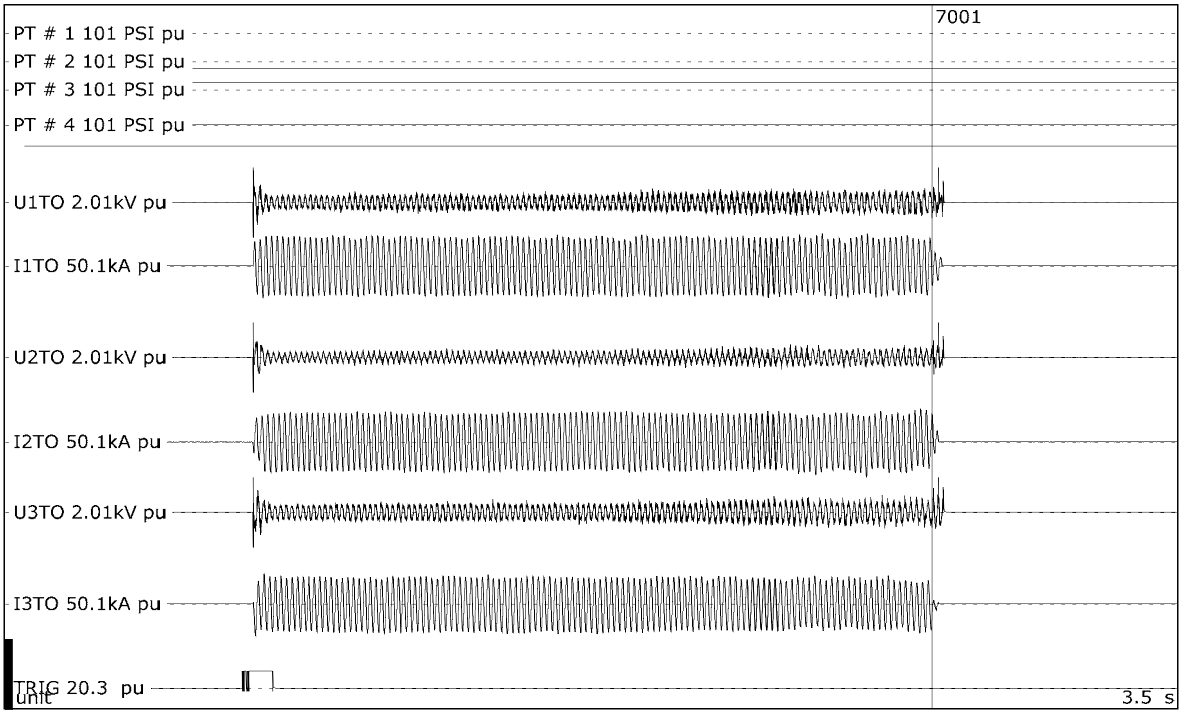
Overview of test numbers

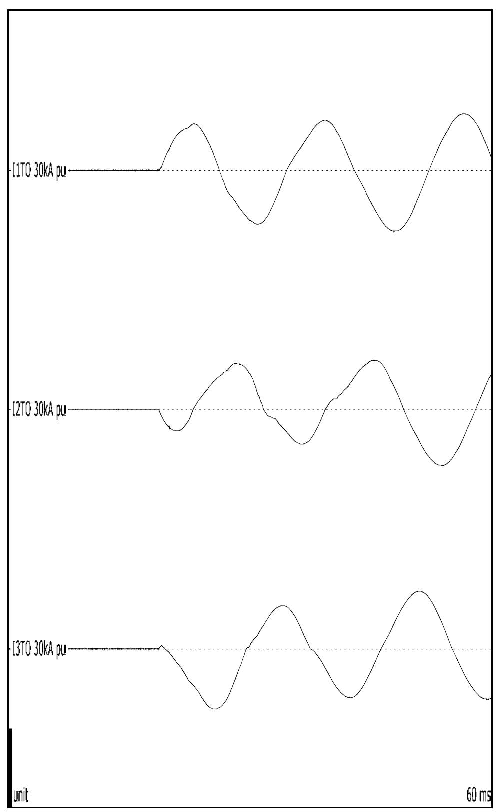
190830-7001

Remarks

-

Open Box Test # 10 - 1000 V, 15 kA





Test number: **190830-7001**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	-22.9	18.6	-22.7
Current, a.c. component, beginning	kA_{RMS}	14.6	14.5	13.7
Current, a.c. component, middle	kA_{RMS}	14.7	14.6	13.9
Current, a.c. component, end	kA_{RMS}	13.7	14.2	12.4
Current, a.c. component, average	kA_{RMS}	14.4	13.7	13.5
Current, a.c. component, three-phase average	kA_{RMS}	13.9		
Duration	s	2.02	2.02	2.02
Arc energy	kJ	4395	3277	4317

Observations: Emission of flames and gas observed.

26.4 Condition / inspection after test

Hole burned through bottom of box. Sides and rear of box heavily burned, but not completely through.

27 OPEN BOX TEST # 11 (OB03) - 1000 V, 15 KA

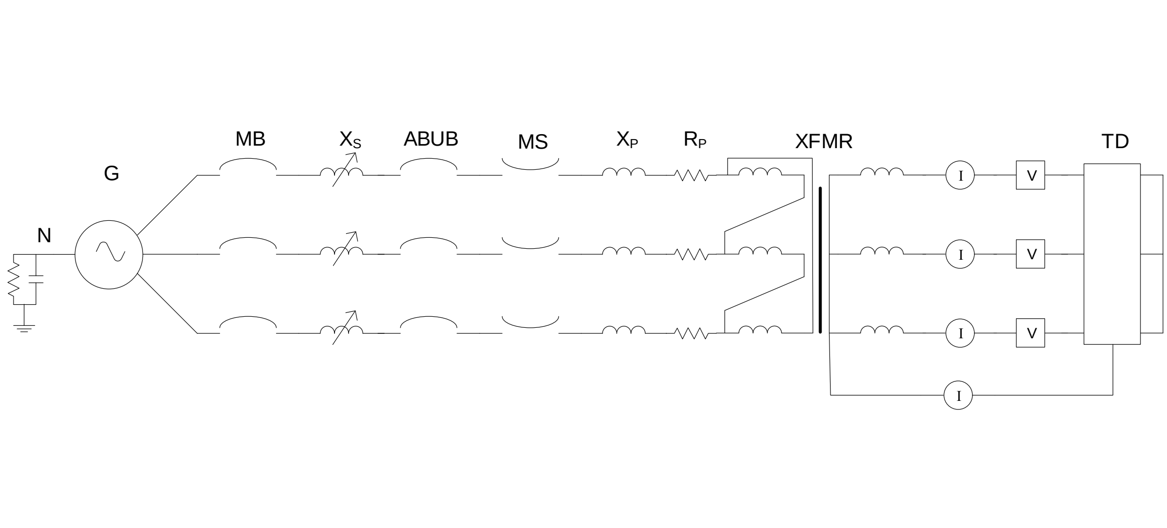
Standard and date

Standard	Client's instructions
Test date	30 August 2019

27.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rods. Test duration is 3 seconds.

27.2 Test circuit S03



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks: -

27.3 Test results and oscillograms

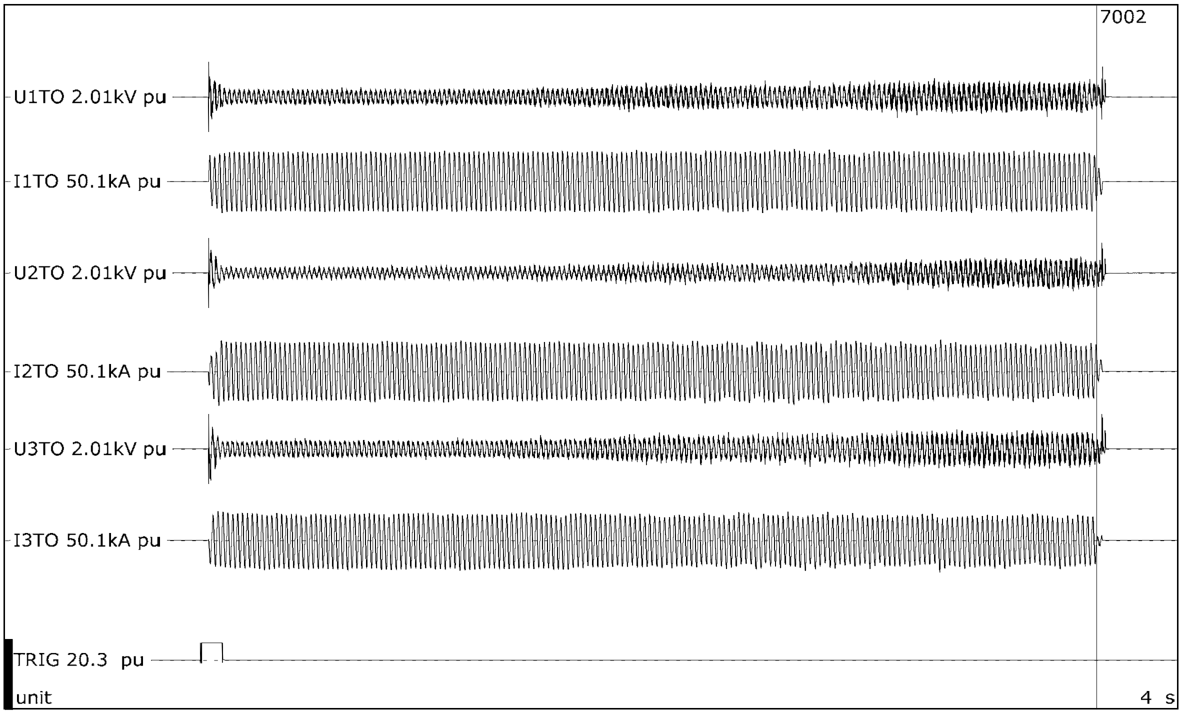
Overview of test numbers

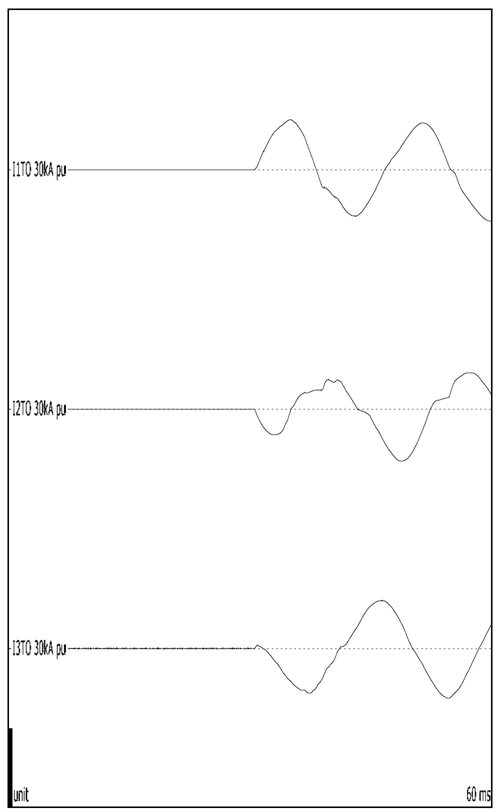
190830-7002

Remarks

-

Open Box Test # 11 (OB03) - 1000 V, 15 kA





Test number: 190830-7002

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	-19.4	-19.6	20.9
Current, a.c. component, beginning	kA_{RMS}	14.7	14.6	13.4
Current, a.c. component, middle	kA_{RMS}	14.9	14.2	12.4
Current, a.c. component, end	kA_{RMS}	14.3	13.0	12.4
Current, a.c. component, average	kA_{RMS}	14.4	13.5	13.1
Current, a.c. component, three-phase average	kA_{RMS}	13.6		
Duration	s	3.03	3.03	3.02
Arc energy	kJ	7347	5517	7022

Observations: Emission of flames and gas observed.

27.4 Condition / inspection after test

Bottom of box completely burned through. Sides of box towards bottom of box also burned through.

28 OPEN BOX TEST # 12 (OB04) - 1000 V, 30 KA

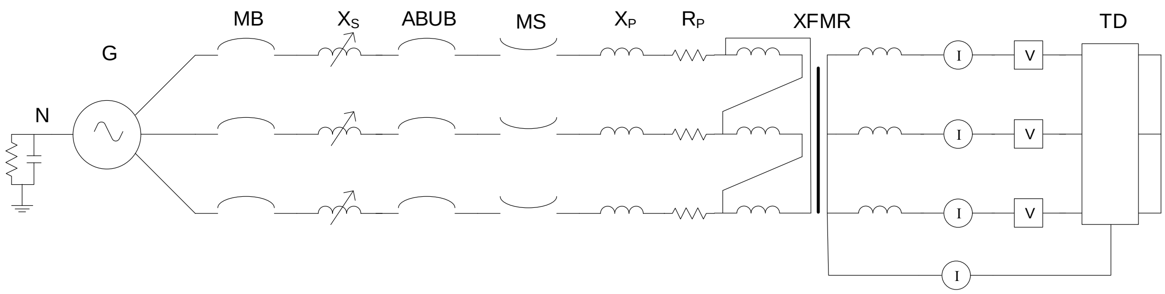
Standard and date

Standard	Client’s instructions
Test date	30 August 2019

28.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rods. Test duration is 1 seconds.

28.2 Test circuit S04



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

Supply		
Power	MVA	55.3
Frequency	Hz	60
Phase(s)		3
Voltage	V	1064
Sym. Current	kA	30
Peak current	kA	79.1
Impedance	Ω	0.020

Remarks: -

28.3 Test results and oscillograms

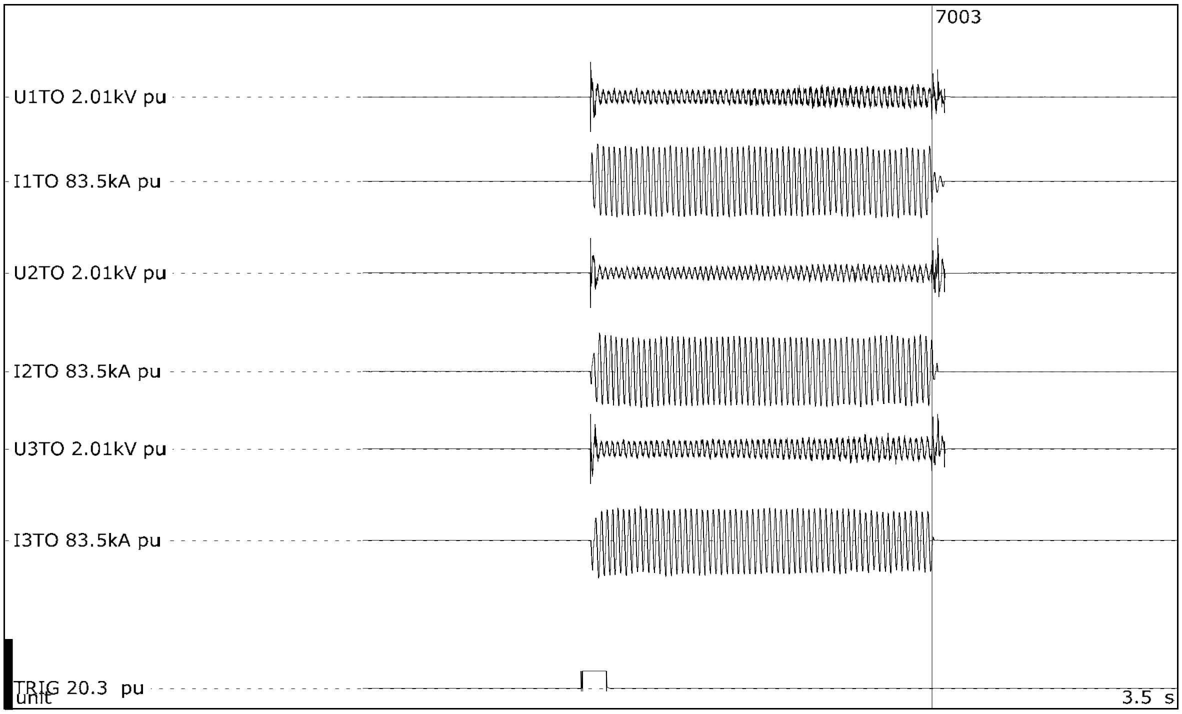
Overview of test numbers

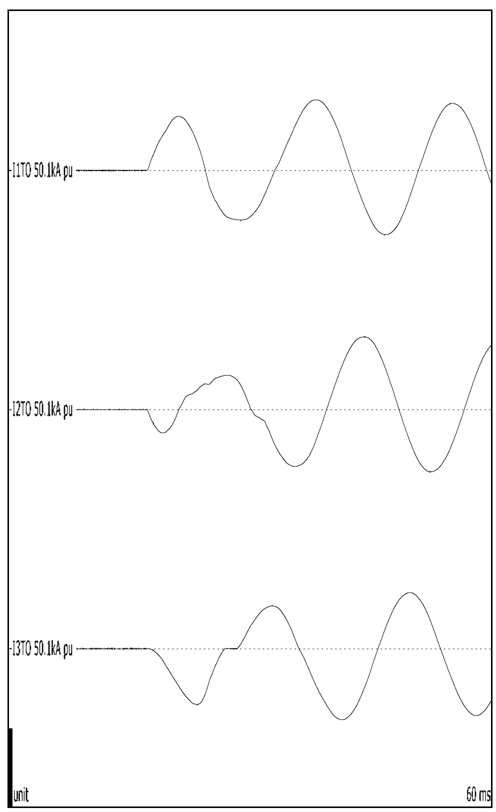
190830-7003

Remarks

-

Open Box Test # 12 - 1000 V, 30 kA





Test number: **190830-7003**

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	614	614	614
Applied voltage, phase-to-phase	V_{RMS}	1063		
Making current	kA_{peak}	44.4	45.7	-44.6
Current, a.c. component, beginning	kA_{RMS}	29.2	28.9	28.1
Current, a.c. component, middle	kA_{RMS}	29.1	28.5	27.0
Current, a.c. component, end	kA_{RMS}	28.0	28.5	25.1
Current, a.c. component, average	kA_{RMS}	28.1	26.9	26.3
Current, a.c. component, three-phase average	kA_{RMS}	27.1		
Duration	s	1.02	1.02	1.02
Arc energy	kJ	4311	3419	4598

Observations: Emission of flames and gas observed.

28.4 Condition / inspection after test

Small hole burned through bottom of box. Sides of box heavily burned, but not completely through.

29 OPEN BOX TEST # 13 (OB16) - SINGLE PHASE INVESTIGATION

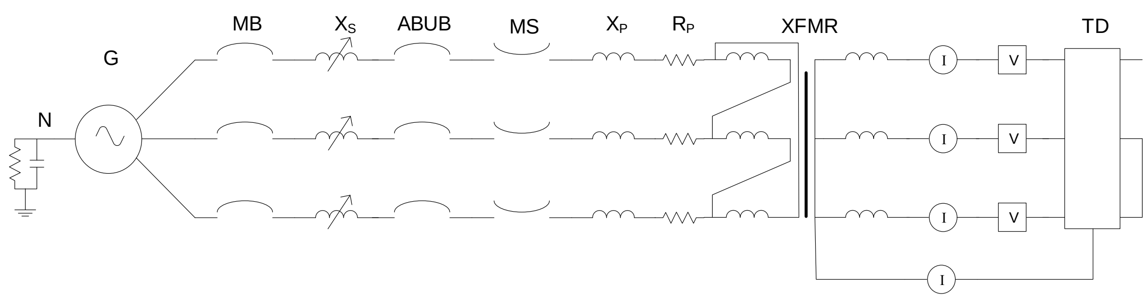
Standard and date

Standard	Client’s instructions
Test date	30 August 2019

29.1 Condition before test

Test box new. Copper rods new. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rods on A & B phase only. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to third phase.

29.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks:	Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

29.3 Test results and oscillograms

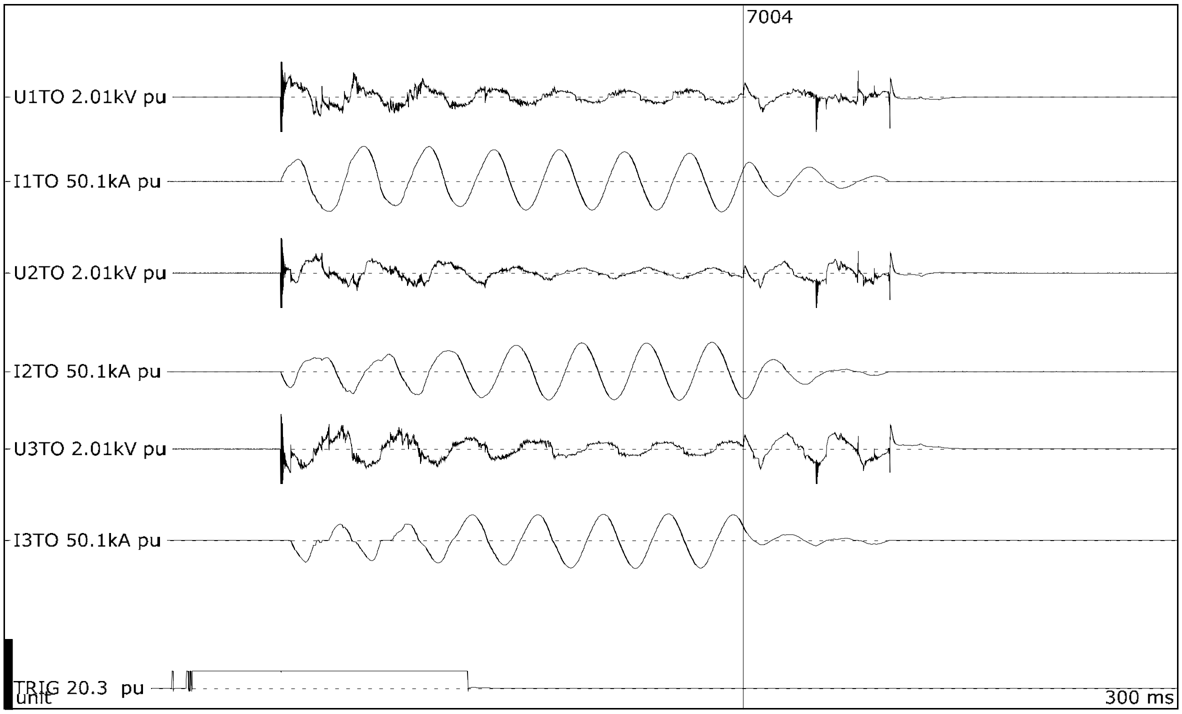
Overview of test numbers

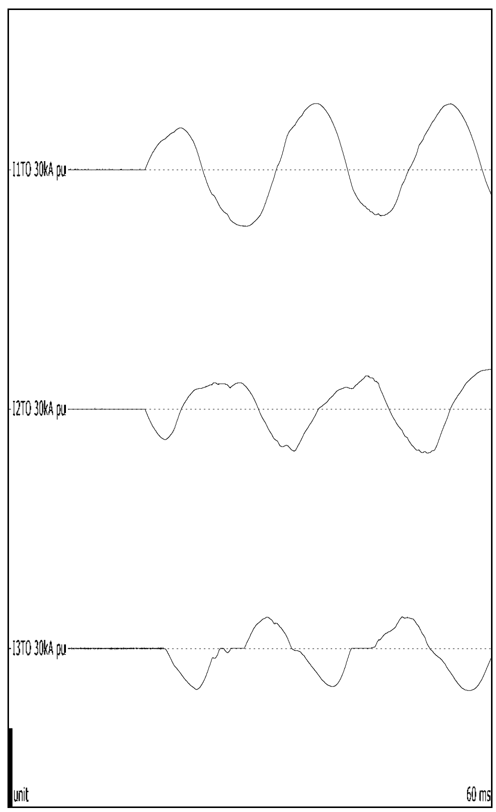
190830-7004

Remarks

-

Open Box Test # 13 - Single Phase Investigation





Test number: 190830-7004

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	24.9	-15.7	-15.3
Current, a.c. component, beginning	kA_{RMS}	16.0	9.35	8.47
Current, a.c. component, middle	kA_{RMS}	15.2	14.1	13.4
Current, a.c. component, end	kA_{RMS}	15.2	14.1	13.4
Current, a.c. component, average	kA_{RMS}	14.9	11.1	11.7
Current, a.c. component, three-phase average	kA_{RMS}	12.6		
Duration	s	0.118	0.118	0.116
Arc energy	kJ	296	186	254

Observations: Emission of flames and gas observed. Arc propagation time is approximately 2.52 ms.

29.4 Condition / inspection after test

Minimal damage to test box observed.

30 OPEN BOX TEST # 14 (OB12(A)) - SINGLE PHASE INVESTIGATION

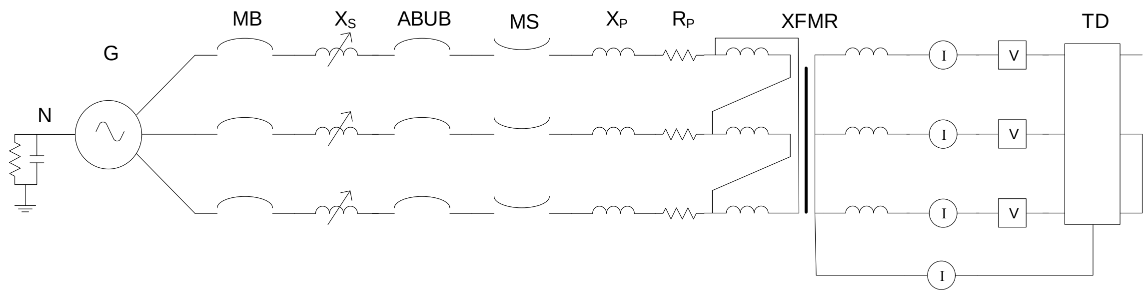
Standard and date

Standard	Client's instructions
Test date	30 August 2019

30.1 Condition before test

Test box in same condition as after trial 190830-7004. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rod on C-phase & enclosure of box. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to other two phases.

30.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks:	Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

30.3 Test results and oscillograms

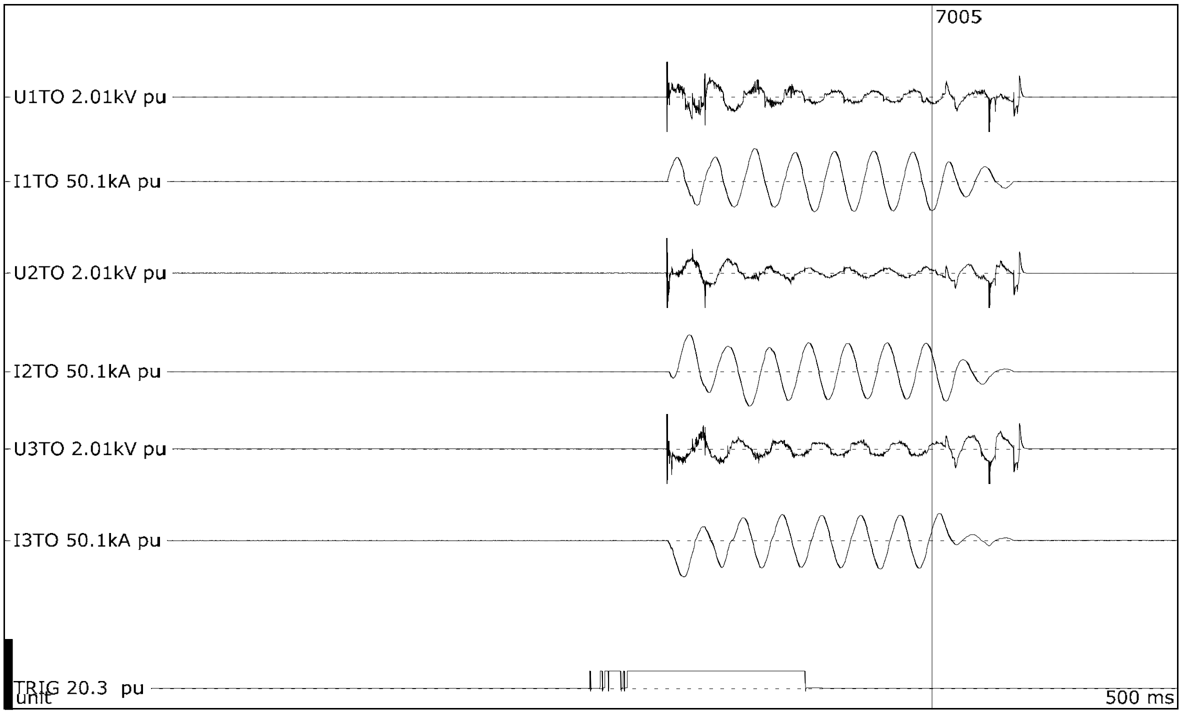
Overview of test numbers

190830-7005

Remarks

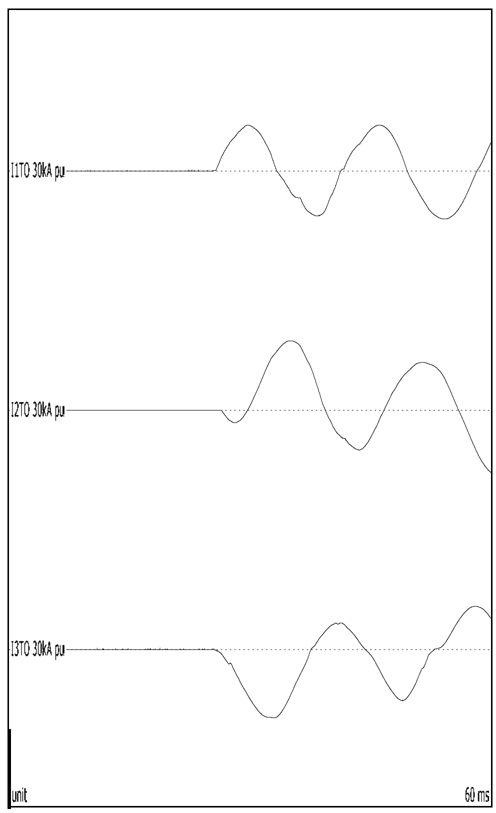
-

Open Box Test # 14 - Single Phase Investigation



Test number: 190830-7005

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	-18.2	26.1	-25.8
Current, a.c. component, beginning	kA_{RMS}	12.1	12.5	11.4
Current, a.c. component, middle	kA_{RMS}	15.1	14.2	13.1
Current, a.c. component, end	kA_{RMS}	15.1	14.2	13.1
Current, a.c. component, average	kA_{RMS}	14.0	13.7	12.7
Current, a.c. component, three-phase average	kA_{RMS}	13.5		
Duration	s	0.113	0.112	0.113
Arc energy	kJ	267	206	230



Observations: Emission of flames and gas observed. Arc propagation time was approximately 400 us.

30.4 Condition / inspection after test

Minimal damage to test box observed.

31 OPEN BOX TEST # 15 (OB15) - SINGLE PHASE INVESTIGATION

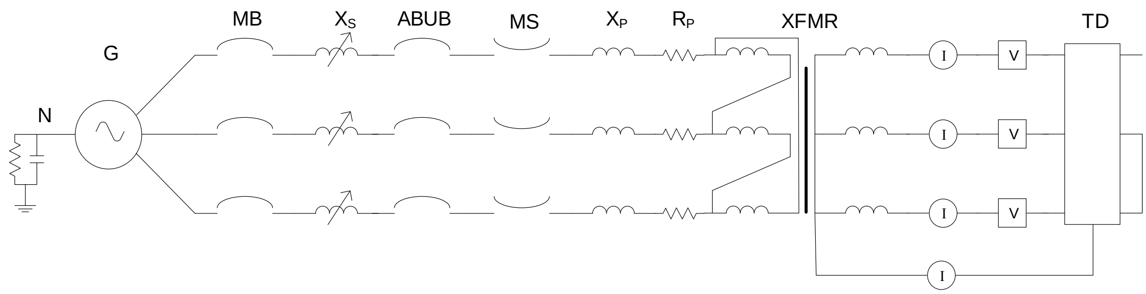
Standard and date

Standard	Client's instructions
Test date	30 August 2019

31.1 Condition before test

Test box in same condition as after trial 190830-7005. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rod on B-phase & enclosure of box. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to other two phases.

31.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks:	Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

31.3 Test results and oscillograms

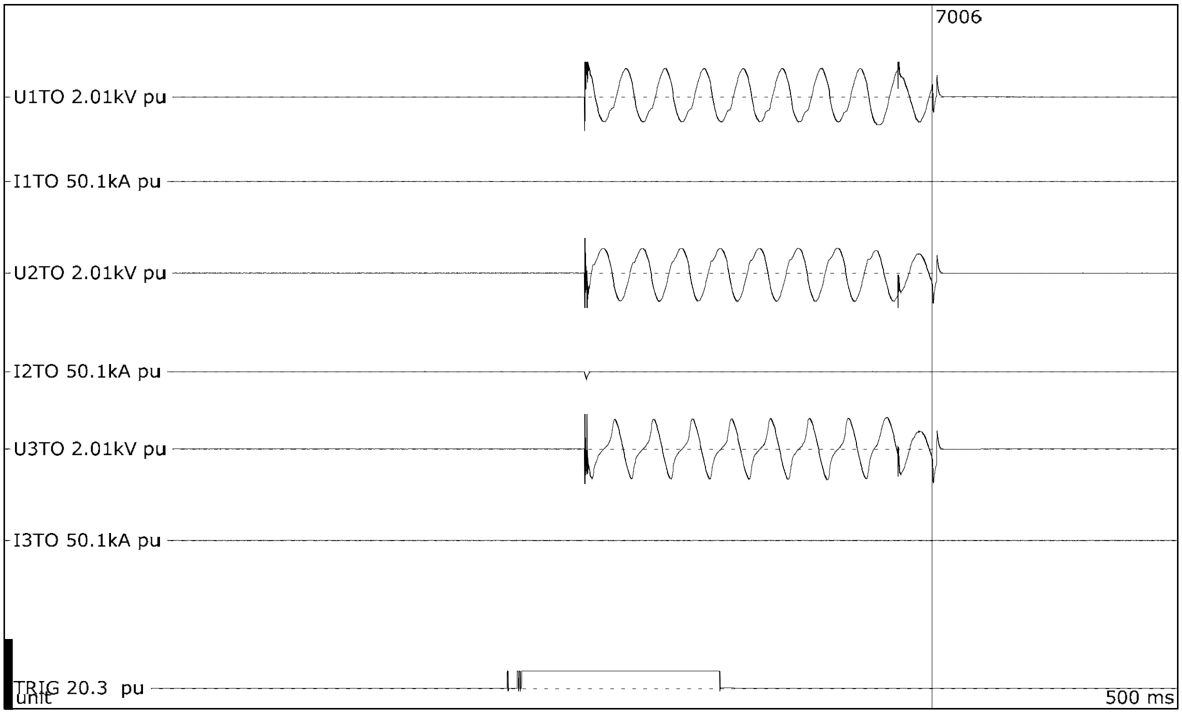
Overview of test numbers

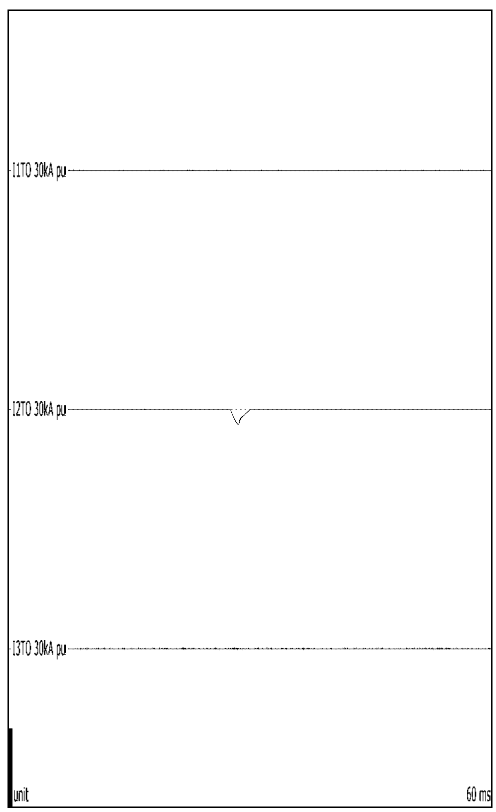
190830-7006

Remarks

-

Open Box Test # 15 - Single Phase Investigation





Test number: 190830-7006

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}		1010	
Making current	kA_{peak}	-	-5.51	-
Current, a.c. component, beginning	kA_{RMS}	-	0.974	-
Current, a.c. component, middle	kA_{RMS}	-	0.000	-
Current, a.c. component, end	kA_{RMS}	0.000	0.000	0.000
Current, a.c. component, average	kA_{RMS}	-	-	-
Current, a.c. component, three-phase average	kA_{RMS}		-	
Duration	s	-	0.148	-
Arc energy	kJ		-	

Observations: Small flash observed. Arc did not propagate to other phases.

31.4 Condition / inspection after test

Arc failed to propagate to other phases.

32 OPEN BOX TEST # 16 (OB14) - SINGLE PHASE INVESTIGATION

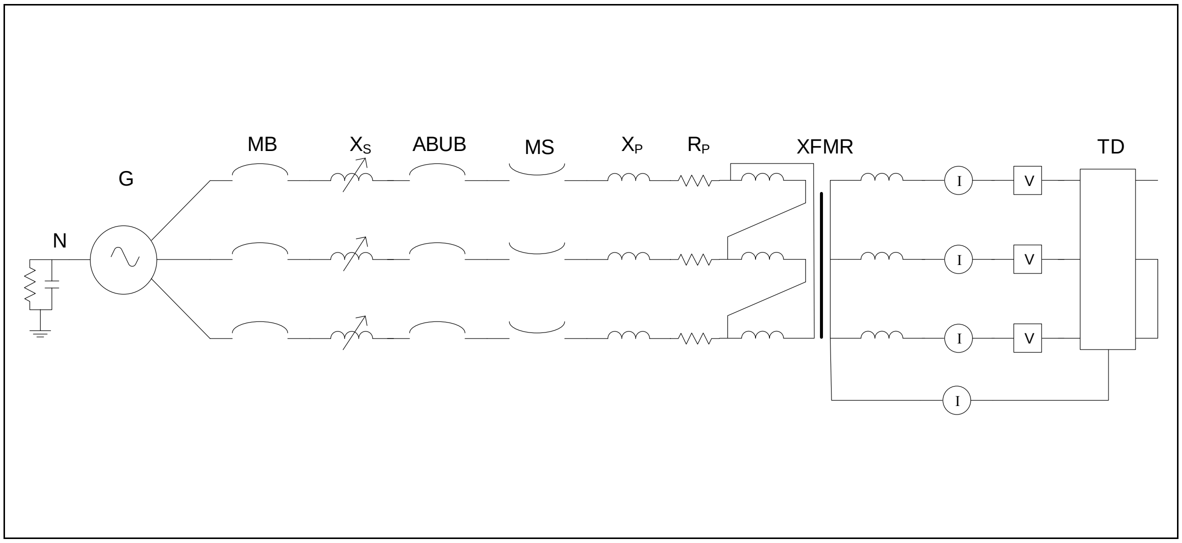
Standard and date

Standard	Client’s instructions
Test date	30 August 2019

32.1 Condition before test

Test box in same condition as after trial 190830-7006. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter aluminum rod on A-phase & enclosure of box. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to other two phases.

32.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks:	Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

32.3 Test results and oscillograms

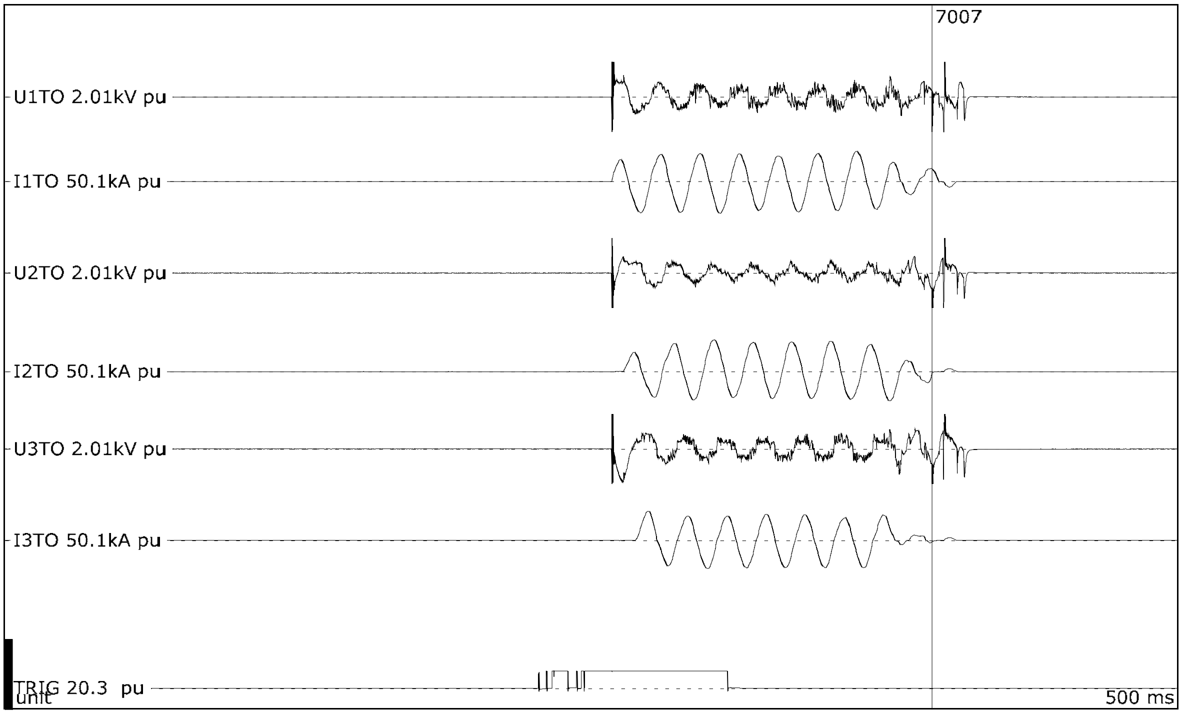
Overview of test numbers

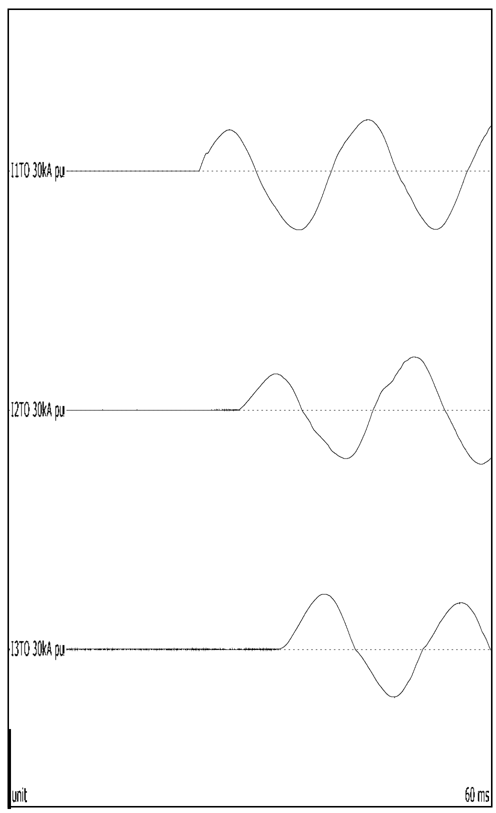
190830-7007

Remarks

-

Open Box Test # 16 - Single Phase Investigation





Test number: 190830-7007

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	-22.3	-20.3	20.8
Current, a.c. component, beginning	kA_{RMS}	14.0	12.4	13.1
Current, a.c. component, middle	kA_{RMS}	14.4	14.3	13.4
Current, a.c. component, end	kA_{RMS}	14.5	14.5	13.0
Current, a.c. component, average	kA_{RMS}	14.4	13.9	13.0
Current, a.c. component, three-phase average	kA_{RMS}	13.8		
Duration	s	0.137	0.132	0.126
Arc energy	kJ	373	257	300

Observations: Emission of flames and gas observed. Arc propagated to B-phase in approximately 4.8 ms. Arc propagated to C-phase in approximately 10 ms.

32.4 Condition / inspection after test

Minimal damage to test box observed.

33 OPEN BOX TEST # 17 (OB12(B) & OB12(C)) - SINGLE PHASE INVESTIGATION

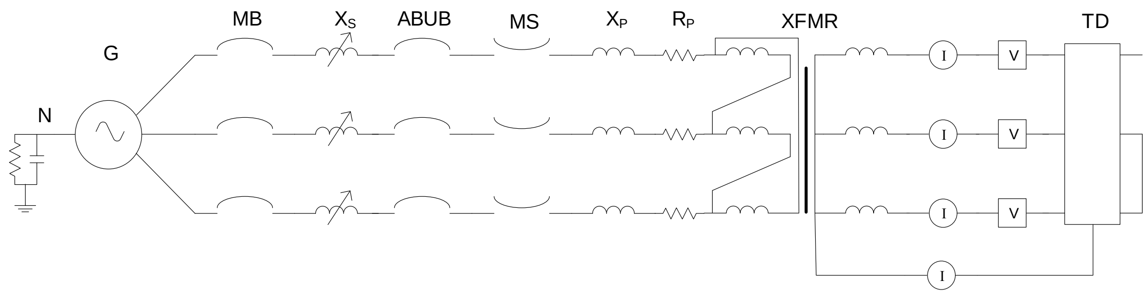
Standard and date

Standard	Client's instructions
Test date	30 August 2019

33.1 Condition before test

Test box in same condition as after trial 190830-7007. Arc to be initiated by #24 AWG wire. Arc wire connected to 1" diameter copper rod on C-phase & enclosure of box. Test duration is 100 milliseconds. Purpose of the test is to measure how long it takes for arc to propagate to other two phases.

33.2 Test circuit S05



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

Supply		
Power	MVA	26.2
Frequency	Hz	60
Phase(s)		3
Voltage	V	1009
Sym. Current	kA	15
Peak current	kA	40.4
Impedance	Ω	0.014

Remarks: Test conducted with arc wire only between two phases. Supply table above shows the available 3-phase circuit when arc propagated from 1-phase arc to 3-phase arc.

33.3 Test results and oscillograms

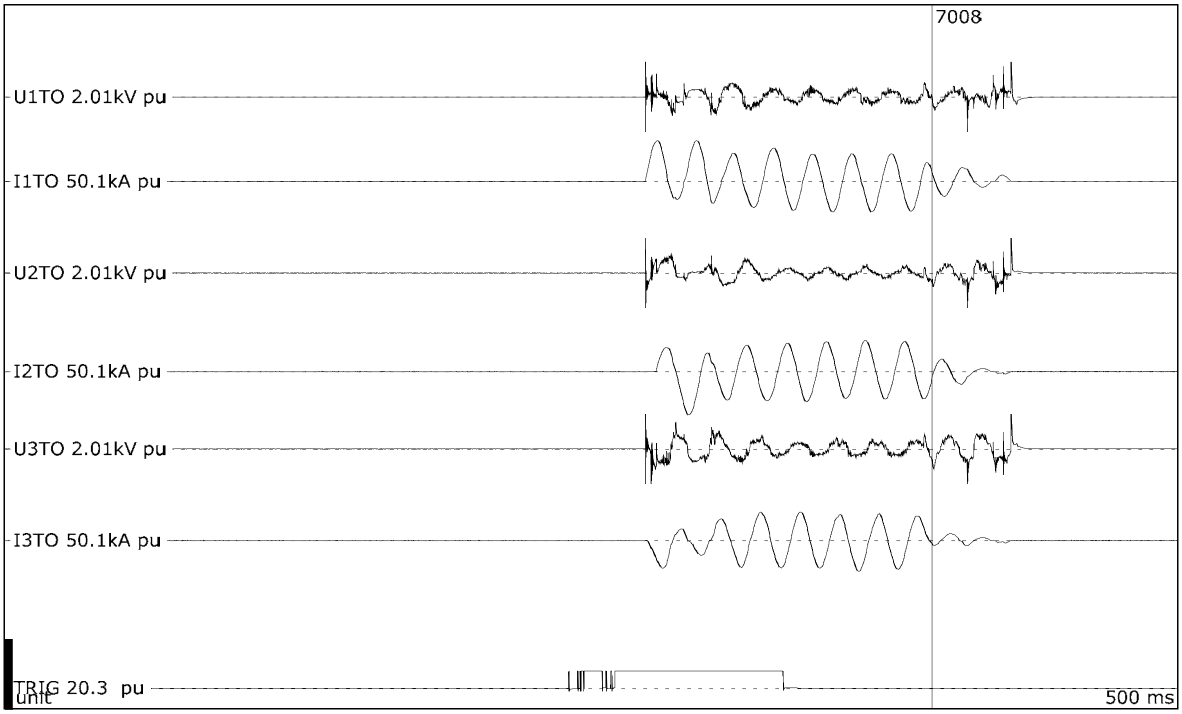
Overview of test numbers

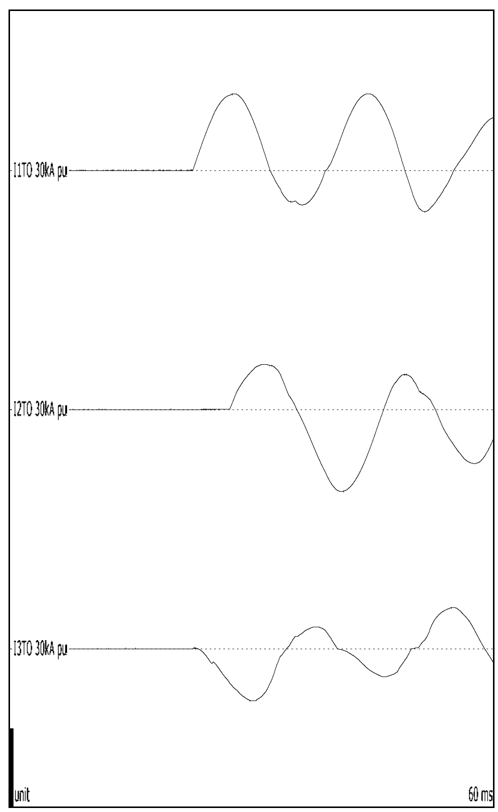
190830-7008, 7009

Remarks

-

Open Box Test # 17 - Single Phase Investigation



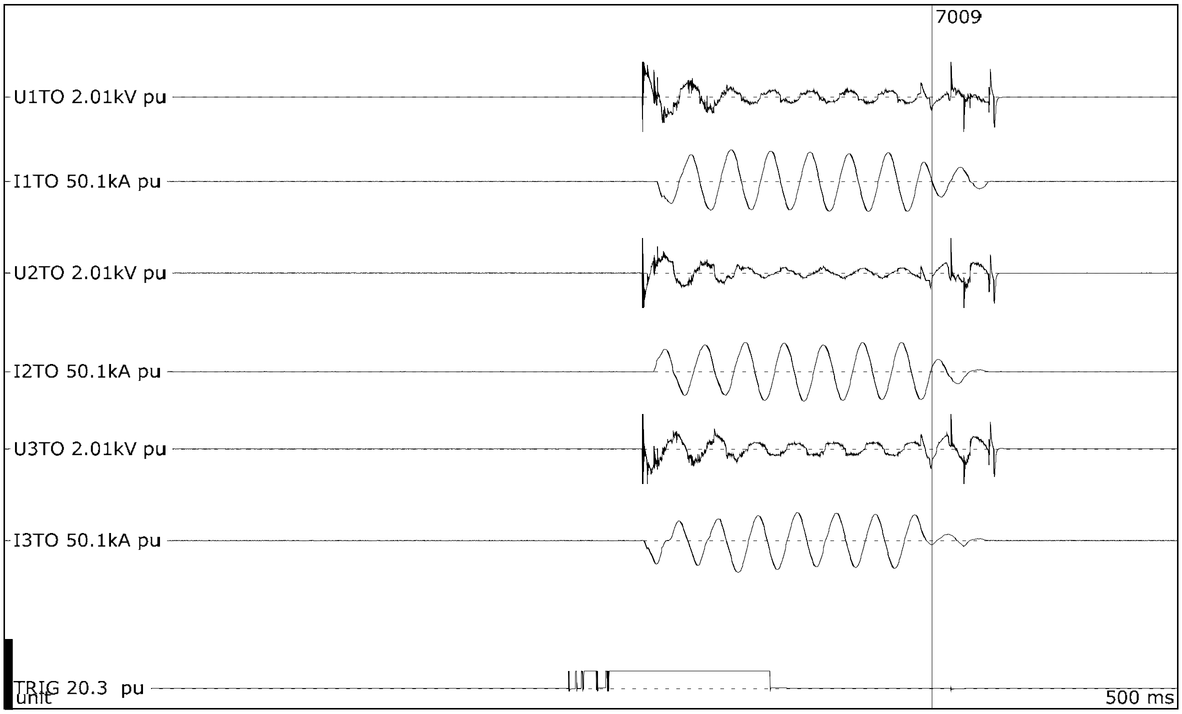


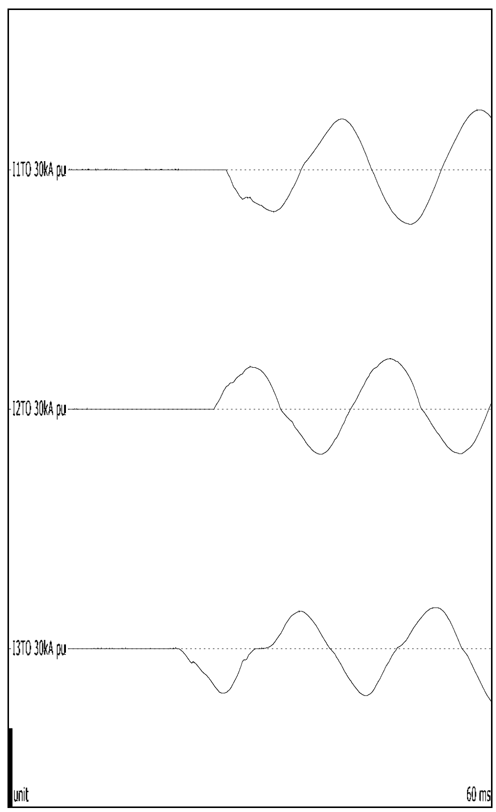
Test number: 190830-7008

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	28.9	-30.9	-19.7
Current, a.c. component, beginning	kA_{RMS}	14.8	16.2	8.35
Current, a.c. component, middle	kA_{RMS}	14.3	14.7	13.8
Current, a.c. component, end	kA_{RMS}	14.6	14.7	13.8
Current, a.c. component, average	kA_{RMS}	14.6	14.5	12.4
Current, a.c. component, three-phase average	kA_{RMS}	13.8		
Duration	s	0.122	0.118	0.121
Arc energy	kJ	269	211	267

Observations: Emission of flames and gas observed. Current was present on both A and C phases immediately upon closing onto the test device. This test will be repeated.

Open Box Test # 17 - Single Phase Investigation





Test number: 190830-7009

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	583	583	583
Applied voltage, phase-to-phase	V_{RMS}	1010		
Making current	kA_{peak}	22.5	19.0	-17.8
Current, a.c. component, beginning	kA_{RMS}	13.1	12.2	11.1
Current, a.c. component, middle	kA_{RMS}	14.7	14.1	13.6
Current, a.c. component, end	kA_{RMS}	14.7	14.1	13.6
Current, a.c. component, average	kA_{RMS}	14.5	13.7	13.1
Current, a.c. component, three-phase average	kA_{RMS}	13.8		
Duration	s	0.117	0.119	0.123
Arc energy	kJ	269	206	258

Observations: Emission of flames and gas observed. Arc propagated to B phase in 4.4 ms, to A phase in 5.9 ms.

33.4 Condition / inspection after test

Box sustained minimal damage.

34 OPEN BOX TEST # 18 - 480 V, 13.5 KA

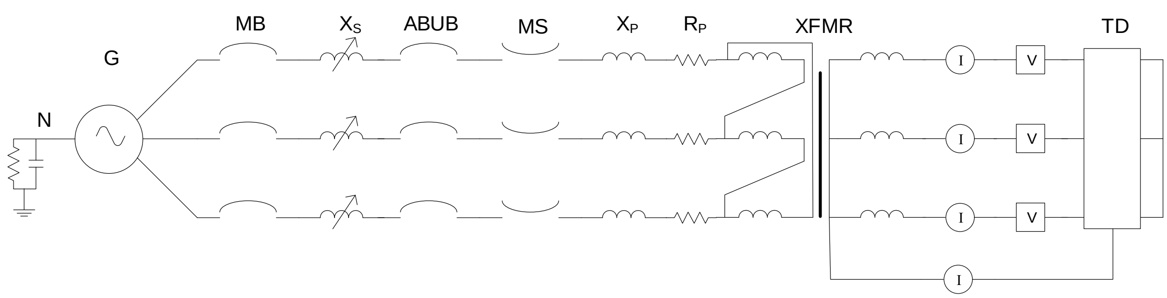
Standard and date

Standard	Client’s instructions
Test date	30 August 2019

34.1 Condition before test

Test box in same condition as after trial 190830-7009. Arc to be initiated by #10 AWG wire. Arc wire connected to 1" diameter copper rods. Test duration is 2 seconds.

34.2 Test circuit S06



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

Supply		
Power	MVA	11.4
Frequency	Hz	60
Phase(s)		3
Voltage	V	489
Sym. Current	kA	13.5
Peak current	kA	35.5
Impedance	Ω	0.021

Remarks: -

34.3 Test results and oscillograms

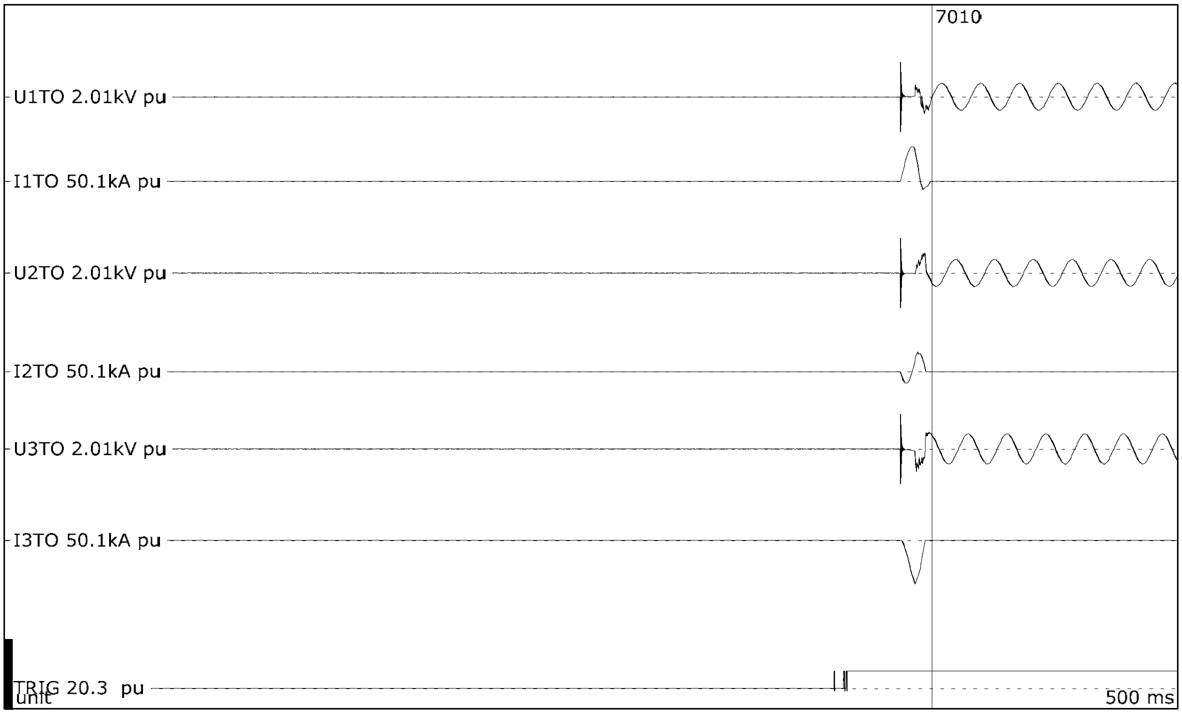
Overview of test numbers

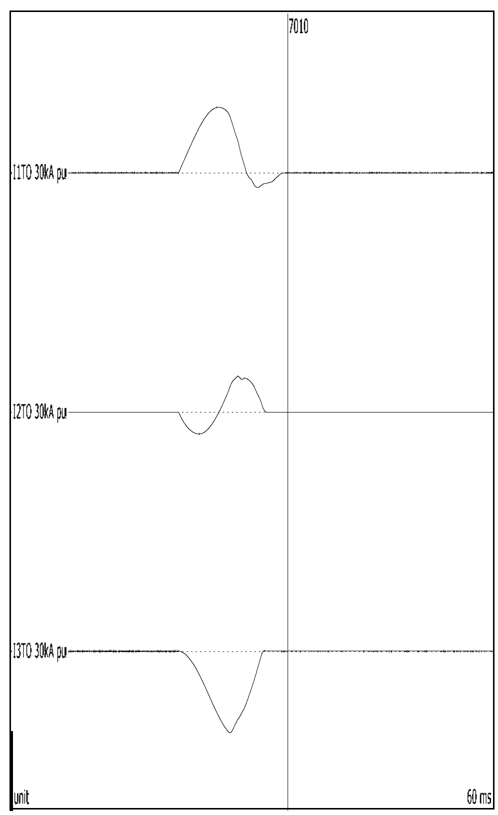
190830-7010

Remarks

-

Open Box Test # 18 - 480 V, 13.5 kA





Test number: 190830-7010

Phase		A	B	C
Applied voltage, phase-to-ground	V_{RMS}	282	282	282
Applied voltage, phase-to-phase	V_{RMS}	488		
Making current	kA_{peak}	24.7	13.1	-30.6
Current, a.c. component, beginning	kA_{RMS}	3.19	5.07	5.41
Current, a.c. component, middle	kA_{RMS}	0.975	2.32	0.000
Current, a.c. component, end	kA_{RMS}	0.000	0.000	0.000
Current, a.c. component, average	kA_{RMS}	0.000	0.000	-
Current, a.c. component, three-phase average	kA_{RMS}	-		
Duration	ms	12.7	10.9	10.6
Arc energy	kJ	11.4	13.2	34.9

Observations:	Emission of flames and gas observed.

34.4 Condition / inspection after test

Box sustained minimal damage. Arc self-extinguished.

35 CHECKING THE PROSPECTIVE CURRENT

Standard and date

Standard	Client’s instructions
Test date	16 September 2019

35.1 Condition before test

Shorting bar connected at station terminals directly prior to test device.

35.2 Test results and oscillograms

Overview of test numbers

190916-9002 to 9005

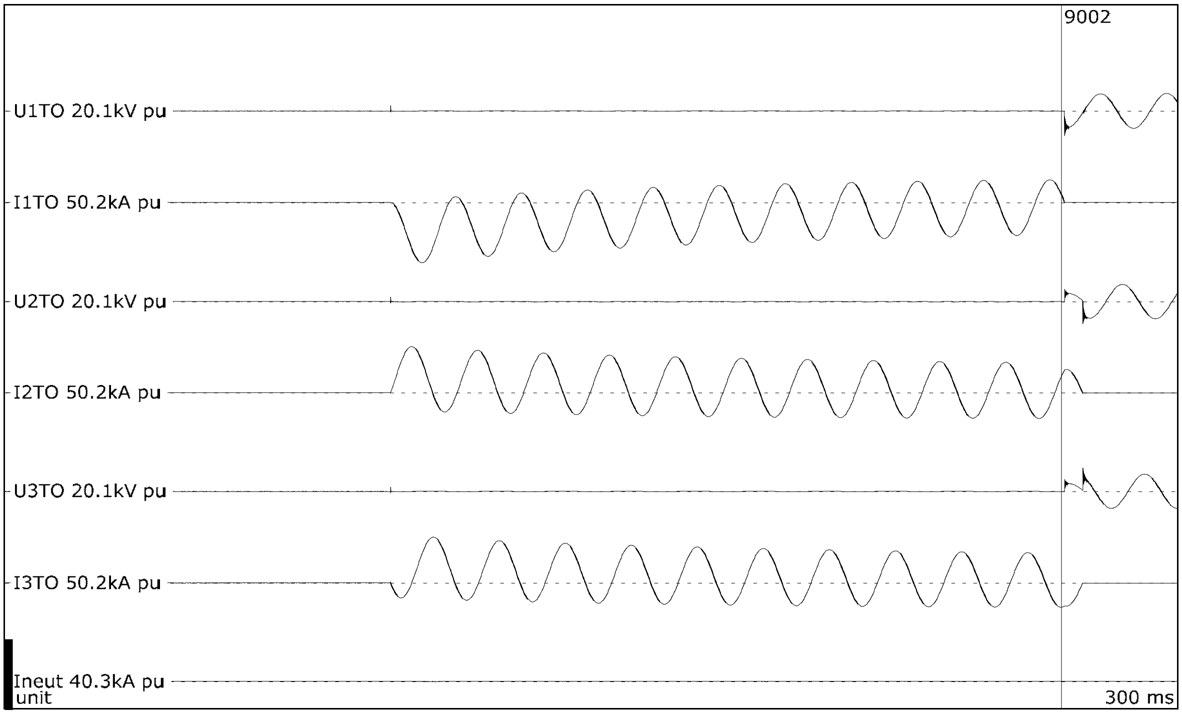
Remarks

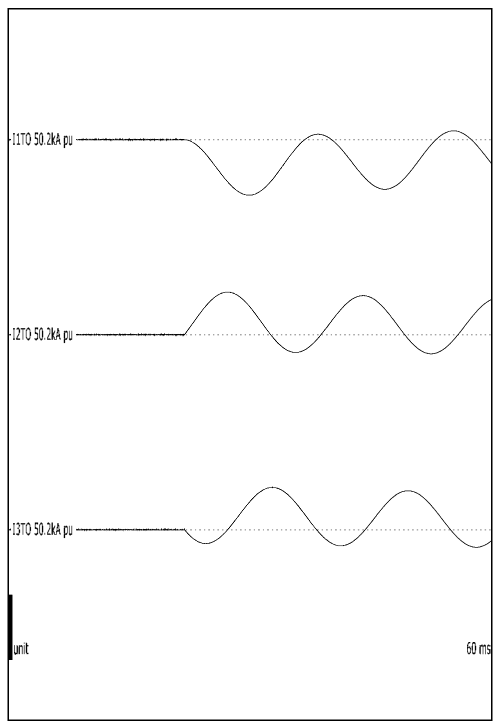
Prospective circuit parameters calibrated in this test duty:

190916-9002→9003: 6900 V, 15.3 kA, 42.9 kA peak.

190916-9004→9005: 6900 V, 30.6 kA, 86.5 kA peak.

Checking the prospective current



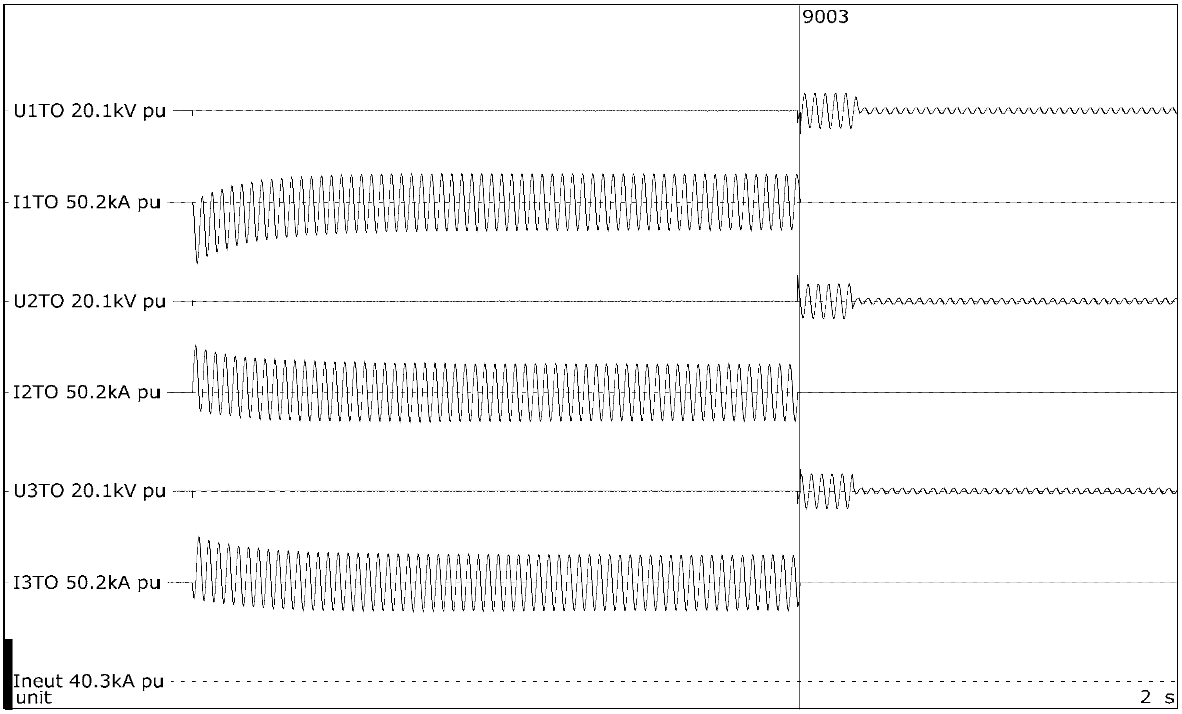


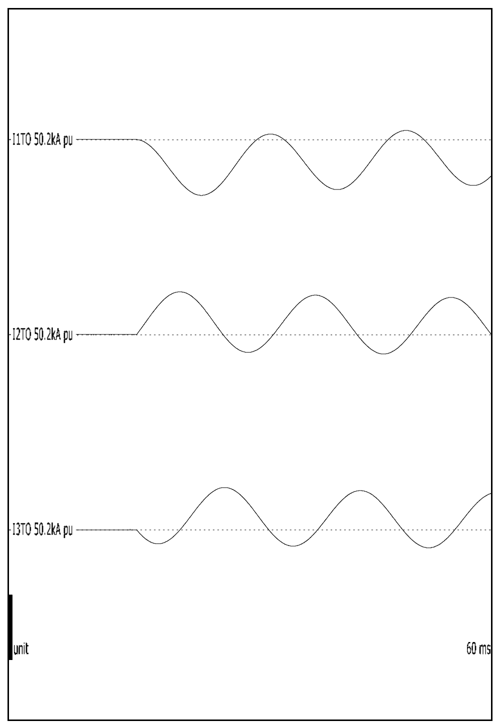
Test number: 190916-9002

Phase		A	B	C
Current	kA_{peak}	-42.9	32.8	32.6
Current, a.c. component	kA_{RMS}	15.4	15.5	15.1
Current, a.c. component, three-phase average	kA_{RMS}	15.3		
Duration, current	s	0.171	0.171	0.171

Observations: No visible disturbance.

Checking the prospective current



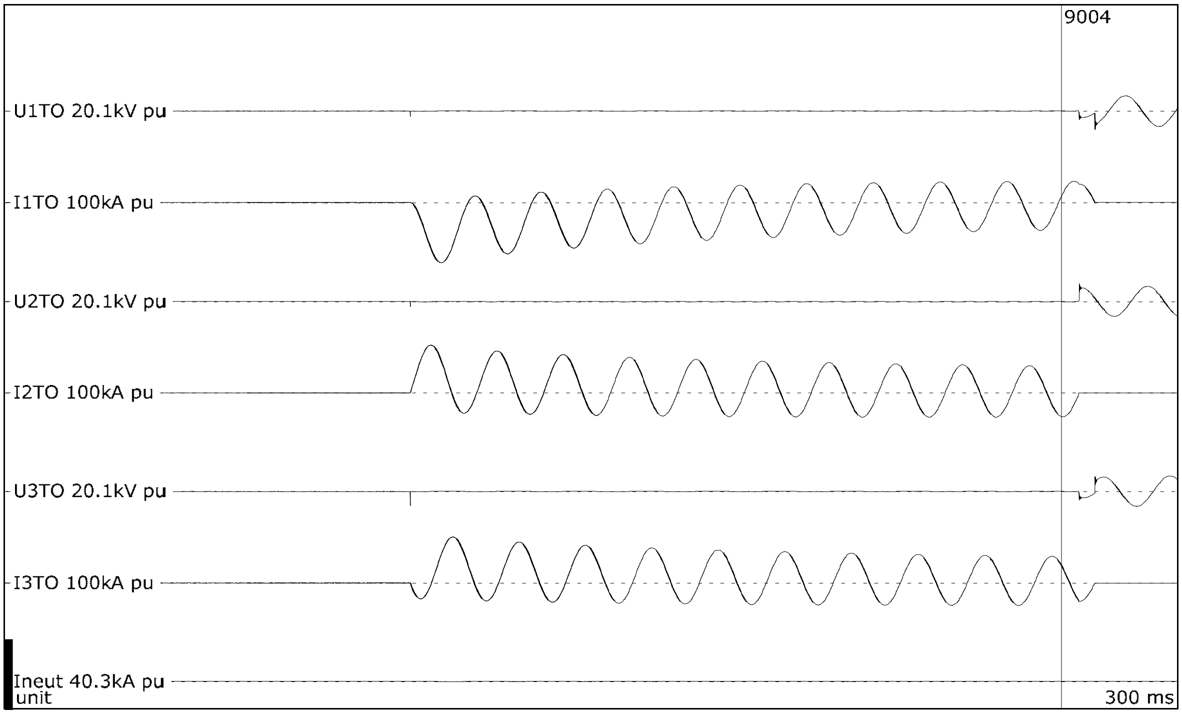


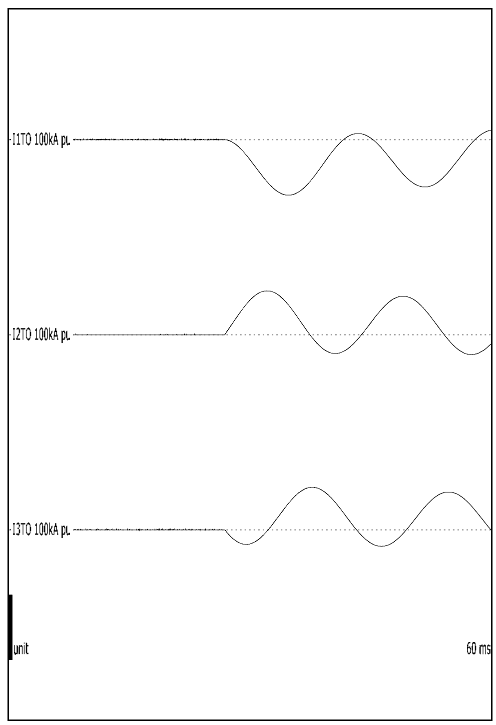
Test number: **190916-9003**

Phase		A	B	C
Current	kA_{peak}	-43.0	33.1	32.5
Current, a.c. component	kA_{RMS}	14.0	14.2	13.4
Current, a.c. component, three-phase average	kA_{RMS}		13.9	
Duration, current	s	1.03	1.03	1.03

Observations:	No visible disturbance.

Checking the prospective current



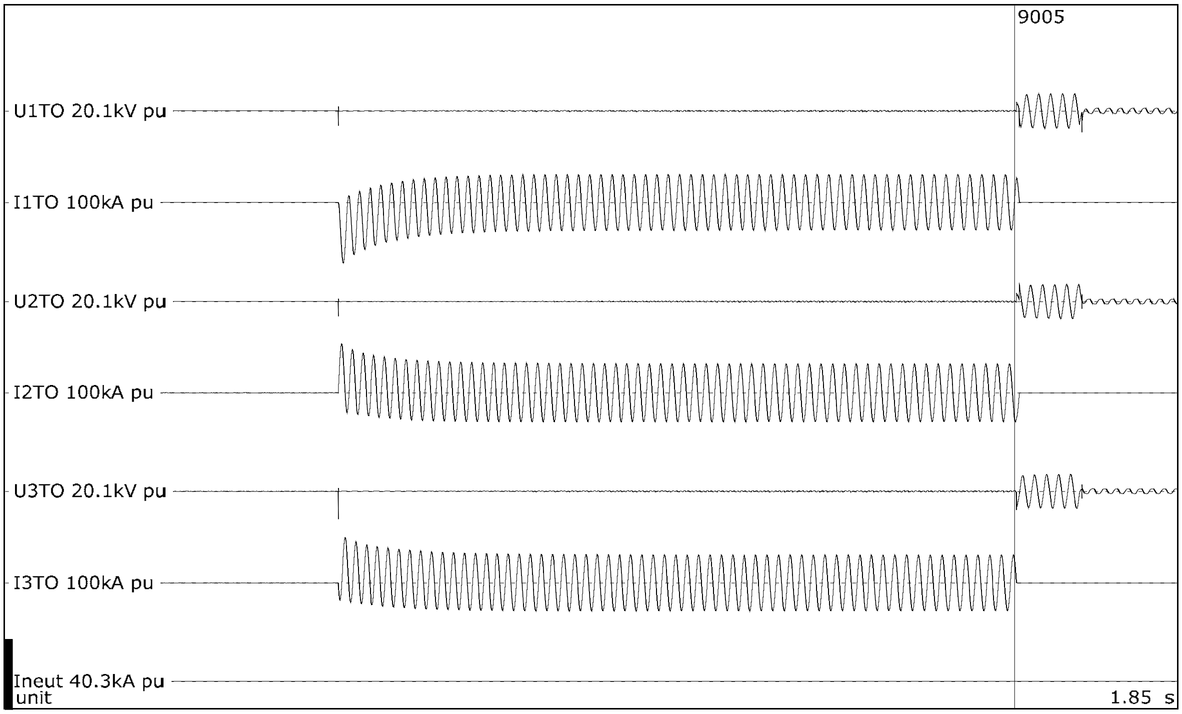


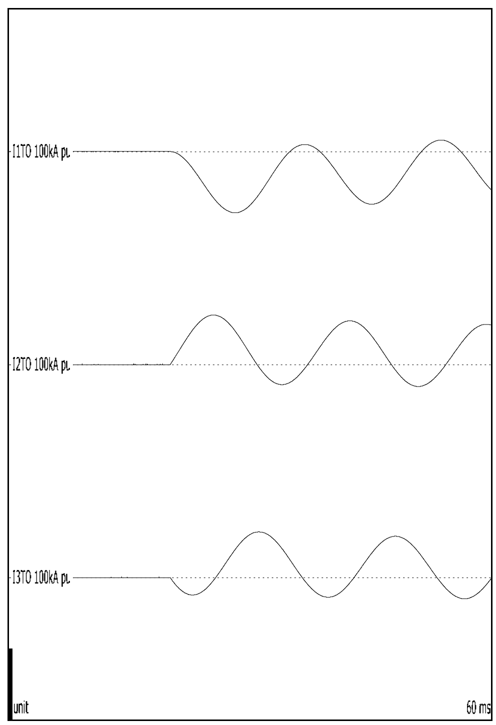
Test number: 190916-9004

Phase		A	B	C
Current	kApeak	-85.8	67.7	65.4
Current, a.c. component	kARMS	30.2	31.6	30.0
Current, a.c. component, three-phase average	kARMS		30.6	
Duration, current	s	0.166	0.166	0.166

Observations: No visible disturbance.

Checking the prospective current





Test number: 190916-9005

Phase		A	B	C
Current	kA$_{peak}$	-86.5	70.0	64.6
Current, a.c. component, beginning	kA$_{RMS}$	30.1	31.3	30.2
Current, a.c. component, middle	kA$_{RMS}$	28.2	29.4	28.3
Current, a.c. component, end	kA$_{RMS}$	28.0	29.2	28.1
Current, a.c. component, average	kA$_{RMS}$	29.0	30.2	29.1
Current, a.c. component, three-phase average	kA$_{RMS}$		29.4	
Duration, current	s	1.07	1.07	1.07

Observations: No visible disturbance.

36 OBMV # 5

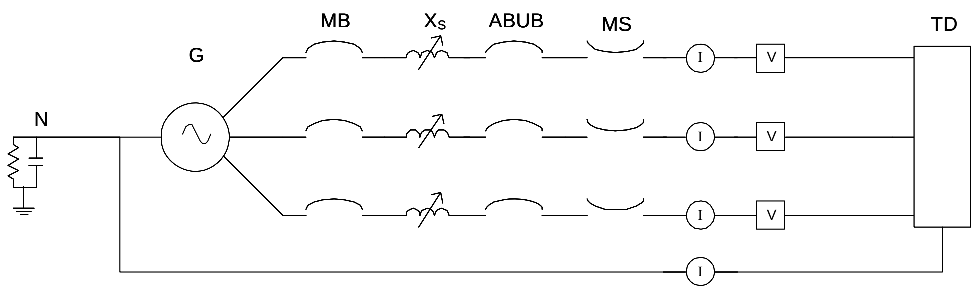
Standard and date

Standard	Client’s instructions
Test date	16 September 2019

36.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to copper bus. Test duration is 2 seconds.

36.2 Test circuit S11



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

Supply		
Power	MVA	366
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	30.6
Peak current	kA	86.5
Impedance	Ω	0.130

Remarks: -

36.3 Test results and oscillograms

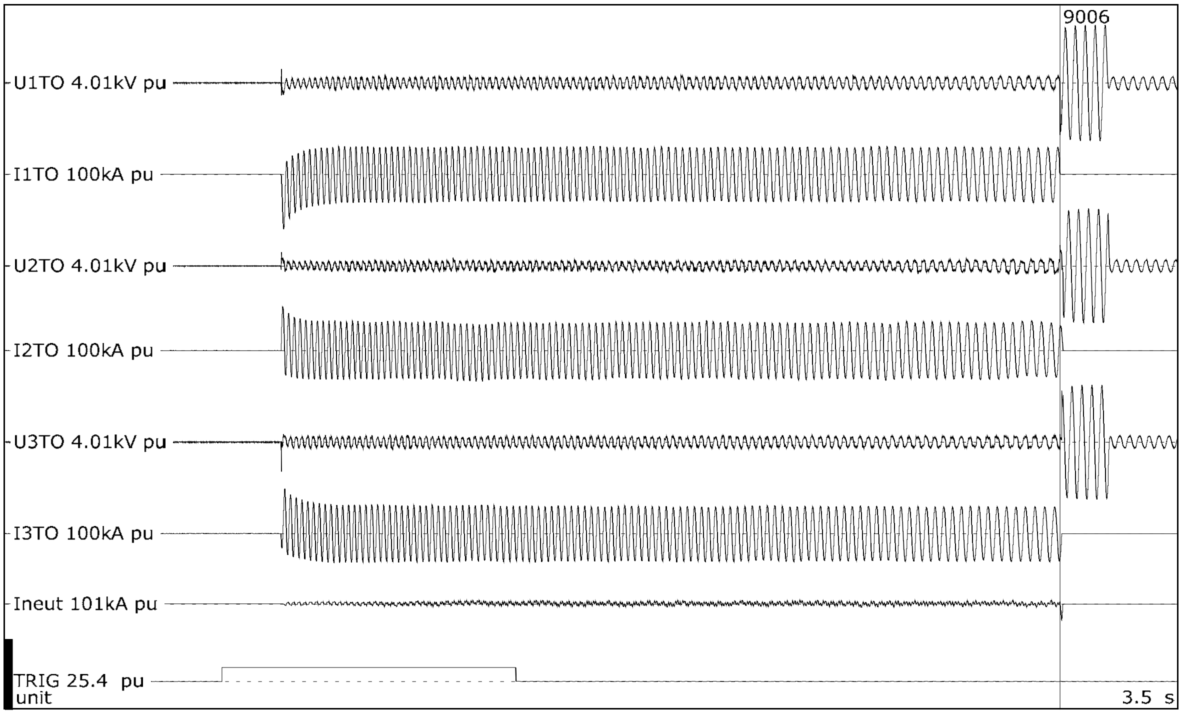
Overview of test numbers

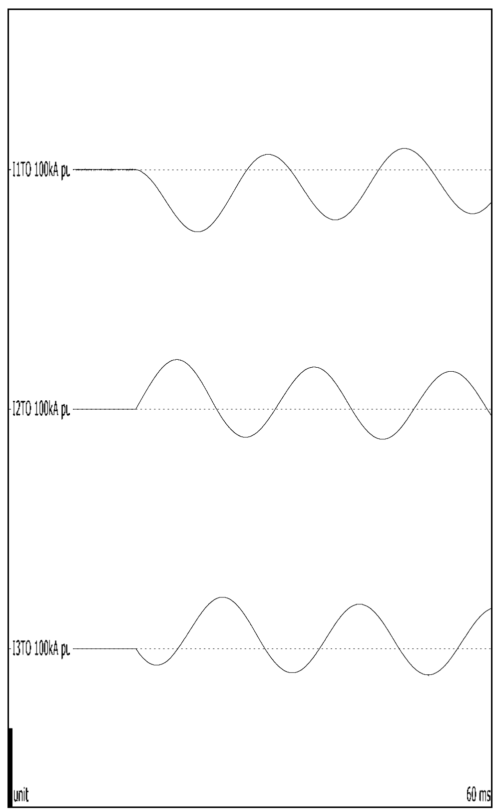
190916-9006

Remarks

-

OBMV # 5





Test number: 190916-9006

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.90	
Making current	kA_{peak}	-78.3	62.1	64.5
Current, a.c. component, beginning	kA_{RMS}	31.7	32.9	31.9
Current, a.c. component, middle	kA_{RMS}	27.3	28.3	27.9
Current, a.c. component, end	kA_{RMS}	27.4	28.2	27.4
Current, a.c. component, average	kA_{RMS}	28.3	29.1	28.6
Current, a.c. component, three-phase average	kA_{RMS}		28.7	
Duration	s	2.32	2.32	2.32
Arc energy	MJ	15.7	12.7	15.1

Observations: Emission of flames and gas observed.

36.4 Condition / inspection after test

Left and right side of box burned through. Bottom of box melted and heavily distorted, but no burn-throughs evident.

37 OBMV # 2

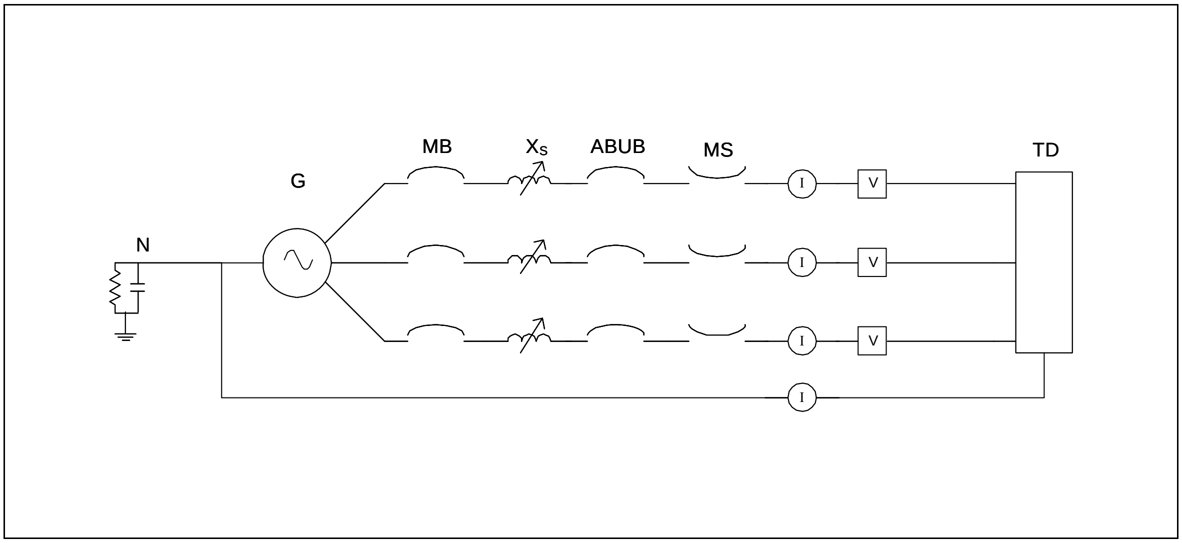
Standard and date

Standard	Client’s instructions
Test date	17 September 2019

37.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to aluminum bus. Test duration is 1 seconds.

37.2 Test circuit S11



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

Supply		
Power	MVA	366
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	30.6
Peak current	kA	86.5
Impedance	Ω	0.130

Remarks: -

37.3 Test results and oscillograms

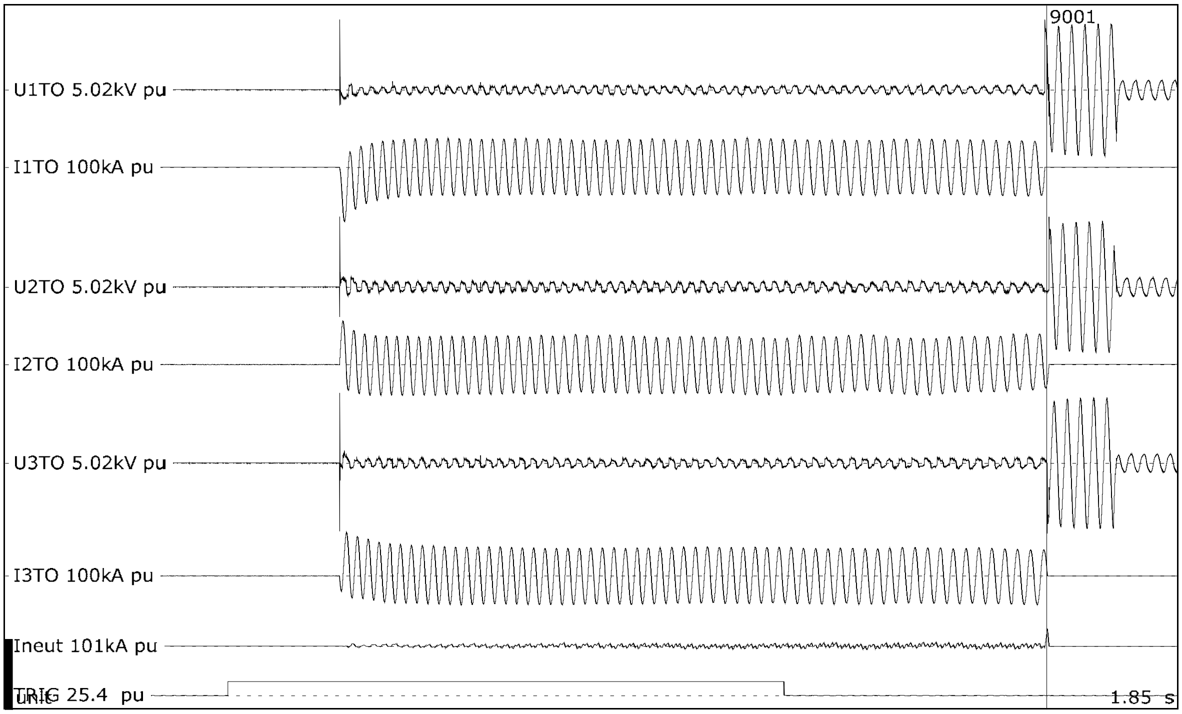
Overview of test numbers

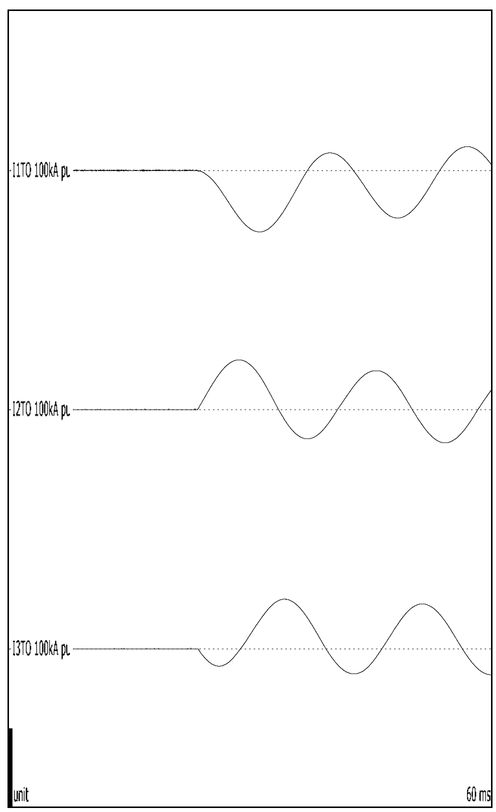
190917-9001

Remarks

-

OBMV # 2





Test number: 190917-9001

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.89	
Making current	kA_{peak}	-77.4	62.5	62.2
Current, a.c. component, beginning	kA_{RMS}	32.0	32.7	31.5
Current, a.c. component, middle	kA_{RMS}	27.7	28.5	28.5
Current, a.c. component, end	kA_{RMS}	27.8	28.5	27.9
Current, a.c. component, average	kA_{RMS}	28.7	29.5	29.0
Current, a.c. component, three-phase average	kA_{RMS}		29.0	
Duration	s	1.11	1.11	1.11
Arc energy	MJ	6.58	8.07	6.77

Observations: Emission of flames and gas observed.

37.4 Condition / inspection after test

No complete burn throughs evident.

38 OBMV # 4

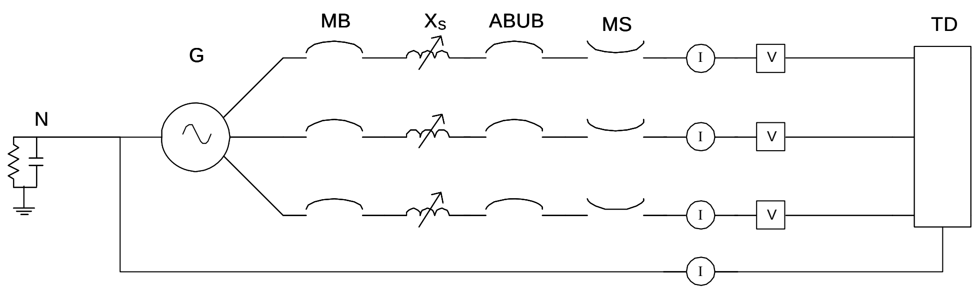
Standard and date

Standard	Client’s instructions
Test date	17 September 2019

38.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to copper bus. Test duration is 5 seconds.

38.2 Test circuit S10



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

Supply		
Power	MVA	182
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	15.3
Peak current	kA	42.9
Impedance	Ω	0.260

Remarks: -

38.3 Test results and oscillograms

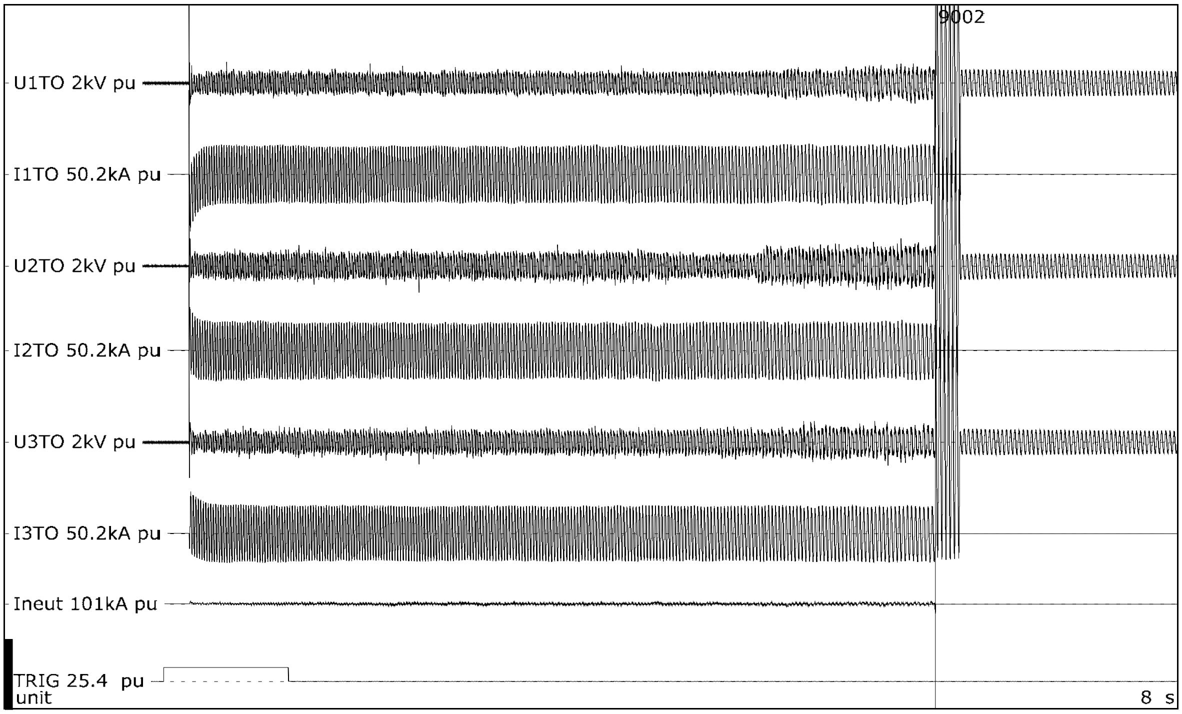
Overview of test numbers

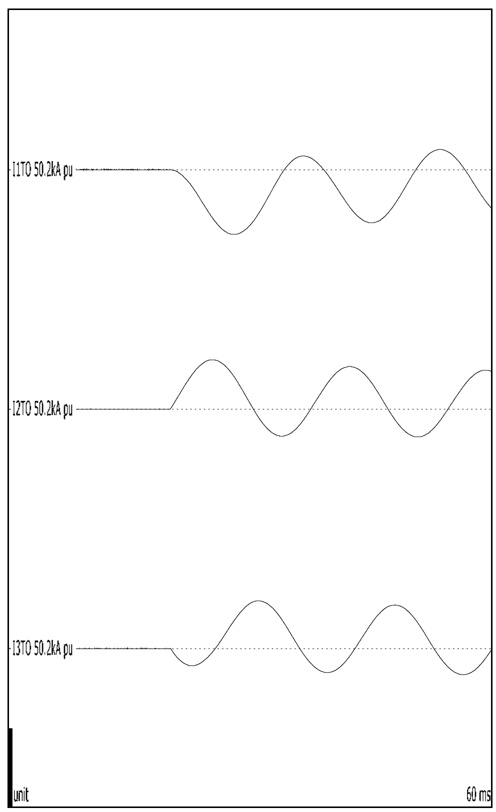
190917-9002

Remarks

-

OBMV # 4





Test number: 190917-9002

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.89	
Making current	kA_{peak}	-40.7	31.0	29.9
Current, a.c. component, beginning	kA_{RMS}	16.1	16.2	15.2
Current, a.c. component, middle	kA_{RMS}	14.1	14.0	13.7
Current, a.c. component, end	kA_{RMS}	14.5	14.2	14.0
Current, a.c. component, average	kA_{RMS}	14.6	14.5	14.1
Current, a.c. component, three-phase average	kA_{RMS}		14.4	
Duration	s	5.08	5.08	5.08
Arc energy	MJ	16.7	19.1	16.0

Observations: Emission of flames and gas observed.

38.4 Condition / inspection after test

Bottom of box burned completely through. Large burn throughs evident on sides of box.

39 OBMV # 1

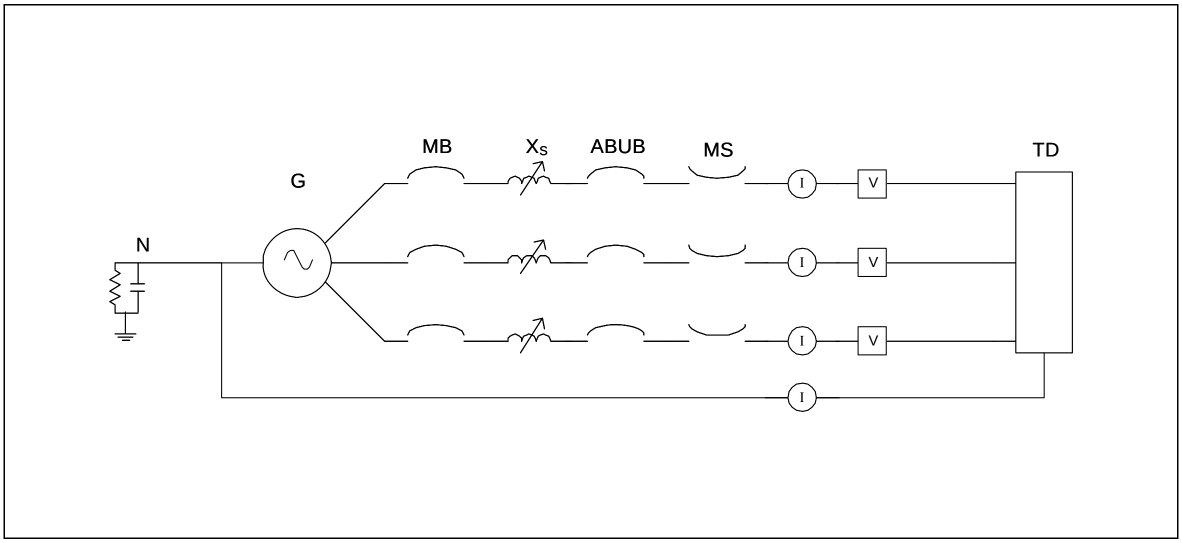
Standard and date

Standard	Client's instructions
Test date	18 September 2019

39.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to aluminum bus. Test duration is 2 seconds.

39.2 Test circuit S10



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

Supply		
Power	MVA	182
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	15.3
Peak current	kA	42.9
Impedance	Ω	0.260

Remarks: -

39.3 Test results and oscillograms

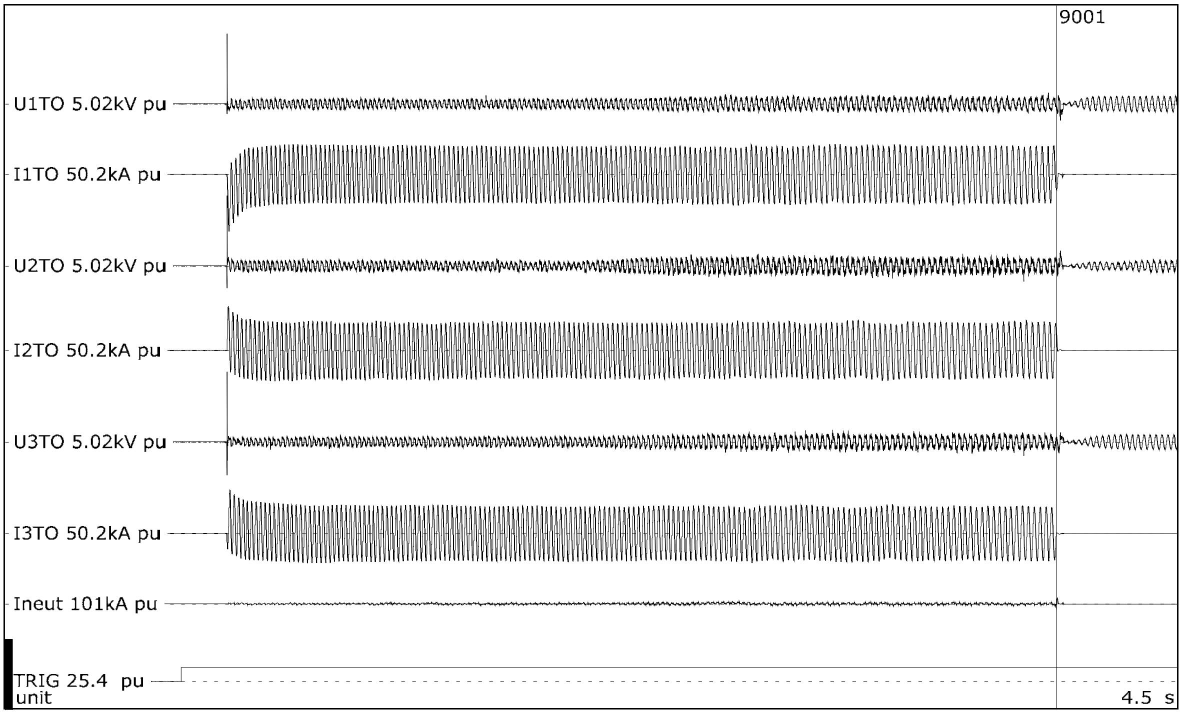
Overview of test numbers

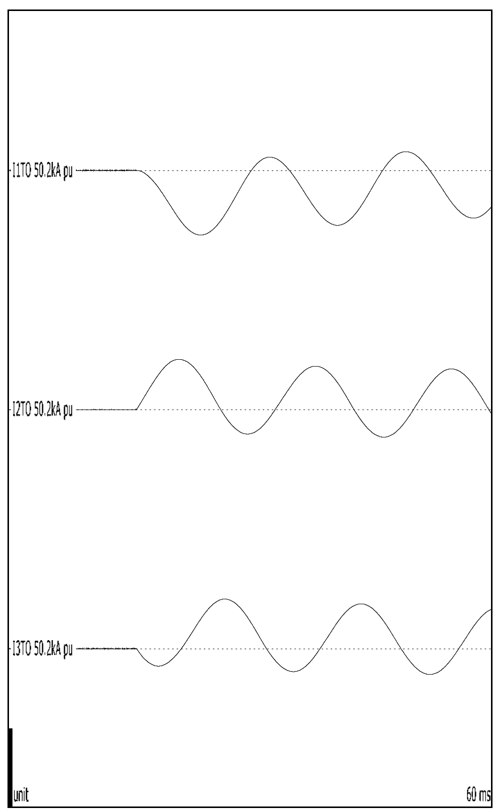
190918-9001

Remarks

-

OBMV # 1





Test number: 190918-9001

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.89	
Making current	kA_{peak}	-40.6	31.6	31.2
Current, a.c. component, beginning	kA_{RMS}	16.2	15.8	15.5
Current, a.c. component, middle	kA_{RMS}	14.2	14.2	13.6
Current, a.c. component, end	kA_{RMS}	14.3	14.4	13.6
Current, a.c. component, average	kA_{RMS}	14.7	14.5	14.1
Current, a.c. component, three-phase average	kA_{RMS}		14.4	
Duration	s	3.18	3.18	3.18
Arc energy	MJ	12.4	13.3	11.8

Observations: Emission of flames and gas observed. Station timer malfunctioned during test, causing duration to be extended to 3.18 seconds.

39.4 Condition / inspection after test

Bottom and sides of box completely burned through. Test duration was longer than expected due to station timer malfunction.

40 OBMV # 3

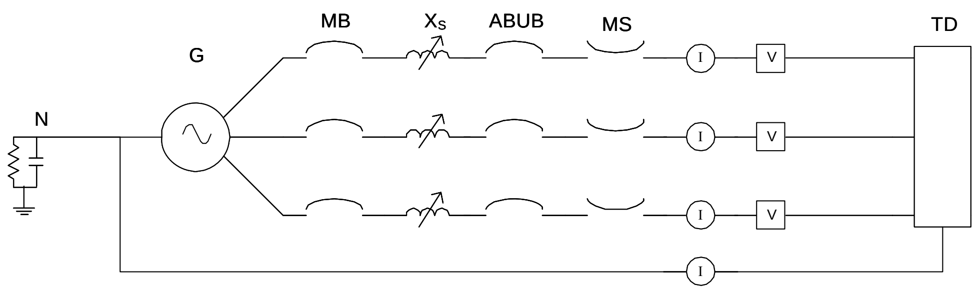
Standard and date

Standard	Client’s instructions
Test date	18 September 2019

40.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to aluminum bus. Test duration is 5 seconds.

40.2 Test circuit S10



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

Supply		
Power	MVA	182
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	15.3
Peak current	kA	42.9
Impedance	Ω	0.260

Remarks: -

40.3 Test results and oscillograms

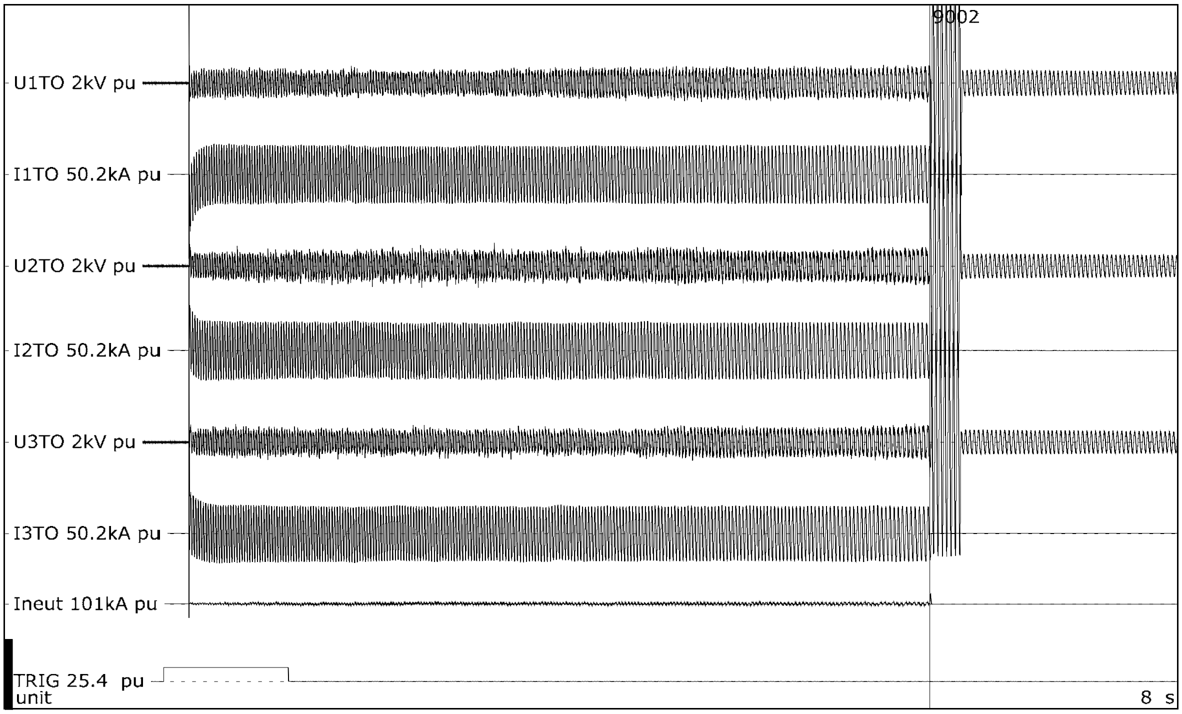
Overview of test numbers

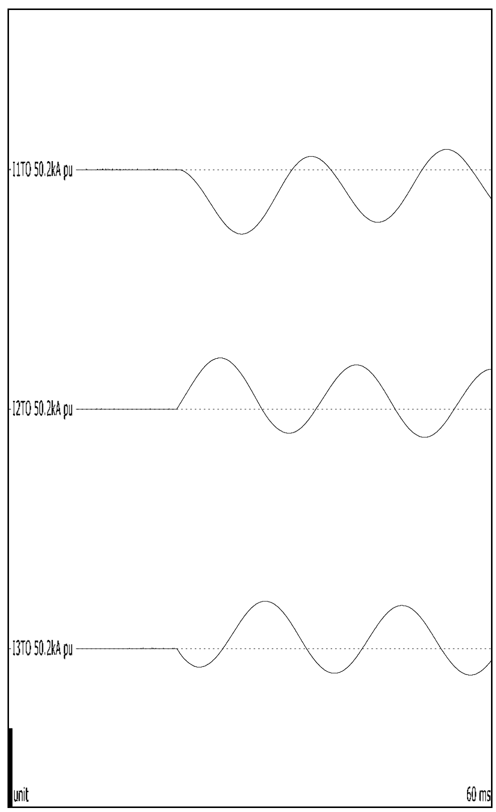
190918-9002

Remarks

-

OBMV # 3





Test number: 190918-9002

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.89	
Making current	kA_{peak}	-40.5	32.1	29.7
Current, a.c. component, beginning	kA_{RMS}	15.9	15.9	15.3
Current, a.c. component, middle	kA_{RMS}	14.2	14.0	13.9
Current, a.c. component, end	kA_{RMS}	14.7	14.1	14.1
Current, a.c. component, average	kA_{RMS}	14.7	14.4	14.1
Current, a.c. component, three-phase average	kA_{RMS}		14.4	
Duration	s	5.05	5.05	5.05
Arc energy	MJ	19.1	19.6	17.0

Observations: Emission of flames and gas observed.

40.4 Condition / inspection after test

Bottom and sides of box completely burned through.

41 OBMV # 6

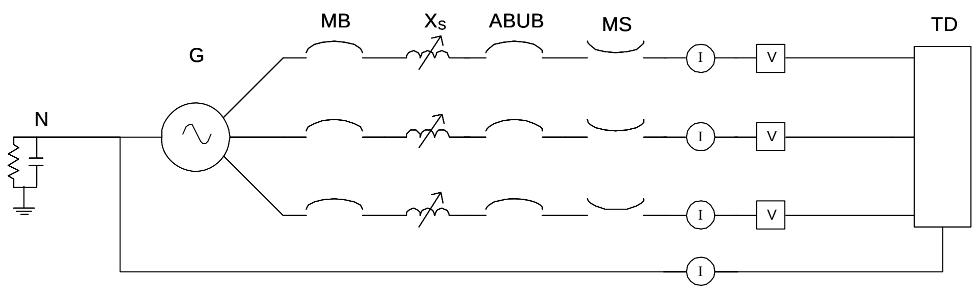
Standard and date

Standard	Client's instructions
Test date	18 September 2019

41.1 Condition before test

Test device new. Arc to be initiated by #24 AWG wire. Arc wire connected to aluminum bus. Test duration is 2 seconds.

41.2 Test circuit S10



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

Supply		
Power	MVA	182
Frequency	Hz	60
Phase(s)		3
Voltage	V	6900
Sym. Current	kA	15.3
Peak current	kA	42.9
Impedance	Ω	0.260

Remarks: -

41.3 Test results and oscillograms

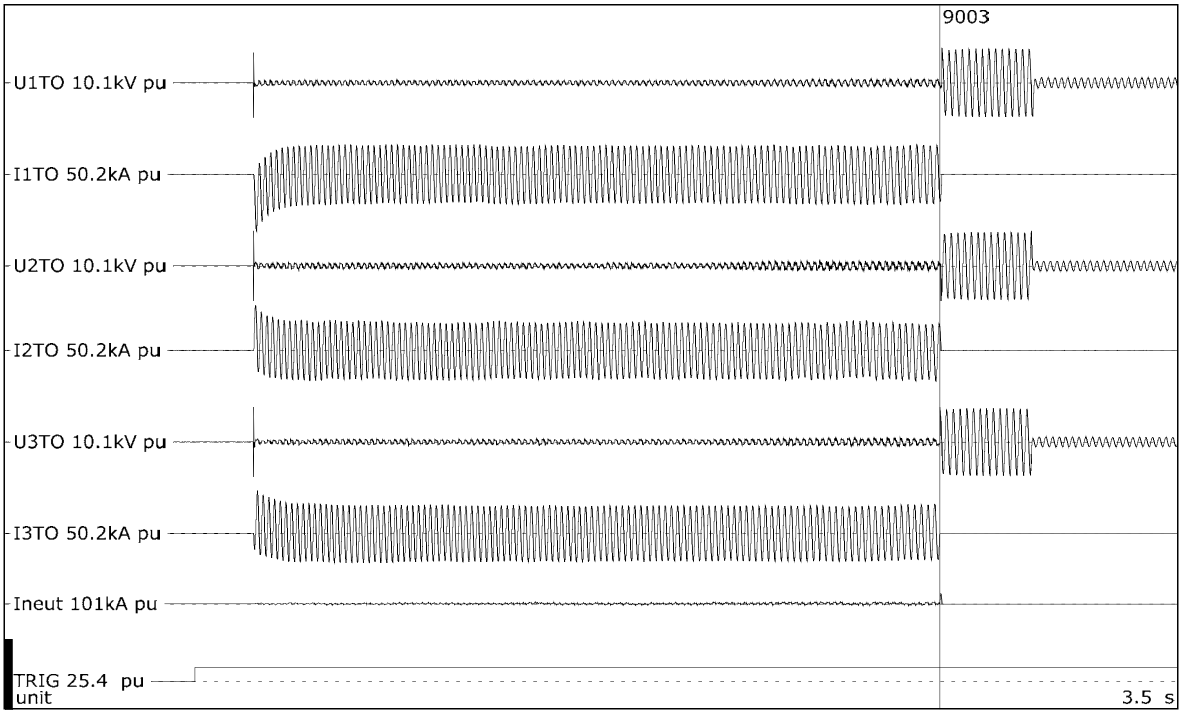
Overview of test numbers

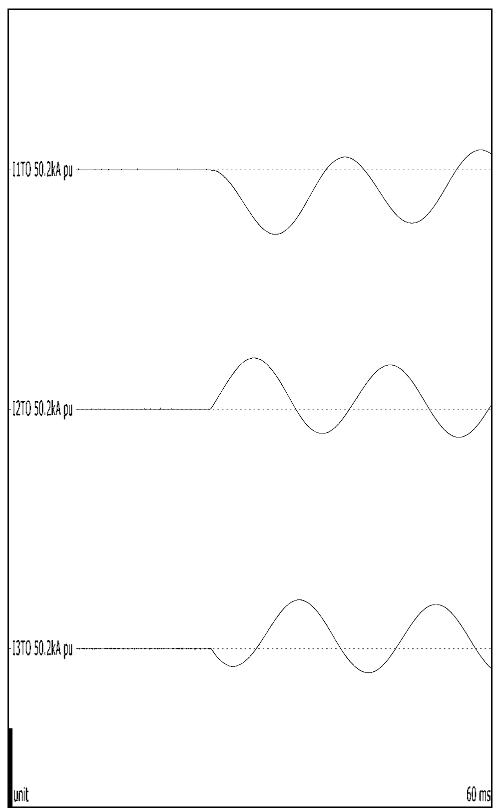
190918-9003

Remarks

-

OBMV # 6





Test number: 190918-9003

Phase		A	B	C
Applied voltage, phase-to-ground	kV_{RMS}	3.98	3.98	3.98
Applied voltage, phase-to-phase	kV_{RMS}		6.89	
Making current	kA_{peak}	-40.7	32.1	30.5
Current, a.c. component, beginning	kA_{RMS}	15.9	16.0	15.5
Current, a.c. component, middle	kA_{RMS}	14.5	14.1	13.9
Current, a.c. component, end	kA_{RMS}	14.7	13.9	13.9
Current, a.c. component, average	kA_{RMS}	14.8	14.6	14.3
Current, a.c. component, three-phase average	kA_{RMS}		14.6	
Duration	s	2.05	2.05	2.05
Arc energy	MJ	7.66	7.89	7.17

Observations: Emission of flames and gas observed.

41.4 Condition / inspection after test

Bottom and sides of box completely burned through.

42 ATTACHMENTS

1. Calorimeter Data Records [15 PAGES]
2. Instrumentation Information Sheets [2 PAGES]
3. Photographs (269) [135 PAGES]

Test Number:	24512323	Date and Time:	
Trial Number:	190826-7003		8/26/2019
DAS Operator:	Joe Duffy		4:18:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	44.6	44.6	N/A	1,2
B	23.8	23.8	N/A	1
C	23.9	23.9	N/A	1
D	23.3	23.3	N/A	1
E	24.6	24.6	N/A	1
F	40.7	40.7	N/A	1,2
G	24.8	24.8	N/A	1
H	43.7	43.7	N/A	1,2
I	50.7	50.7	N/A	1,2
J	24.5	24.5	N/A	1

Comments: 1) Due to the arc self-extinguishing, no noticeable differences in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference.

Test Number:	24512323	Date and Time:	
Trial Number:	190827-7001		8/27/2019
DAS Operator:	Joe Duffy		9:16:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	32.0	32.1	N/A	1,2
B	18.2	18.2	N/A	1
C	18.9	18.9	N/A	1
D	18.4	18.9	N/A	1
E	18.5	19.0	N/A	1
F	26.3	26.8	55	2
G	19.7	20.8	30	
H	29.8	31.0	58	2
I	36.0	36.8	23	2
J	19.0	19.4	11	

Comments: 1) Due to the arc self-extinguishing, no noticeable differences in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference.

Test Number:	24512323	Date and Time:	
Trial Number:	190827-7002		8/27/2019
DAS Operator:	Joe Duffy		10:25:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	41.3	41.7	N/A	1,2
B	20.1	20.3	N/A	1
C	20.5	20.6	N/A	1
D	19.7	19.8	N/A	1
E	20.1	21.0	101	
F	34.7	35.6	110	2
G	20.4	21.4	9	
H	38.4	39.6	17	2
I	44.4	45.1	30	2
J	20.5	21.2	33	

Comments: 1) Due to the arc self-extinguishing, no noticeable differences in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference.

Test Number:	24512323	Date and Time:	
Trial Number:	190827-7003		8/27/2019
DAS Operator:	Joe Duffy		1:24:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	50.0	50.4	N/A	1,2
B	23.1	23.2	N/A	1
C	23.8	23.8	N/A	1
D	22.4	22.5	N/A	1
E	23.7	26.7	158	
F	43.1	45.2	151	2
G	23.5	26.4	80	
H	46.6	50.3	171	2
I	52.3	54.1	99	2
J	23.2	24.2	140	

Comments: 1) Due to the arc self-extinguishing, no noticeable differences in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference.

Test Number:	24512323	Date and Time:	
Trial Number:	190827-7004		8/27/2019
DAS Operator:	Joe Duffy		2:54:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	53.6	53.8	N/A	1,2
B	24.6	24.7	N/A	1
C	24.8	26.2	11	
D	23.8	24.9	137	
E	24.7	25.5	33	
F	47.1	50.0	>10 minutes	2,3
G	24.6	40.5	9	
H	50.8	57.0	147	2
I	56.7	56.5	11	2
J	25.4	28.7	9	

Comments: 1) No significant difference in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference. 3) Temperature appears to still be rising at the end of the data capture window.

Test Number:	24512323	Date and Time:	
Trial Number:	190828-7001		8/28/2019
DAS Operator:	Joe Duffy		10:14:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	64.5	70.9	7	1
B	30.5	41.2	4	
C	26.3	27.0	260	
D	24.8	25.3	260	
E	29.5	30.5	124	
F	56.5	58.1	290	1,2
G	27.2	28.5	135	
H	59.1	60.4	101	1
I	63.7	64.4	160	1
J	27.3	28.2	290	2

Comments: 1) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference. 2) Temperature appears to still be rising at the end of the data capture window.

Test Number:	24512323	Date and Time:	
Trial Number:	190828-7002		8/28/2019
DAS Operator:	Joe Duffy		10:53:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	61.2	74.3	6	2
B	28.1	47.5	6	
C	27.8	27.9	N/A	1
D	26.9	27.0	N/A	1
E	27.8	29.4	6	
F	54.6	56.3	290	2,3
G	27.7	30.7	47	
H	58.0	63.0	10	2
I	63.9	65.6	58	2
J	27.8	29.7	9	

Comments: 1) No significant difference in temperature during the event were recorded. 2) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference. 3) Temperature appears to still be rising at the end of the data capture window.

Test Number:	24512323	Date and Time:
Trial Number:	190829-7005	8/29/2019
DAS Operator:	Joe Duffy	11:21:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	62.8	73.0	6	1
B	31.8	46.6	5	
C	27.1	28.0	>7 minutes	2
D	26.3	27.1	>7 minutes	2
E	28.7	33.4	234	
F	54.3	58.5	>7 minutes	1,2
G	28.7	40.2	176	
H	59.3	75.3	21	1
I	64.0	68.7	277	1
J	30.1	35.2	9	
K	30.0	32.5	268	
L	28.0	30.7	>7 minutes	2

Comments: 1) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference. 2) Temperature appears to still be rising at the end of the data capture window.

Test Number:	24512323	Date and Time:	
Trial Number:	190829-7006		8/29/2019
DAS Operator:	Joe Duffy		2:31:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	56.2	120.0	10	1
B	28.6	108.1	9	
C	27.9	33.6	15	
D	27.4	31.5	>17 minutes	2
E	28.2	60.4	84	
F	51.0	86.0	632	1
G	28.7	145.3	15	
H	53.9	219.5	15	1
I	59.5	102.1	19	1
J	29.4	80.4	15	
K	27.6	58.9	325	
L	27.6	58.8	507	

Comments: 1) Ambient temperature readings were much higher than actual ambient, client agreed to proceed with testing despite this difference. 2) Temperature appears to still be rising at the end of the data capture window.

Test Number:	24512323	Date and Time:	
Trial Number:	190916-9006		9/16/2019
DAS Operator:	Joe Duffy		2:10:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	28.6	378.8	4	
B	28.7	135.4	34	

Comments:

Test Number:	24512323	Date and Time:	
Trial Number:	190917-9001		9/17/2019
DAS Operator:	Joe Duffy		10:03:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	26.6	402.3	2	
B	N/A	N/A	N/A	1

Comments: 1) Calorimeter B was not available for this test. Prior to test, it was discovered that thermocouple was reading as an open circuit. It was confirmed in the test cell that the issue was with the thermocouple wire, and not the data system. Client agreed to proceed with the test without calorimeter B due to the time it would take to replace the thermocouple wire.

Test Number:	24512323	Date and Time:	
Trial Number:	190917-9002		9/17/2019
DAS Operator:	Joe Duffy		3:35:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	25.9	227.5	6	
B	25.5	480.4	8	

Comments:

Test Number:	24512323	Date and Time:	
Trial Number:	190918-9001		9/18/2019
DAS Operator:	Joe Duffy		9:20:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	22.2	155.1	6	
B	28.7	>836	5	1

Comments: 1) Maximum temperature that can be recorded by thermal data system is 836° C.

Test Number:	24512323	Date and Time:	
Trial Number:	190918-9002		9/18/2019
DAS Operator:	Joe Duffy		10:04:00 AM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	22.5	281.0	9	
B	23.2	388.7	32	

Comments:

Test Number:	24512323	Date and Time:	
Trial Number:	190918-9003		9/18/2019
DAS Operator:	Joe Duffy		2:49:00 PM

Calorimeter	Avg Start Temp (°C)	Max Temp (°C)	Time to max heat (sec)	Comments
A	22.9	106.4	8	
B	22.8	405.7	4	

Comments:

KEMA-Powertest, Inc.
Instrumentation Information Sheet

TEST NO: 24512323 **DATE:** 09/19/2019

TEST DEVICE: Medium & Low Voltage Switchgear

TESTED BY: J. Duffy, B. Swartz

CODE#	TYPE	MANUFACTURER	MODEL#	SERIAL#	CALIBRATION LAST	CALIBRATION DUE
DAS20	DAS	NI/DEWETRON	DEWE-30-16	V08X02F33	10/16/2019	5/3/2020
PAV37	PNL.VOLTMTR	SIMPSON	F45-1-34	N/A	6/17/2019	1/3/2020
PAV24	PNL.VOLTMTR	WESTON	1234	N/A	6/17/2019	1/3/2020
ISO141	ISO AMP	DEWETRON	HIS-LV	504659	10/16/2019	5/3/2020
ISO142	ISO AMP	DEWETRON	HIS-LV	504660	10/16/2019	5/3/2020
ISO143	ISO AMP	DEWETRON	HIS-LV	504661	10/16/2019	5/3/2020
ISO144	ISO AMP	DEWETRON	HIS-LV	504662	10/16/2019	5/3/2020
ISO145	ISO AMP	DEWETRON	HIS-LV	508022	10/16/2019	5/3/2020
ISO146	ISO AMP	DEWETRON	HIS-LV	508021	10/16/2019	5/3/2020
ISO147	ISO AMP	DEWETRON	HIS-LV	508020	10/16/2019	5/3/2020
ISO149	ISO AMP	DEWETRON	HIS-LV	416717	10/16/2019	5/3/2020
ISO150	ISO AMP	DEWETRON	HIS-LV	416728	10/16/2019	5/3/2020
ISO151	ISO AMP	DEWETRON	HIS-LV	416698	10/16/2019	5/3/2020
CTX15	C.T.	ITE	TR	56571	1/17/2019	1/17/2021
CTX16	C.T.	ITE	TR	56573	1/17/2019	1/17/2021
CTX17	C.T.	ITE	TR	56572	1/17/2019	1/17/2021
CTX214	ROGOWSKI CT	PEM	CWT75LFxB	37226-29255	10/16/2019	5/3/2020
CTX215	ROGOWSKI CT	PEM	CWT75LFxB	37226-29256	10/16/2019	5/3/2020
CTX216	ROGOWSKI CT	PEM	CWT75LFxB	37226-29257	10/16/2019	5/3/2020
CTS51	CT SHUNT	DALE	NH-250	N/A	7/8/2019	1/24/2020
CTS52	CT SHUNT	DALE	NH-250	N/A	7/8/2019	1/24/2020
CTS53	CT SHUNT	DALE	NH-250	N/A	7/8/2019	1/24/2020
VDR38	RES.VOL.DIV	POWERTEST	189:1	38	7/8/2019	1/24/2020
VDR39	RES.VOL.DIV	POWERTEST	189:1	39	7/8/2019	1/24/2020
VDR40	RES.VOL.DIV	POWERTEST	189:1	40	7/8/2019	1/24/2020
VDR92	V.DIVIDER	NORTH STAR	PVM-11	1716317	6/21/2019	1/7/2020
VDR93	V.DIVIDER	NORTH STAR	PVM-11	1716417	10/16/2019	5/3/2020
VDR94	V.DIVIDER	NORTH STAR	PVM-11	1716517	10/16/2019	5/3/2020
KPT101	PRESS.TRANS	OMEGA	PX329	030318I148	7/16/2019	2/1/2020
KPT102	PRESS.TRANS	OMEGA	PX329	030318I131	7/16/2019	2/1/2020
AMP41	FO ISO AMP	AAA LAB SYST	AFL-300	1	8/12/2019	2/28/2020
AMP43	FO ISO AMP	AAA LAB SYST	AFL-300	3	8/12/2019	2/28/2020
AMP44	FO ISO AMP	AAA LAB SYST	AFL-300	4	8/12/2019	2/28/2020
AMP45	FO ISO AMP	AAA LAB SYST	AFL-300	5	8/12/2019	2/28/2020
KPT87	PRES.TRANS.	OMEGA	PX329	072613I064	10/24/2019	5/11/2020
KPT98	PRESS.TRANS	OMEGA	PX329	071114I076	4/5/2019	10/22/2019

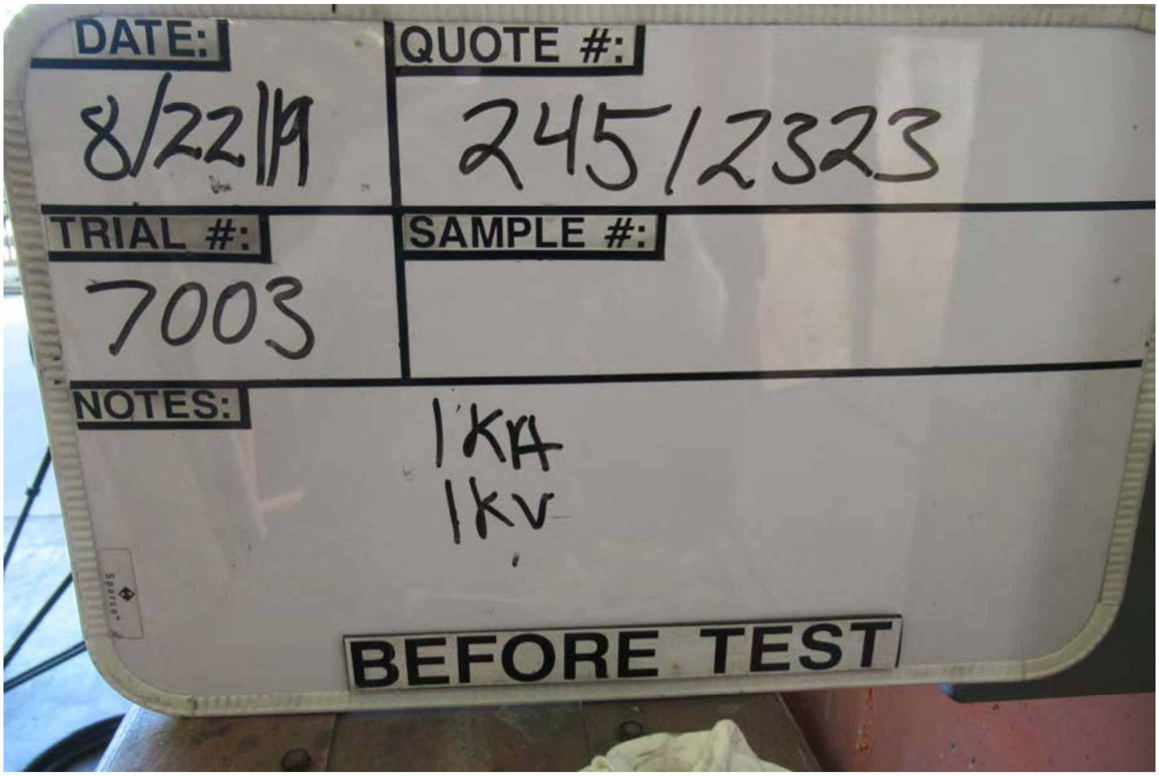
KEMA-Powertest, Inc.
Instrumentation Information Sheet

TEST NO: 24512323* **DATE:** 09/19/2019

TEST DEVICE: Low & Medium Voltage Switchgear

TESTED BY: J. Duffy, B. Swartz

CODE#	TYPE	MANUFACTURER	MODEL#	SERIAL#	CALIBRATION LAST	CALIBRATION DUE
TEM89	TEMP.LOGGER	DEWESoft	KRYPTONi	D05980d869	5/30/2019	12/16/2019
TEM92	TEMP.LOGGER	DEWESoft	KRYPTONi	D05980F2EB	5/30/2019	12/16/2019
DAS17	DAS	NI/DEWETRON	DEWE-30-16	0195BB69	9/23/2019	4/10/2020
ISO132	ISO AMP	DEWETRON	HIS-LV	437726	9/23/2019	4/10/2020
ISO117	ISO AMP	DEWETRON	HIS-LV	437711	9/23/2019	4/10/2020
ISO118	ISO AMP	DEWETRON	HIS-LV	437712	9/23/2019	4/10/2020
ISO119	ISO AMP	DEWETRON	HIS-LV	437713	9/23/2019	4/10/2020
ISO124	ISO AMP	DEWETRON	HIS-LV	437718	9/23/2019	4/10/2020
ISO125	ISO AMP	DEWETRON	HIS-LV	437719	9/23/2019	4/10/2020
ISO126	ISO AMP	DEWETRON	HIS-LV	437720	9/23/2019	4/10/2020
CTX172	ROGOWSKI CT	PEM	SDS0680	0002-0100A	10/11/2019	4/28/2020
CTX173	ROGOWSKI CT	PEM	SDS0680	0002-0100B	10/11/2019	4/28/2020
CTX174	ROGOWSKI CT	PEM	SDS0680	0002-0100C	10/11/2019	4/28/2020
CTX175	ROGOWSKI CT	PEM	SDS0680	0002-0100D	10/11/2019	4/28/2020
VDR84	V.DIVIDER	NORTH STAR	VD-150	1	6/21/2019	1/7/2020
VDR86	V.DIVIDER	NORTH STAR	VD-150	3	6/21/2019	1/7/2020
VDR90	V.DIVIDER	NORTH STAR	VD-150	7	6/21/2019	1/7/2020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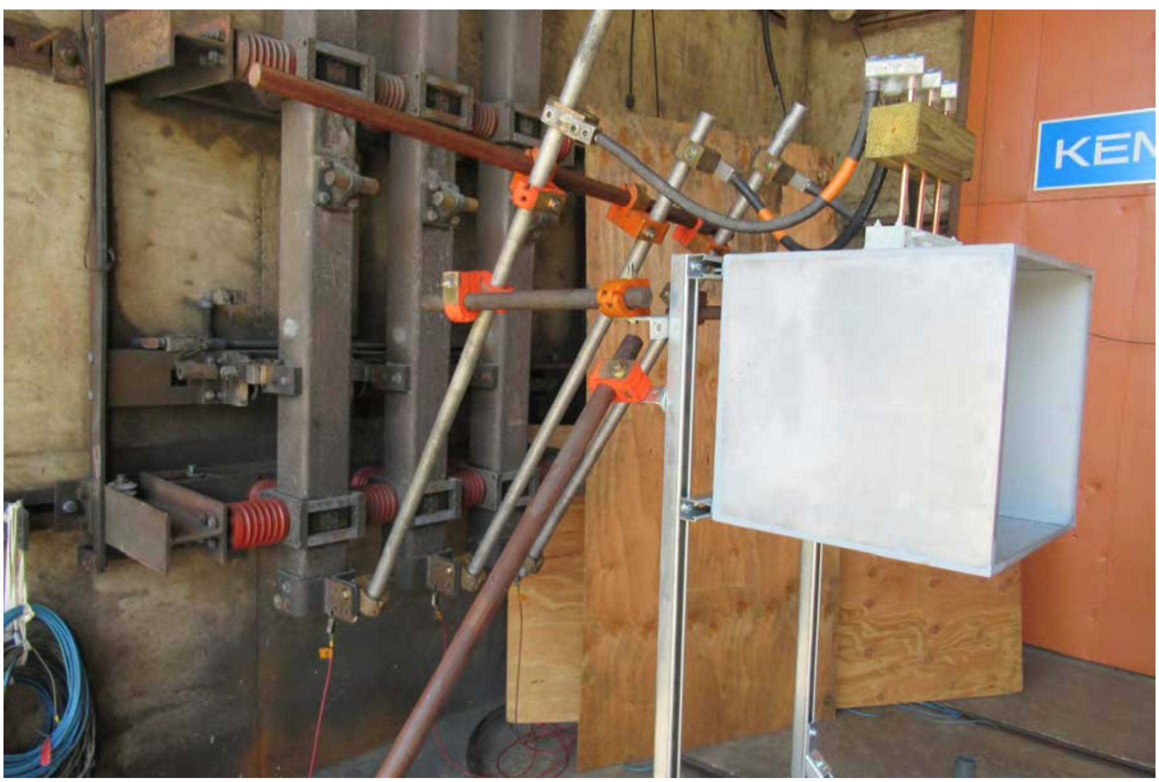
QUOTE #:
245/2323
TRIAL #:
7003
SAMPLE #:
NOTES:
1 KA
1 kV
BEFORE TEST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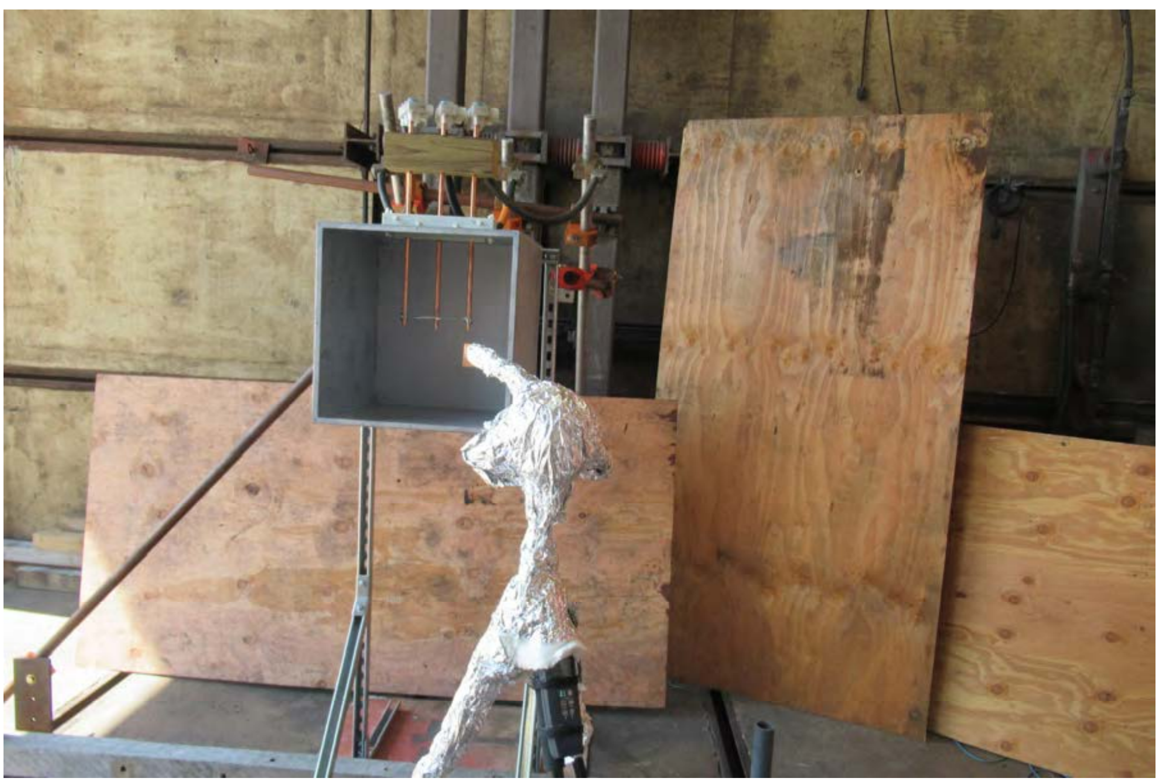

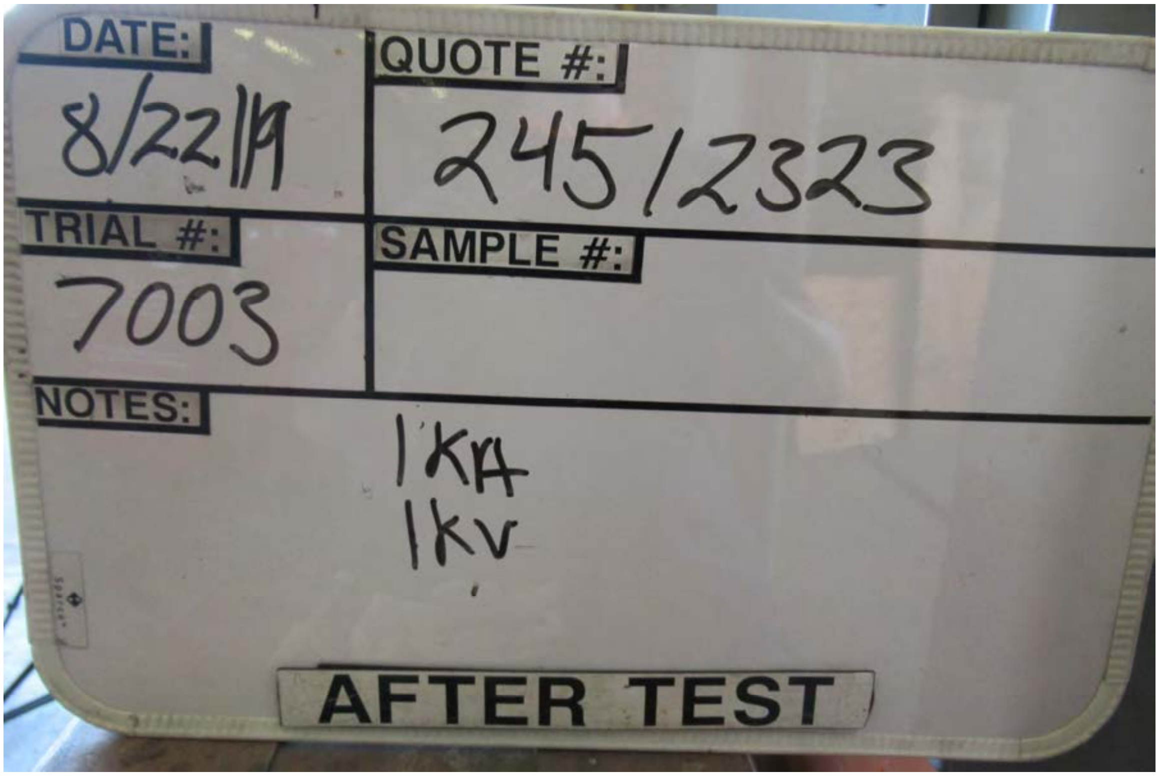
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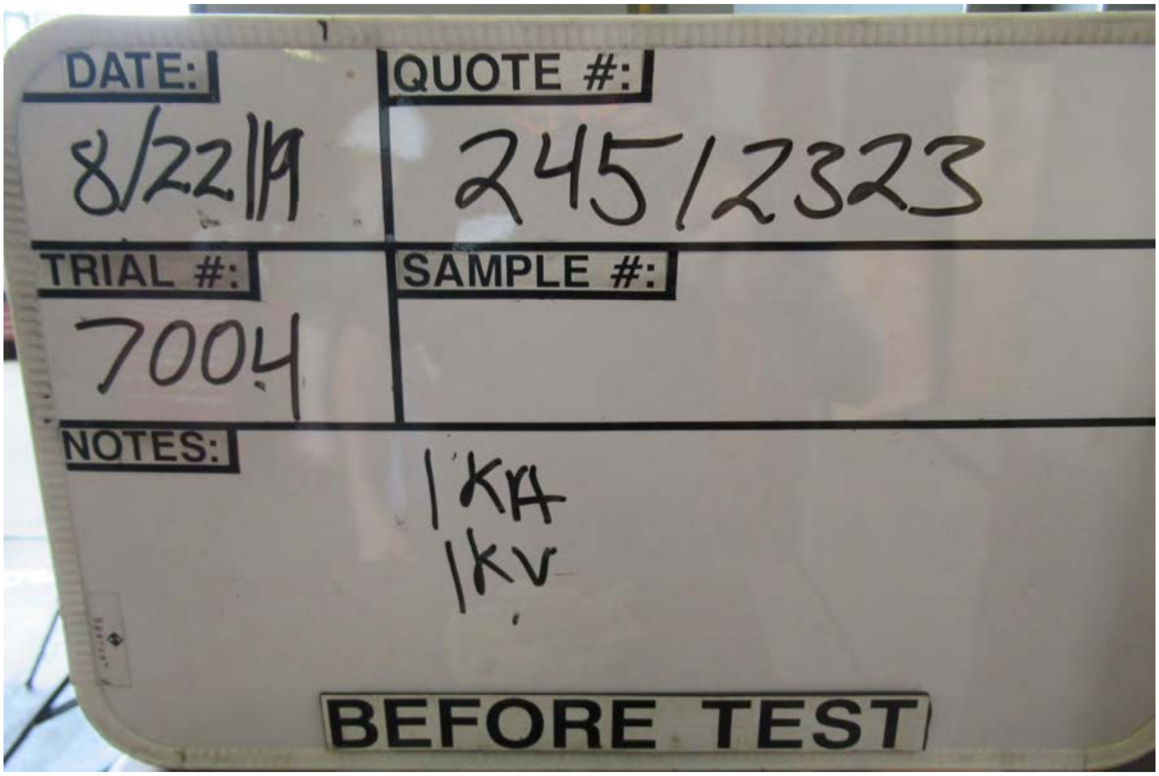
QUOTE #:
245/2323
TRIAL #:
7003
SAMPLE #:
NOTES:
1KA
1KV
AFTER TEST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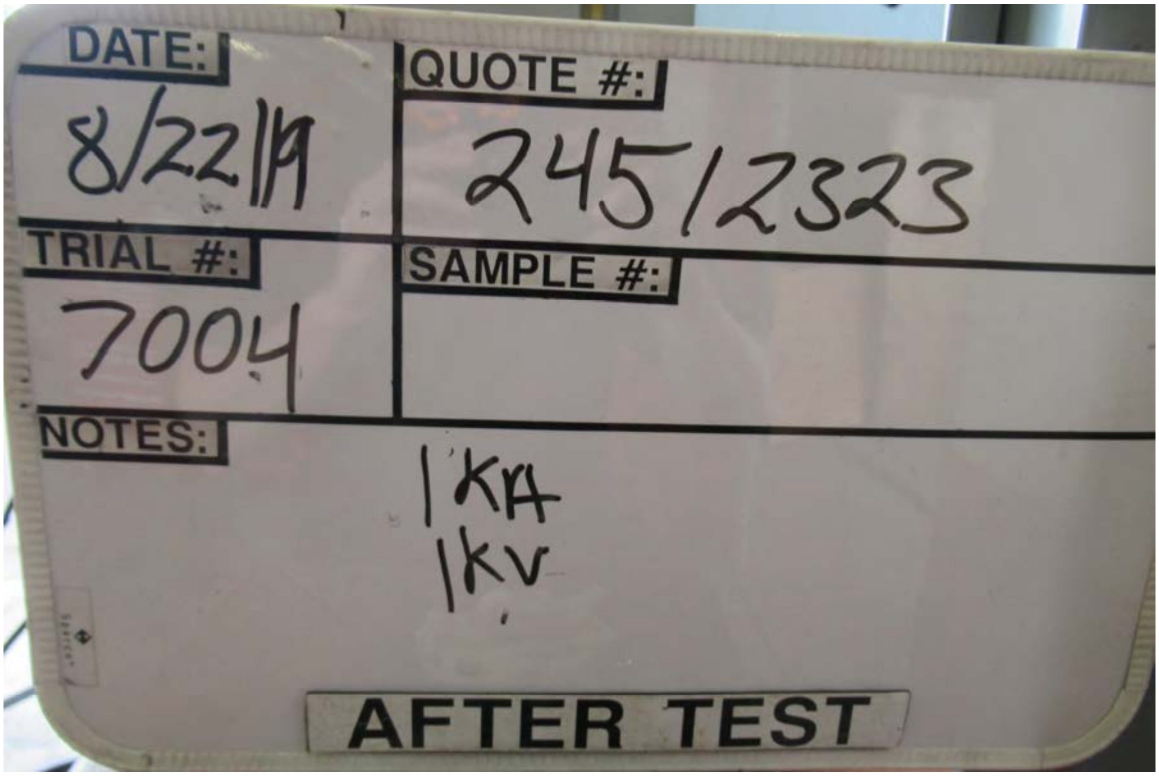
QUOTE #:
24512323
TRIAL #:
7004
SAMPLE #:
NOTES:
1KA
1KV
BEFORE TEST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TRIAL #:
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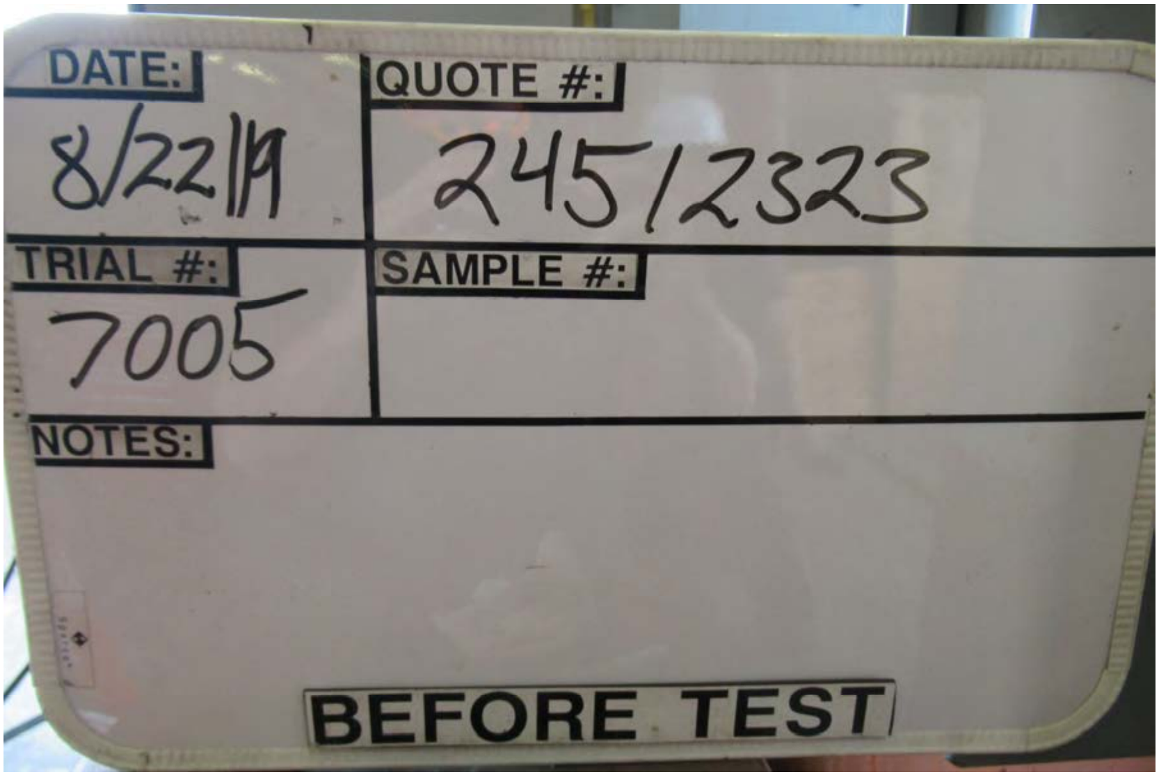
SAMPLE #:
NOTES:
1KA
1KV
AFTER TEST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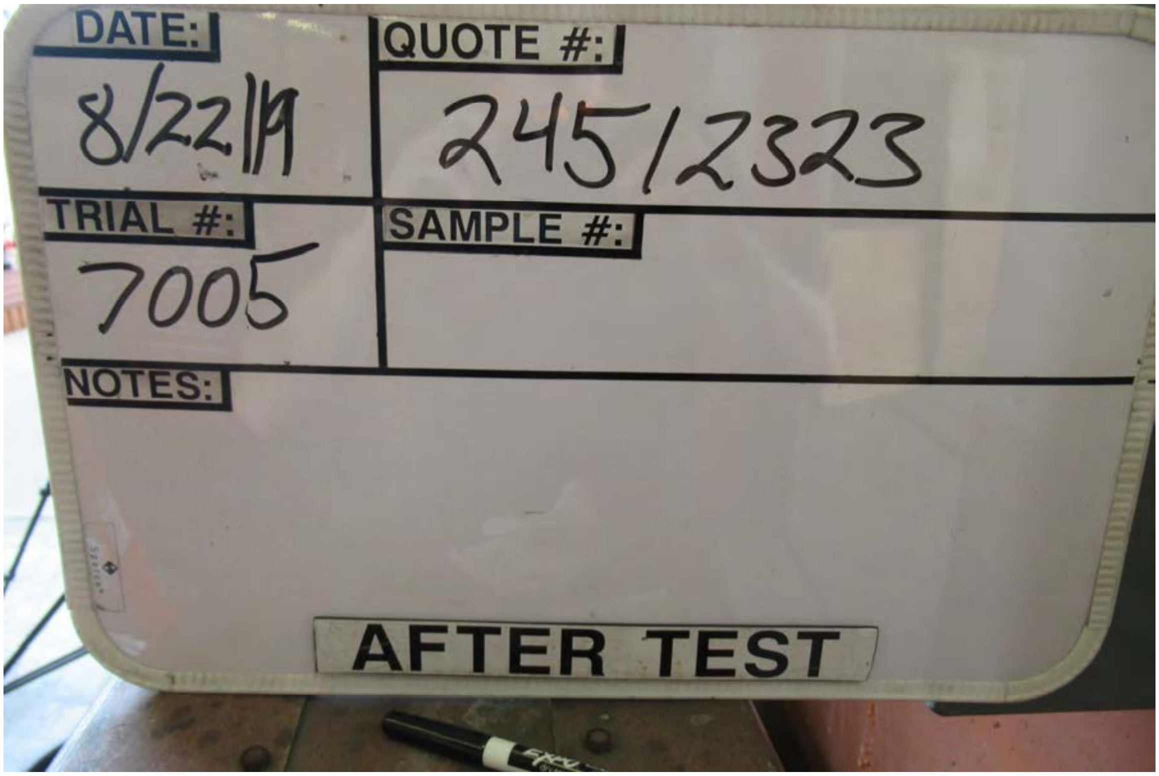
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SAMPLE #:
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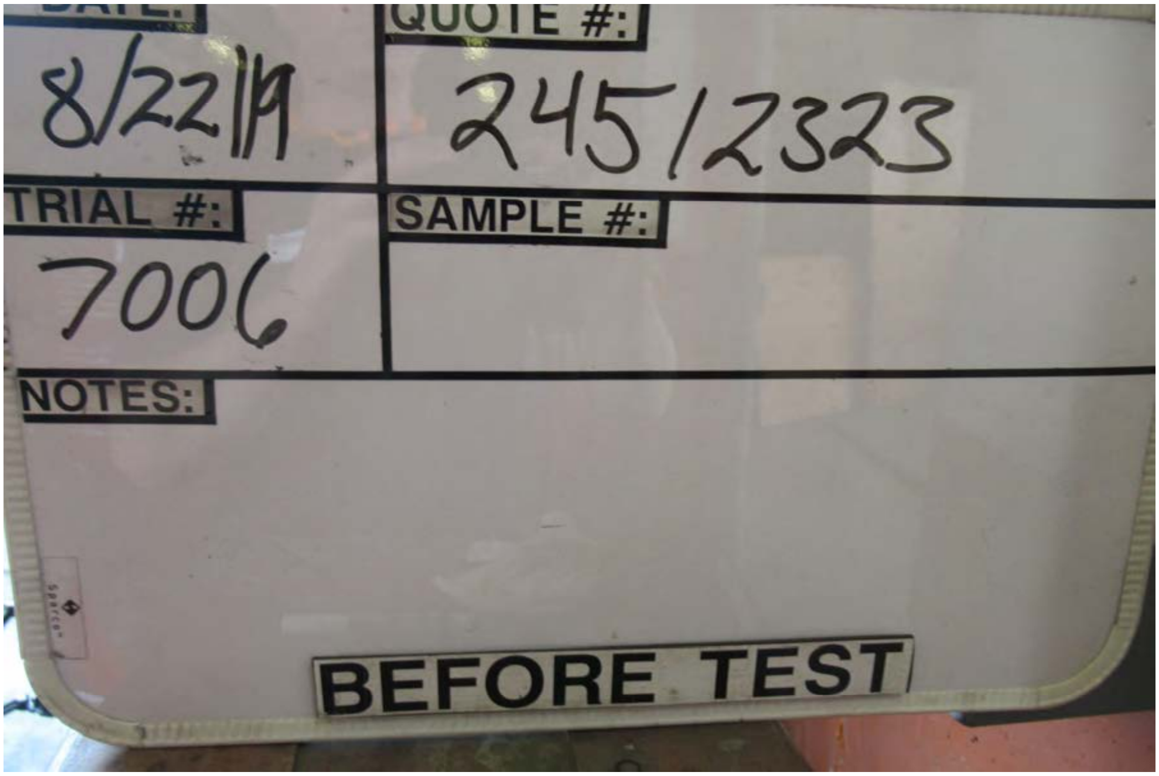
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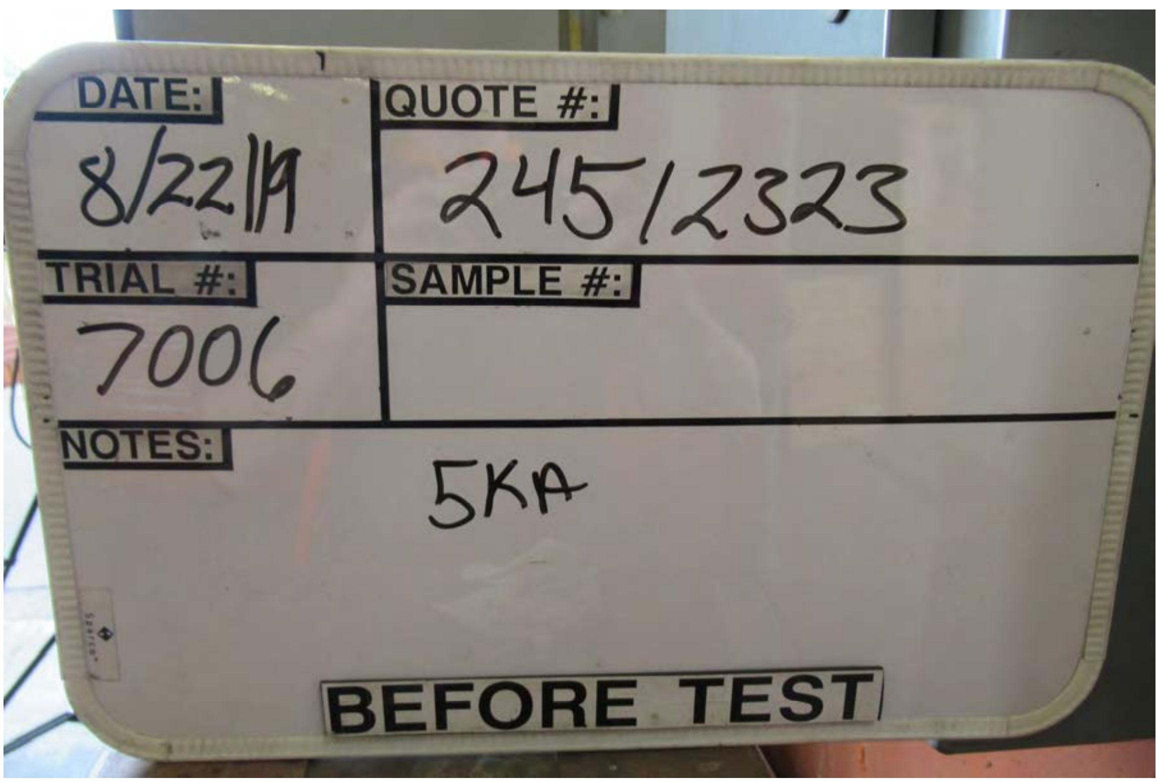
245/2323
TRIAL #:
SAMPLE #:
7006
NOTES:
BEFORE TEST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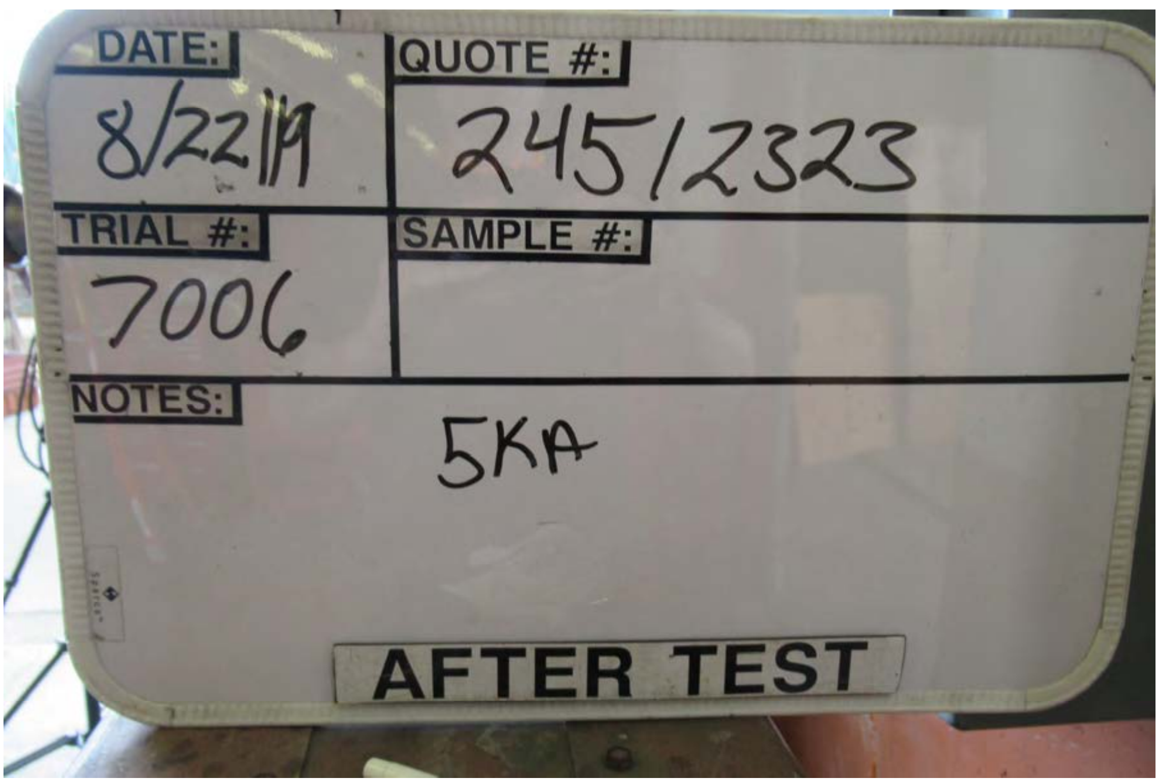
245/2323
TRIAL #:
SAMPLE #:
7006
NOTES:
5KA
BEFORE TEST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QUOTE #:
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TRIAL #:
7006
SAMPLE #:
NOTES:
5KA
AFTER TEST


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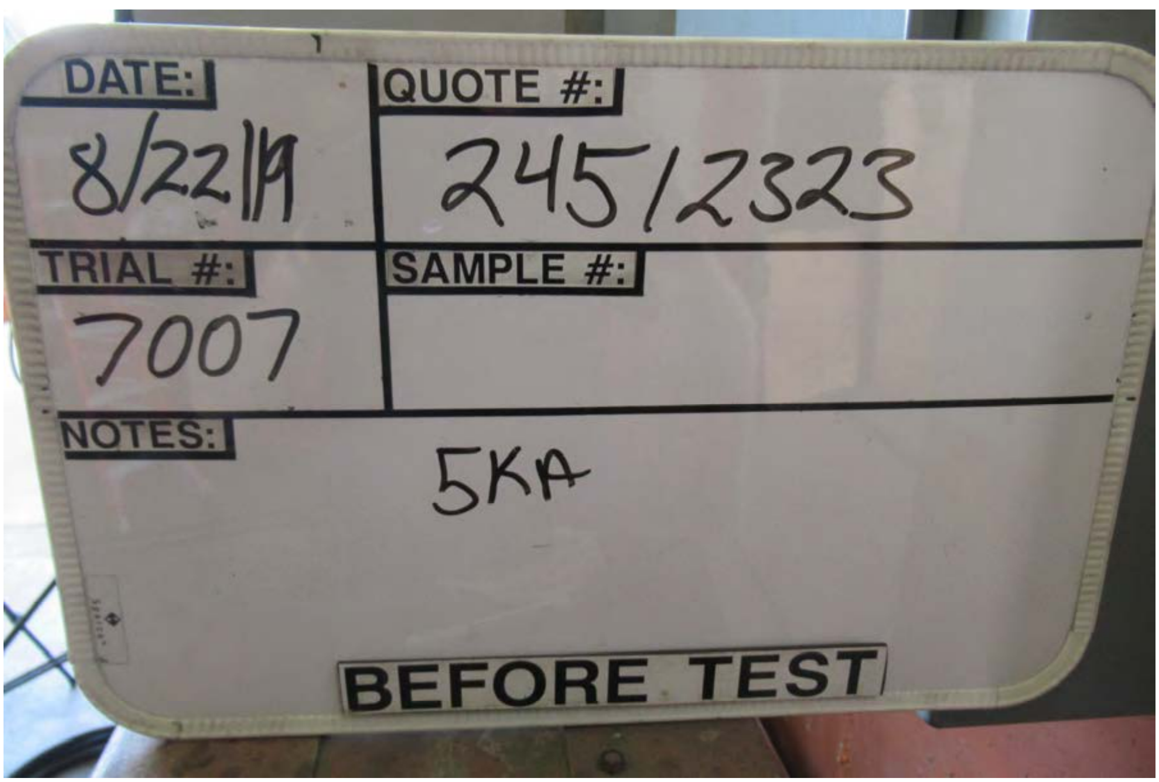
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QUOTE #:
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TRIAL #:
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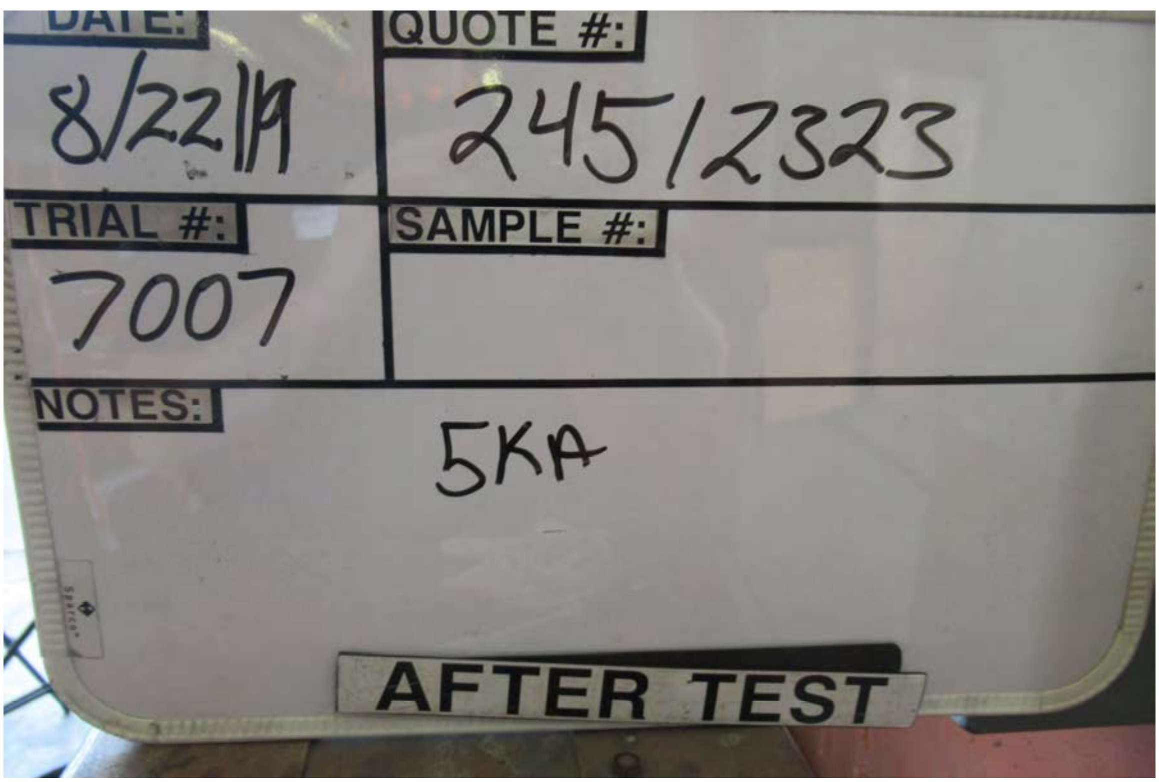
SAMPLE #:
NOTES:
5KA
BEFORE TEST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QUOTE #:
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TRIAL #:
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SAMPLE #:
NOTES:
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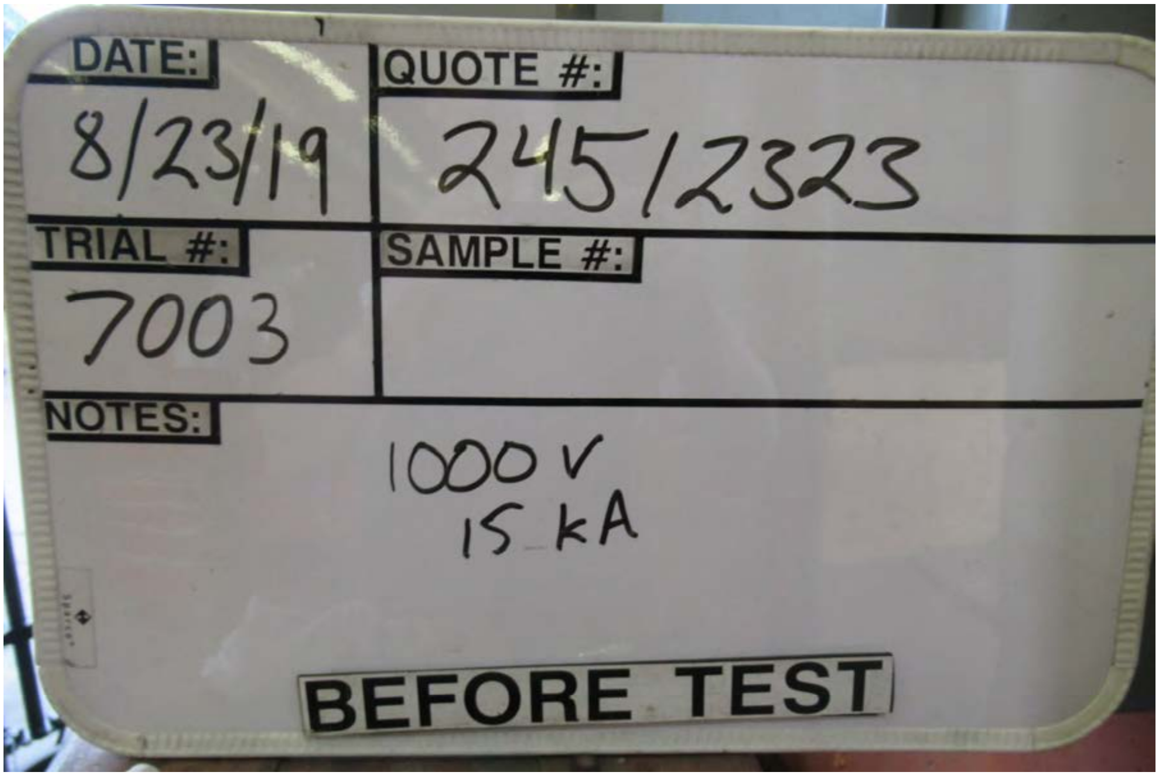
AFTER TEST


DATE:
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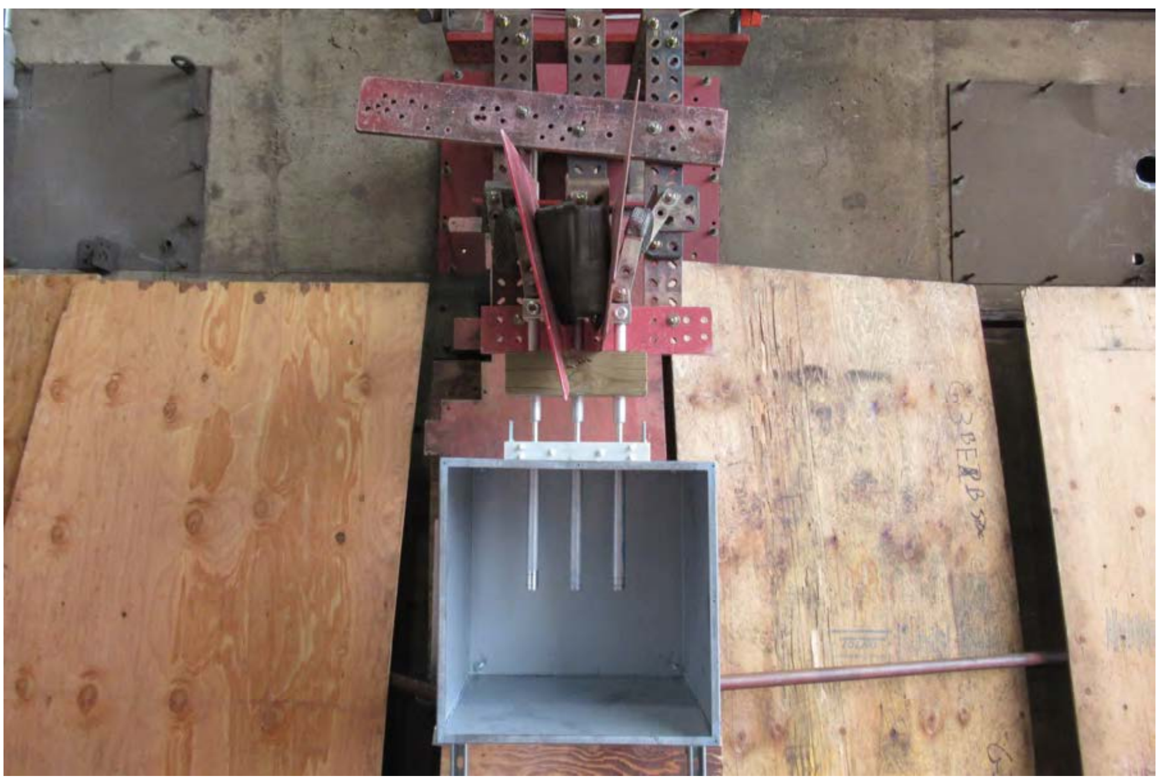
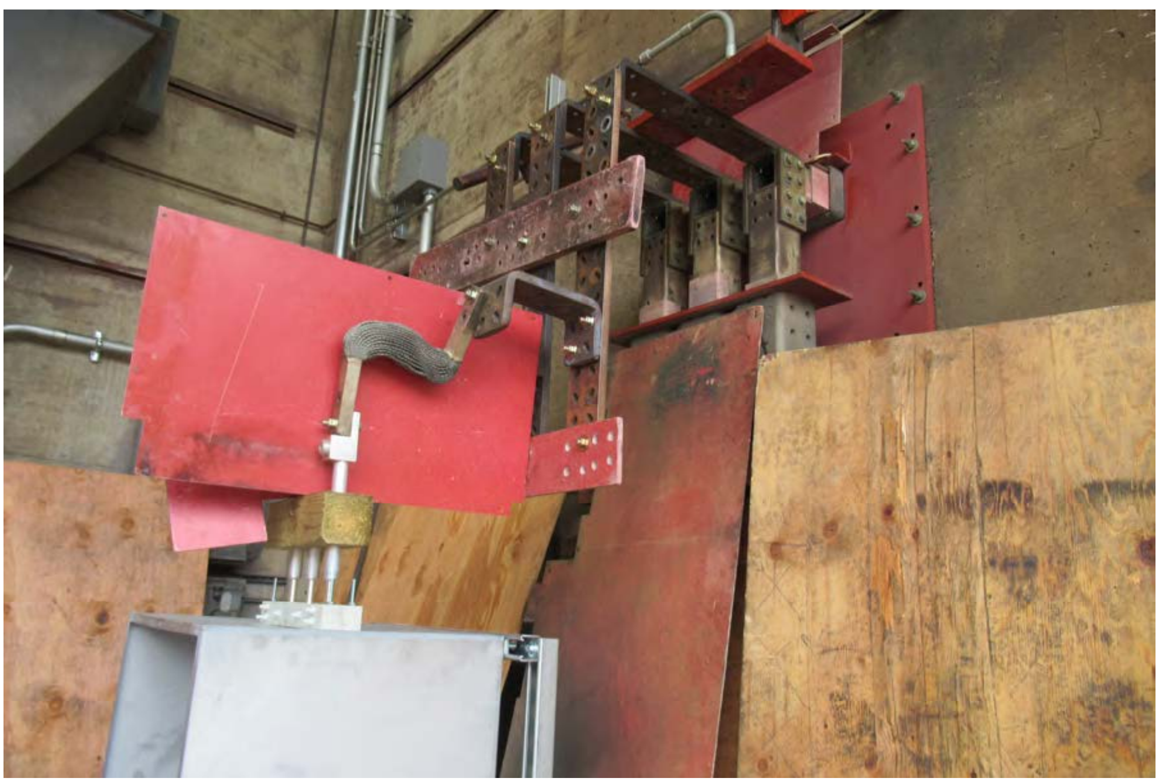
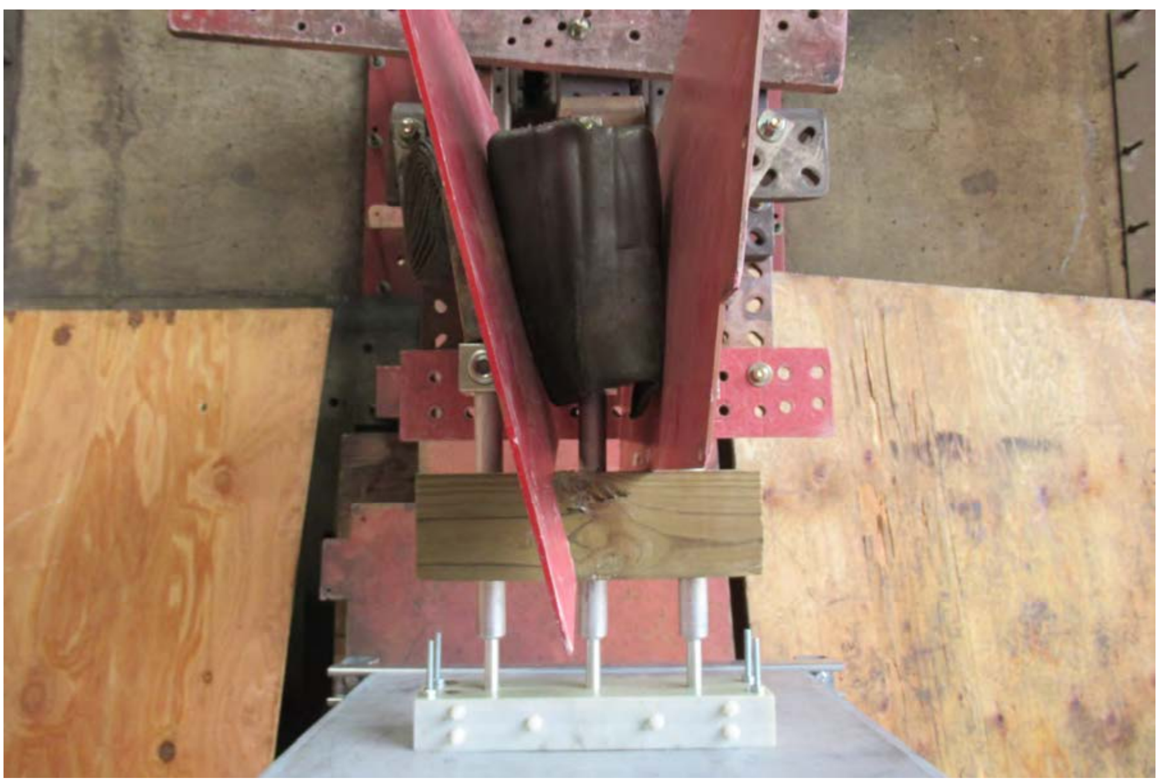
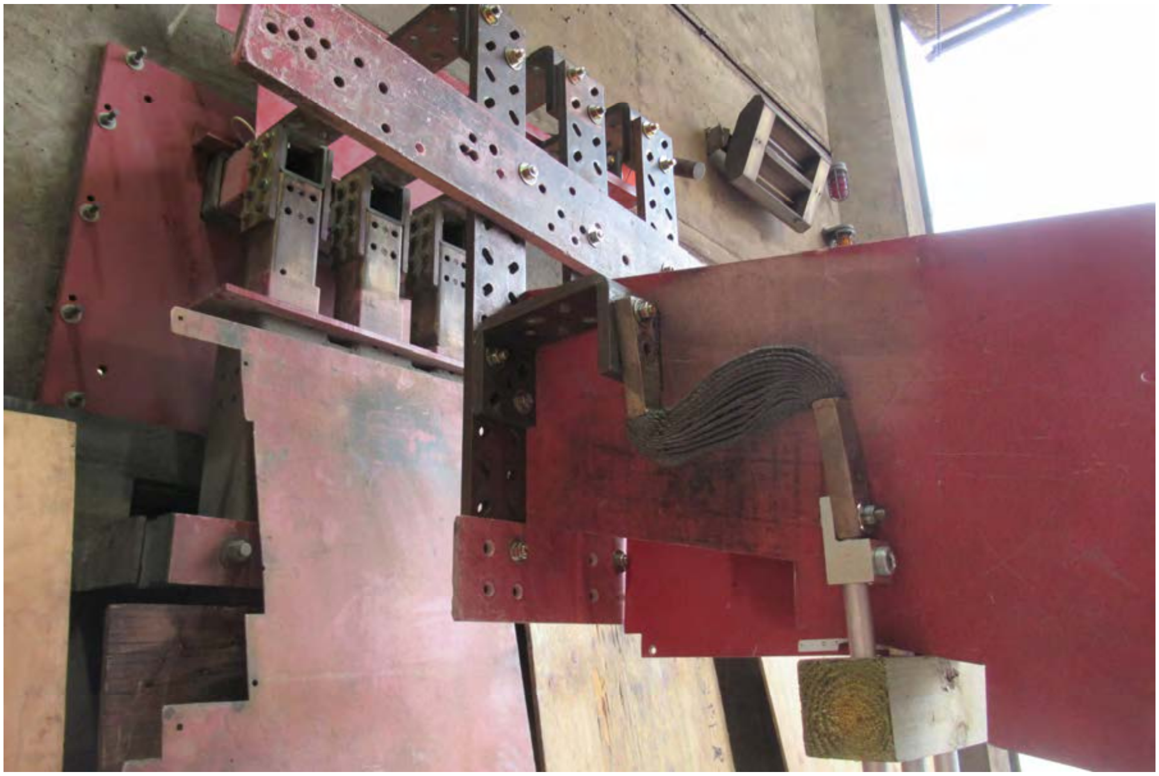
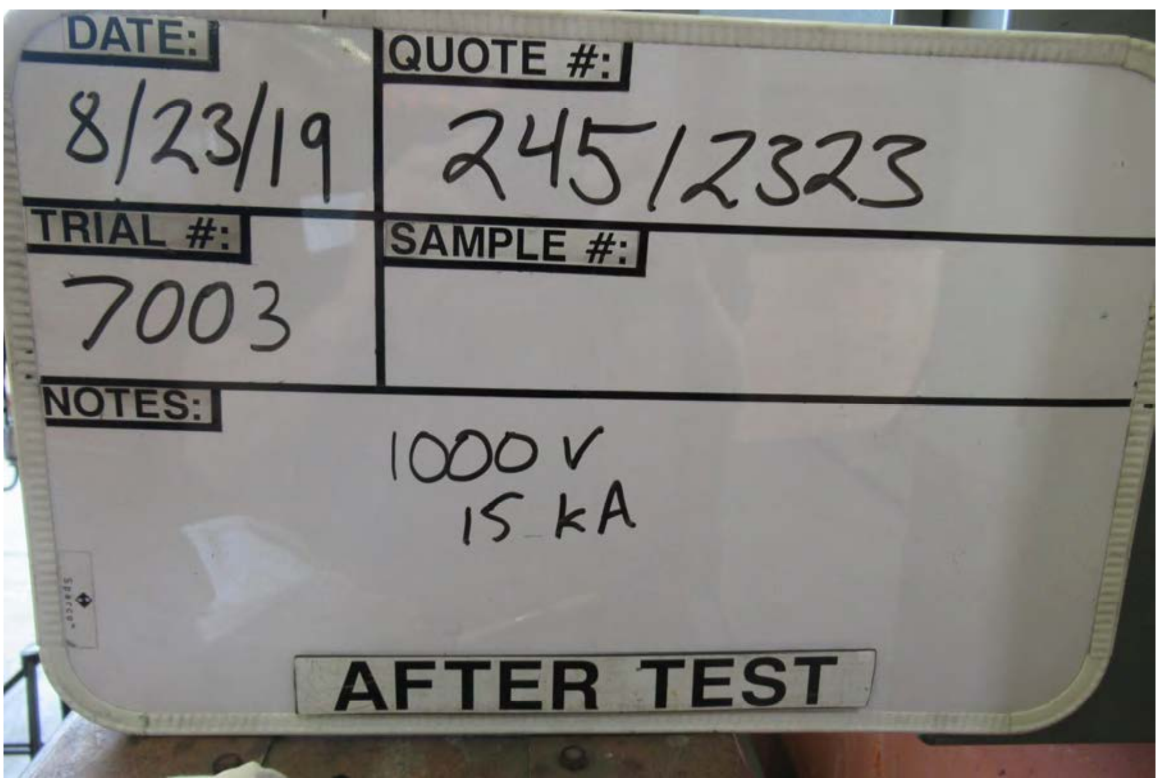
QUOTE #:
245 12323
TRIAL #:
7003
SAMPLE #:
NOTES:
1000 V
15 kA
BEFORE TEST







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245/2323
TRIAL #:
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SAMPLE #:
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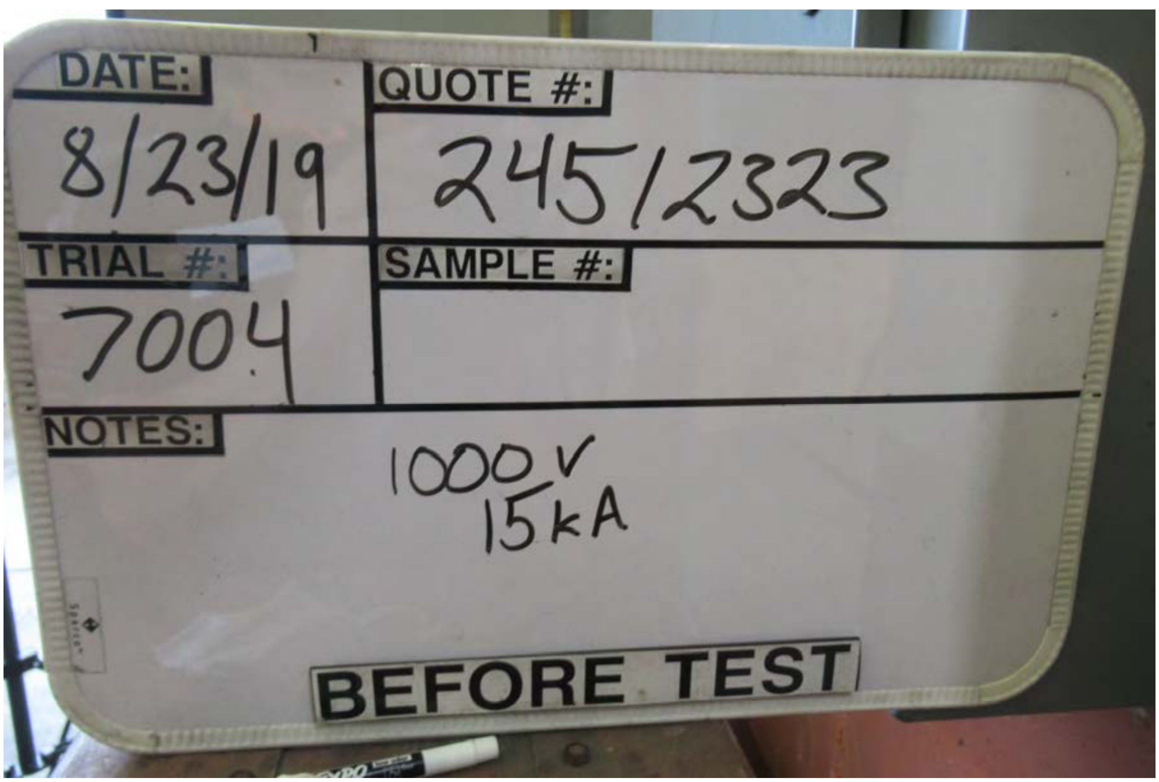
15 kA
AFTER TEST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TRIAL #:
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SAMPLE #:
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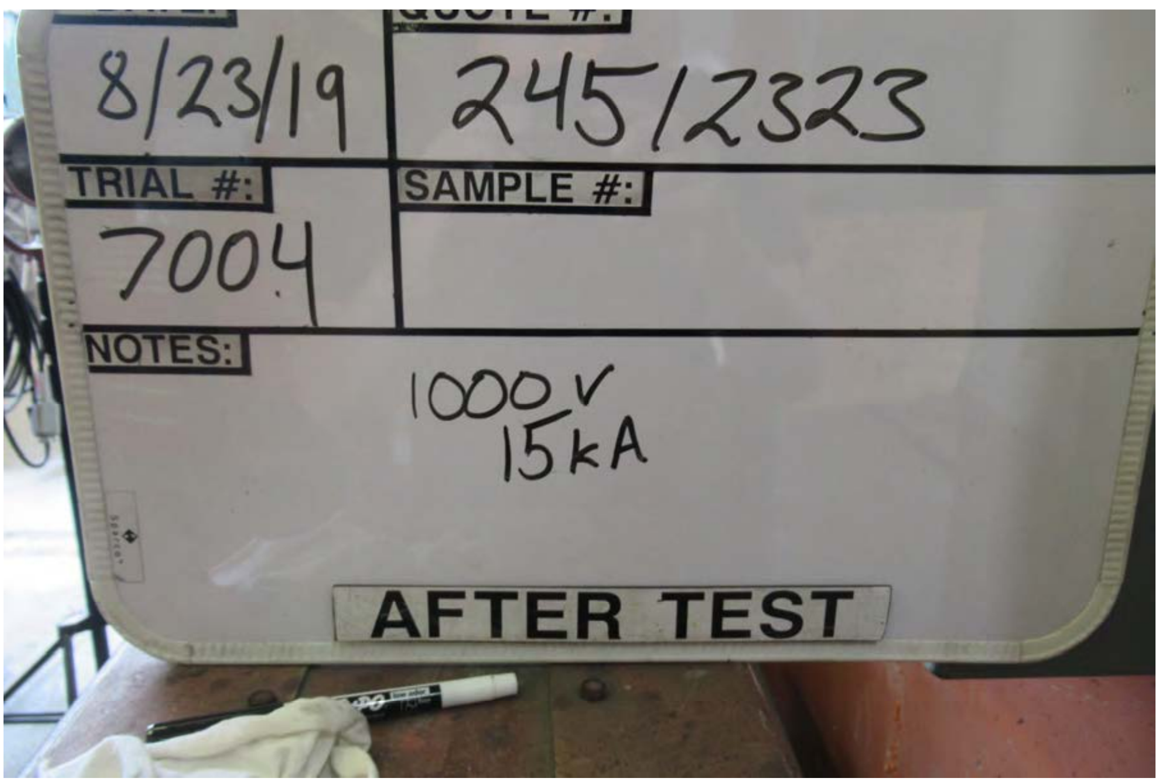
BEFORE TEST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TRIAL #:
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SAMPLE #:
NOTES:
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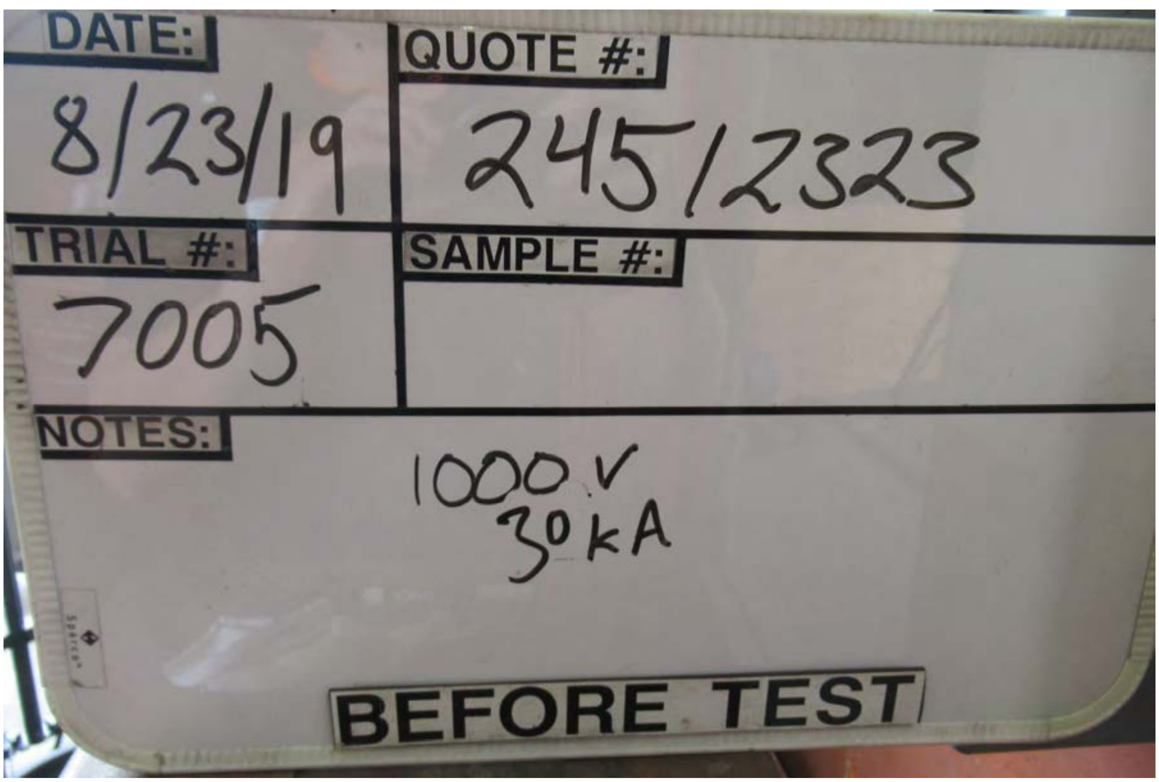
15 kA
AFTER TEST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QUOTE #:
245/2323
TRIAL #:
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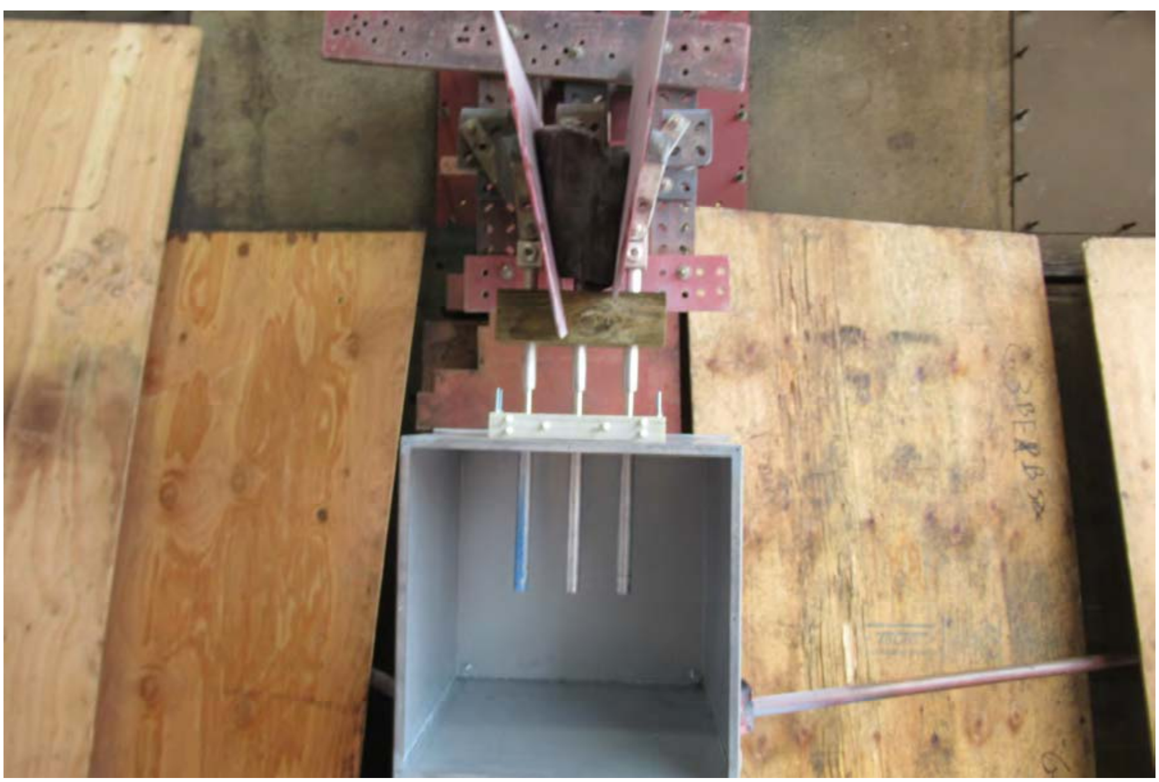
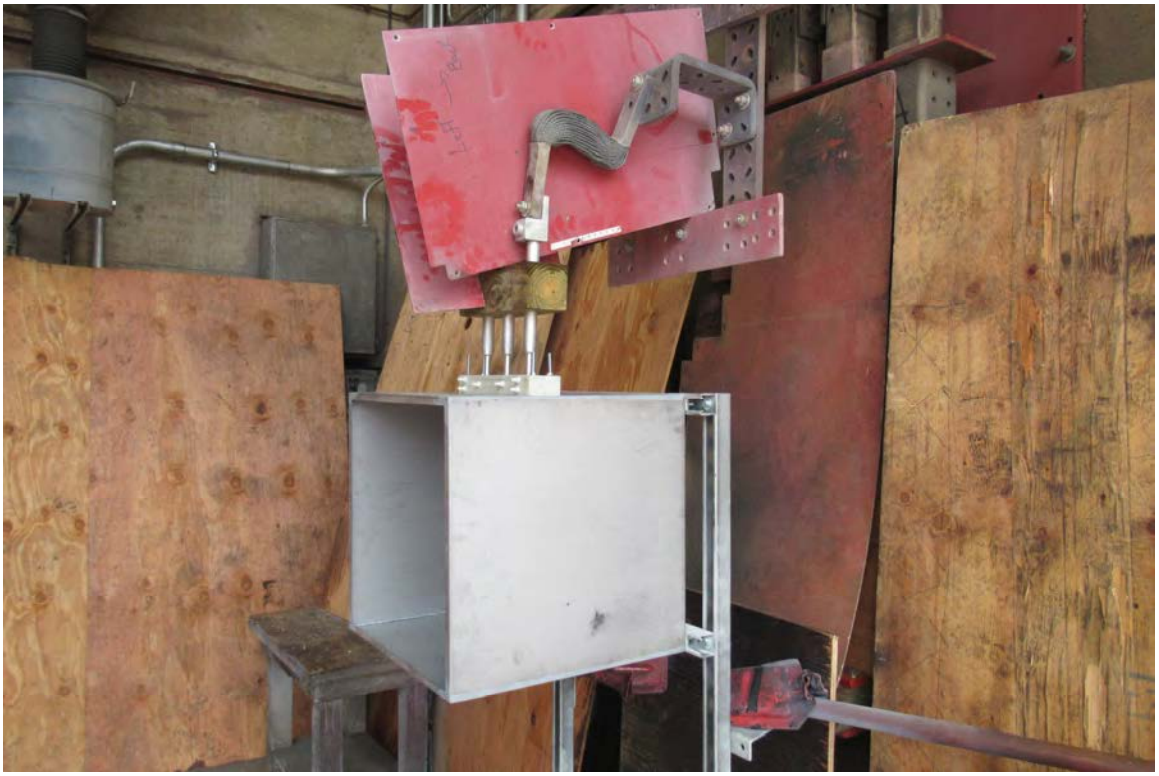
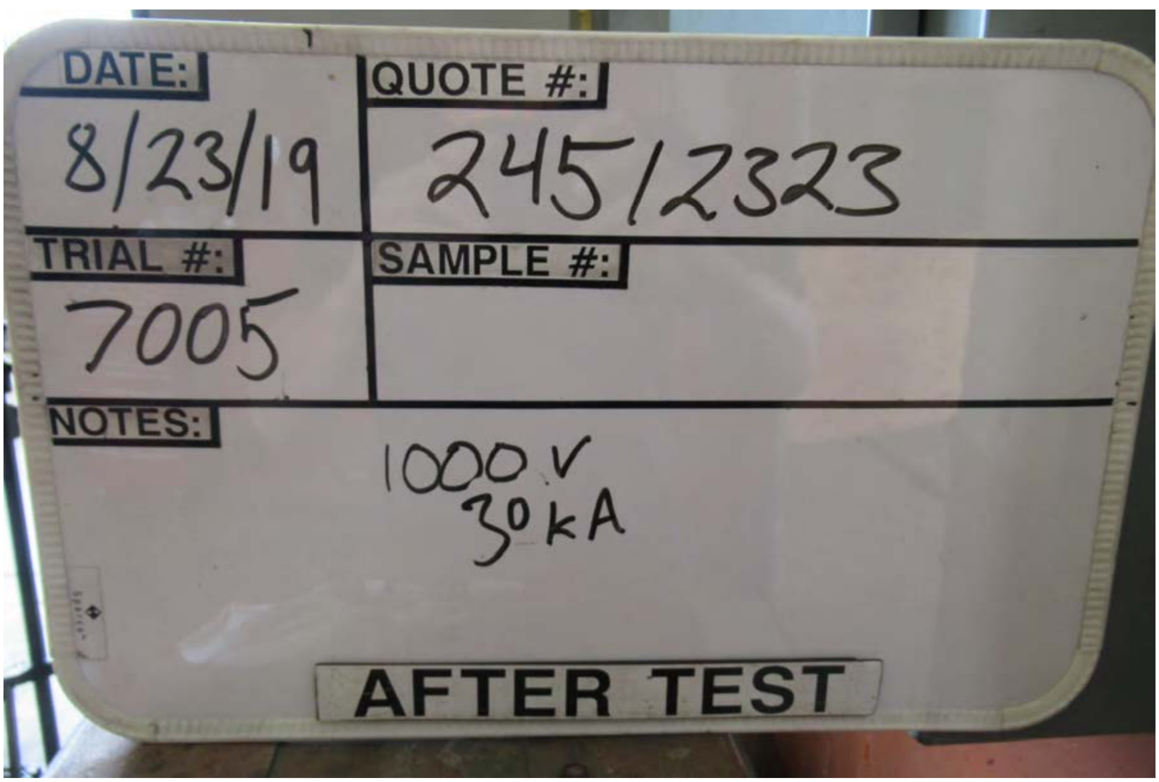
SAMPLE #:
NOTES:
1000 V
30 kA
BEFORE TEST



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TRIAL #:
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SAMPLE #:
NOTES:
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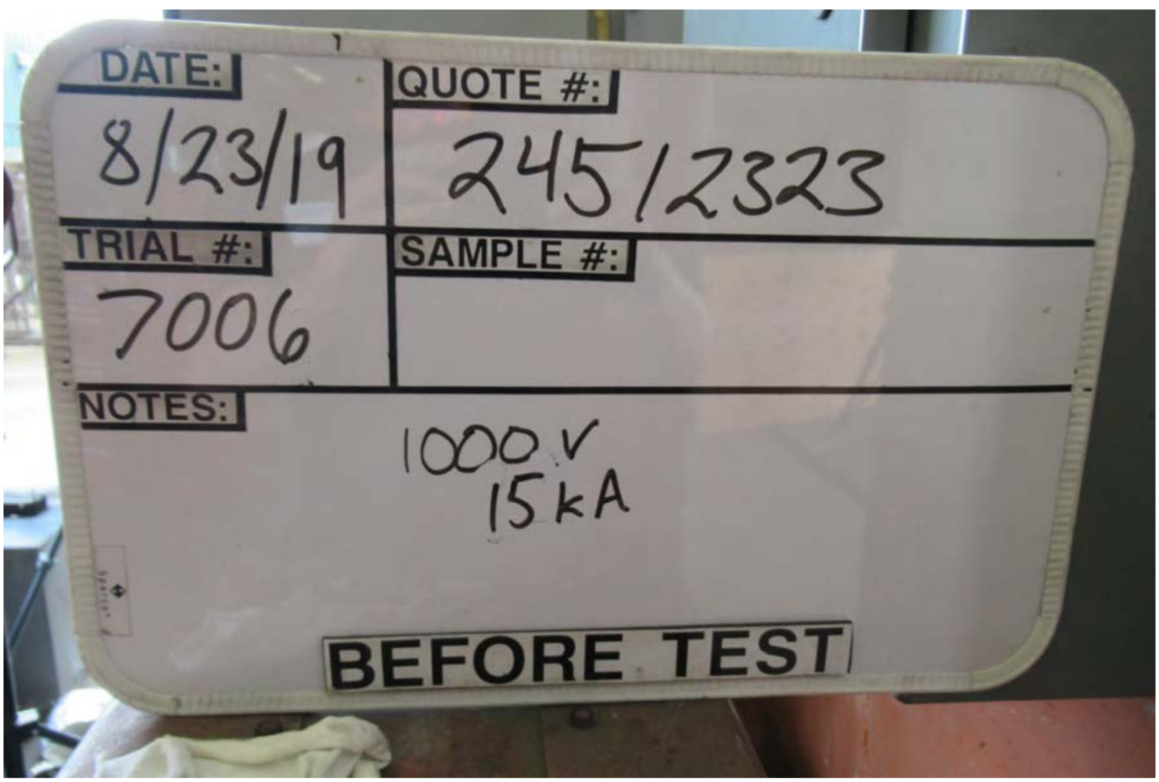
30 kA
AFTER TEST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TRIAL #:
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SAMPLE #:
NOTES:
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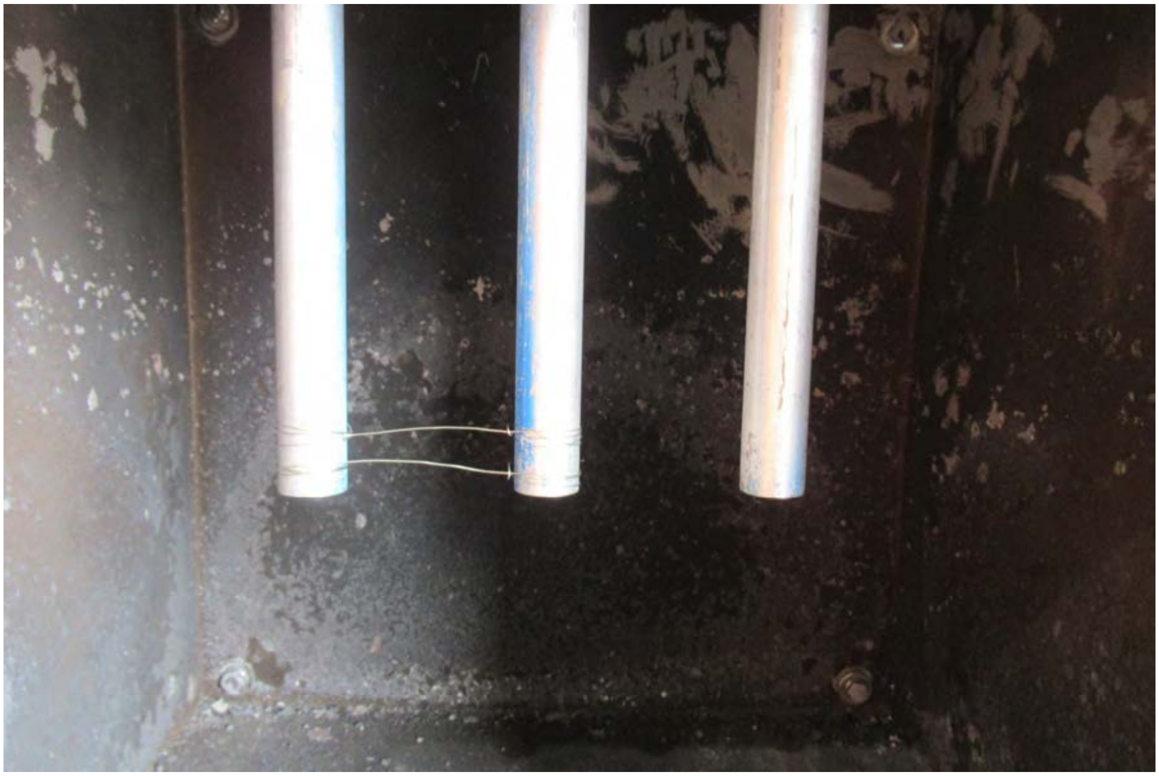
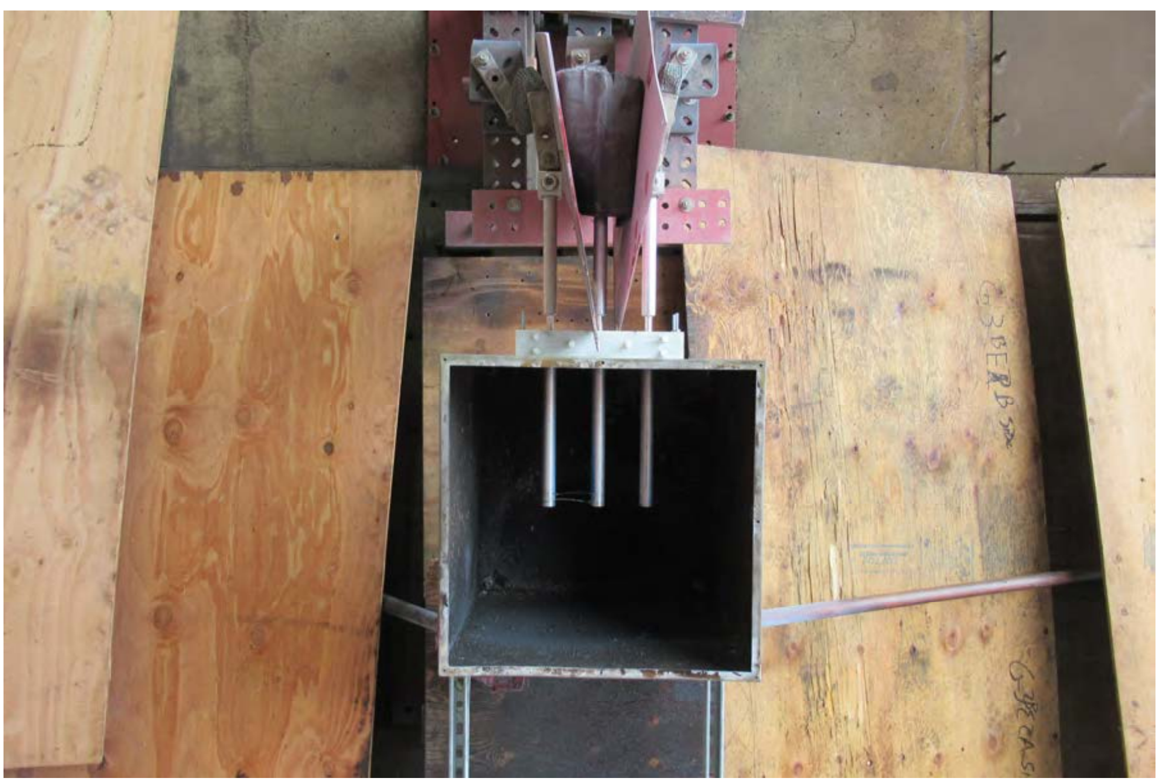
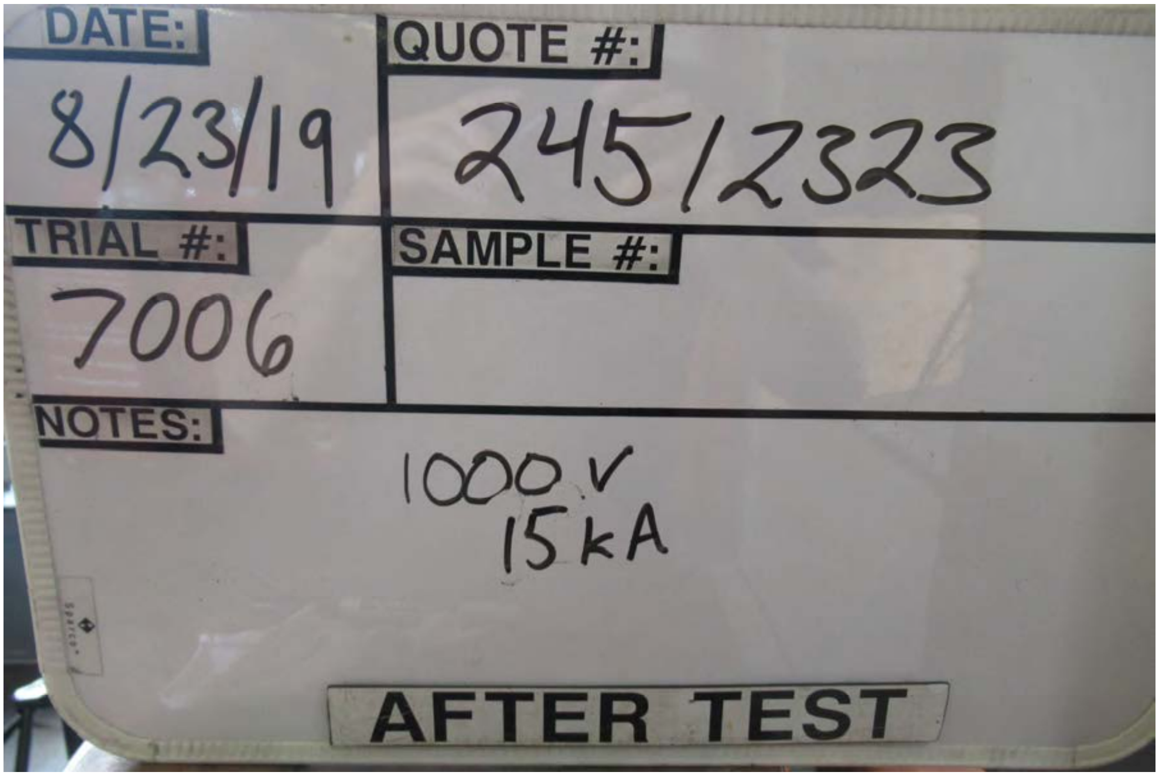
15 kA
BEFORE TEST



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QUOTE #:
245/2323
TRIAL #:
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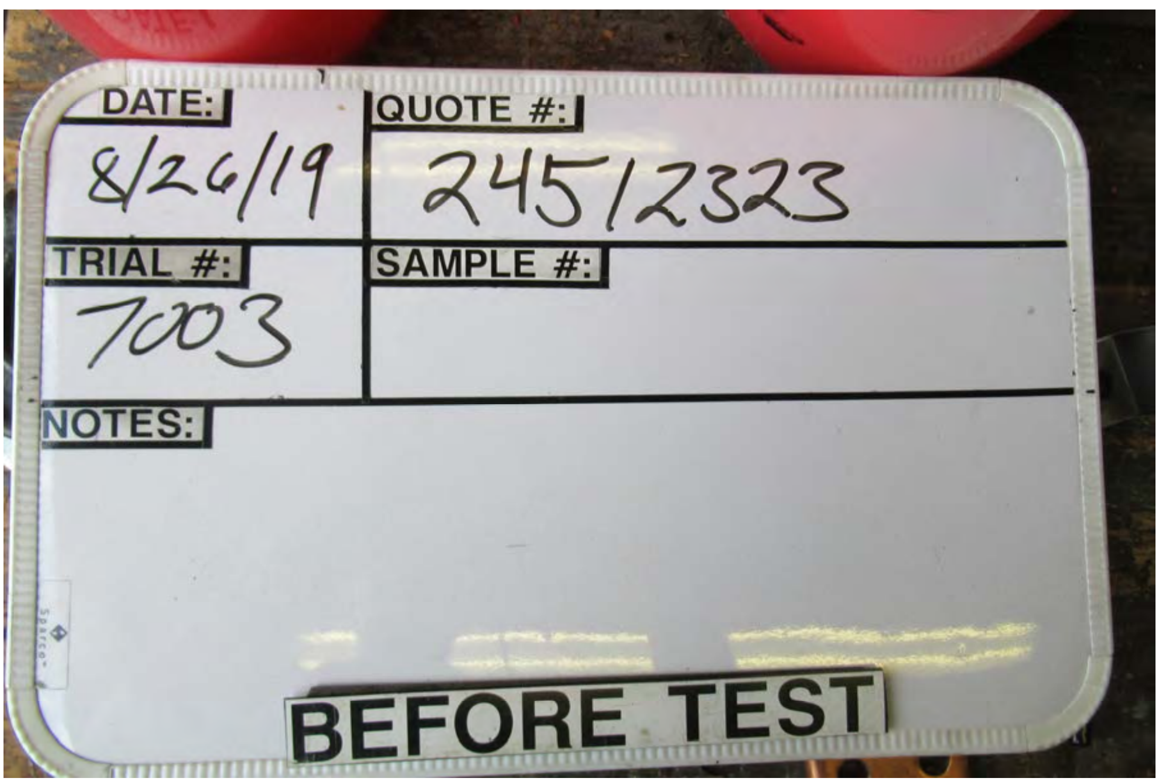
SAMPLE #:
NOTES:
1000 V
15 kA
AFTER TEST


DATE:
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QUOTE #:
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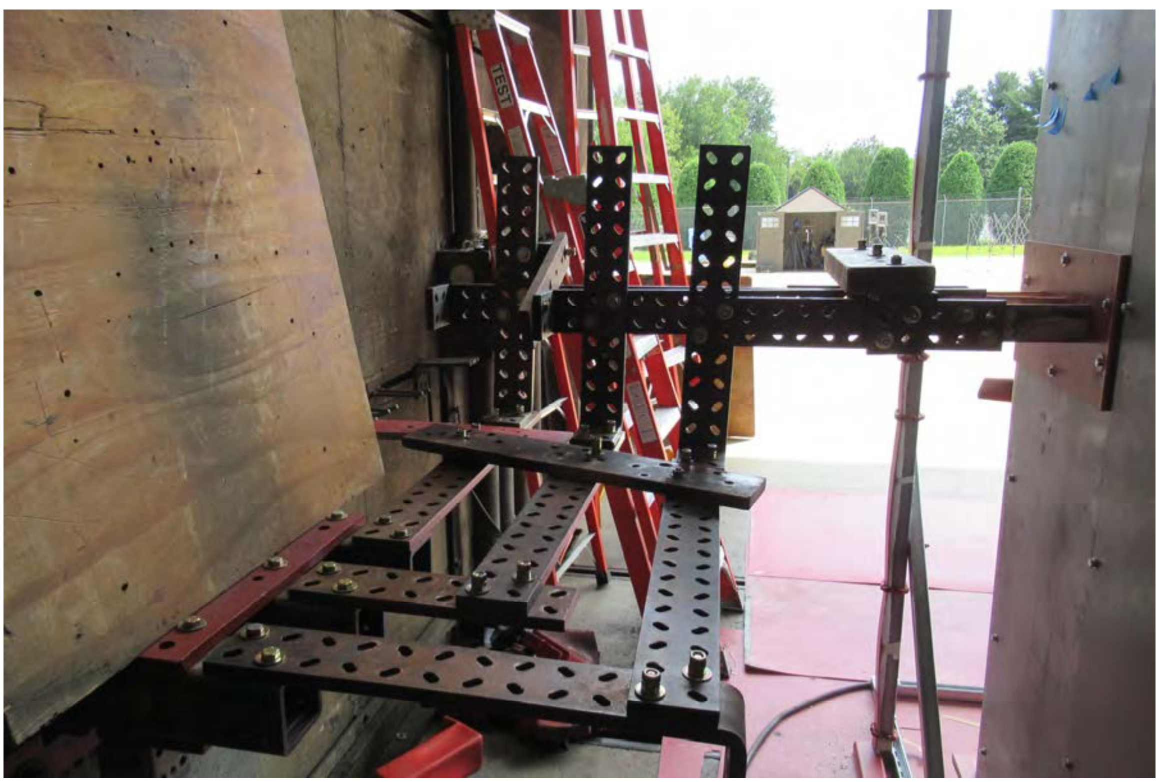
TRIAL #:
7003
SAMPLE #:
NOTES:
BEFORE TEST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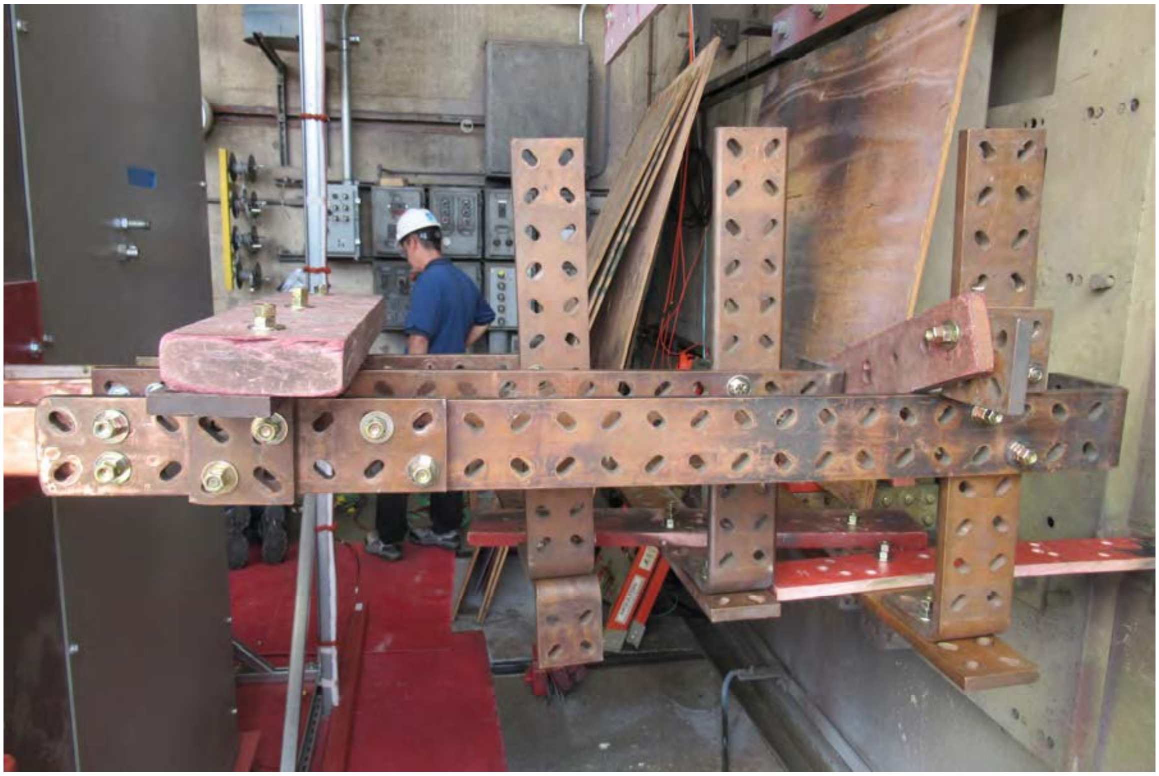

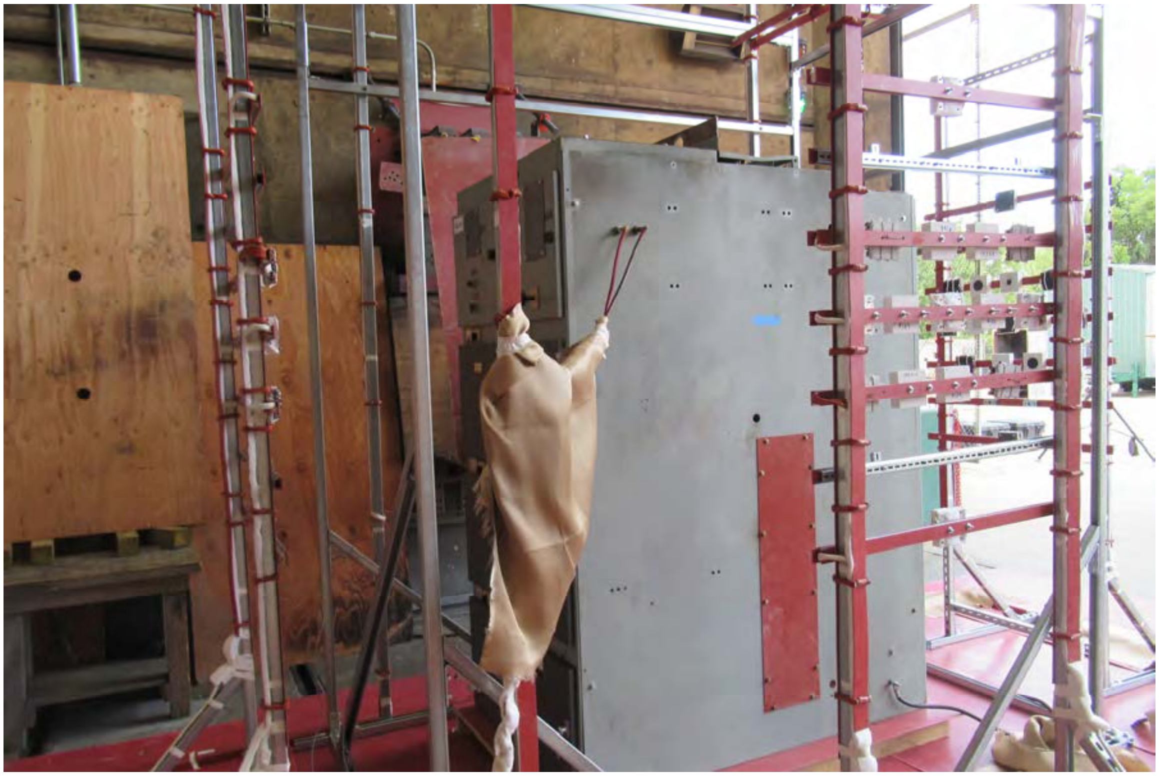

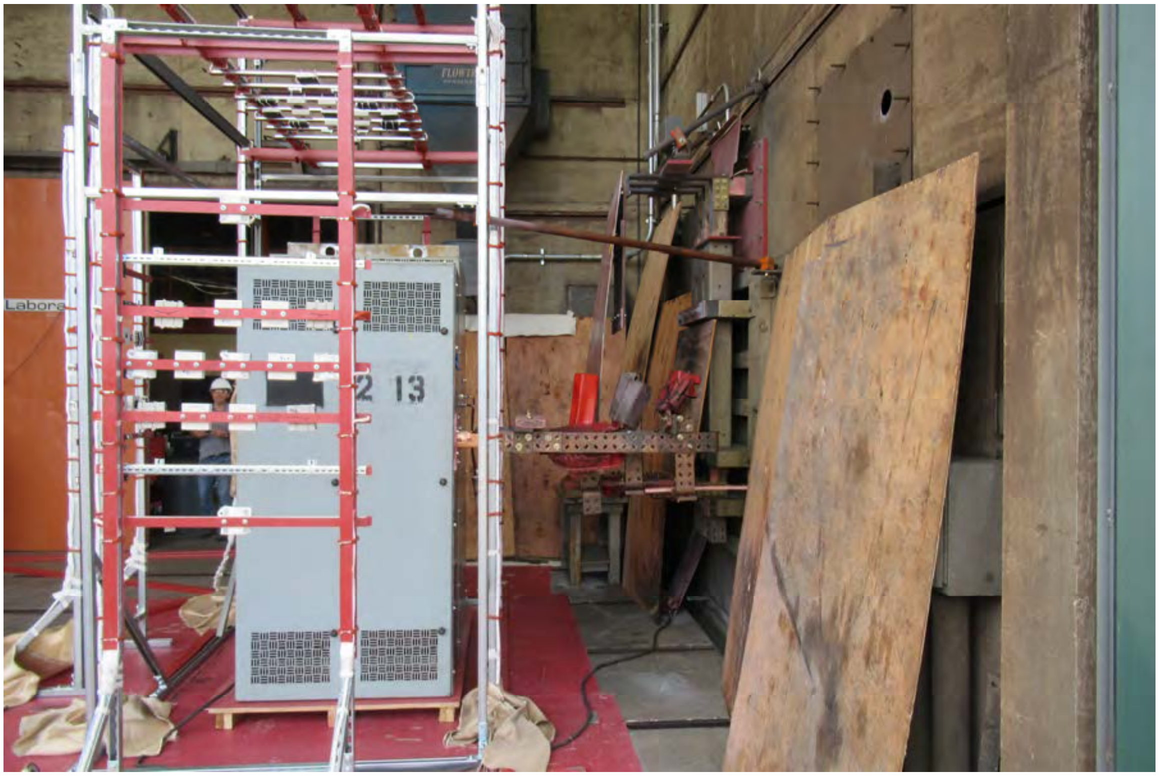

2 13

KEMA
Laboratories


2 13


DATE:
8/26/19
QUOTE #:
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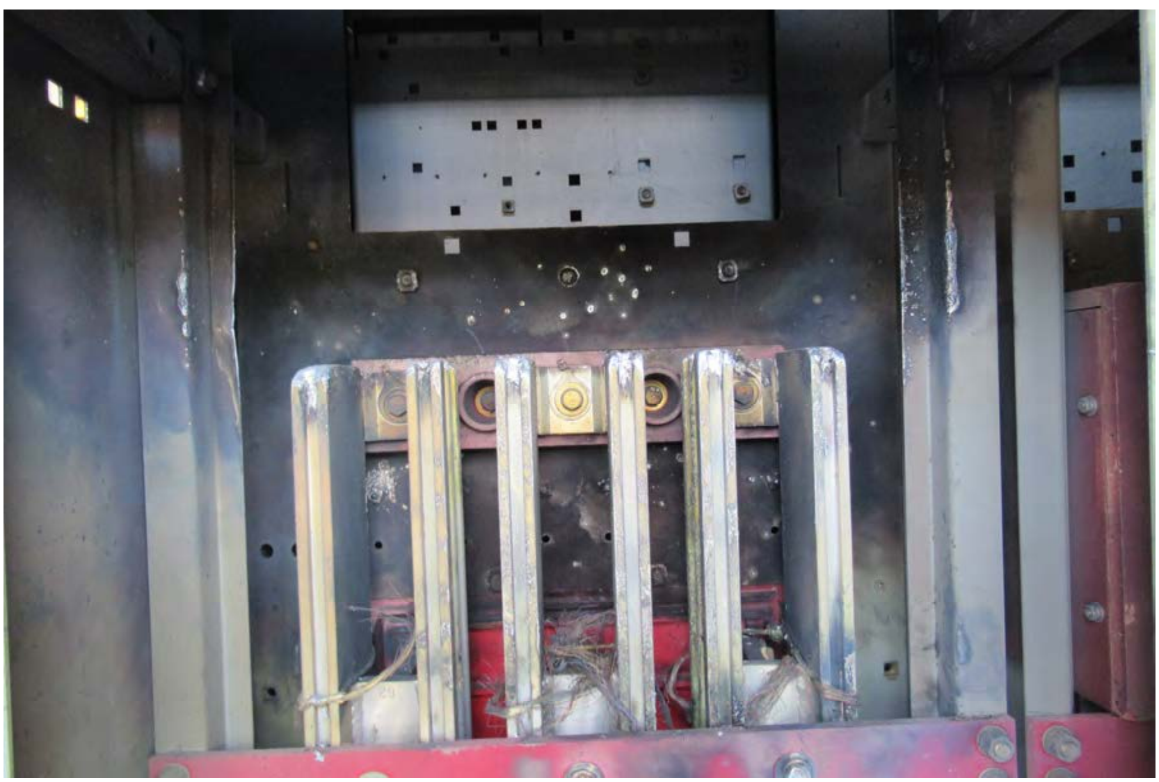
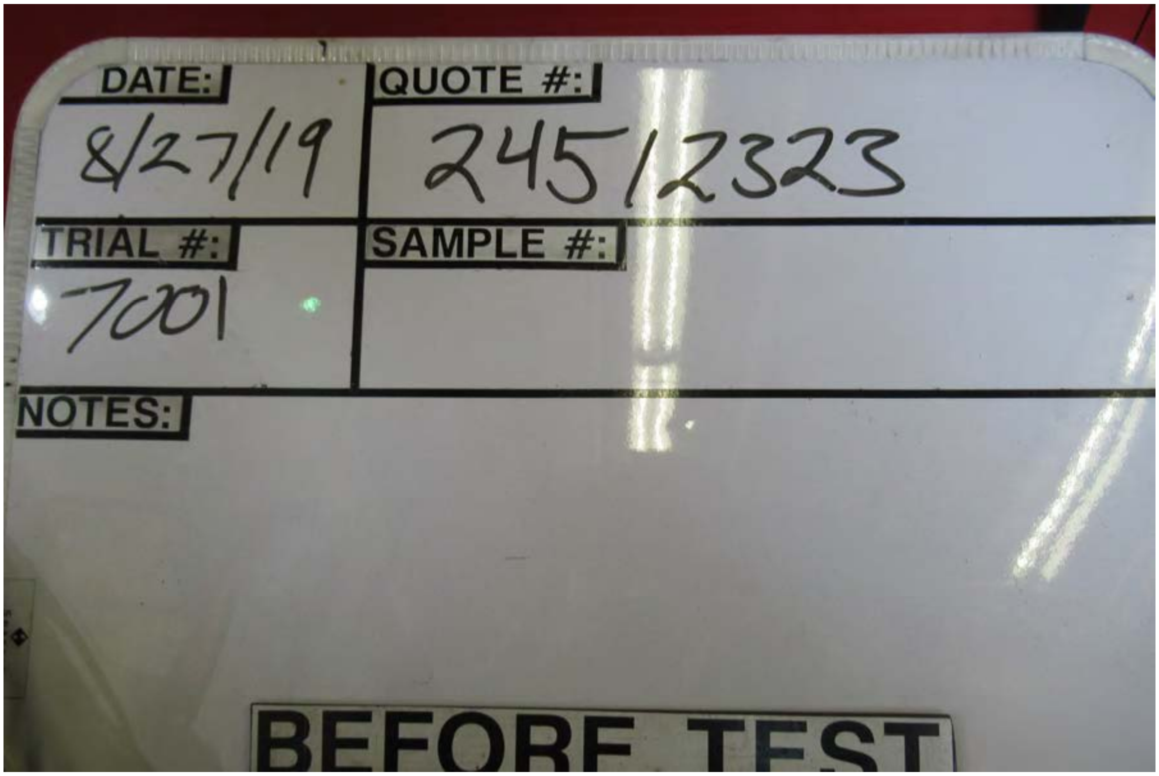
TRIAL #:
7003
SAMPLE #:
NOTES:
AFTER TEST

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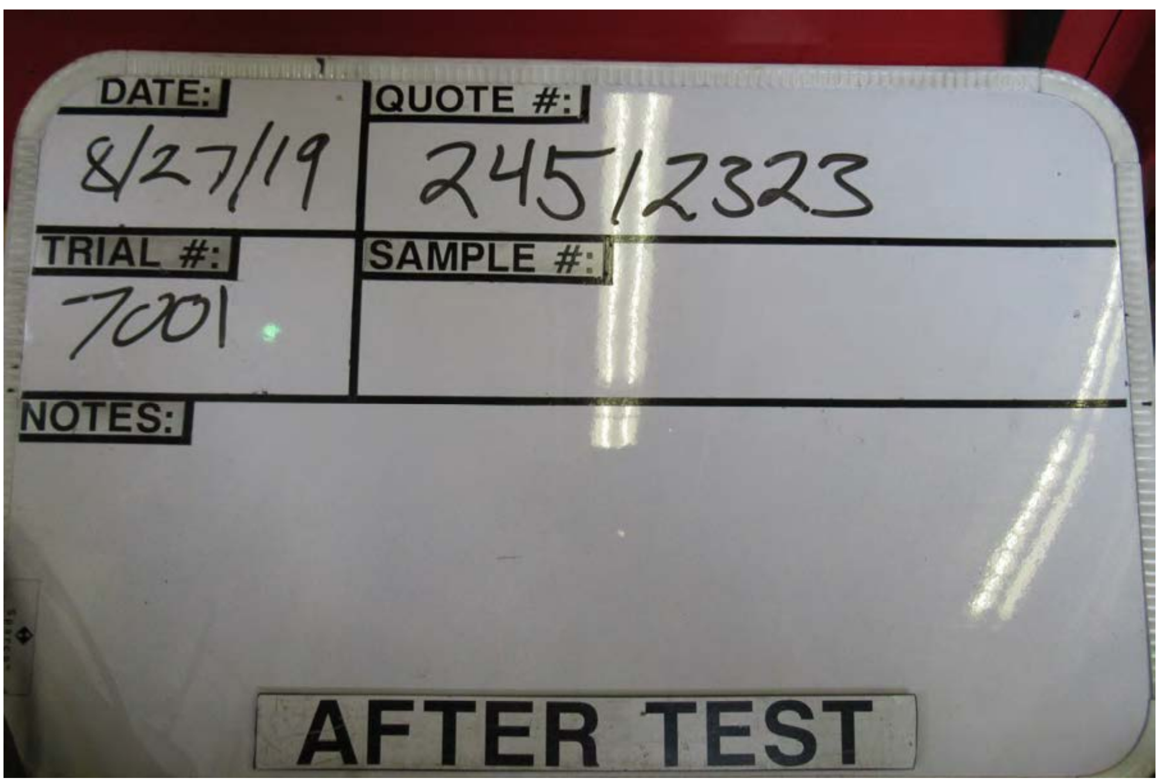
8/27/19
QUOTE #:
24512323
TRIAL #:
7001
SAMPLE #:
NOTES:
BEFORE TEST


2 13
B


DATE:
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QUOTE #:
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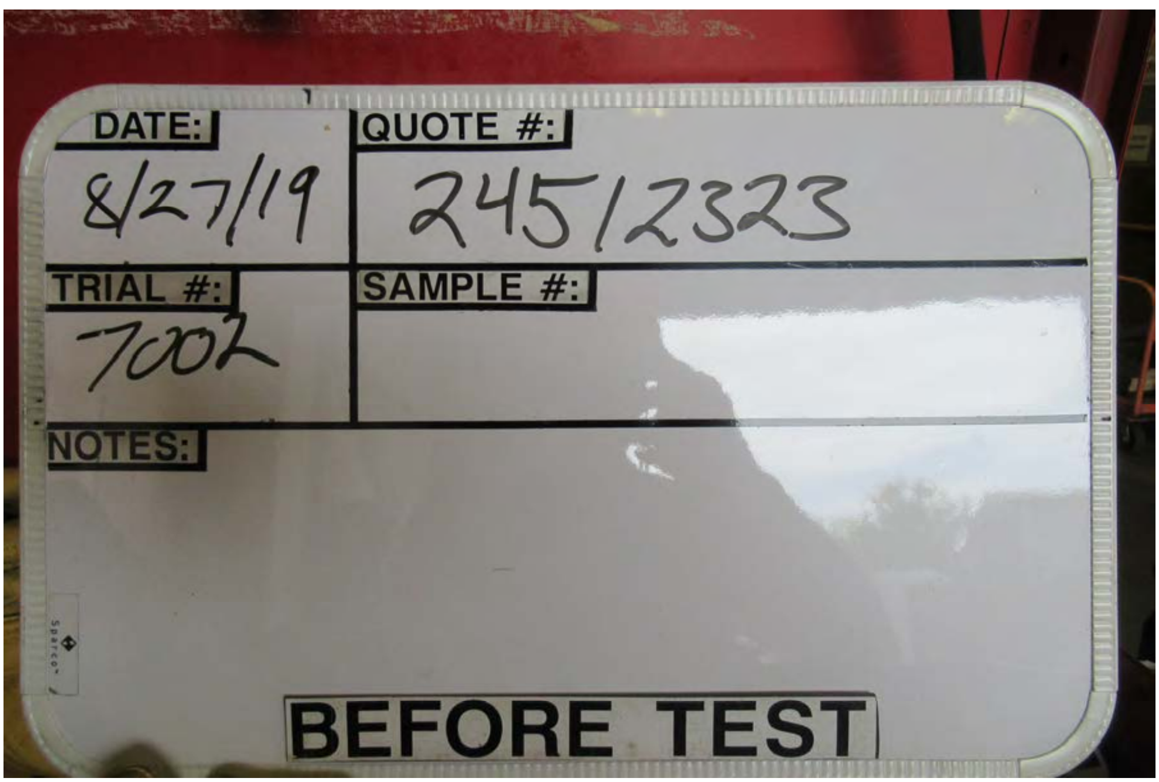
TRIAL #:
7001
SAMPLE #:
NOTES:
AFTER TEST



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QUOTE #:
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TRIAL #:
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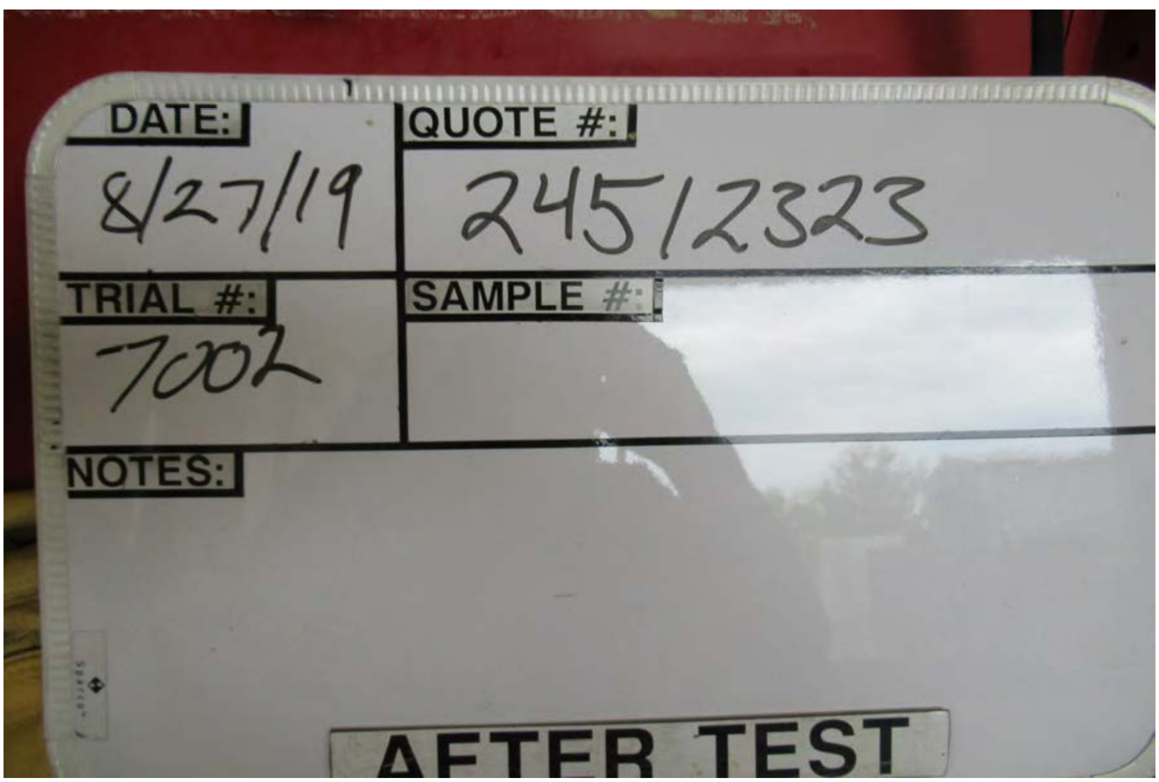
BEFORE TEST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QUOTE #:
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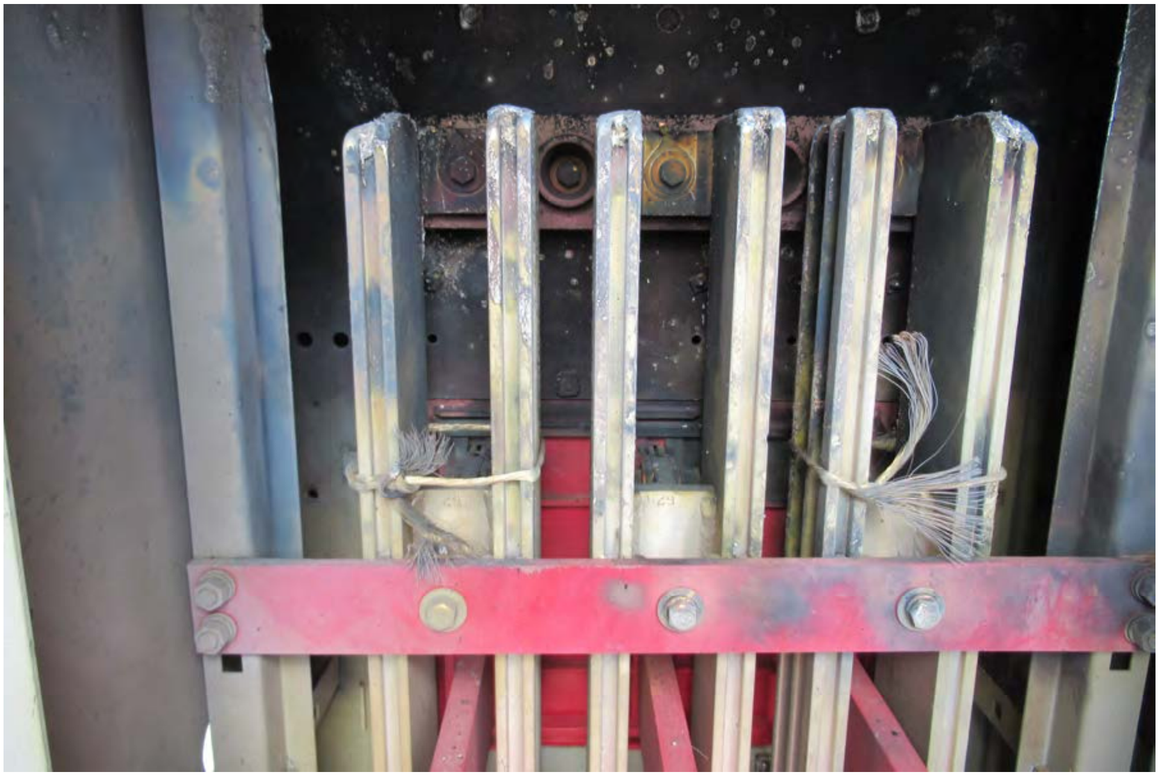
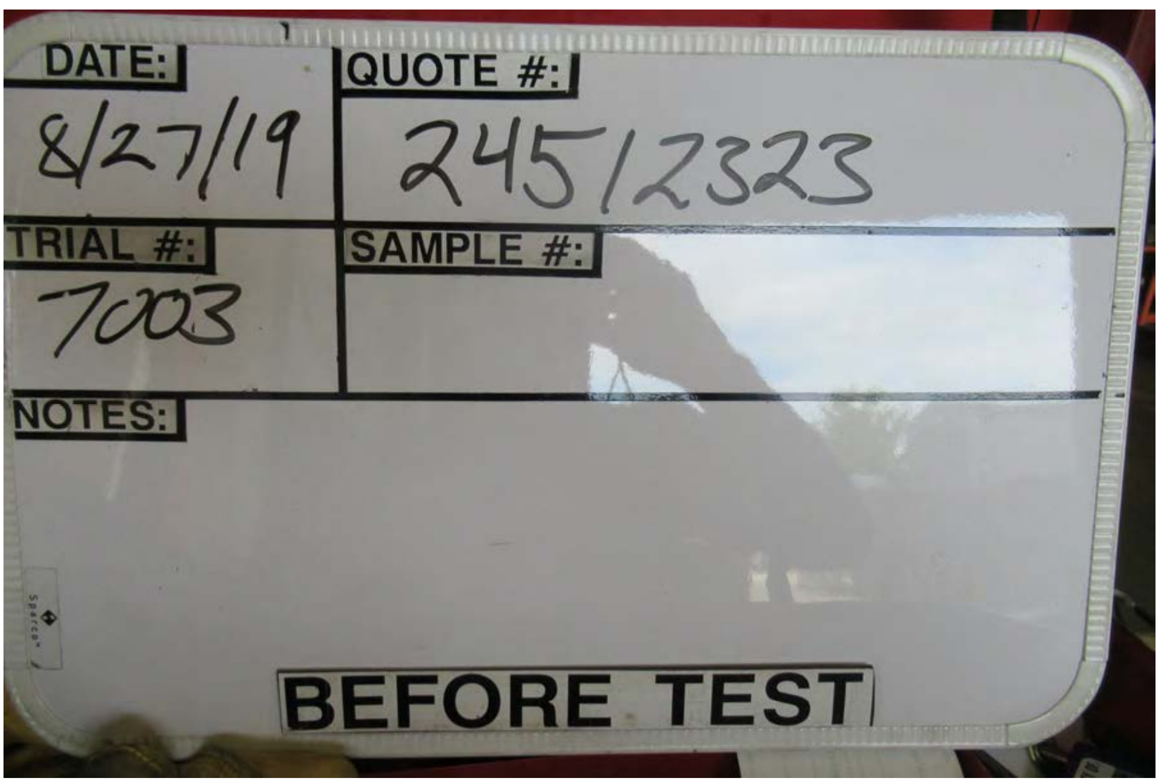
TRIAL #:
7002
SAMPLE #:
NOTES:
AFTER TEST




DATE:
8/27/19
QUOTE #:
24512323
TRIAL #:
7003
SAMPLE #:
NOTES:
BEFORE TEST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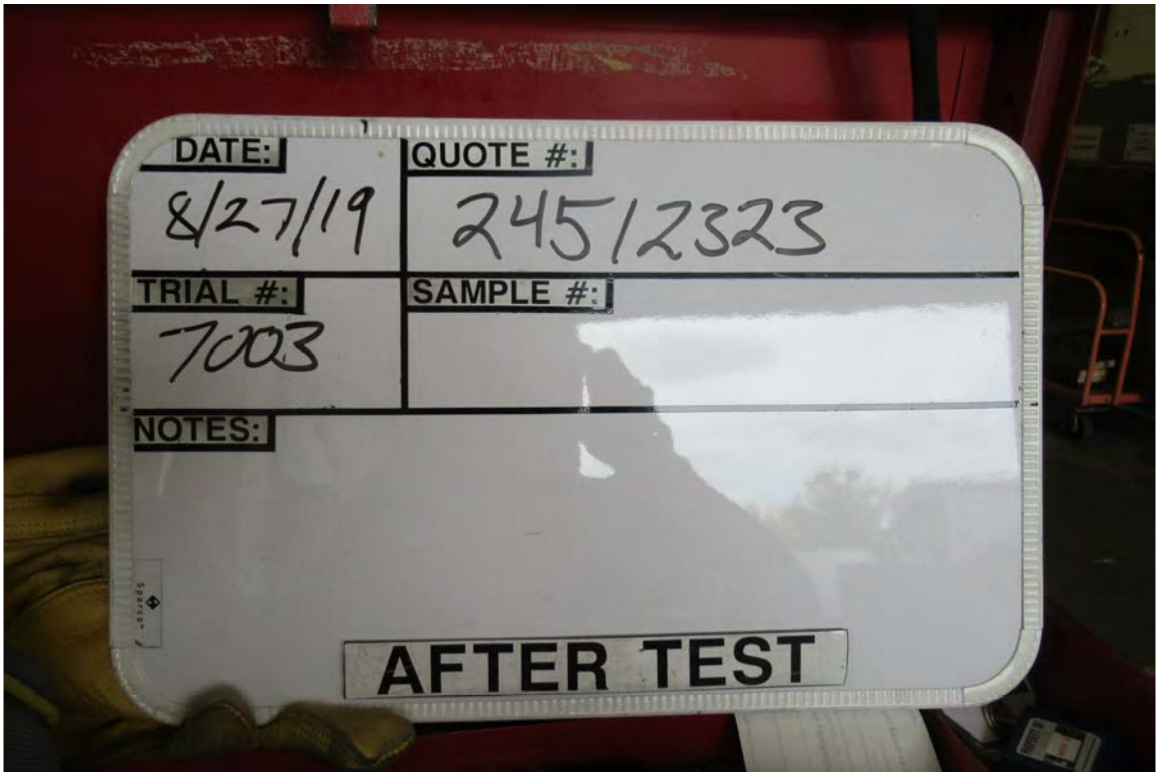
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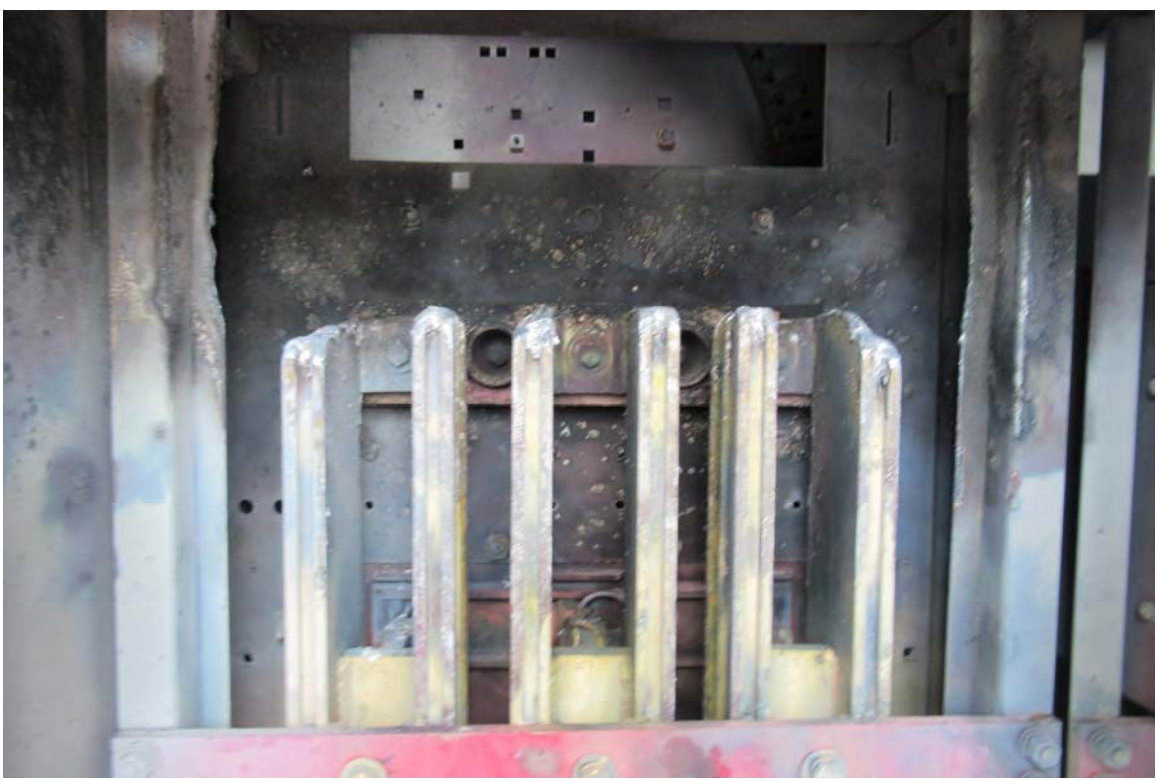

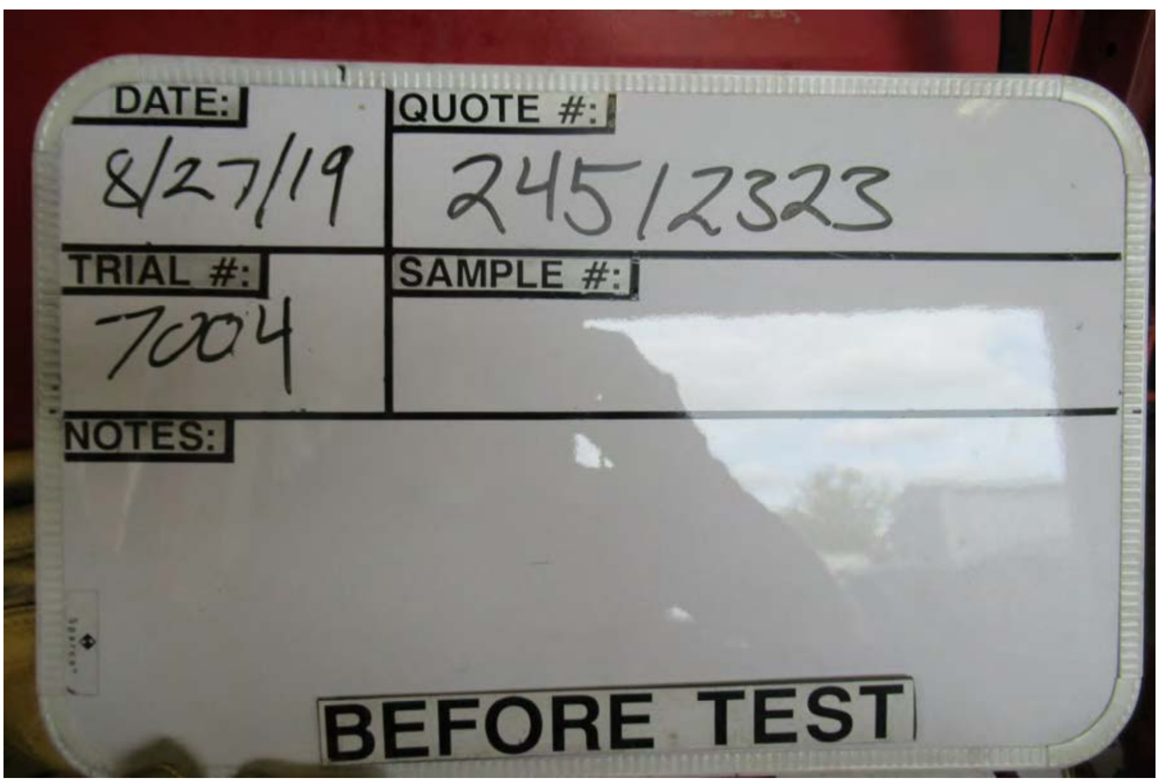

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TRIAL #:
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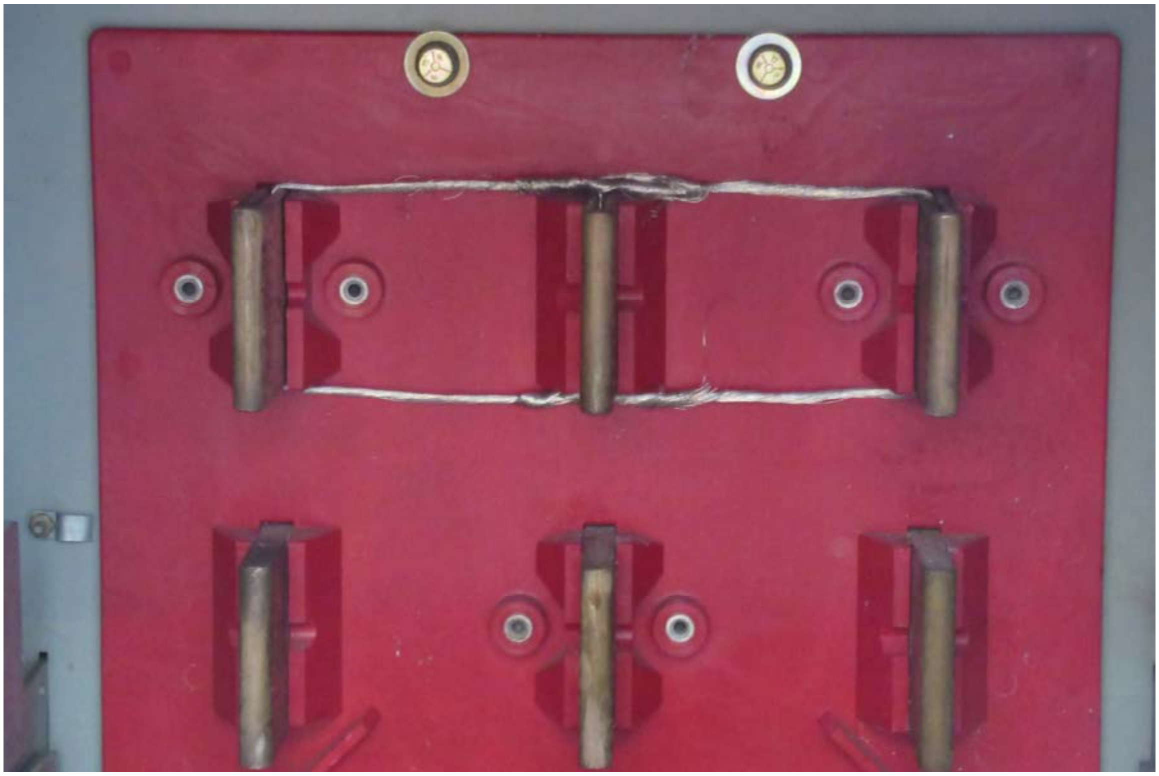
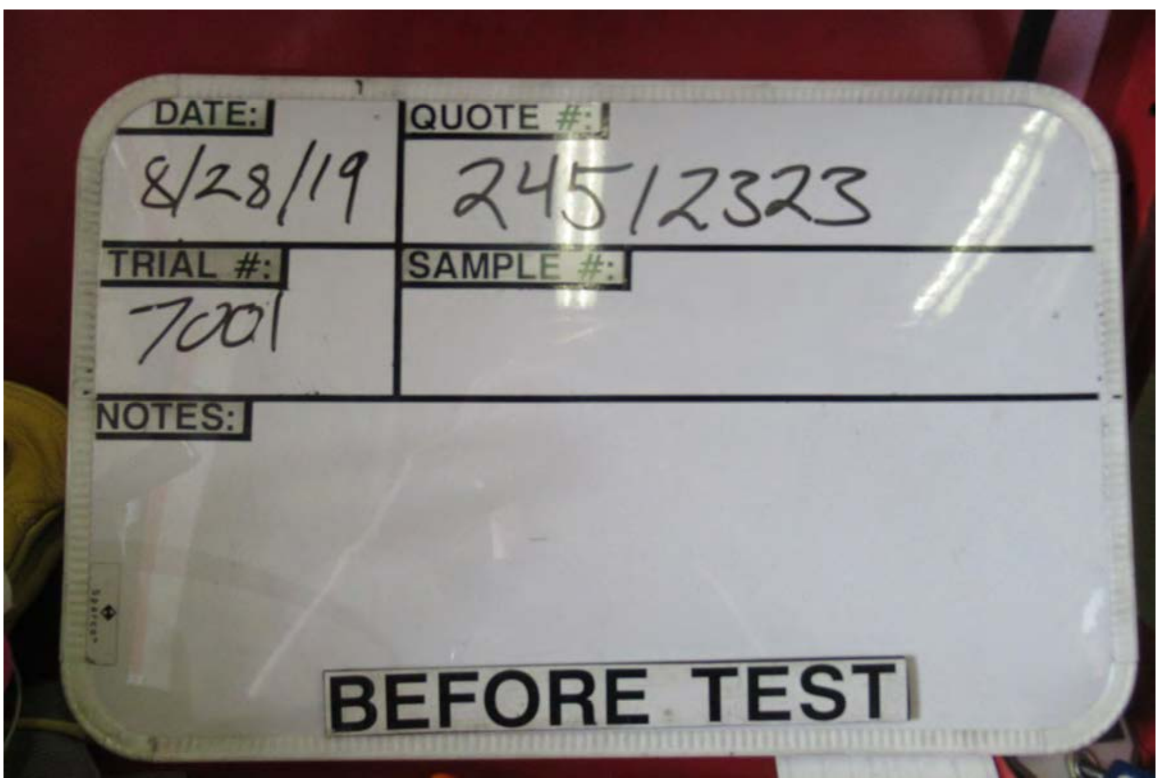
SAMPLE #:
NOTES:
BEFORE TEST

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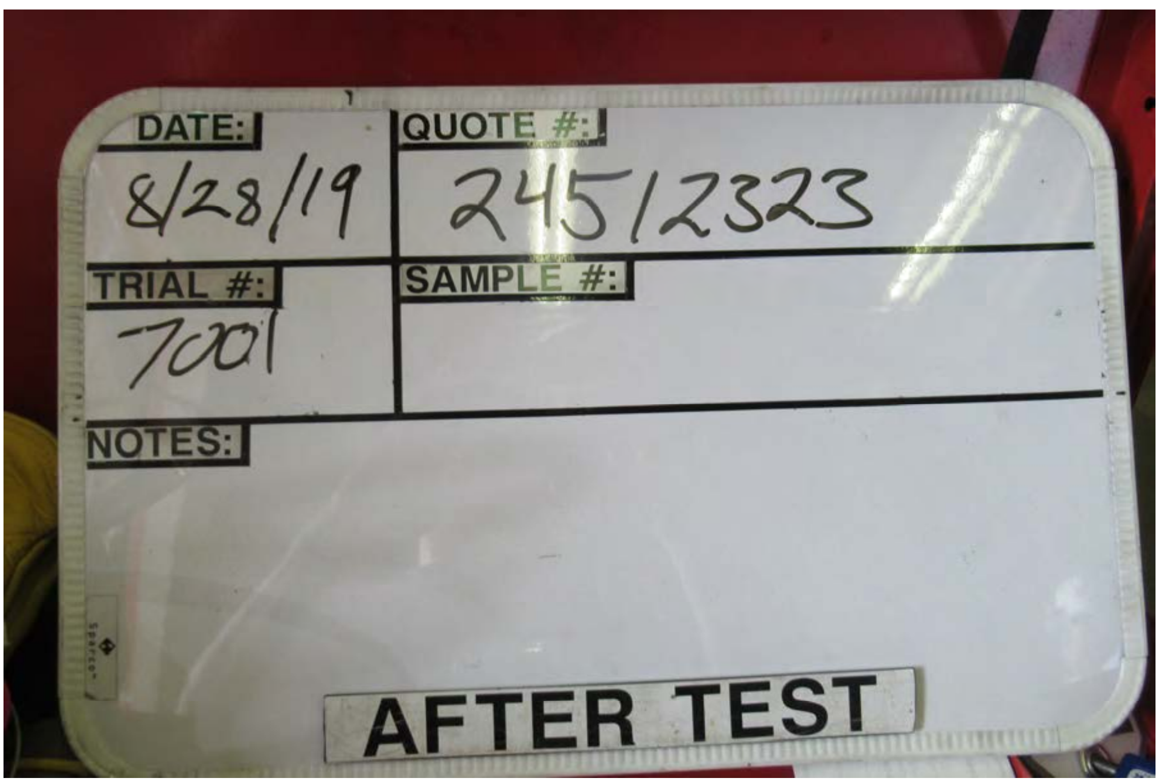
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QUOTE #:
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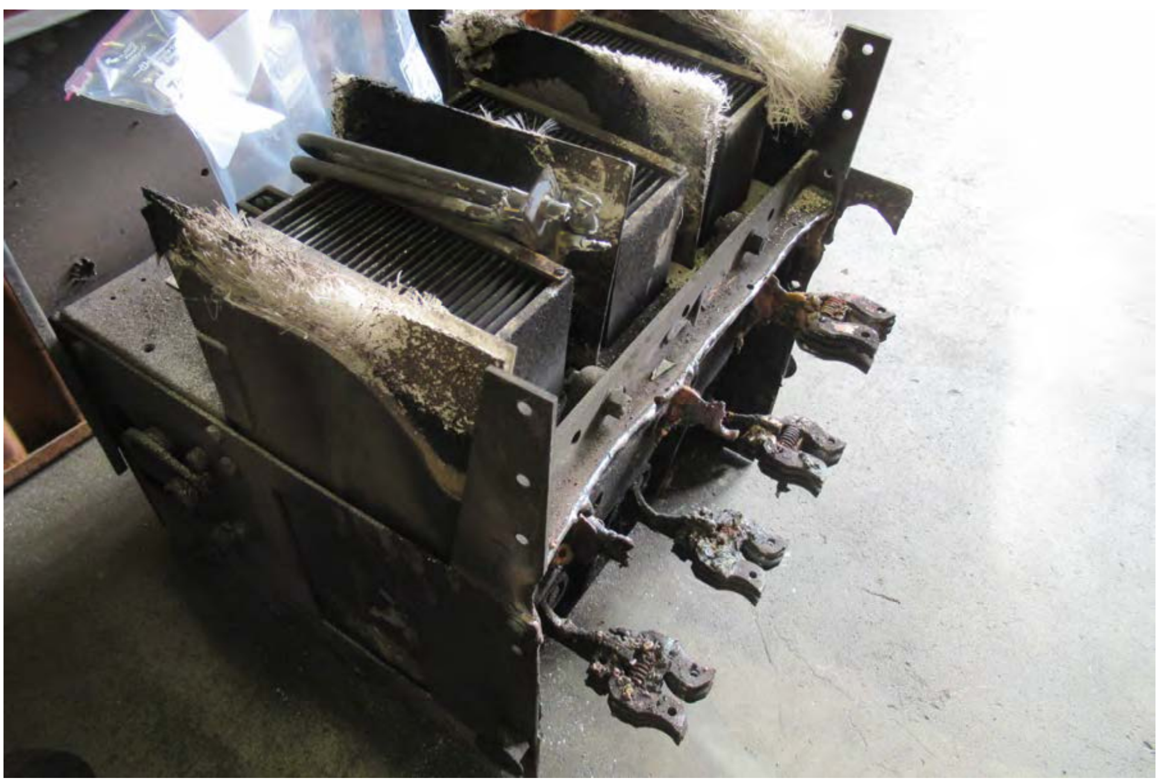
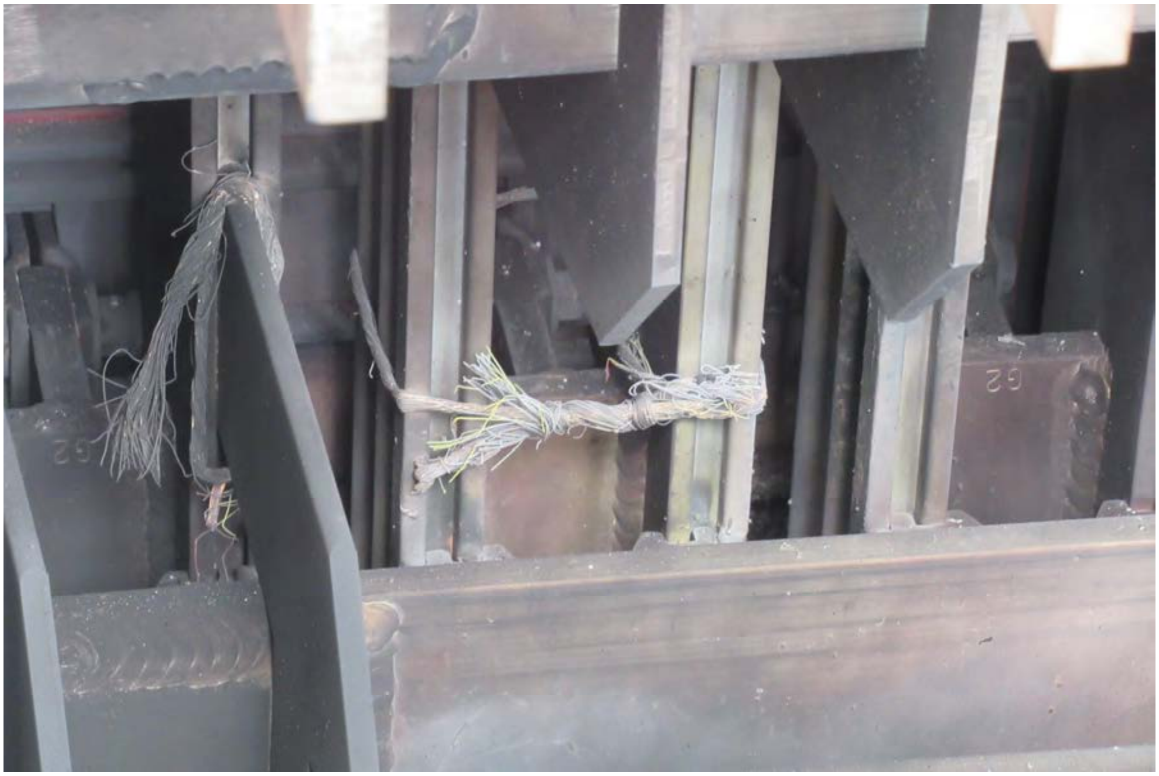
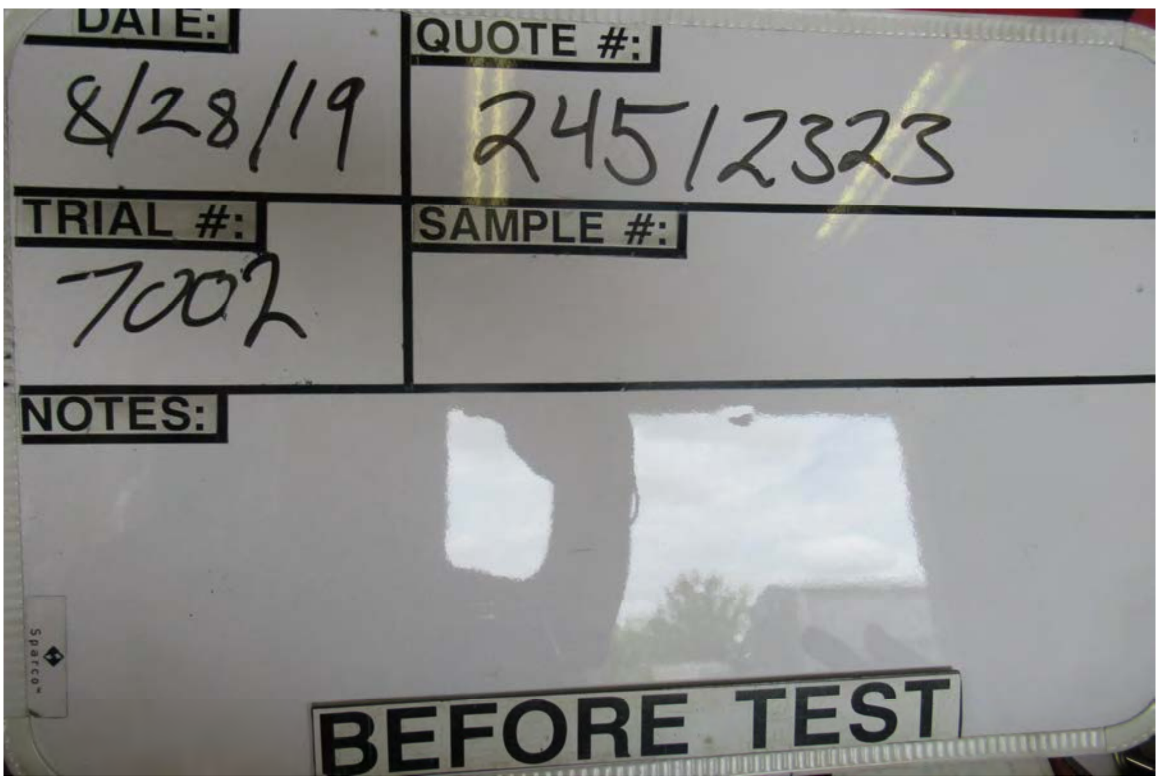
TRIAL #:
7001
SAMPLE #:
NOTES:
AFTER TEST






DATE:
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QUOTE #:
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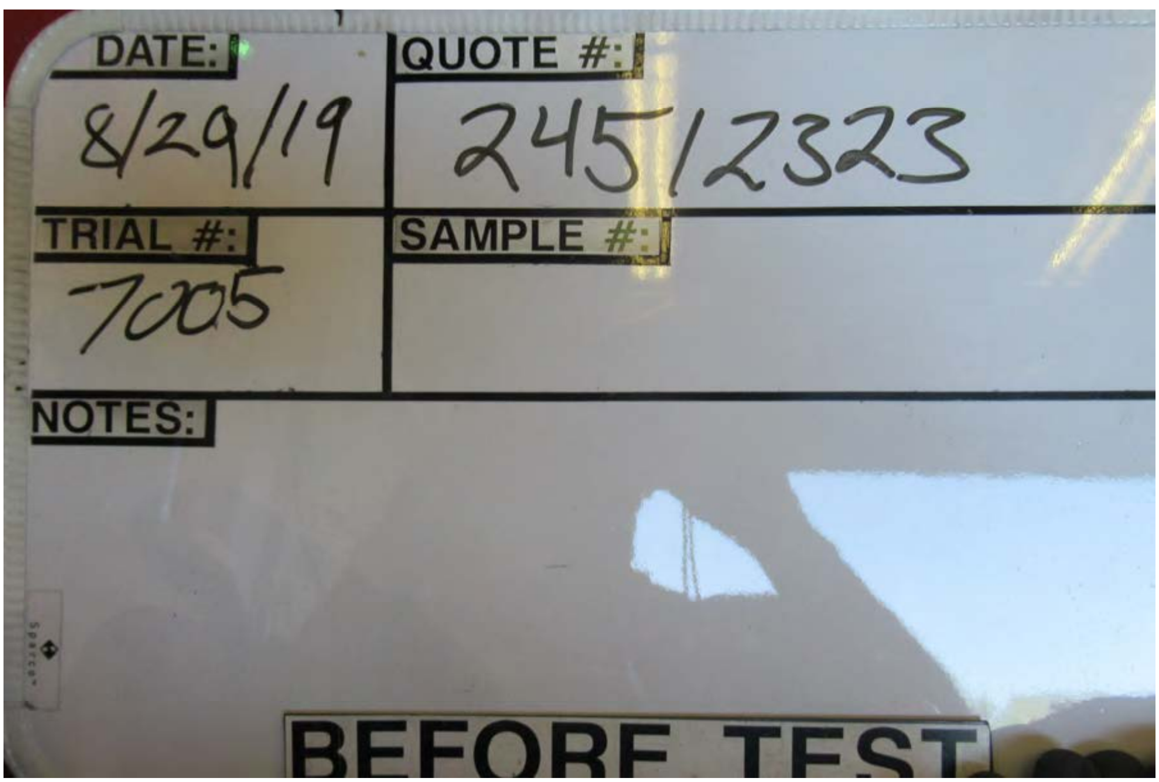
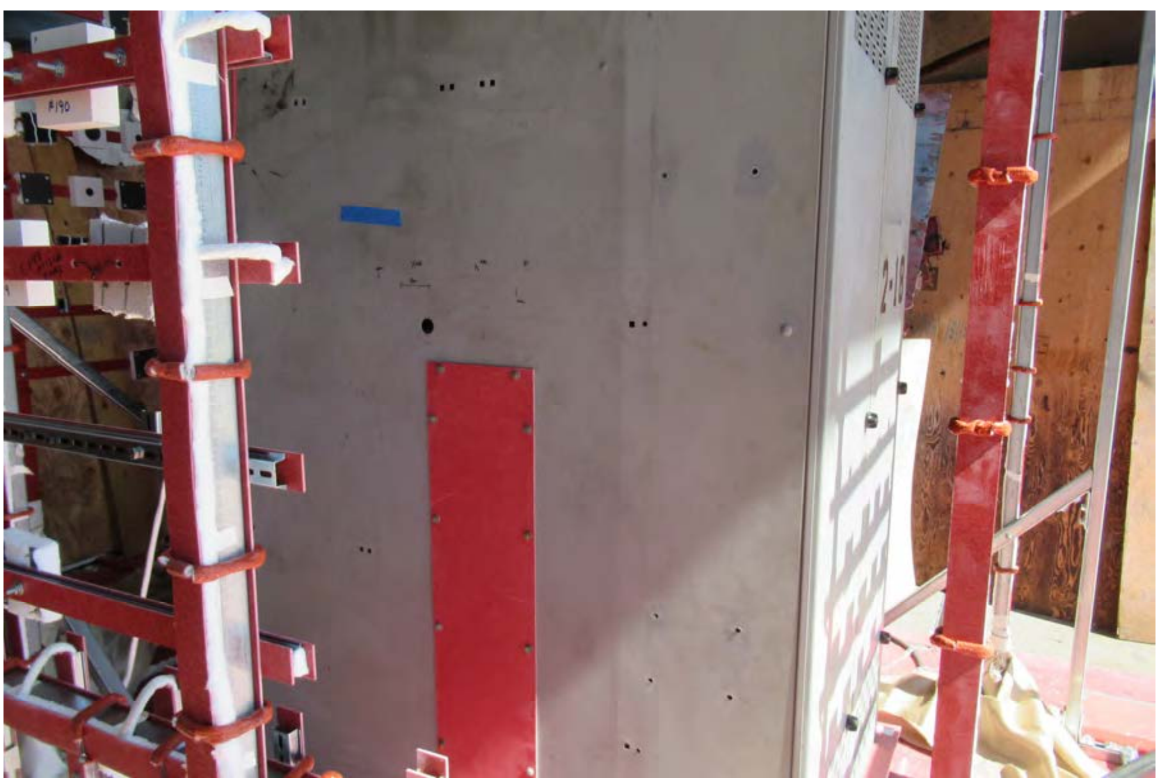
TRIAL #:
7002
SAMPLE #:
NOTES:
BEFORE TEST

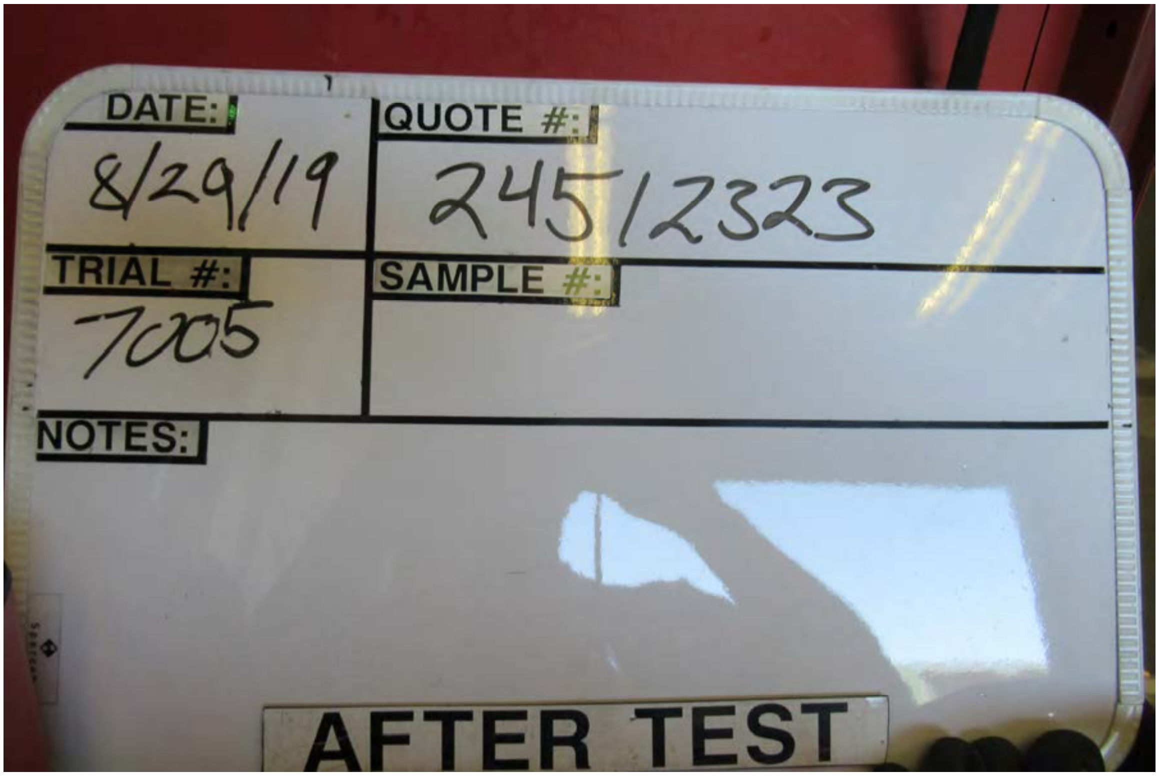

DATE:
8/29/19
QUOTE #:
24512323
TRIAL #:
7005
SAMPLE #:
NOTES:
BEFORE TEST


FLOWTRON


2-18


2-18

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QUOTE #:
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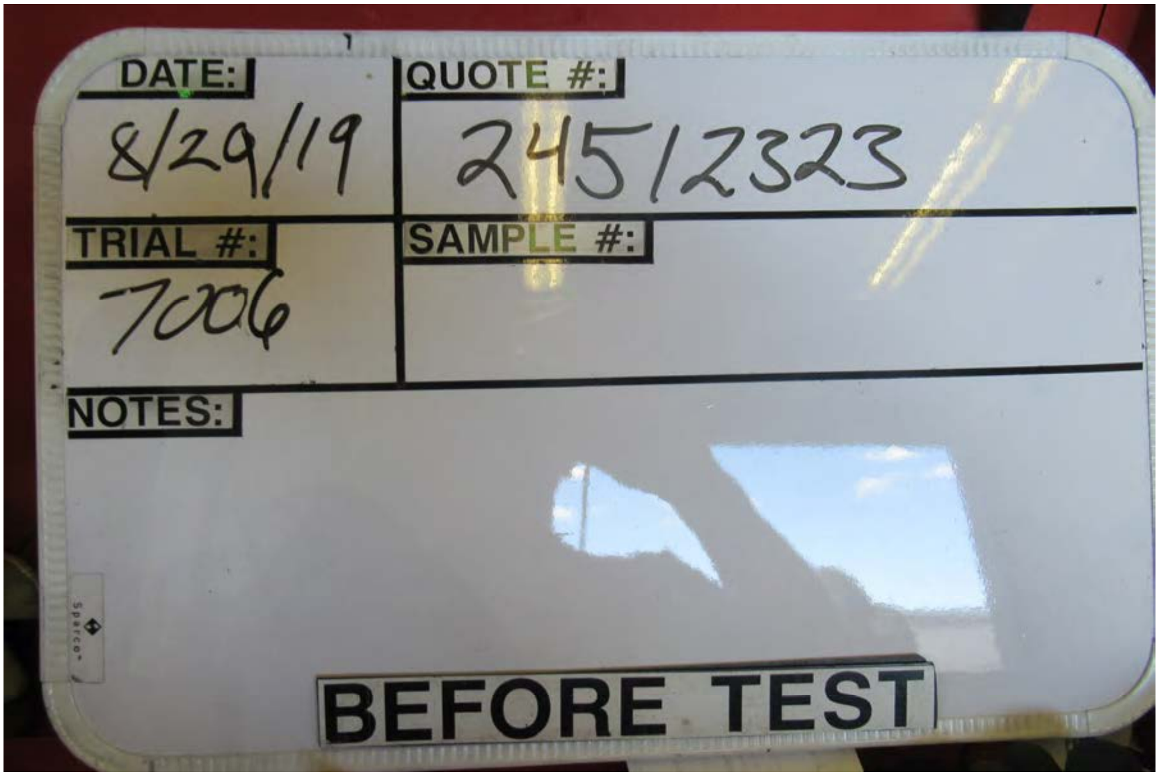
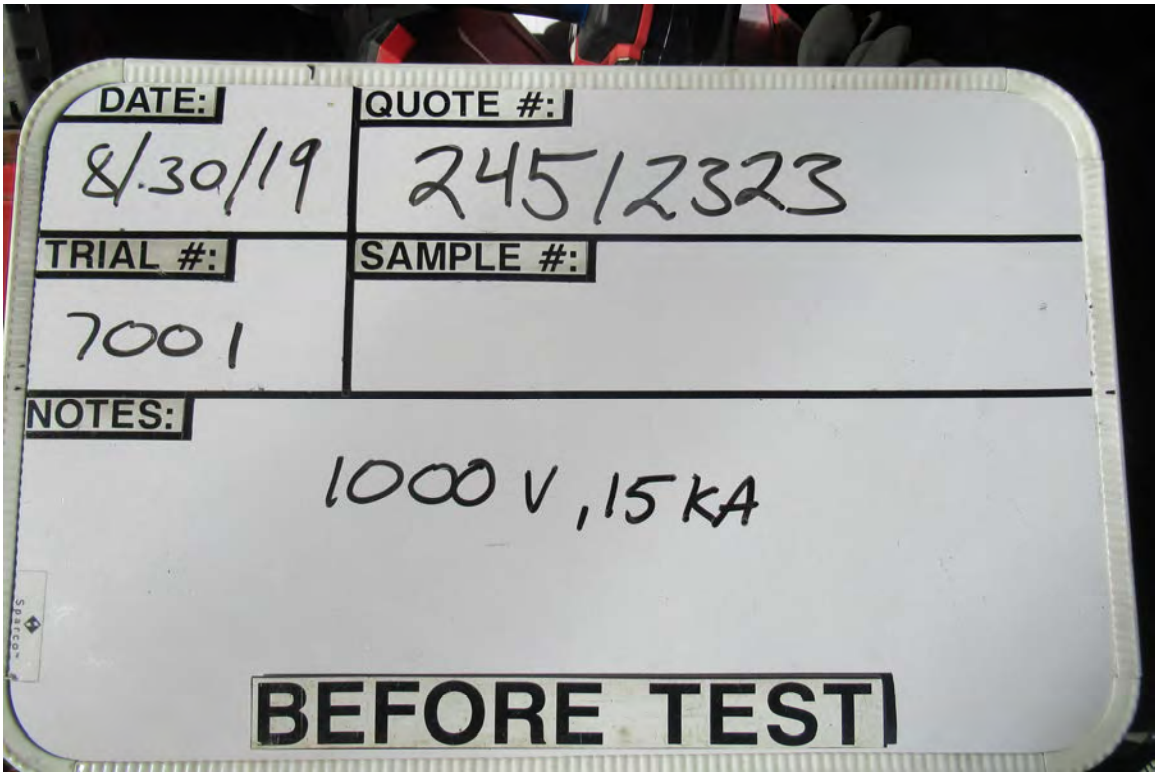
TRIAL #:
7005
SAMPLE #:
NOTES:
AFTER TEST


DATE:
8/29/19
QUOTE #:
24512323
TRIAL #:
7006
SAMPLE #:
NOTES:
BEFORE TEST


2-18
B


DATE:
8/29/19
QUOTE #:
24512323
TRIAL #:
7006
SAMPLE #:
NOTES:
AFTER TEST

Trip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QUOTE #:
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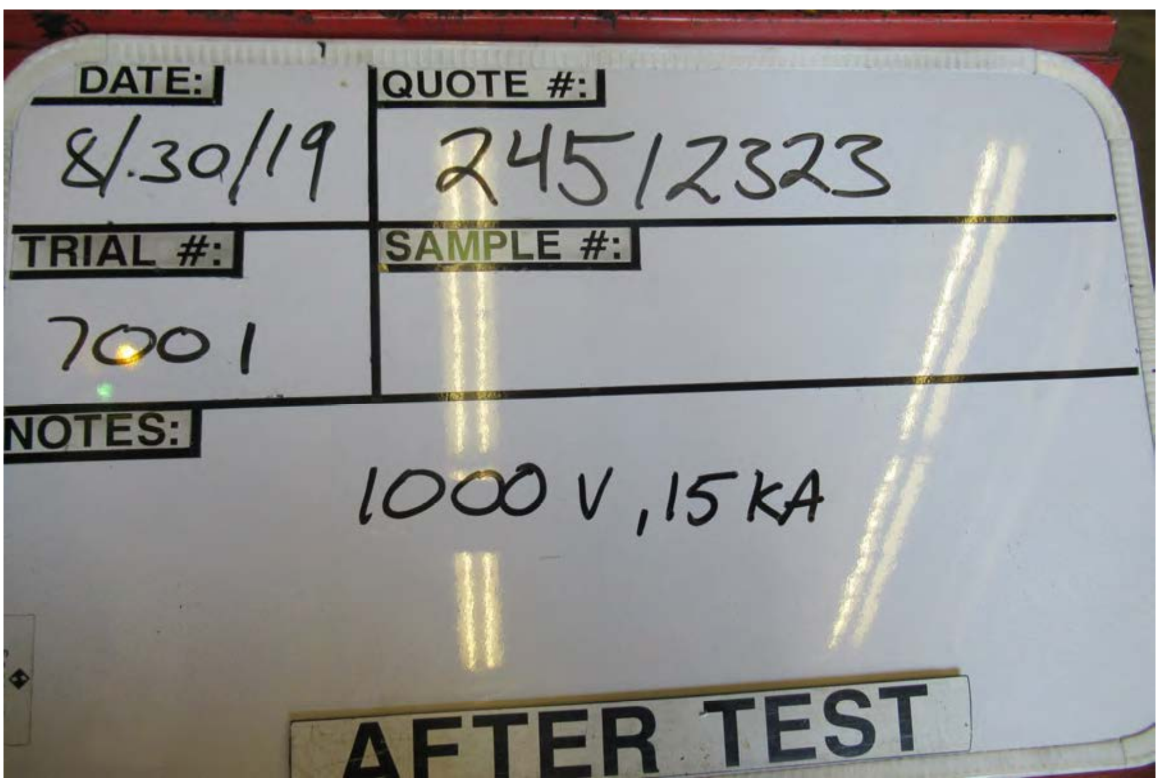
TRIAL #:
7001
SAMPLE #:
NOTES:
1000 V, 15 kA
BEFORE TEST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TRIAL #:
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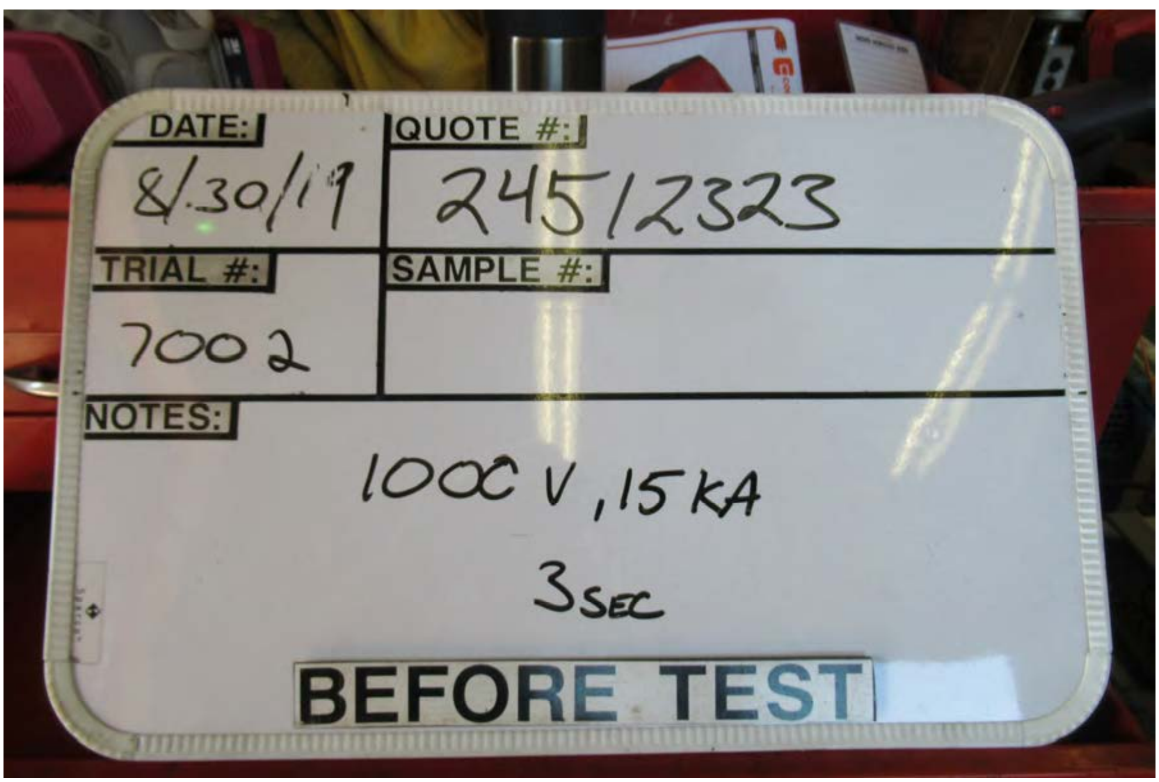
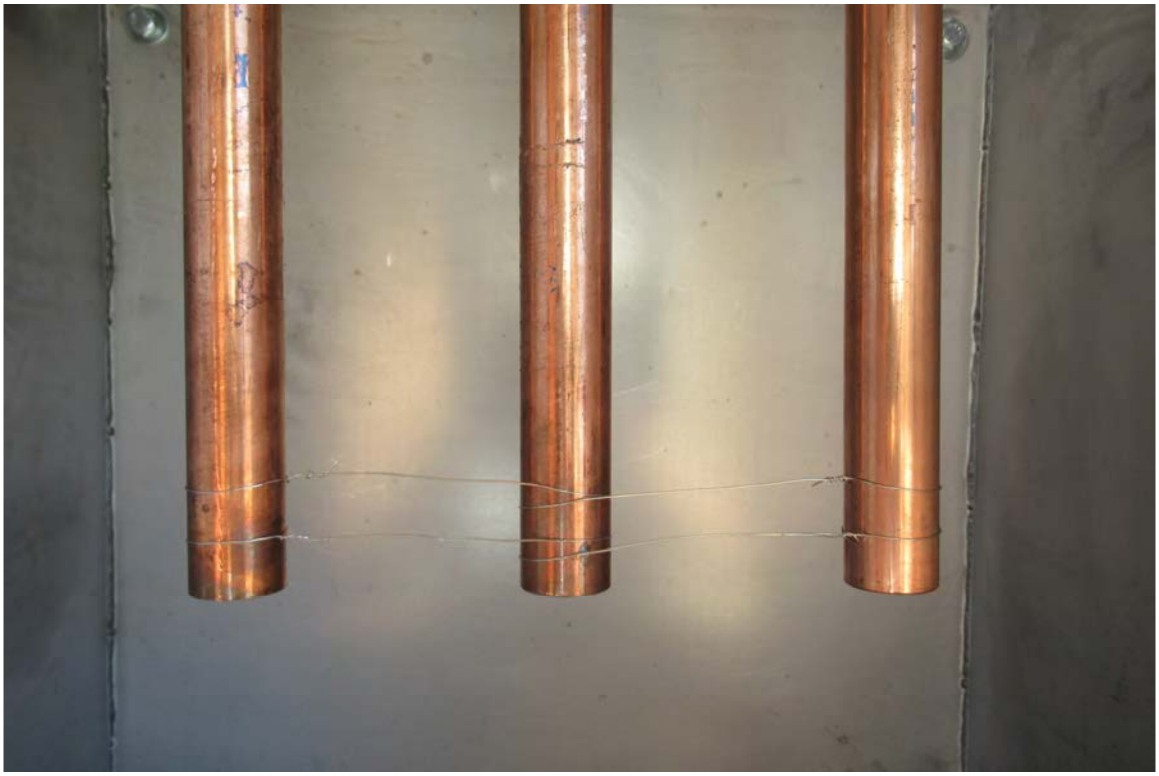
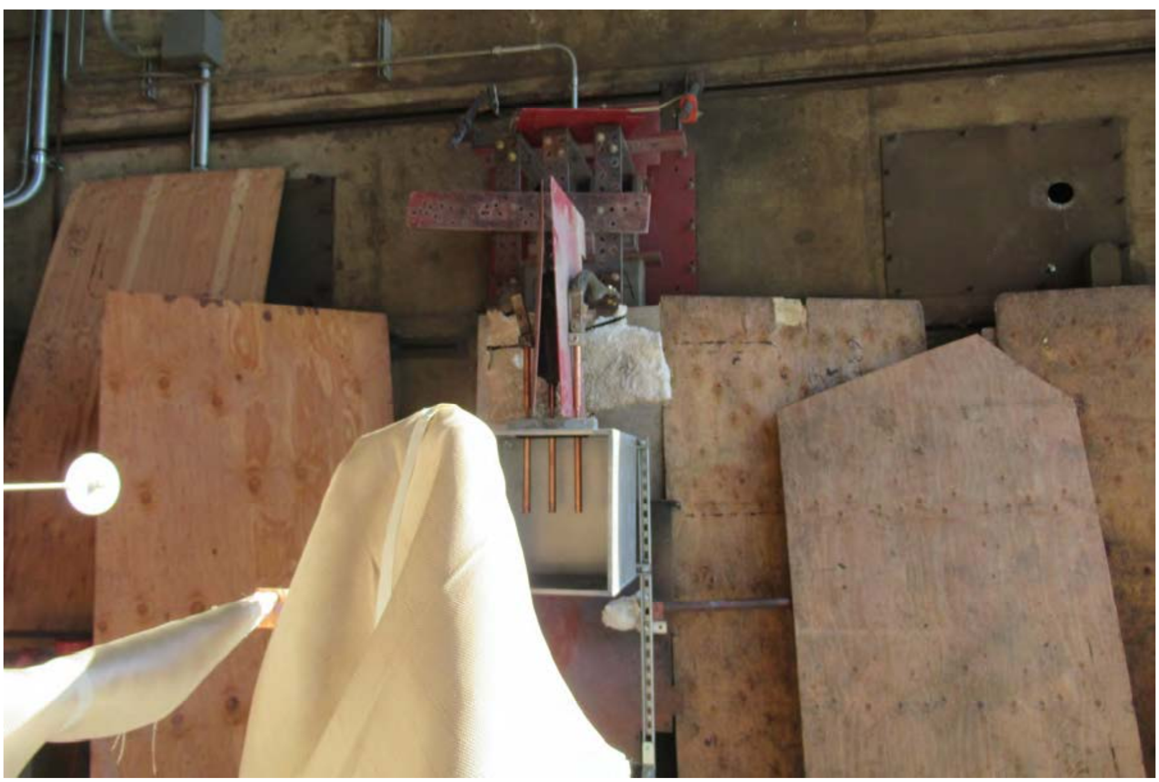
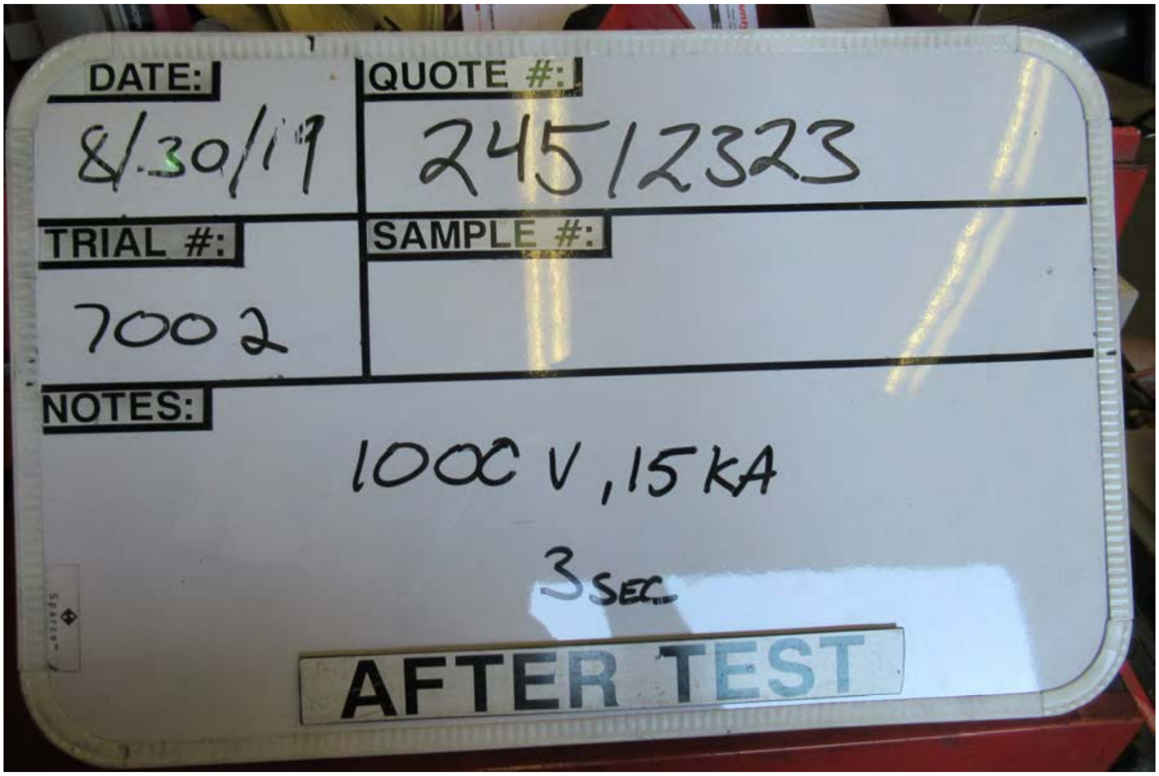
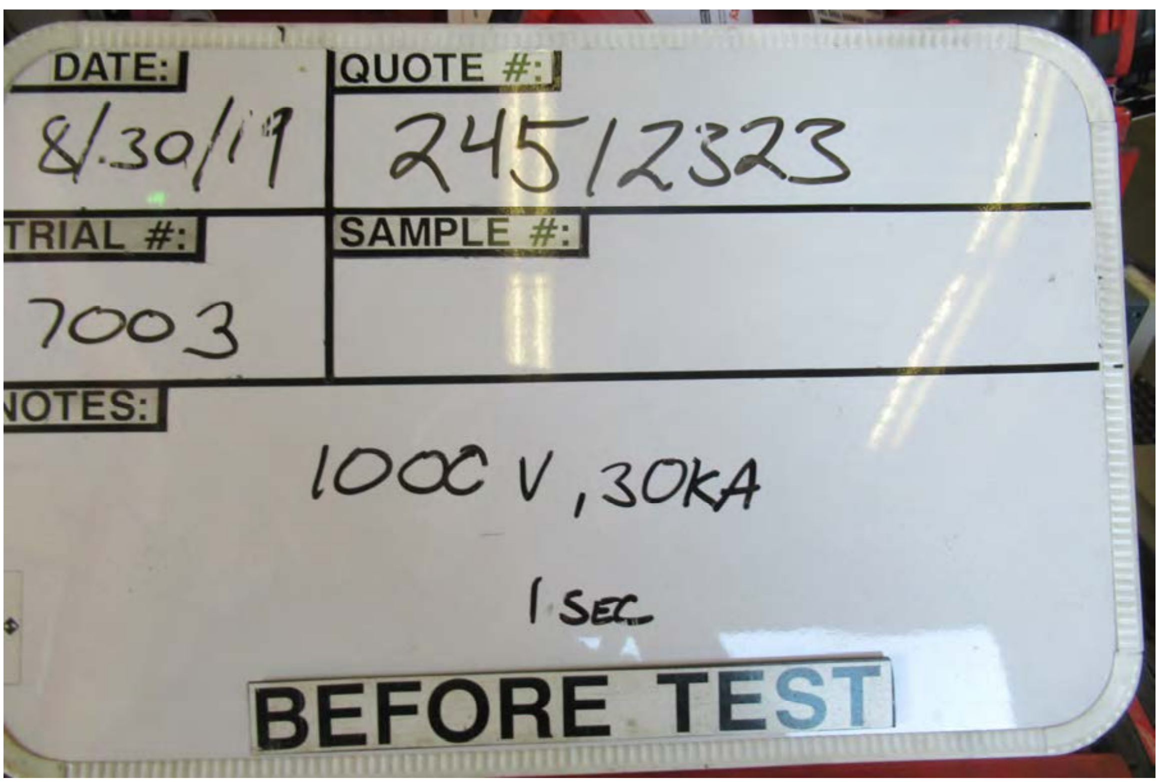
SAMPLE #:
NOTES:
1000 V, 15 KA
AFTER TEST


DATE:
8/30/19
QUOTE #:
24512323
TRIAL #:
7002
SAMPLE #:
NOTES:
1000 V, 15 KA
3SEC
BEFORE TEST






DATE:
8/30/19
QUOTE #:
24512323
TRIAL #:
7002
SAMPLE #:
NOTES:
1000 V, 15 KA
3 SEC
AFTER TEST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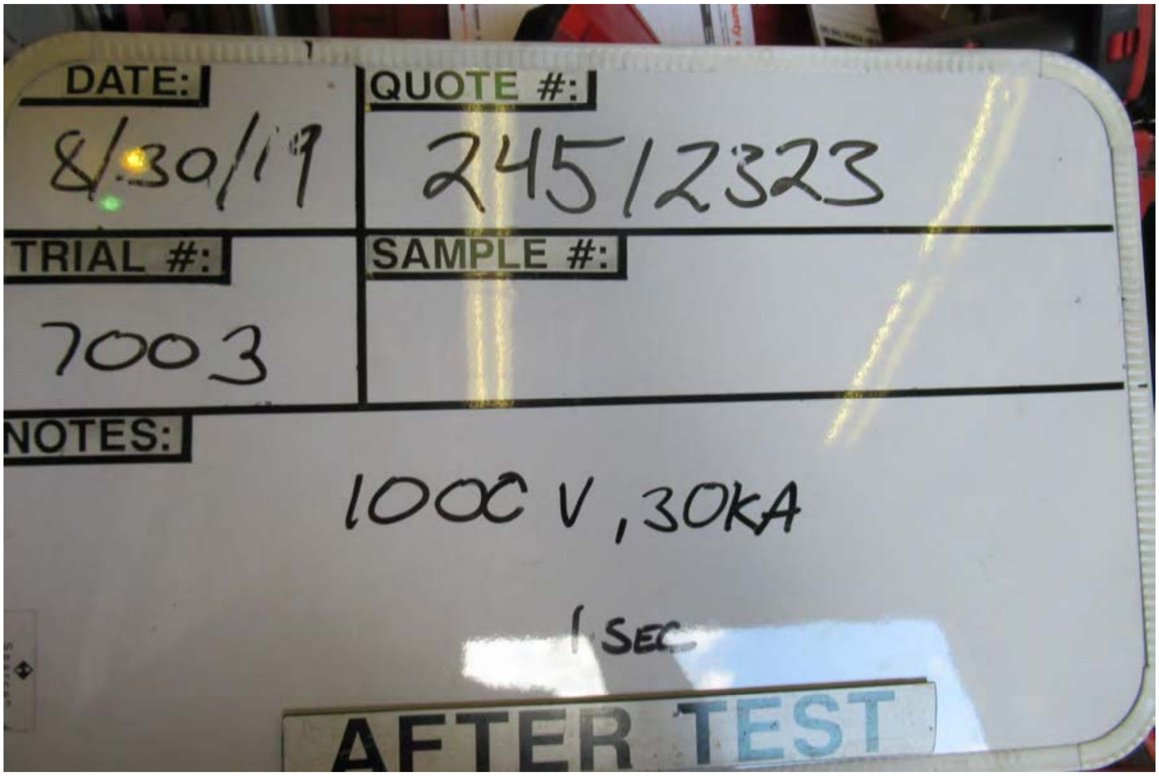
TRIAL #:
7003
SAMPLE #:
NOTES:
1000 V, 30KA
1 SEC
BEFORE TEST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TRIAL #:
7003
SAMPLE #:
NOTES:
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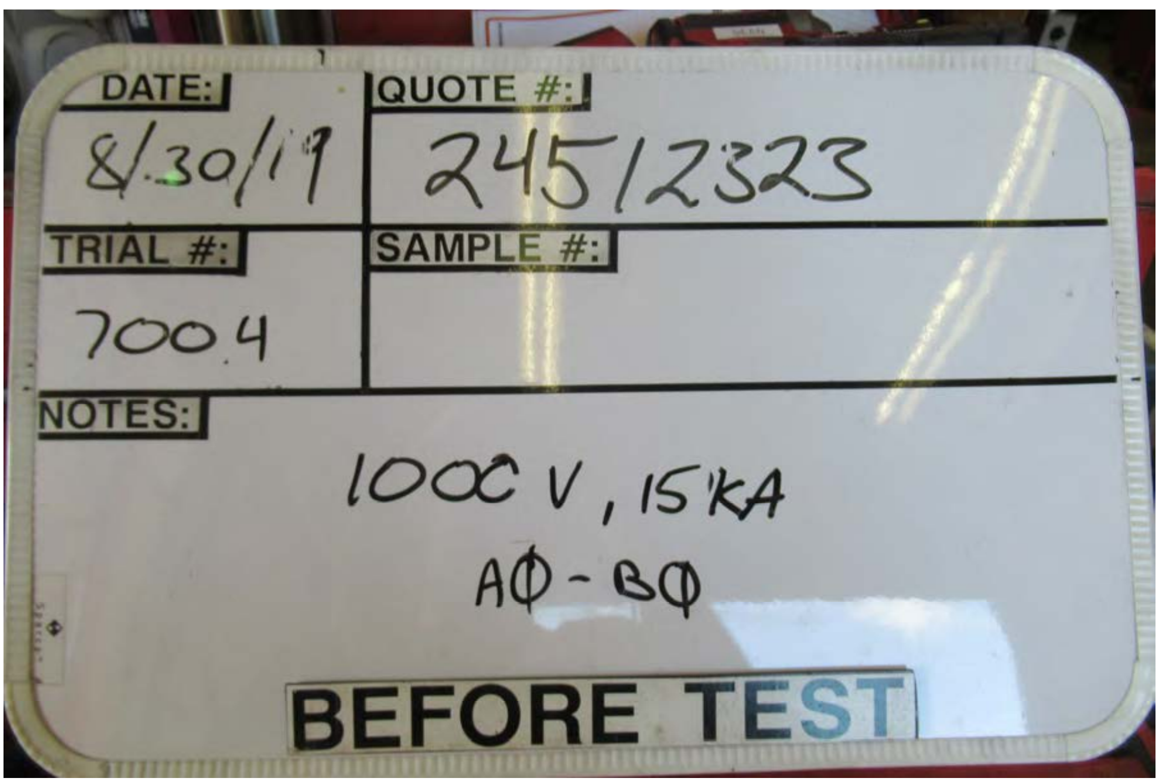
1 SEC
AFTER TEST


DATE:
8/30/19
QUOTE #:
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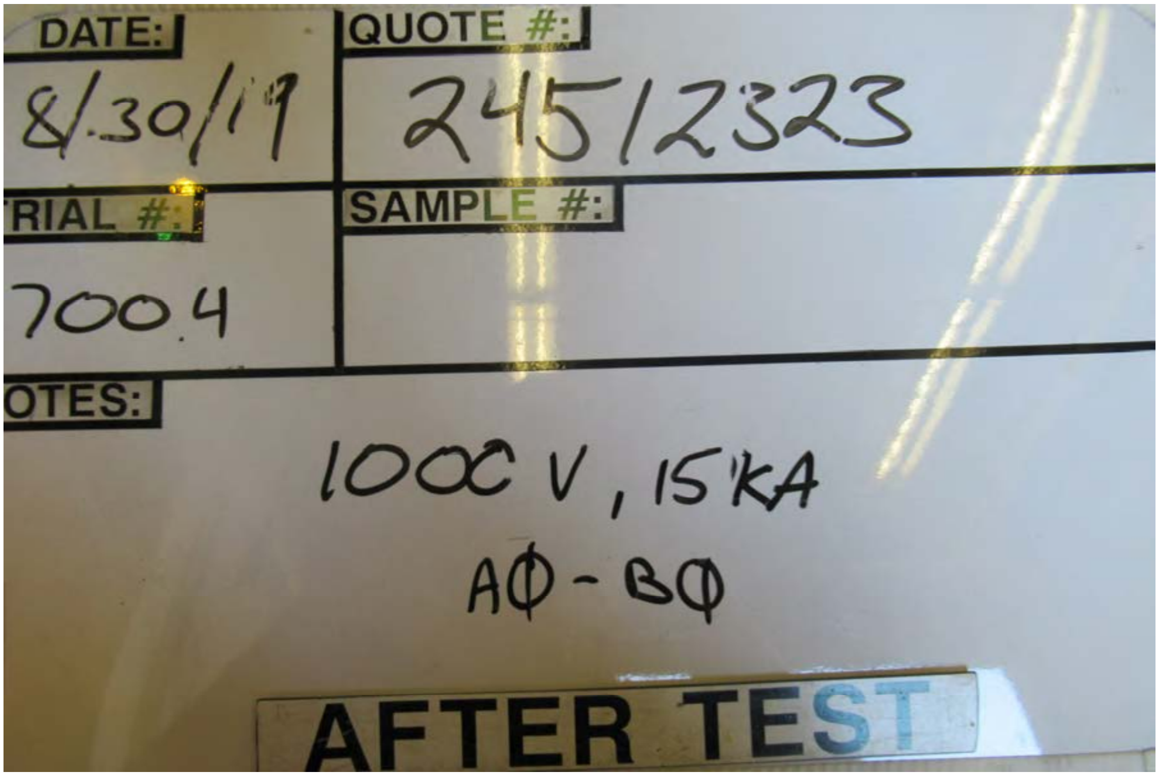
TRIAL #:
700.4
SAMPLE #:
NOTES:
100C V, 15KA
AΦ - BΦ
BEFORE TEST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8/30/19
QUOTE #:
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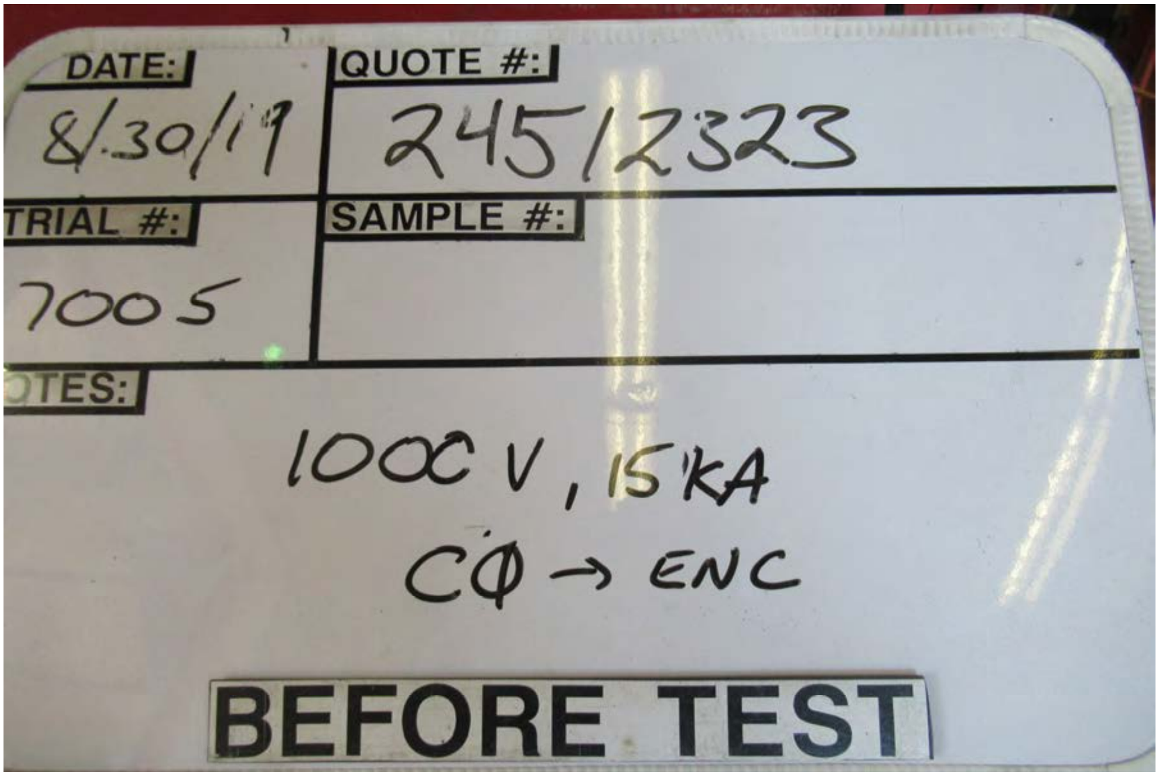
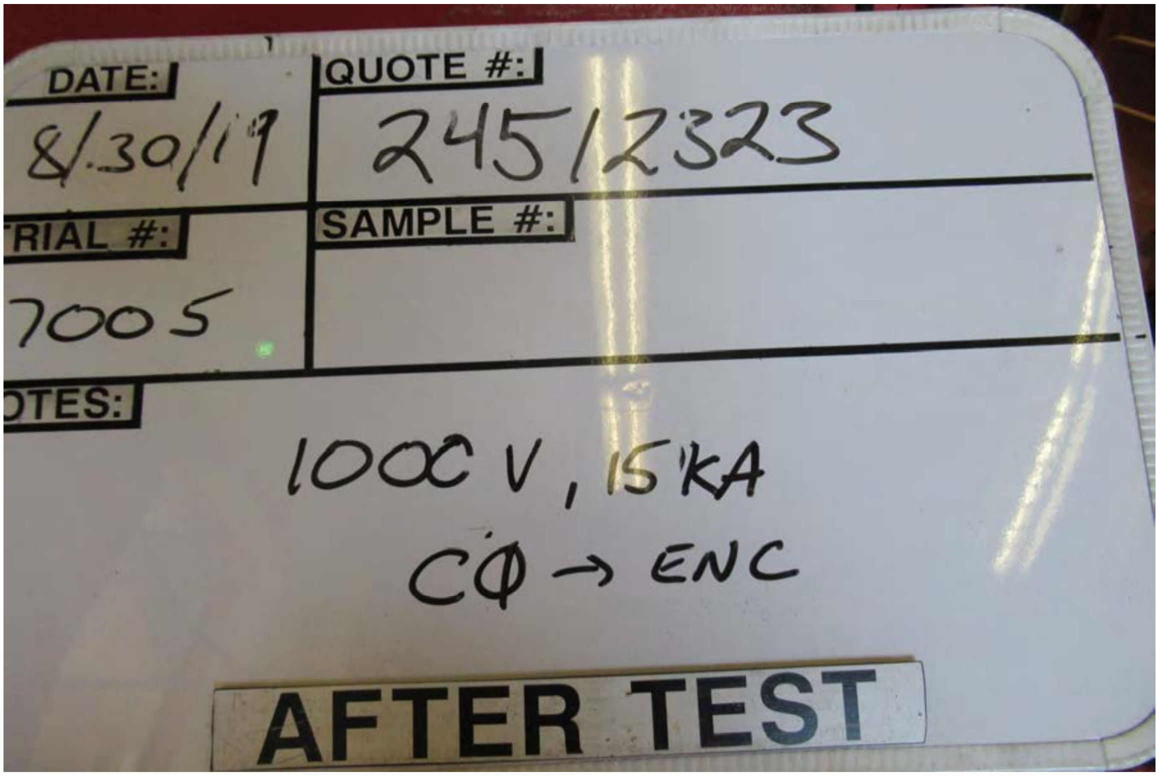
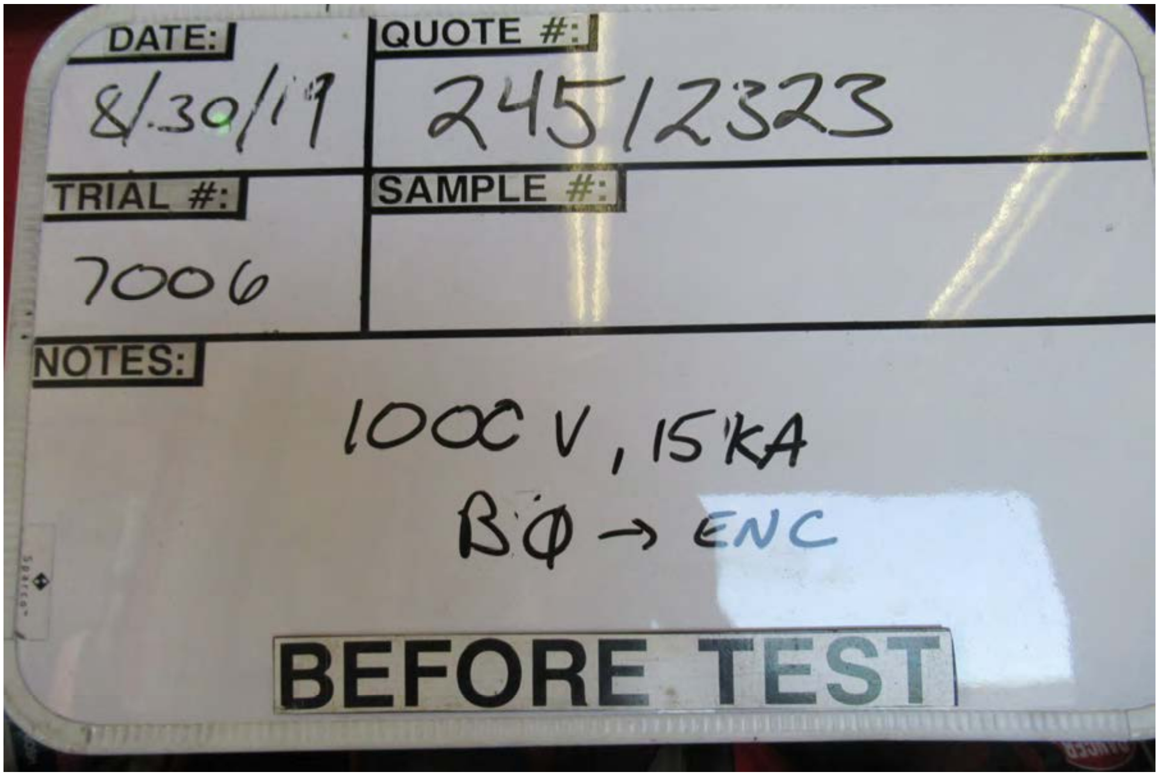
TRIAL #:
700.4
SAMPLE #:
OTES:
1000 V, 15KA
AΦ - BΦ
AFTER TEST


DATE:
8/30/19
QUOTE #:
24512323
TRIAL #:
7005
SAMPLE #:
TES:
1000 V, 15 KA
CΦ → ENC
BEFORE TEST


DATE:
8/30/19
QUOTE #:
24512323
RIAL #:
7005
SAMPLE #:
OTES:
1000 V, 15kA
CΦ → ENC
AFTER TEST


DATE:
8/30/19
QUOTE #:
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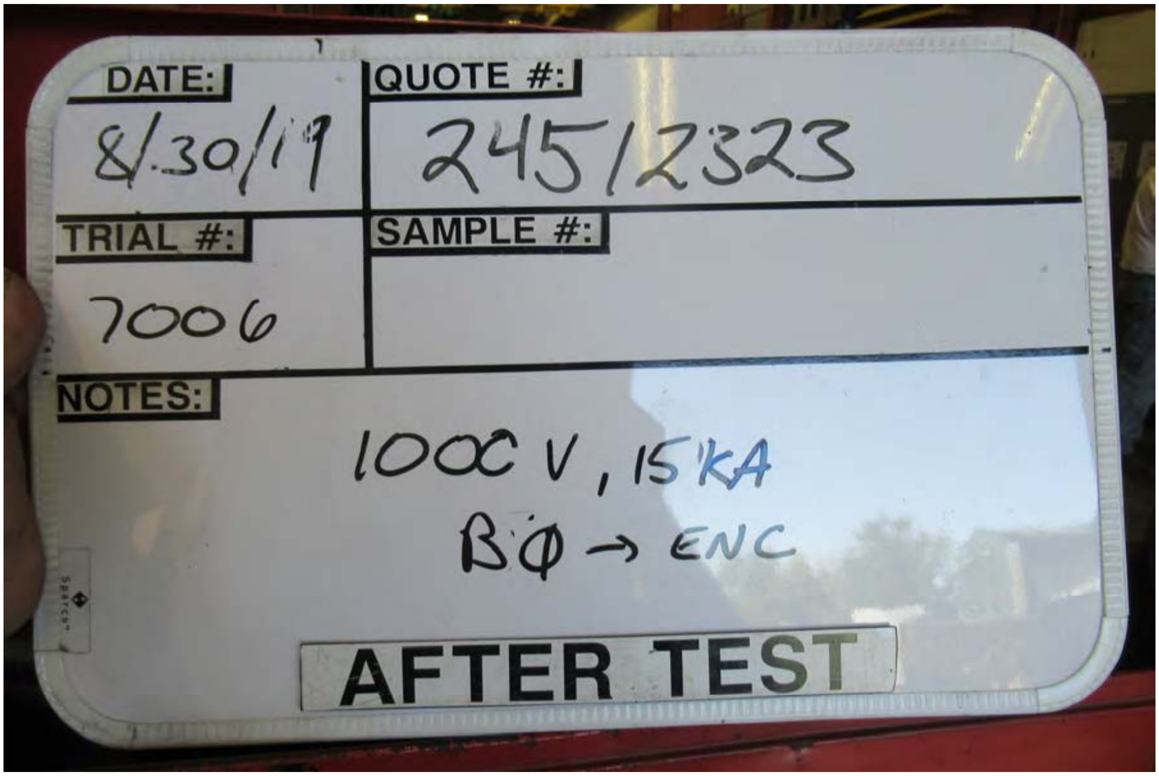
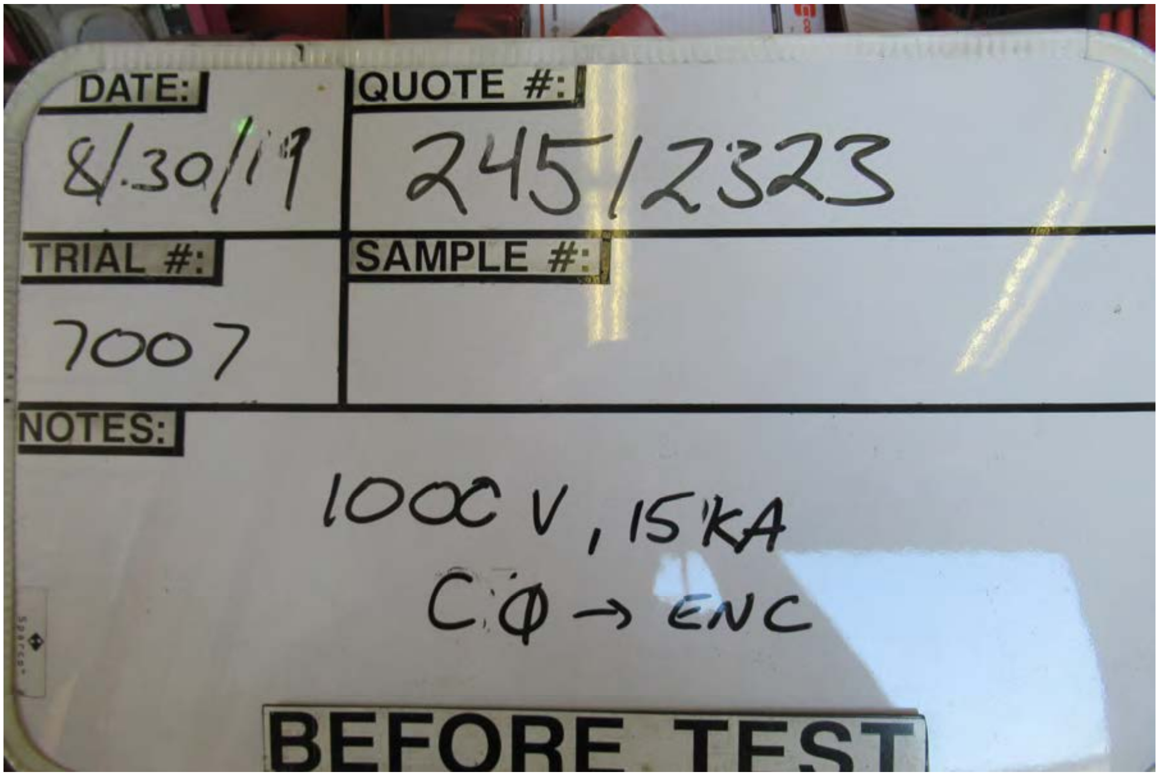
TRIAL #:
7006
SAMPLE #:
NOTES:
1000 V, 15KA
BΦ → ENC
BEFORE TEST


DATE:
8/30/19
QUOTE #:
24512323
TRIAL #:
7006
SAMPLE #:
NOTES:
1000 V, 15 KA
BΦ → ENC
AFTER TEST


DATE:
8/30/19
QUOTE #:
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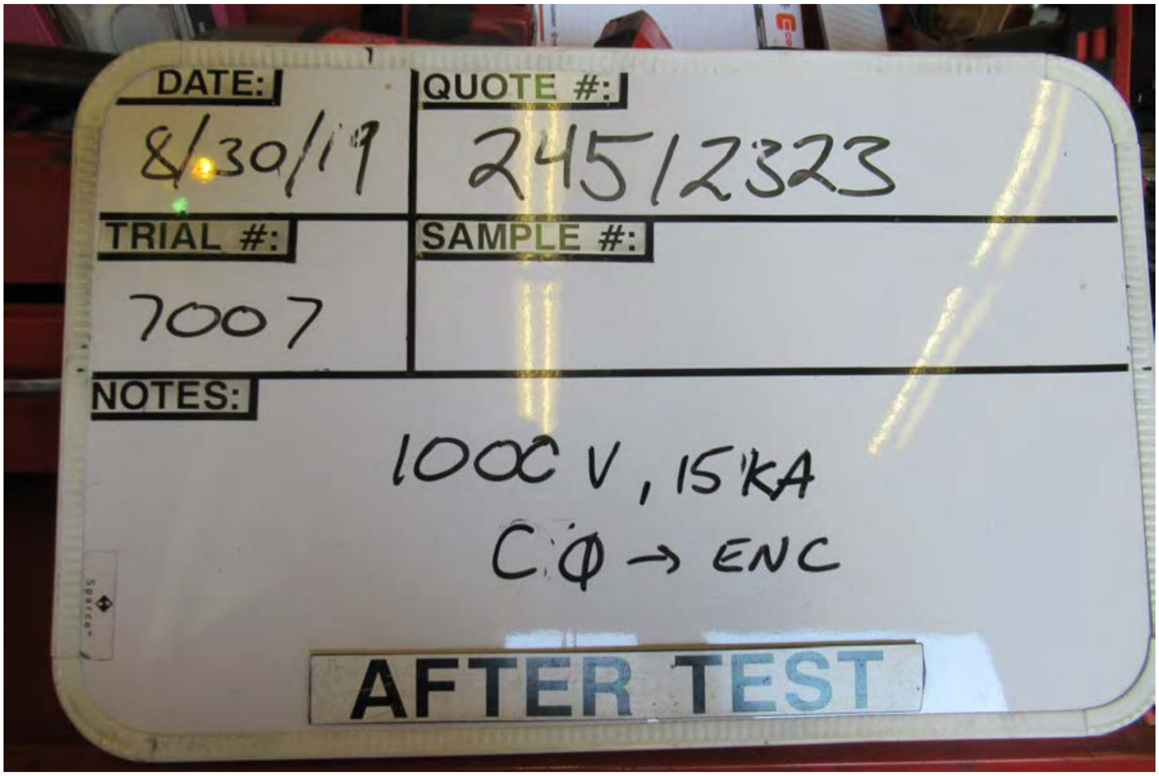
TRIAL #:
7007
SAMPLE #:
NOTES:
1000 V, 15 KA
C:Φ → ENC
BEFORE TEST


DATE:
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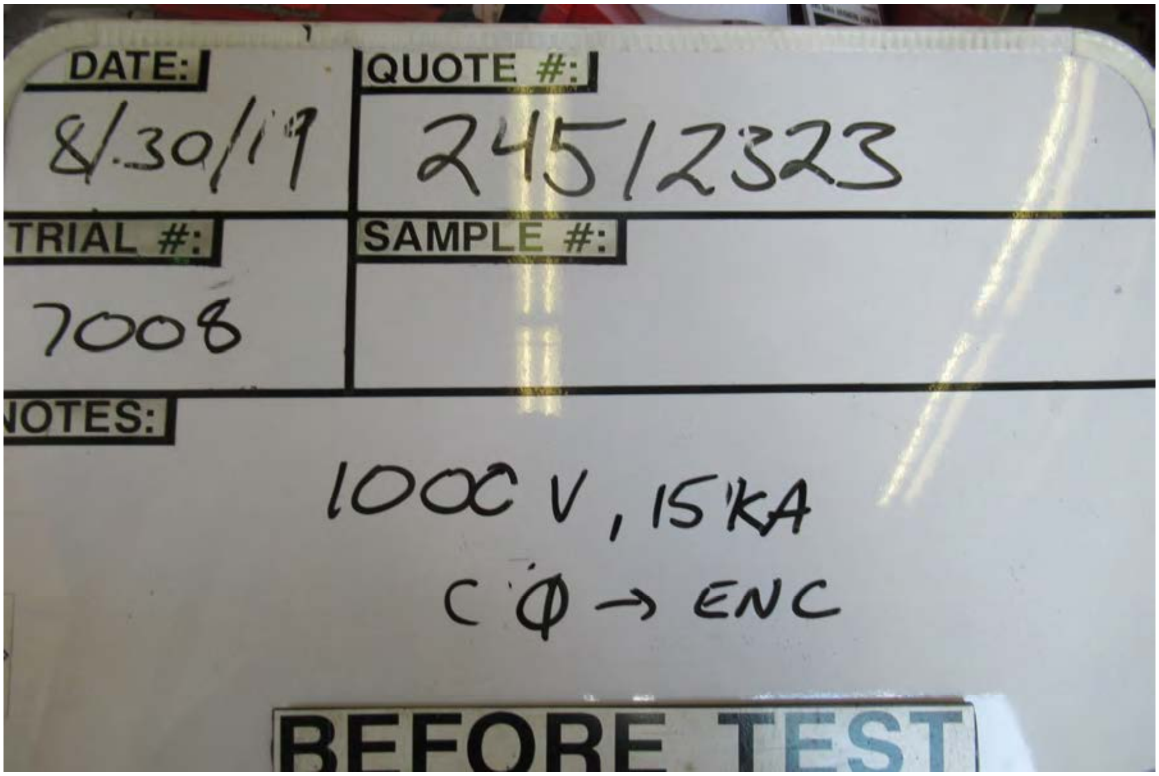
TRIAL #:
7007
SAMPLE #:
NOTES:
1000 V, 15 KA
C:Φ → ENC
AFTER TEST


DATE:
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TRIAL #:
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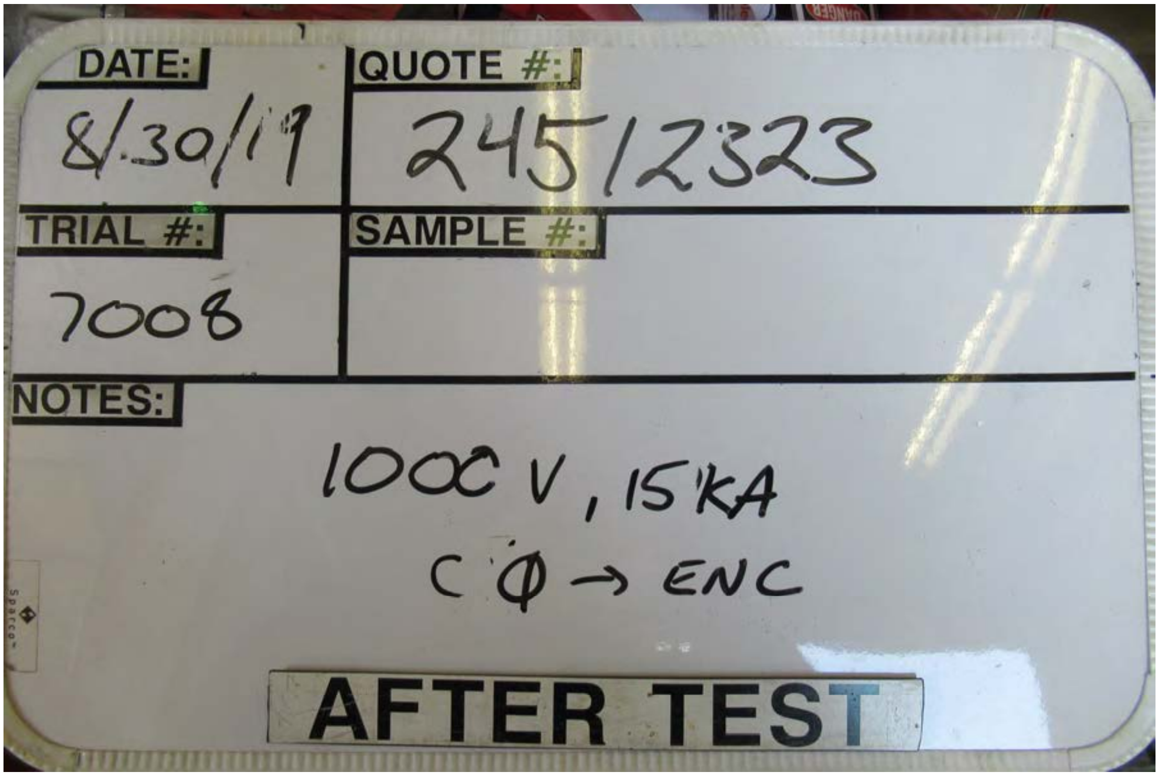
SAMPLE #:
NOTES:
1000 V, 15 KA
C Φ → ENC
BEFORE TEST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8/30/19
QUOTE #:
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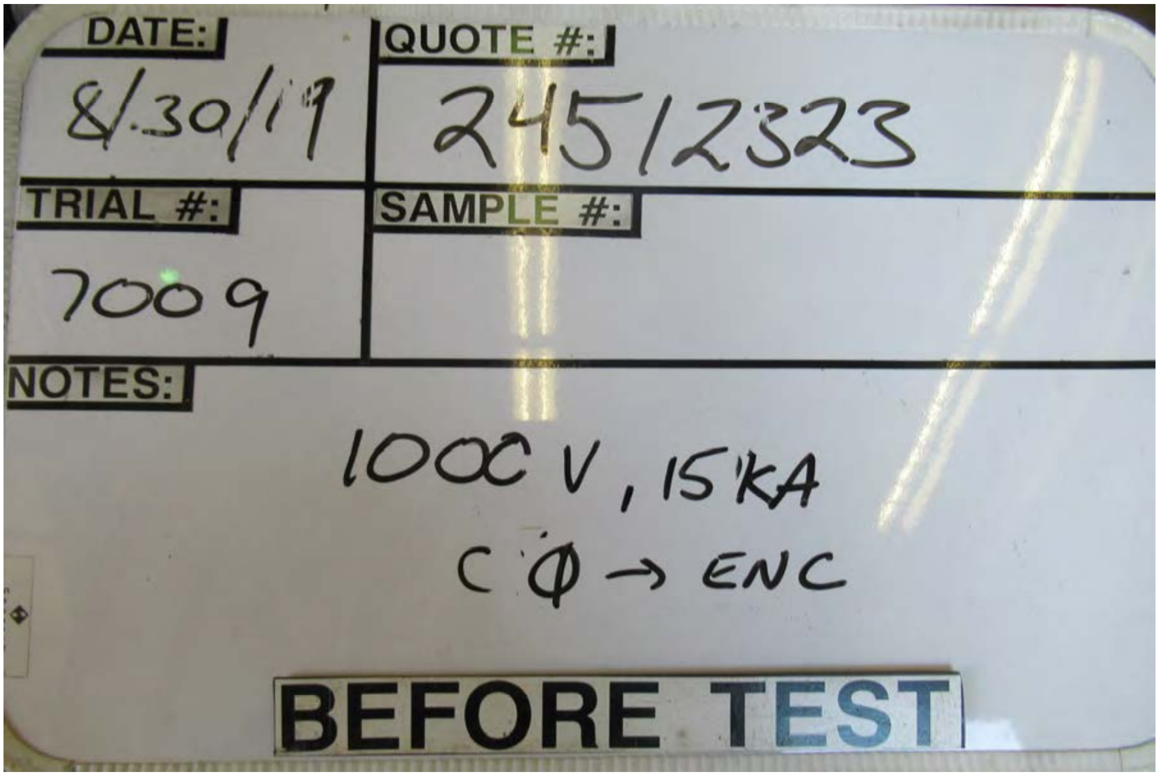
NOTES:
1000 V, 15KA
C Φ → ENC
AFTER TEST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24512323
TRIAL #:
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SAMPLE #:
NOTES:
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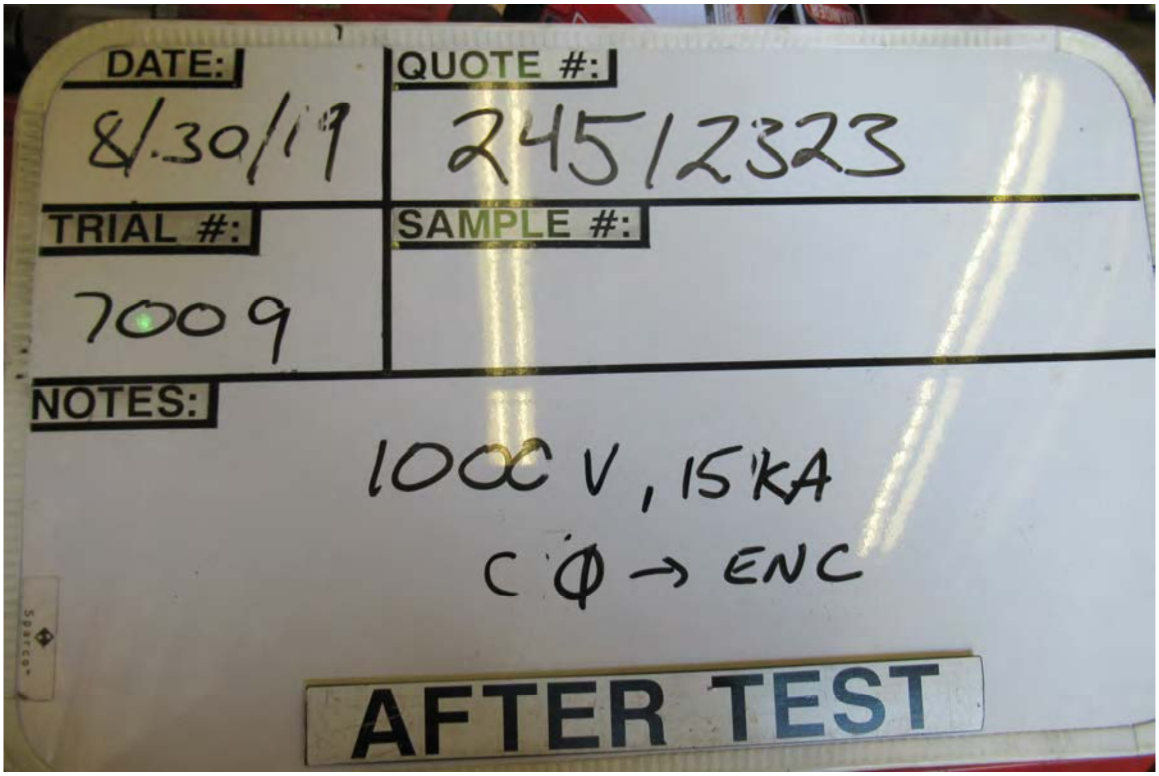
C Φ → ENC
BEFORE TEST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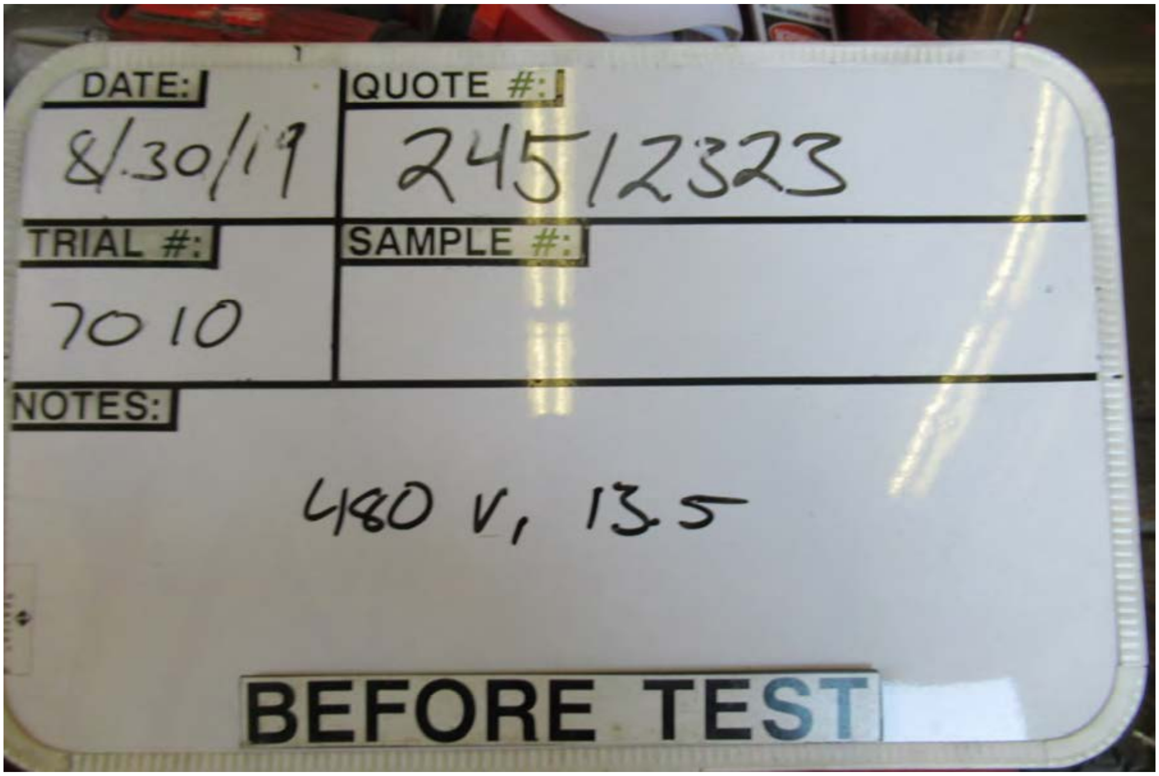
24512323
TRIAL #:
7009
SAMPLE #:
NOTES:
1000 V, 15KA
C Φ → ENC
AFTER TEST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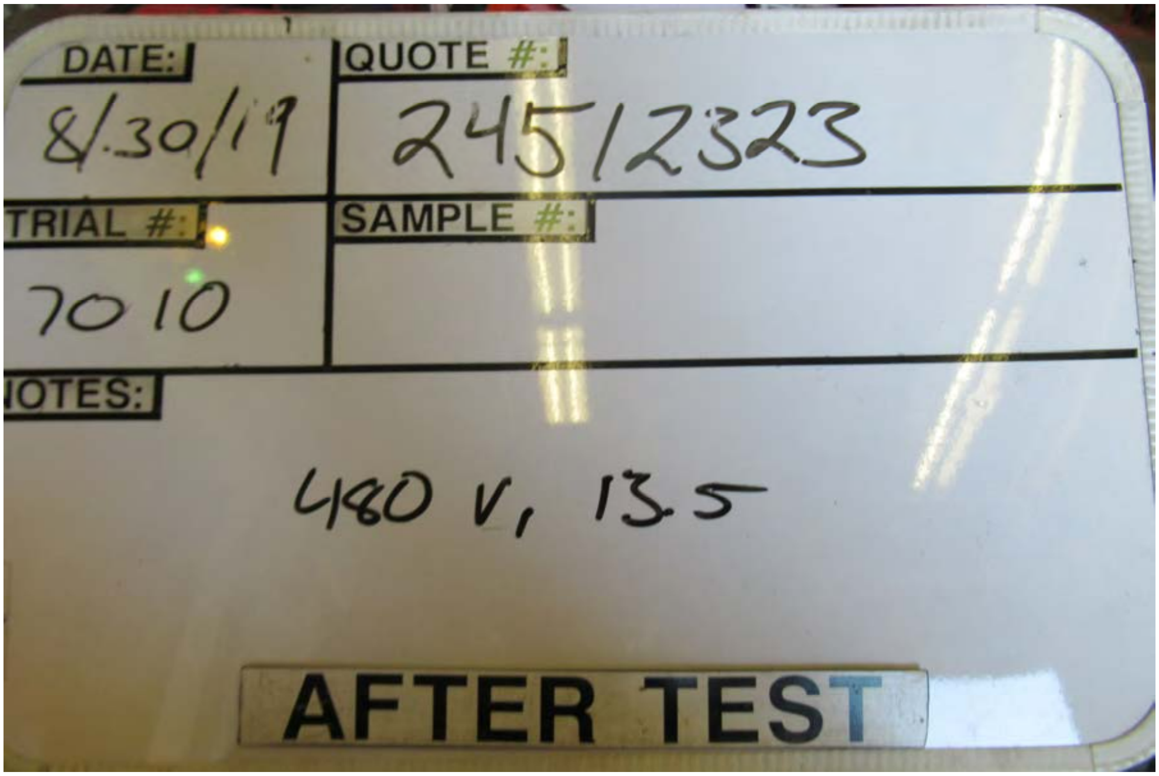
TRIAL #:
7010
SAMPLE #:
NOTES:
480 V, 13.5
BEFORE TEST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QUOTE #:
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TRIAL #:
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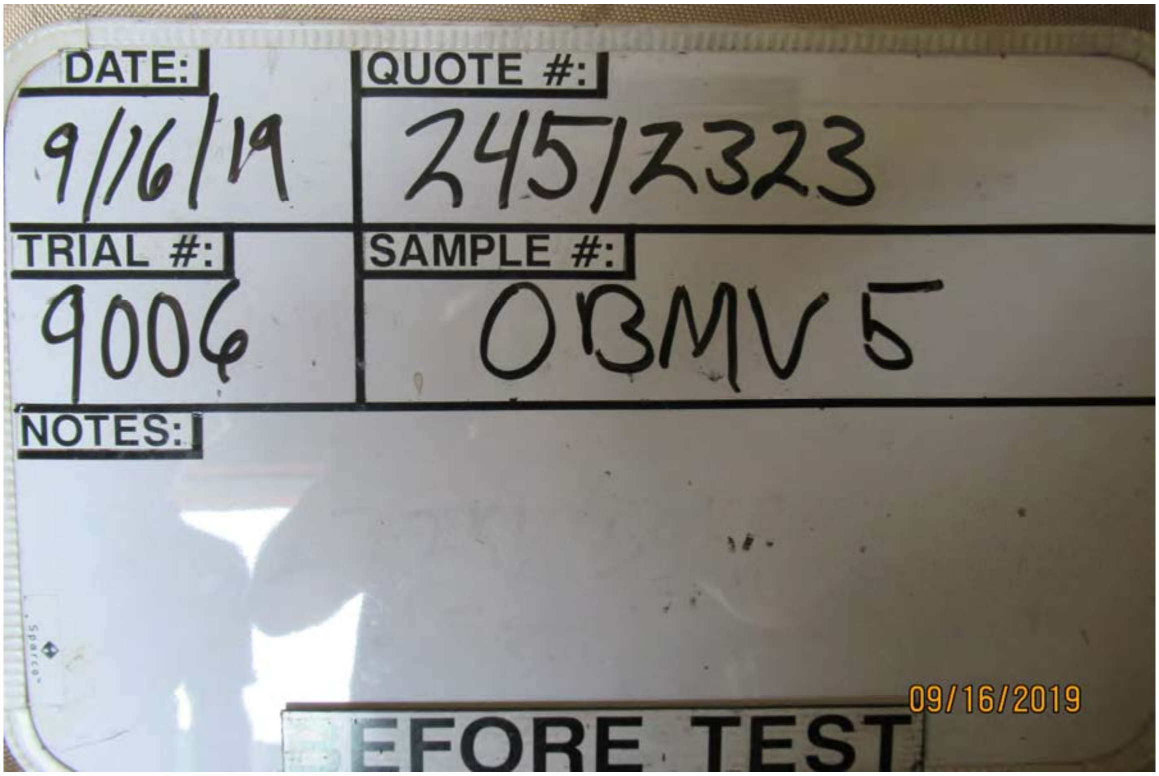
SAMPLE #:
OTES:
480 V, 13.5
AFTER TEST


DATE:
9/16/19
QUOTE #:
24512323
TRIAL #:
9006
SAMPLE #:
OBMV5
NOTES:
09/16/2019
EFORE TEST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OBMV
5
09/16/2019


09/16/2019


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OBMV
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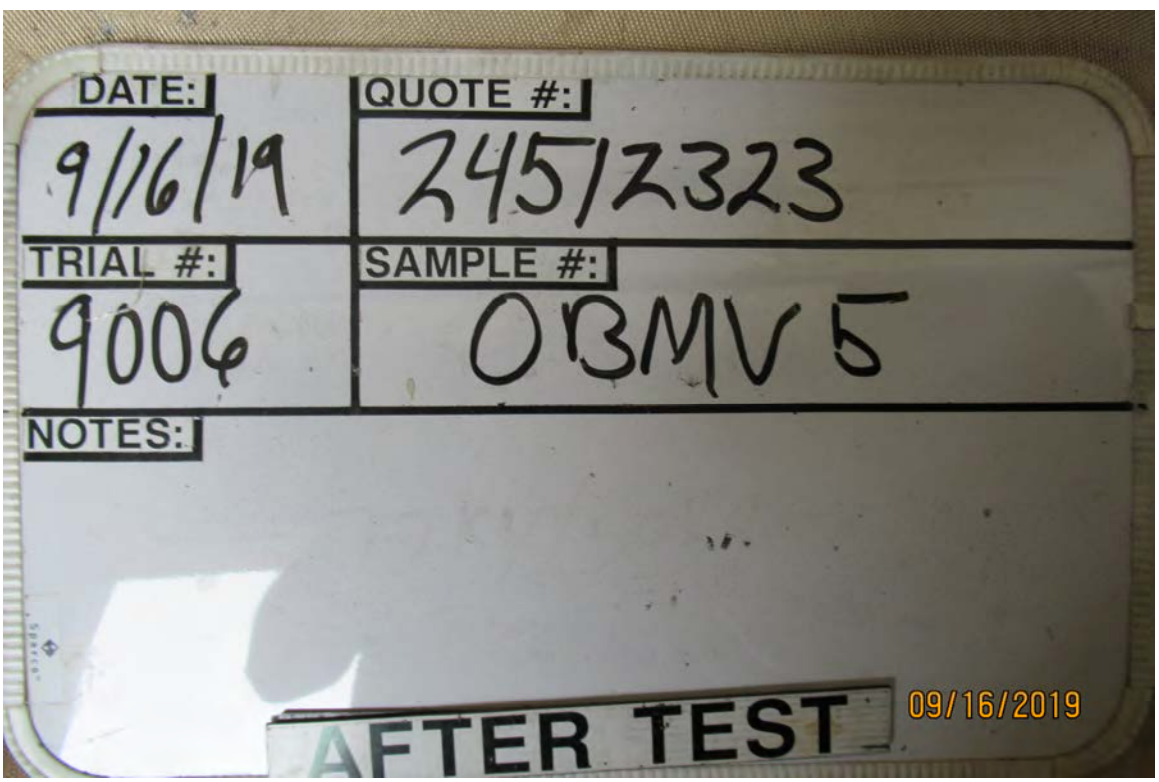
09/16/2019


DATE:
9/16/19
QUOTE #:
24512323
TRIAL #:
9006
SAMPLE #:
OBMV 5
NOTES:
AFTER TEST
09/16/2019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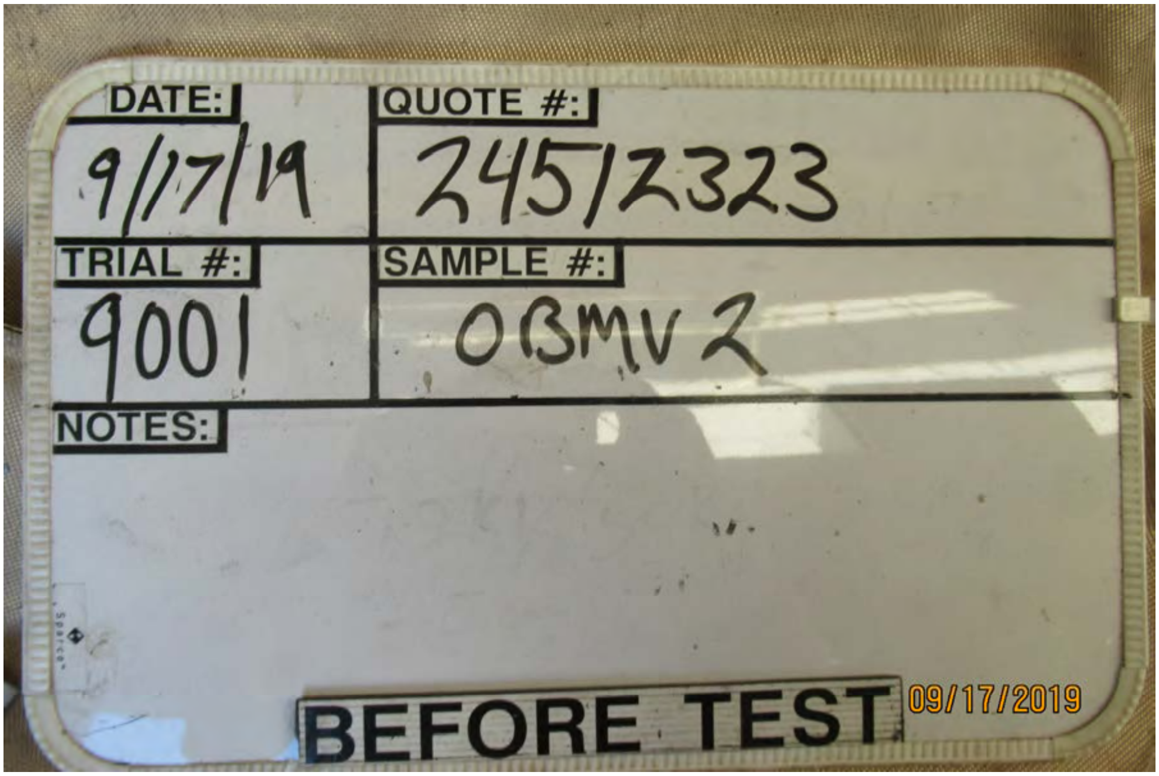
DATE:
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TRIAL #:
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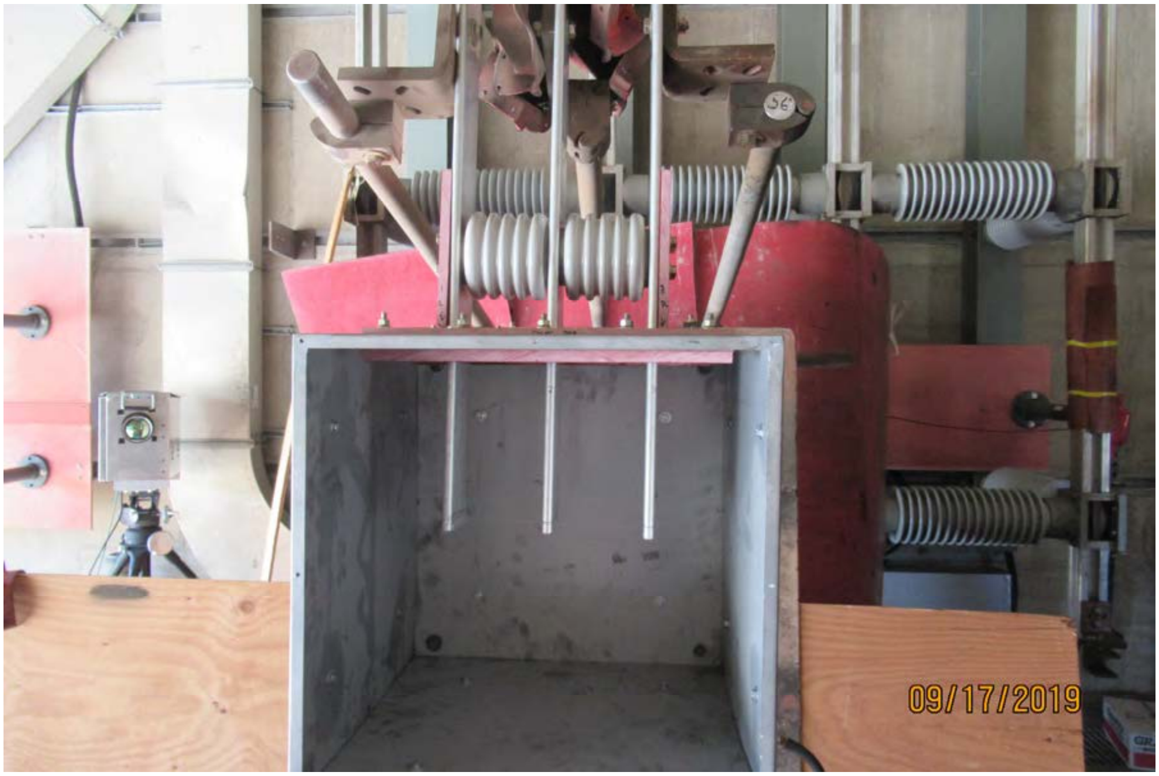
SAMPLE #:
OBMV2
NOTES:
BEFORE TEST
09/17/2019


09/17/2019


09/17/2019


OBMV
2
09/17/2019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OBMV
2
09/17/2019


OBMV
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09/17/2019


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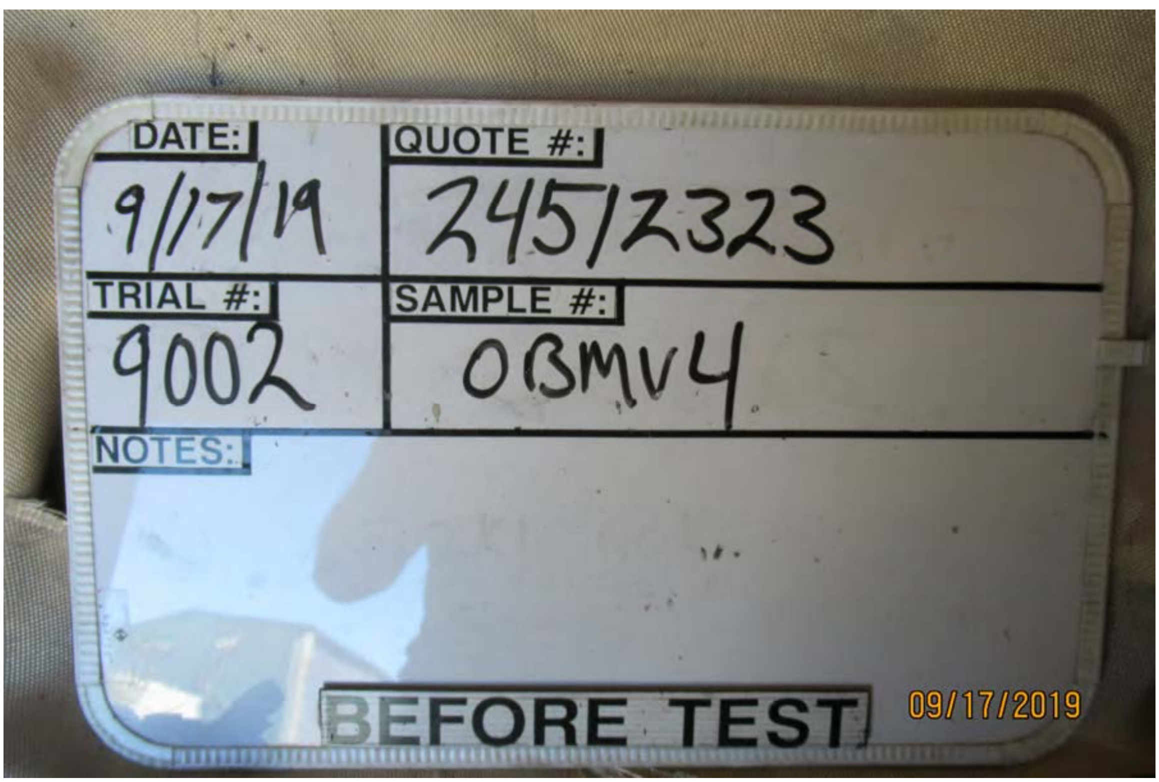
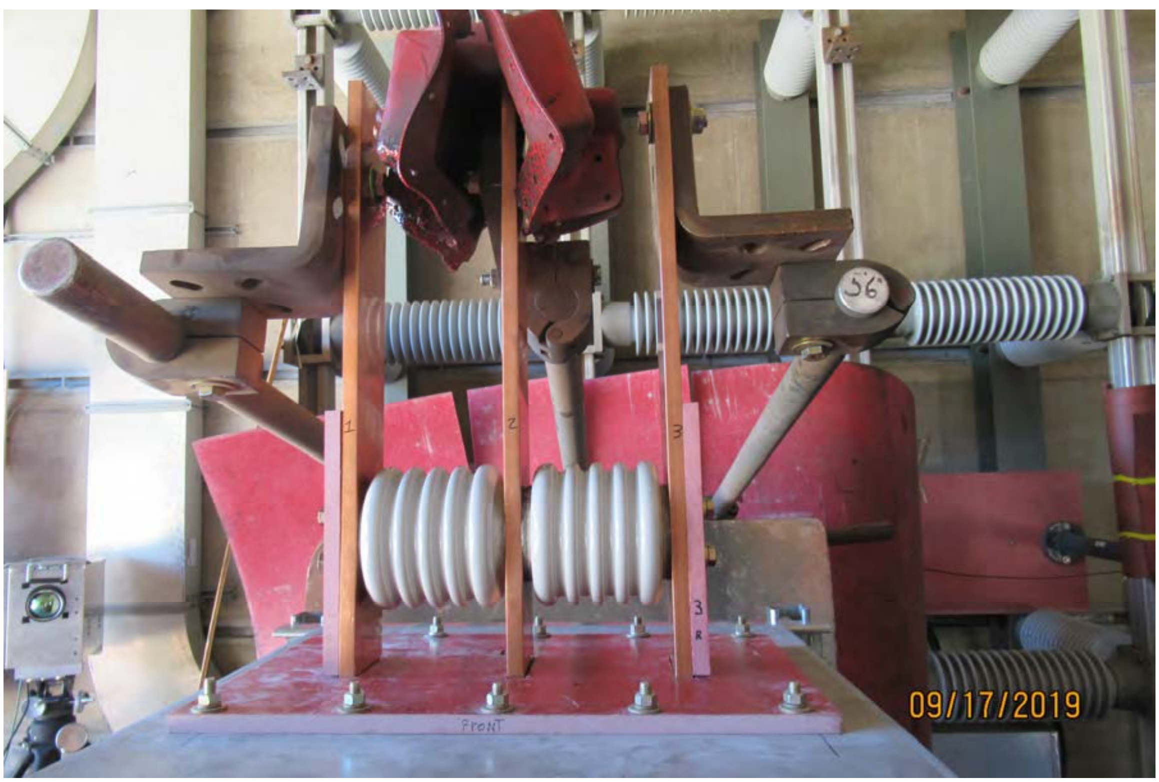

DATE:
9/17/19
QUOTE #:
24512323
TRIAL #:
9002
SAMPLE #:
OBMV4
NOTES:
BEFORE TEST
09/17/2019

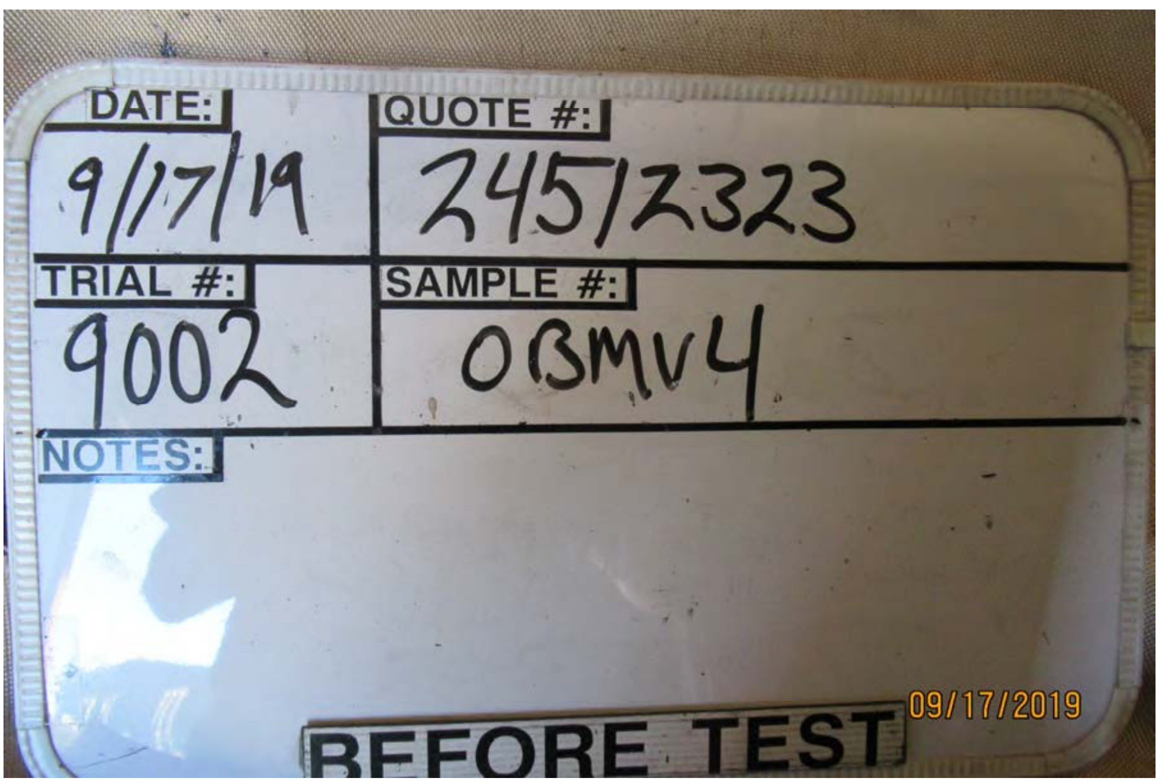

1
2
3
09/17/2019


09/17/2019


09/17/2019


OBMV
4
09/17/2019


09/17/2019


DATE:
9/17/19
QUOTE #:
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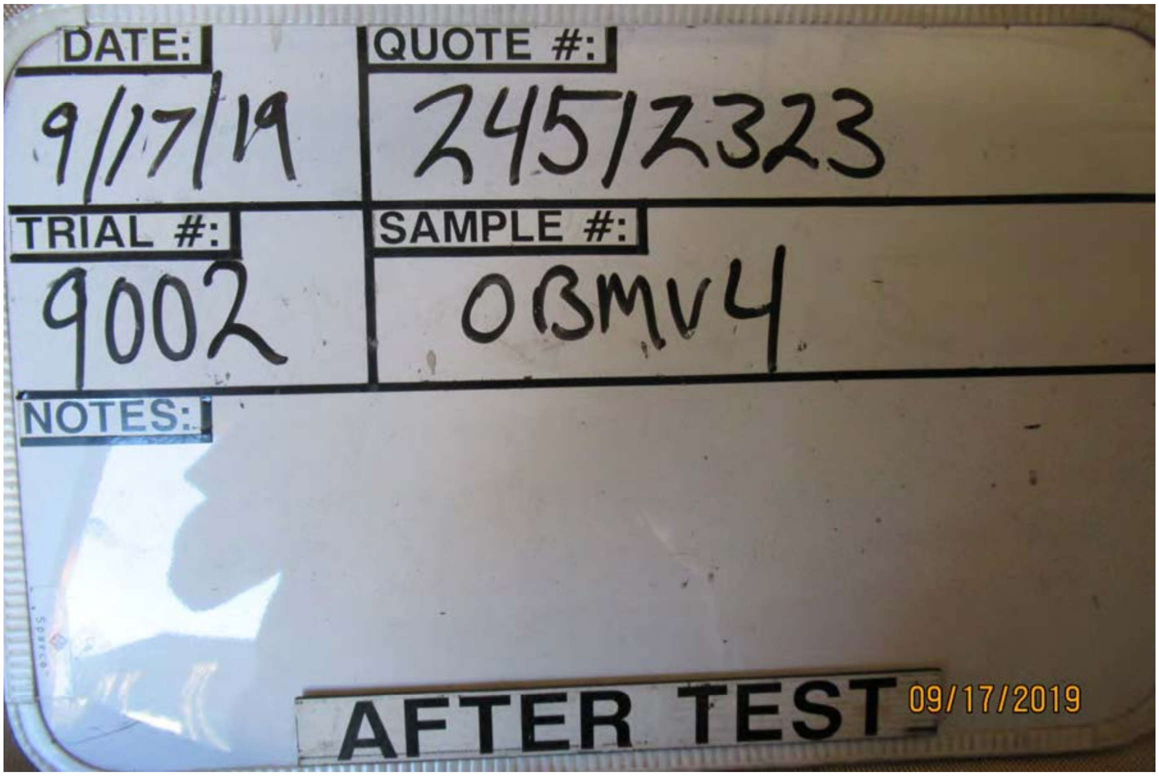
TRIAL #:
9002
SAMPLE #:
OBMV4
NOTES:
BEFORE TEST
09/17/2019


DATE:
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QUOTE #:
24512323
TRIAL #:
9002
SAMPLE #:
OBMV4
NOTES:
AFTER TEST
09/17/2019


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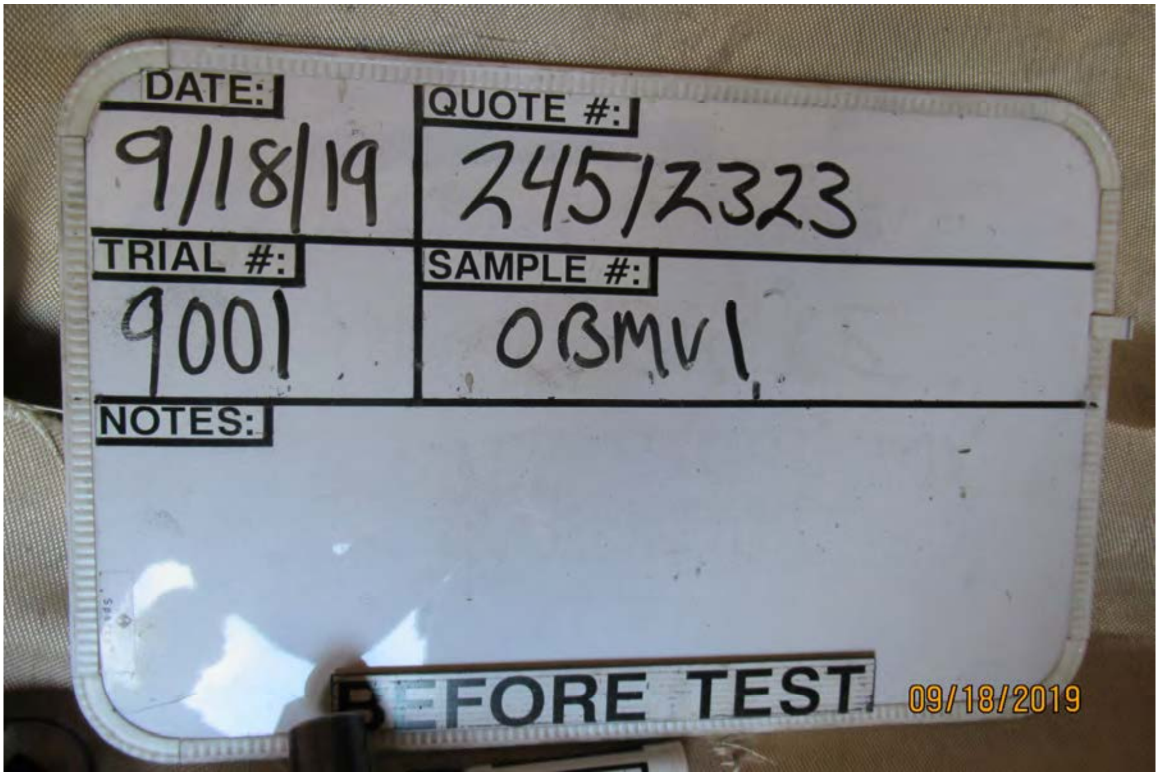
09/17/2019


09/17/2019


09/17/2019


DATE:
9/18/19
QUOTE #:
24512323
TRIAL #:
9001
SAMPLE #:
OBMV1
NOTES:
BEFORE TEST
09/18/2019


09/18/2019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OBMV
1
09/18/2019


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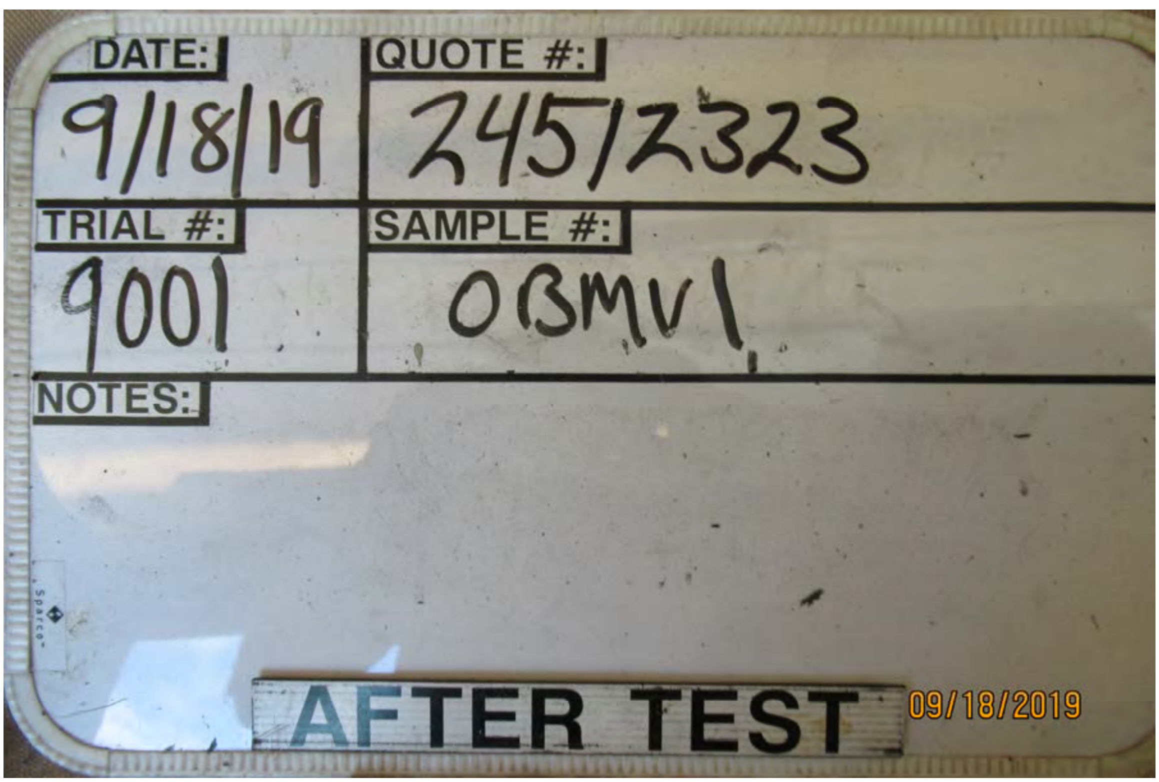
09/18/2019


DATE:
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QUOTE #:
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TRIAL #:
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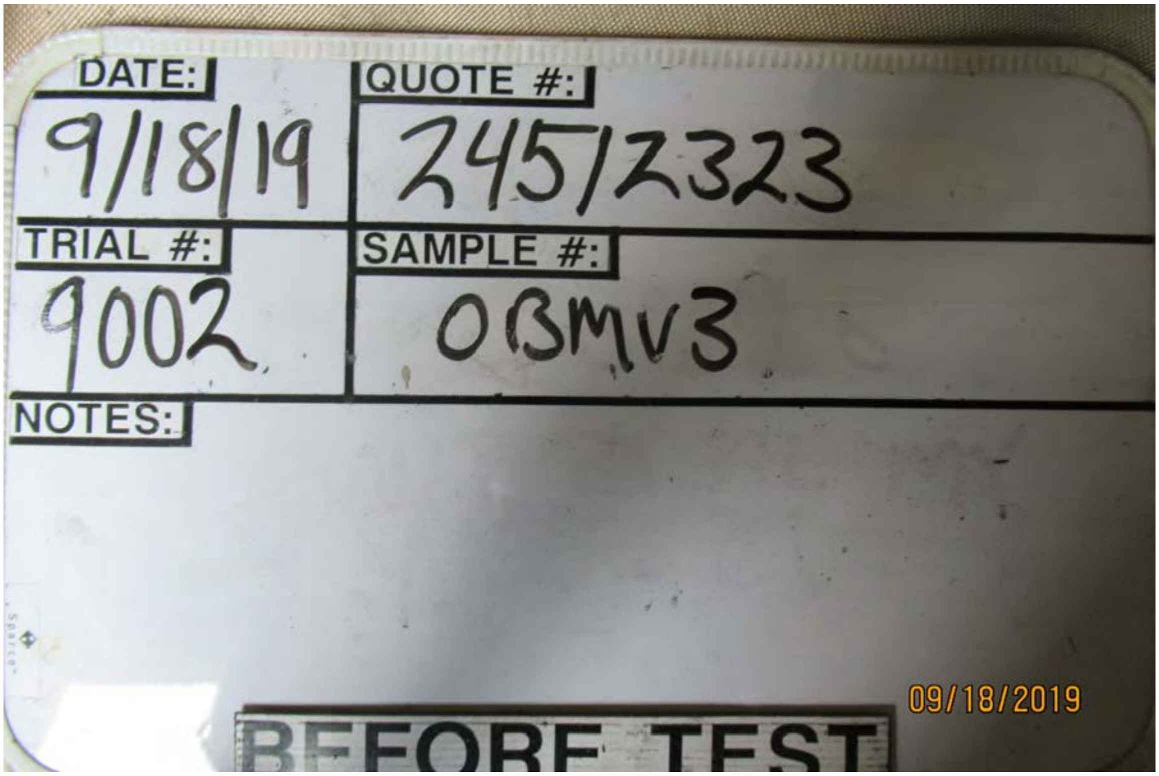
SAMPLE #:
OBMV1
NOTES:
AFTER TEST
09/18/2019


09/18/2019


09/18/2019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QUOTE #:
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TRIAL #:
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SAMPLE #:
OBMV3
NOTES:
09/18/2019
BEFORE TEST


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09/18/2019


OBMV
3
09/18/2019


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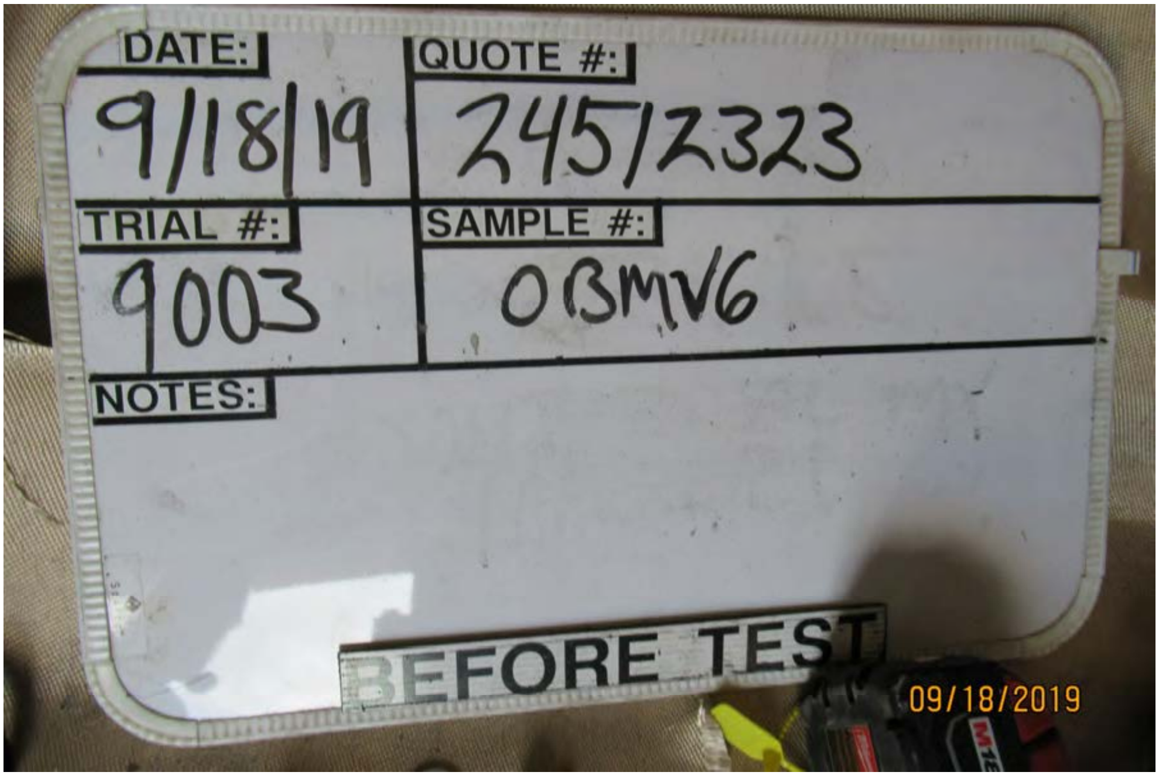
DATE:
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QUOTE #:
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TRIAL #:
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SAMPLE #:
0BMV6
NOTES:
BEFORE TEST
09/18/2019


09/18/2019


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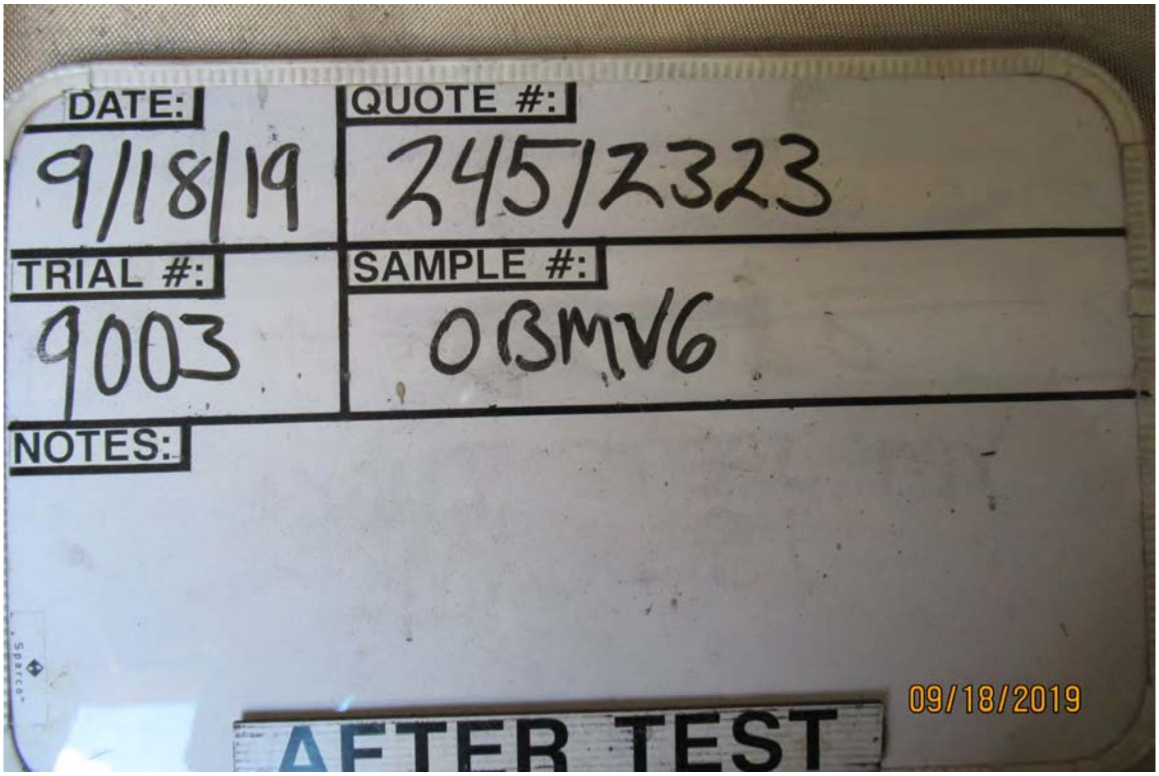
OBMV
6
09/18/2019


09/18/2019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QUOTE #:
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TRIAL #:
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NOTES:
AFTER TEST
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