**DC ARC FLASH IN STATIONARY BATTERY SYSTEMS**


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## Abstract

The purpose of this paper is to provide insight into the arc point energy and incident energy at a distance from the arc point that is present when an arc flash fault occurs inside of a cabinet containing a string of forty 12-volt VRLA batteries.

It is known that a DC arc flash is different than an AC arc flash due to the self-extinguishing of the arc that occurs when an AC voltage and current pass through the zero crossing. Even though the arc will be extinguished, it will self-ignite due to the heat generated by the plasma. This self-extinguish and re-ignition results in less arc energy and incident energy. The DC arc does not self-extinguish in the same way and will continue if the source voltage and available current is sufficient to sustain the arc.

Experiments were conducted to characterize the arc energy and incident energy present when a DC arc flash was created. These experiments used a continuous source of DC power to make measurements of incident energy and effects of widening of the arc gap. Further testing characterized how a limited power source i.e., a battery string, is used to sustain the arc flash. The fact that the arc energy and incident energy are functions of available power and time, it is necessary to determine how long an arc can be sustained by a continuously diminishing power source. The results of an attempt to eliminate several of the factors that determine the arc duration by using Tungsten for the arc electrodes have been included.

This paper provides the results of experimentation with a fixed power source and the results of testing using batteries as the source. The amount of incident energy from both sources is compared showing the dependence of other variables effect on the magnitude and duration of arc flashes created. Included are the test set up, equipment required and test results from the experiments.

## Purpose of Testing

The NFPA has requirements for specifying the arc flash hazard level of incident energy in terms of calories per square centimeter (cal/ $cm^2$) present on a surface at a specified distance from an arc flash point. This incident energy level is used to determine the grade of personal protective equipment (PPE) required to be worn by a person working in a potential arc flash environment. The hazard level is determined using a calculation based on several variables that include the source voltage, the bolted-fault current available, arc duration, arc gap length, and distance from the arc point. The NFPA equation[1] is used to determine the PPE level for the calculated incident energy. To account for the effects of the arc flash occurring within an enclosure, it is suggested that additional PPE protection be provided. Testing was performed to determine the magnitude of the incident energy and the effect of the arc fault occurring within an enclosure.

## Introduction

We worked closely with Kinectrics High Energy Laboratory in Toronto, Canada to measure the incident energy released from an arc fault within the supplied 5-tiered front access battery cabinet. The testing at the Kinectrics facility used a constant power source to create and sustain the arc. Figure 3.2 and 3.3 shows the test cabinet with the electrodes mounted adjacent to the circuit breaker with and without a shield.

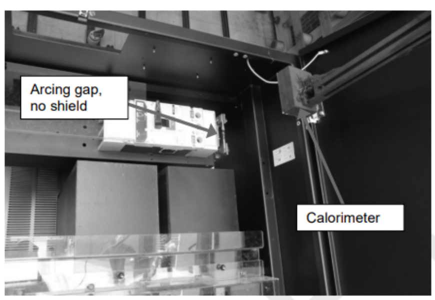


**Figure 3-2: Test Fixture Mounted on Source Side of Circuit Breaker, No Shield**

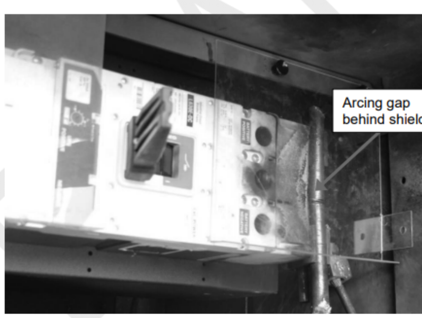


**Figure 3-3: Test Fixture Mounted on Source Side of Circuit Breaker, with Shield**

**Arc Flash/Arc Blast**

An arc flash is accompanied by an arc blast occurring almost simultaneously. The effect of the blast can be harmful to a person near the arc point. The arc blast, although not quantified in this report, is a result of an explosion and pressure wave occurring when the surrounding air ionizes and expands due to the heat produced by the arc. The brightness of the arc flash can cause temporary or permanent eye damage. The arc blast explosion noise can cause hearing problems, and the force of the explosion can knock a person off their feet. The ionized air is plasma whose temperature can be in the range of 30,000 degrees F. In addition to the PPE rated clothing, ear plugs, and a tinted face mask are recommended.

The magnitude of the arc flash event is a function of many parameters. The voltage and bolted-fault current produce the power necessary to create the arc. The electrode material, diameter, and melting point temperature contribute to the duration. The length of the arc gap, orientation of cables and resistance of the cabling from the power source to the arc point also contribute to the duration and arc point energy.
The higher arc energy contributes to the incident energy that would impinge on a person in proximity of the arc causing potentially severe burns unless they are wearing protective clothing rated to the level of incident energy.

**Test Set-Up**

Arc flash testing of a battery cabinet was performed at the Kinectrics, Inc. High Energy Laboratory in Toronto, Canada. An external DC power supply was used in place of batteries as the energy source. The cabinet included a circuit breaker assembly mounted in its normal cabinet location that creates a constricted area. The arc electrodes were mounted in this area for the tests. The purpose of the constriction was to determine the multiplication factor effect on the measured incident energy. This location is also the most likely location in the cabinet where an arc of the largest magnitude would be created. The cabinet was placed in a protected outdoor test cell configured for arc flash measurement purposes. Figure 1A shows the test set-up for this series of tests.

Arc Flash in Stationary Battery Systems

Kinectrics Lab Test Setup

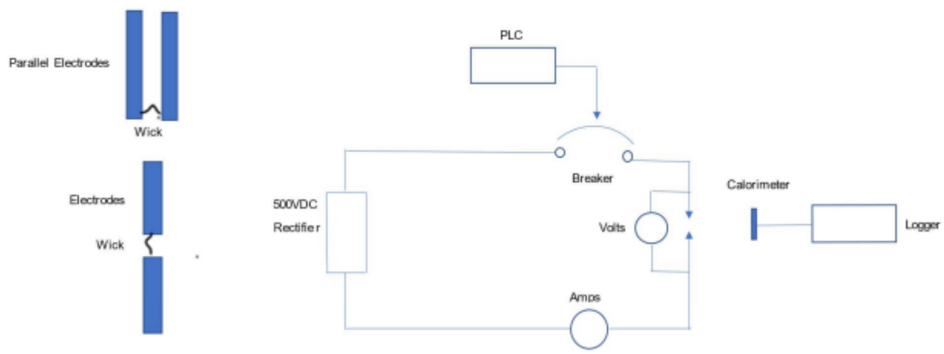


Figure 1A

All tests were conducted using a fixed DC voltage of 500V and a bolted-fault current of 5000A. Several experiments were conducted using various electrode sizes and fixed time durations as a part of setting up the measuring instruments and recording devices. Referring to Table 1, tests 4282 through 4287 used a time duration set to 2.0 seconds and the electrodes were sized at ¾”. These parameters were chosen as representative of what would be the worst case for the battery cabinet. The arc electrodes were solid Copper rods ¾” in diameter. The rods were initially placed parallel to each other with a ½” gap between them. To ignite the arc, the gap between the rods was wicked with a small gauge wire. Several tests were conducted and resulted in the arc self-extinguishing after a short duration (less than 100 ms) due to the arc traveling beyond the end of the rods. Traveling of the arc is due to the magnetic field created by the current in the rods and associated connecting cables. The intent of the test was to have a sustained arc lasting 2 seconds which would not be possible with the parallel rods. The electrodes were re-oriented, so they were end to end with a gap length of ½”. The power source was set to turn off after 2 seconds if the arc did not self-extinguish. A calorimeter was placed at 18” from the arc point to measure the incident energy in conformance with the NFPA guidelines. The test setup allowed for remote monitoring of the arc flash event and a high-speed camera photographed the entire arc flash event from the start of the plasma and burn back of the Copper rods until the end of the 2 second window.

Arc voltage and current waveforms were captured for each test event and the resultant incident energy was determined for each test.

The next phase of testing was conducted at our facility. Figure 1B shows the test setup used to perform the testing using a string of forty 12V VRLA batteries. This series of tests are intended to determine the magnitude and duration of the arc flash point energy and the resultant incident energy when the power source is a string of VRLA batteries. The battery voltage is 516VDC and the bolted current is 4800A +/- 5%. The electrodes are 350kcmil THHN cables spaced 1/4” end to end. A small gauge wire is placed in the gap to ignite the arc when the voltage is applied. Three Calorimeters are placed 18” from the arc point to measure the incident energy. Instrumentation: 2 oscilloscopes, high voltage isolation probe, current sensor, PLC sequence controller, data logger and high-speed camera are set to measure and record the arc voltage, current and duration to determine the arc energy. The calorimeter readings collected by the data logger are used to determine the level of incident energy. The energy levels are then used to determine the PPE level that would be required when servicing a cabinet of batteries with similar ratings.

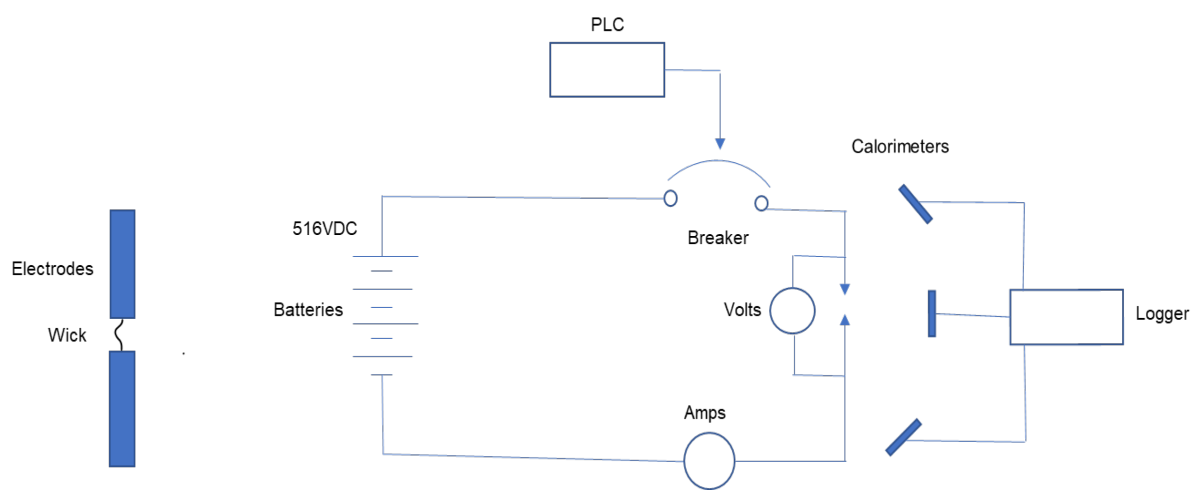


Figure 1B Arc Flash Testing set up.

## Measurements

### Fixed Power Measurements

Initial tests were conducted with the arc point located adjacent to the circuit breaker where a cavity is formed. Numerous tests were performed to ensure consistent readings. It is interesting to note that the burn back of the Copper rods formed a gap of 3" during the arcing period.

The battery cabinet is designed to accommodate a polycarbonate shield that covers the terminal wiring connections of the batteries and the circuit breaker. Tests were performed to determine if the shield had an impact on the incident energy readings from an arc created behind the shield. The results showed that the incident energy was the same as without the shield, but the shield did retain the arc blast spray of molten Copper. The arc point was then moved to a different location in the cabinet to determine if a multiplication of energy was occurring. The new location was the front center of the cabinet. It was expected the amount of reflection would be less than what would be occurring from the smaller cavity. This was found to be true. The energy measured was one and a half times less than the readings from the original location.

A test dummy wearing a PPE rated T shirt was placed at the distance of 18" from the arc point to determine if the incident energy was of sufficient magnitude to cause the shirt to catch fire. High speed photography showed the spray of molten Copper caused by the arc blast impinging on the dummy resulted in burn spots on the shirt that likely would have been felt by a human. This suggests that a higher rating PPE would be required.

The use of a fixed power source allowed for determining the effects of the variables; rod size, gap width, and arc time on the resultant incident energy created by the arc flash. Testing the incident energy levels showed that the calculated incident energy is more than what is measured.

### Observations

It was noted that an incident energy level difference was occurring between the two locations in the cabinet. The measured level of the incident energy at the front center of the cabinet was about half of the measured energy when the arc point was located next to the circuit breaker. It was also noted that the measured incident energy with and without the polycarbonate shield showed no difference. The shield prevented the Copper splatter from the electrode burn back from leaving the cabinet. Testing the cabinet with the dummy showed that the incident energy was not sufficient to cause the shirt to catch fire. The Copper splatter did cause burn spots to appear on the shirt. Data collected from the tests performed in the Kinectrics High Energy Laboratory are capsulized in Table 1. The data shows the incident energy levels are higher when the constant power source is used versus what is measured when the power is sourced from a string of batteries.

**Battery Power Measurements**

The battery powered testing consisted of three test configurations. A full string of 40 batteries with Copper electrodes, a half string of 20 batteries with Copper electrodes and a full string of 40 batteries with Tungsten electrodes. The three configurations were tested to observe the variance of the arc point and incident energy at a different voltage level and the effect of what was expected to be a reduced burn back using the Tungsten electrodes.

**Observations**

The initial test of 40 batteries and Copper electrodes spaced at 1/4" created an arc flash lasting 3 seconds with a peak current of 5000 Amps and a voltage rising from 0 to 250 Volts. Calculating the incident energy at the arc point using the average voltage 150V and current 3750A result is 1.71MJoules. The calorimeters measured 3.5 cal/cm$^2$ of incident energy at 18". The Copper cable burned back to a gap of 3 inches.

The calculated incident energy using the NFPA equation is 17.56 cal/cm$^2$.

The conclusion from this test is that the battery string can sustain an arc for 3 seconds. The arc duration is limited by the battery voltage. It is not sufficient to sustain the arc when the gap approaches 3" due to burn back. The size of the cable is also a factor. A smaller cable would burn back faster causing the arc duration to be shorter. A shorter starting gap would produce a longer arc time. It appears that with the battery voltage at 516V the arc lasts until the gap reaches 3 inches.

The voltage and current waveforms captured for this test are Figures 2 and 3

A subsequent test was performed using twenty 12 volt VRLA batteries as a 258 Volt string. The arc gap was set to 1". The arc duration was 240ms. The gap voltage was an average of 150V, and the arc current was 4000A peak and 3000A average. The incident arc energy was 108 Kilojoules. The calorimeters measured the incident energy at 18" of

0.3 cal/cm$^2$. The burn back of the electrodes increased the gap by less than ¼ inch. This test further validates that the incident energy of the arc flash is voltage dependent. Other factors are the size of cable and the initial arc gap length.

The calculated incident energy using the NFPA equation is 0.702 cal/cm$^2$.

The voltage and current waveforms captured for this test are Figures 4 and 5

The next test was intended to determine the duration of the arc when the arc is being sustained by a diminishing energy source, a string of batteries. Prior experiments indicated that the arc duration was more a function of burn back time of the electrodes. To minimize the burn back, 3/4" Tungsten electrodes instead of Copper were used in the experiment. The Tungsten electrodes are spaced at 1/2" and wicked with a small gauge wire. The battery voltage is 516 Volts, and the bolted-fault current is 4800A. The average voltage is 150V and the average current is 3000 Amps. The arc duration was 4.5 seconds. The arc energy is 2.025MJoules. The incident energy at 18 inches measured by the calorimeters is 4.03 cal/cm$^2$.

The calculated incident energy using the NFPA equation is 26.34 cal/cm$^2$.

It was expected that the Tungsten electrodes would have a minimum burn back, and the duration of the arc would be limited only by the available energy from the batteries. The Tungsten did burn back, although slower than Copper, the arc extinguished when the gap exceeded 3". The batteries were able to sustain the arc for 4.5 seconds and would most likely have sustained the arc even longer if the burn back had not occurred. It appears that some burn back may continue due to the heat after the arc energy is removed. The end of test measured burn back of the Tungsten electrodes was 5 ".

The voltage and current waveforms captured for this test are Figures 6 and 7.

Figure 8 is a graph plotting the measured arc point energy, Joules, versus the resultant incident energy in cal/cm$^2$.

The summary of the three test configurations is shown in Table 2.

## Observations

There are differences between an arc flash created using a constant power source versus the arc flash created using batteries. Comparing the arc current and arc duration, of Table 1 test 4286 versus the arc current and duration shown in Table 2 for the 516V Copper electrode test. The test 4286 incident energy is greater for the shorter duration arc.

The arc duration is controlled by a variety of factors i.e., energy source, arc gap width, electrode burn back, electrode size, electrode material, electrode orientation, and connection resistance. Tests 4282 – 4285 showed a much shorter arc duration than the tests that were conducted with the electrodes located in the center front of the cabinet. It appears that the arc was being self-extinguished by a magnetic field created by the electrodes or the cables connecting the electrodes to the energy source.

The lower the source voltage the lower the duration of the arc and the amount of incident energy that is generated.

The speed and amount of burn back that occurs impacts the duration of the arc flash.

The arc blast effects are spectacular to view from a safe distance.

The arc plasma heat can vaporize the electrodes, even the Tungsten, and it did.

## Conclusions

- Lower voltage battery strings produce lower energy and shorter duration arc flashes. The level of the incident energy reduces the category of PPE required for safety but does not eliminate the need for PPE. When working in an environment where the possibility for an arc flash to occur exists, it is important to determine the minimum PPE required. It should also be noted that an arc fault occurring within a battery cabinet on the battery side of the cabinet circuit breaker will not be extinguished by the breaker. The arc duration will be limited by burn back and the energy capacity of the batteries.

- The Tungsten electrodes have a current limiting effect affecting the average arc current due to the higher resistance of Tungsten with respect to Copper. The lower level of arc current reduces the arc incident energy but the longer arc time offsets the reduction. The use of the Tungsten electrodes was contrary to what was expected. The arc duration was longer, but not due to the reduction of the burn back. The higher electrode resistance kept the voltage higher and the current lower. The higher the voltage the longer the arc can be sustained over the wider gap created by the burn back.

- The answer to the original question of how long a string of forty 12V VRLA batteries with a short circuit current rating in the range of 5000A can sustain an arc flash, it is longer than 2 seconds.

- Be very careful when working with battery systems.

- The NFPA equation calculated vs measured incident energy is different.

- A constant power supply vs batteries yield different results.

- There is a multiplication of incident energy depending on the location of the arc within the enclosure.

- The effects of an Arc Blast can be harmful as well as destructive.

    - Plasma temperature can reach 30,000 Degrees F

    - Arc Blast can produce harmful sound levels.

    - Arc Blast explosion forces can cause physical damage.

## Table 1 Kinectrics Inc. Test data

| Test Number | Description | Test Current (kA) | Duration (s) | | Incident Energy Measured (cal/cm²) | Average Heat Flux Cal/cm²/s |
|---|---|---|---|---|---|---|
| | | | Pre-set | Actual | | |
| 4275 | Calibration | 4.09 | 0.20 | 0.09 | N/A | N/A |
| 4276 | Calibration | 4.99 | 0.20 | 0.10 | N/A | N/A |
| 4277 | Calibration | 2.03 | 0.20 | 0.05 | N/A | N/A |
| 4278 | Calibration | 2.56 | 0.20 | 0.03 | N/A | N/A |
| 4279 | Calibration | 3.85 | 0.20 | 0.20 | 0.5 | 2.5 |
| 4280 | Upstream of CB; No Shield; 3/8" rod | 3.75 | 0.25 | 0.25 | 1.1 | 4.4 |
| 4281 | Upstream of CB; No Shield; 1/2" rod | 3.19 | 1.00 | 0.87 | 6.2 | 7.1 |
| 4282 | Upstream of CB; No Shield; 3/4" rod | 3.19 | 2.00 | 0.68 | 4.6 | 6.8 |
| 4283 | Upstream of CB; No Shield; 3/4" rod | 3.44 | 2.00 | 0.59 | 2.5 | 4.2 |
| 4284 | Upstream of CB; No Shield; 3/4" rod | 3.80 | 2.00 | 0.56 | 1.9 | 3.4 |
| 4285 | Upstream of CB; Shielded; 3/4" rod | 3.34 | 2.00 | 0.82 | 3.2 | 3.9 |
| 4286 | Tier Four; No Shield; 3/4" rod | 3.19 | 2.00 | 2.03 | 3.8 | 1.9 |
| 4287 | Tier Four; No Shield; 3/4" rod | 3.18 | 2.00 | 2.03 | Mannequin | Mannequin |

Table 2 Measurement Summary

| | | | |
|---|---|---|---|
| Battery String Voltage | 258 V | 516 V | 516 V |
| Electrodes: | Copper | Copper | Tungsten |
| Ave. Arc Voltage: | 150V | 150V | 150V |
| Ave. Arc Current: | 3000A | 3750A | 3000A |
| Arc Gap: | 1” | 1/4” | 1/2” |
| Arc Duration: | 240ms | 3sec | 4.5sec |
| Arc point Energy | 108 KJoules | 1.71 MJoules | 2.025 MJoules |
| Incident energy at 18 inches | .3 cal/cm$^2$ | 3.5 cal/cm$^2$ | 4.02 cal/cm$^2$ |
| Burn Back Gap | 1 ¼” | 3” | 3” |
| NFPA calculated energy at 18 inches | .702 cal/cm$^2$ | 17.56 cal/cm$^2$ | 26.34cal/cm$^2$ |

## References:


1. NFPA 70E 2021 Annex D Paragraph D. 5.1

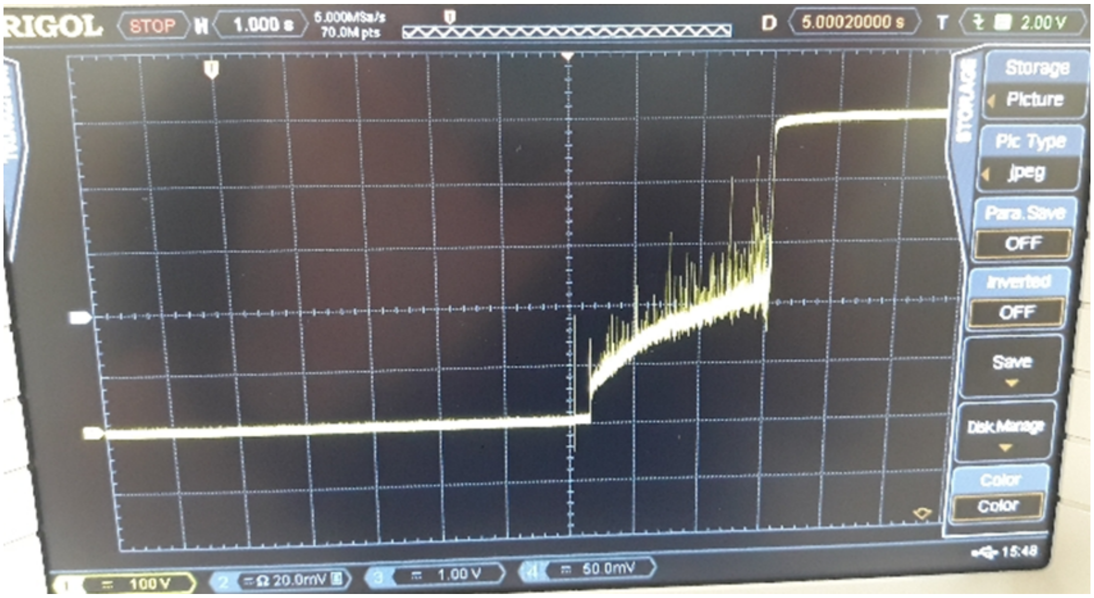


Figure 2 516V Voltage Waveform Horizontal 1 sec./division Vertical 100V/division

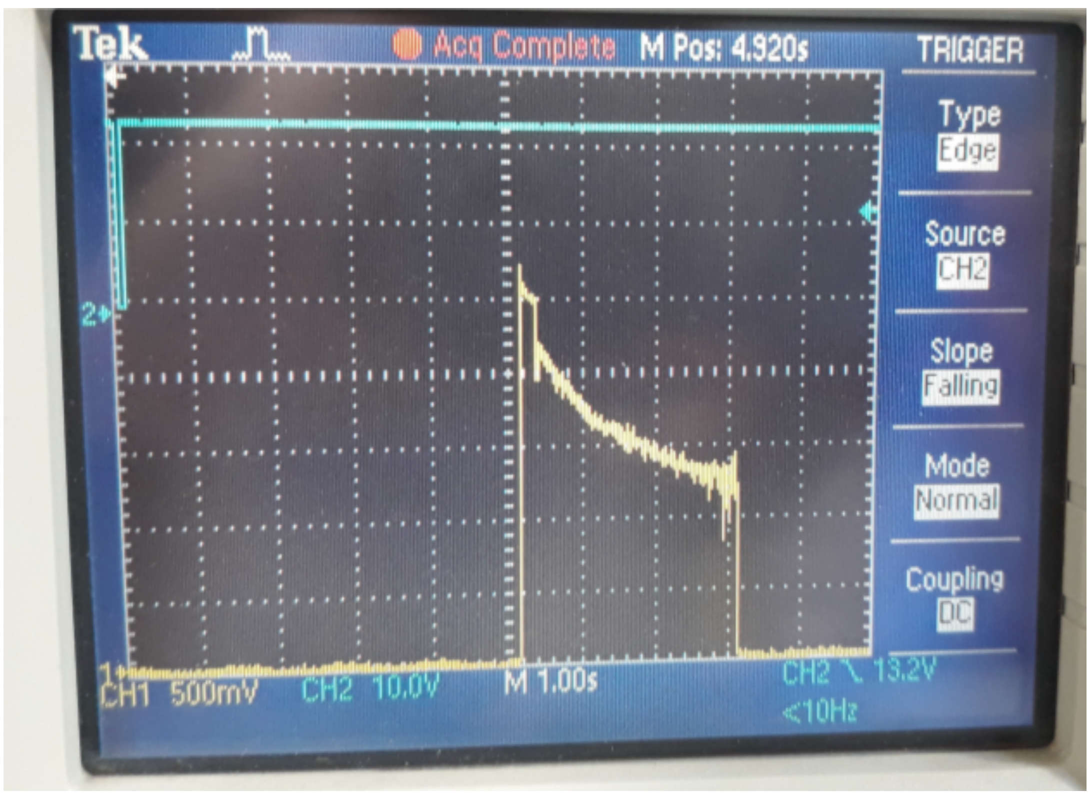


Figure 3 516V Current Waveform Horizontal 1 sec./division Vertical 1000A/division

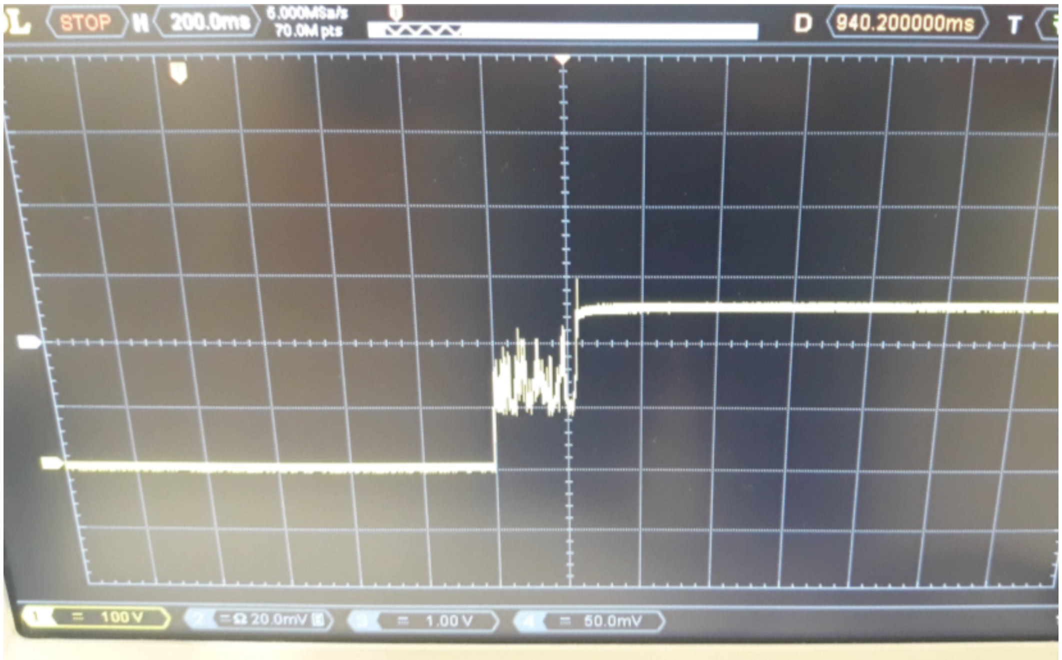


Figure 4 258V Voltage waveform Horizontal 200ms/division Vertical 100V/division

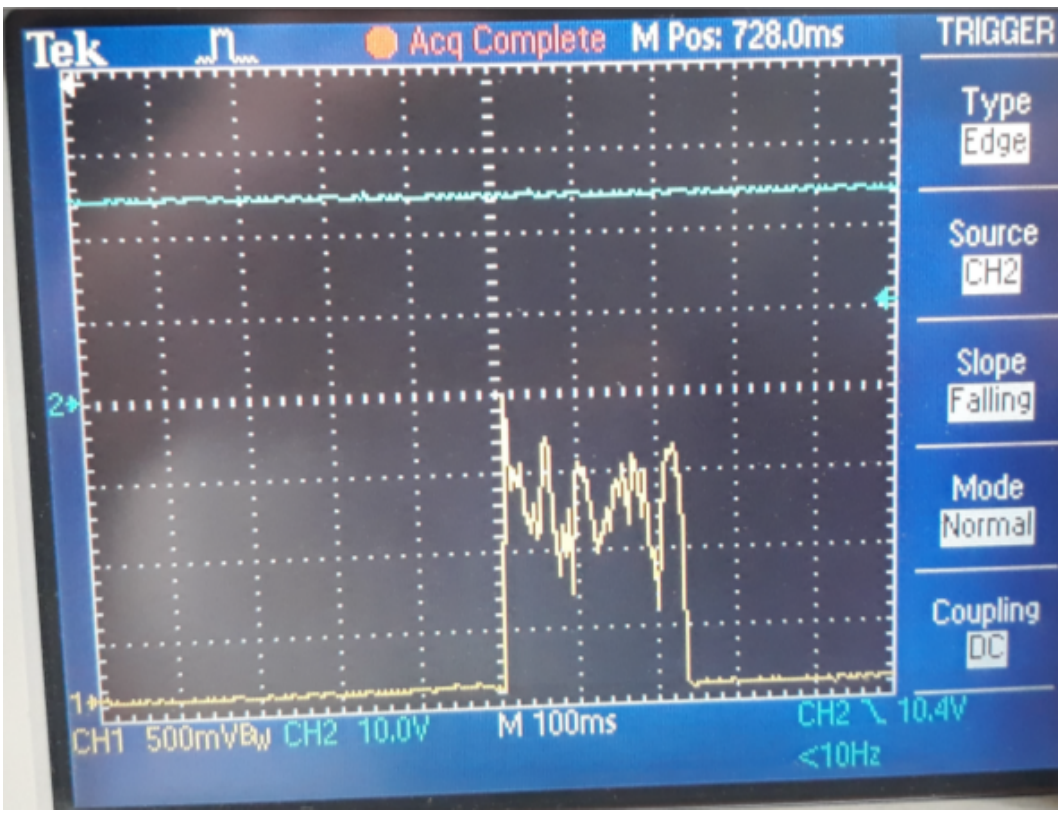


Figure 5 258V Current waveform Horizontal 100ms/division Vertical 1000A/division

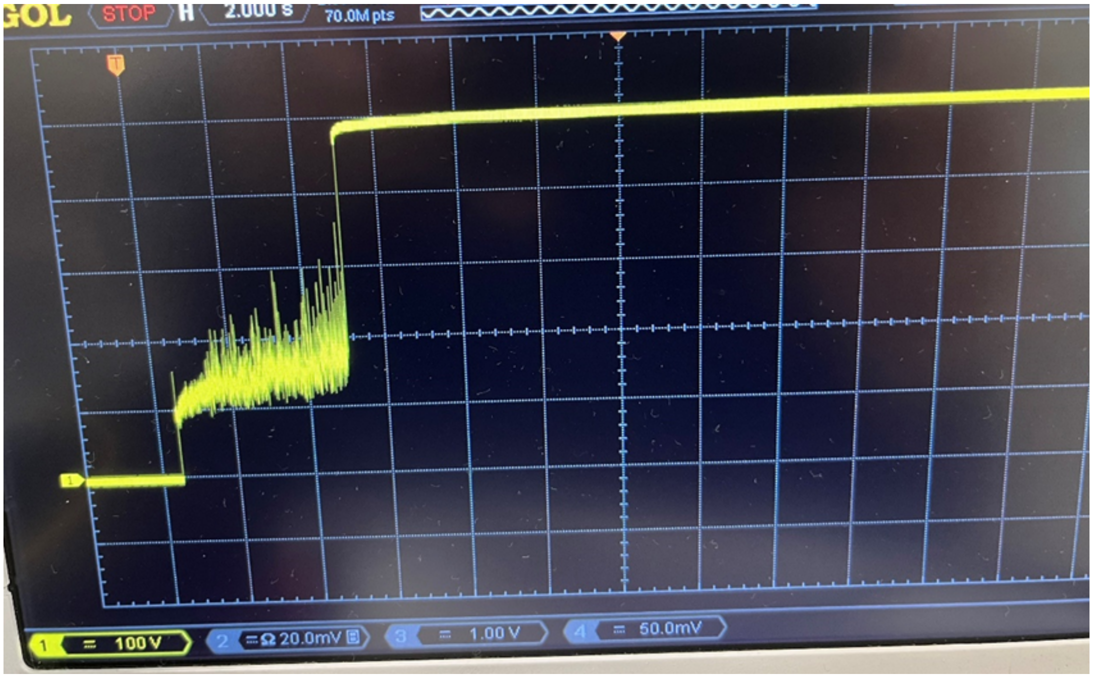


Figure 6 516V Tungsten Voltage waveform Horizontal 2sec/division Vertical 100V/division

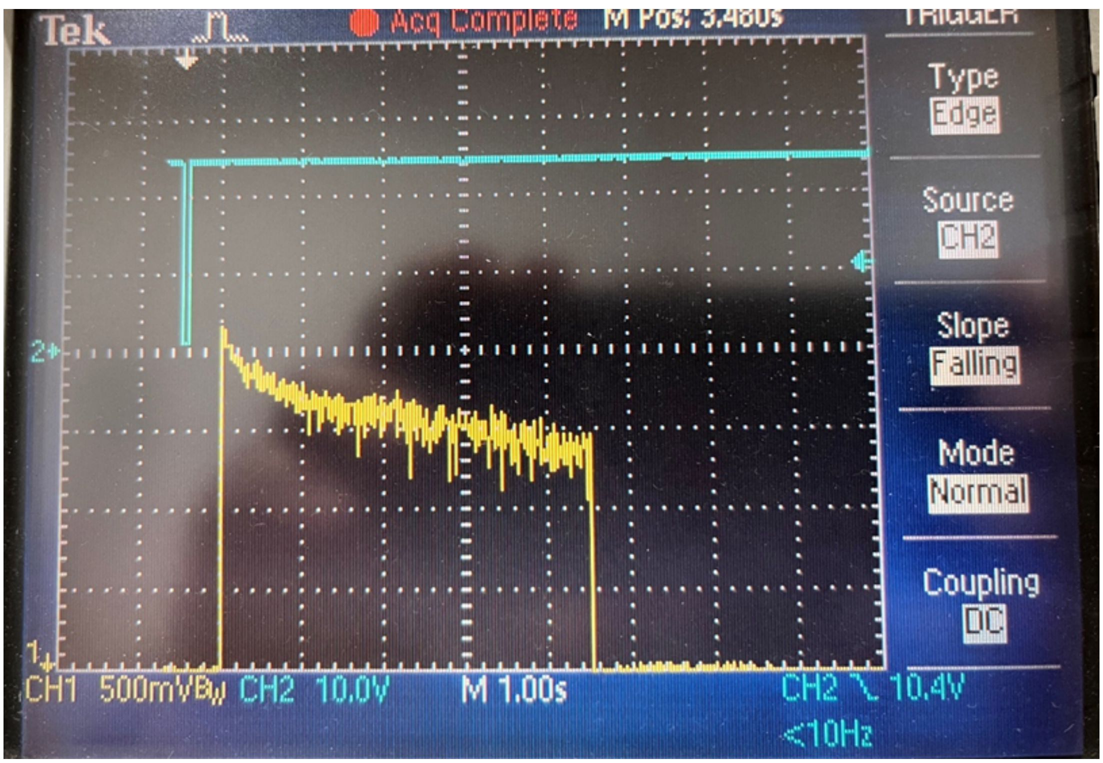


Figure 7 516V Tungsten Current waveform Horizontal 1sec/division Vertical 1000A/division

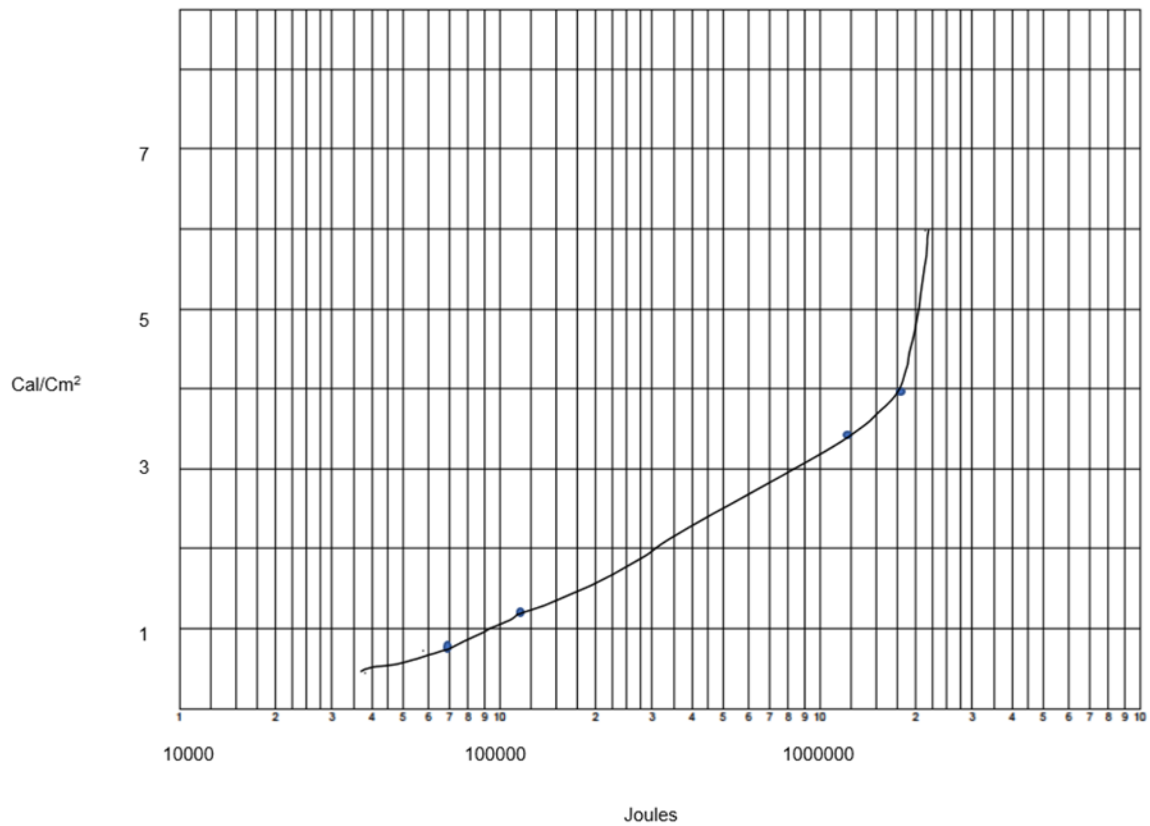


Figure 8. Arc energy (Joules) vs Incident Energy cal/cm2