

## Current Status and Experimental Study of High Energy Arcing Fault in NPPs

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### 1. Introduction

High Energy Arcing Fault (HEAF) can occur in an electrical components or systems through an arc path to ground and has the potential to cause extensive damage to the equipment involved. The intense radiant heat produced by the arc can cause significant damage or even destructions of equipment and can injure people.

HEAF leads to the rapid release of significant electrical energy in the form of heat, vaporized copper, and mechanical force through the air which can act as an ignition source to other adjacent components. This phenomena has been underestimated in the past [1].

Affected components include a specific high-energy electrical devices, such as switchgears, load centers, bus bars/ducts, transformers, cables, etc., operating mainly on voltage levels of more than 380V [2] but the voltage levels in NUREG/CR-6580 is more than 440V [3].

This study reviews the recent HEAF events in nuclear power plants (NPPs) and investigates the HEAF phenomena with the test performed at KEMA supported by OECD/NEA HEAF project.

### 2. Recent Events of HEAF

#### 2.1 H.B Robinson NPPs, USA

On Mar. 28, 2010, H.B. Robinson NPP located near Hartsville, South Carolina had been experienced a HEAF event that involved fires in electrical equipment, a reactor trip and subsequent safety injection actuation, and an alert emergency declaration. During this event, two separate fires occurred approximately four hours apart.

The first fire was caused by a fault on a 4.16kV feeder cable between bus 4 and bus 5 led to an arc flash which caused internal damage to the unit auxiliary transformer and a subsequent fire within the conduit.

The second HEAF and fire occurred due to inappropriate recovery actions. Approximately four hours after the first fire, operators attempted to reset the generator lockout relay per plant procedures without first ensuring the cause of the lockout was cleared. This re-energized a bus damaged by the first fire and caused another electrical fault and fire, which resulted in significant damage to plant equipment.

Both HEAF events caused physical damage to the electrical components and associated cabinets, along with damaging materials in the near vicinity. In the first event, cables located in conduits exiting the top of a cabinet shorted together and damaged the conduit and

potentially damaged electrical cables located in cable trays directly above the damaged conduit.

A detailed evaluation in this event is described in the NRC augmented inspection report [4].

#### 2.2 Onagawa-1 NPP, Japan

On Mar. 11, 2011, the successive fire incident due to HEAF occurred in the electrical cabinet in which the overhang type high voltage breakers were used. The remarkable thermal and structural damage to the cables and equipment of the adjacent cabinets were recognized due to the release of the hot gas propagation and high inner pressure.

Fire took place due to short circuit inside MC 6-1A and subsequently spread to 10 other switch gear systems via power cable ducts. As a result, a pump in the residual heat removal system was inoperative for a short period. Fire could not be suppressed and was allowed to burn out almost 7 hours and electrical cabinets involved were heavily damaged and mostly burned.

In 2012, Nuclear Regulation Authority (NRA) in Japan started HEAF tests at KEMA in USA to understand the HEAF phenomena involved, to develop models for damage prediction, to set zone of influence and to develop regulatory guides for fire hazard analysis for HEAF. Preliminary test results suggested an energy of 25 MJ was required for causing the arcing fire [5].

### 3. HEAF Experiments

#### 3.1 Overview of Test Plan

The objective of OECD/NEA HEAF project is to perform the experiments to obtain scientific fire data on the HEAF phenomenon known to occur in NPPs through carefully designed experiments.

The blast effects including pressures, temperatures, and heat flux created within the equipment are important to understand the initial HEAF impact as well as the potential for equipment failure. Understanding the heat exposure effects is relevant to determining the zone of influence. Quantifying zone of influence from a HEAF is important when analyzing the arc effects on secondary combustible materials [6].

The test instruments are twelve slug calorimeters placed around the exterior of the equipment, two pressure sensors placed to measure the interior pressure of the equipment, and oxygen consumption calorimetry hood in place above the equipment that is intended to collect the products of combustion and exhaust the hot

gases outside, since the arc may start a secondary fire that propagates in the cables and other combustibles in the cabinet.

A slug calorimeter determines heat flux by measuring the rate at which a slug of material heats up while subjected to a heat source. Slug calorimeters are used for calibration of arc-jet test conditions [7]. For arc-jet applications the slug is usually made of oxygen-free high conductivity (OFHC) copper. Figure 1 shows a typical assembly drawing of an arc-jet slug calorimeter [8].

The location of the slug calorimeters and the configuration of the calorimetry hood are shown in Figures 2 and 3, respectively [9].

26 full scale HEAF tests with above equipment had been conducted at KEMA in Chalfont, Pennsylvania, over a three year period from June, 2014 to Oct., 2015.

Under the agreement of OECD/NEA HEAF project, Korean consortium provided the four equipment to be tested such as ① class “M” metal-clad medium voltage air break switchgear (GEC\_480V), ② type DS metal-enclosed low voltage power circuit breaker switchgear (DS 416 W 480V), ③ class E7 & E8 high voltage air breaker switchgear (GEC\_6.9kV), and ④ porcel-line type DHP magnetic air circuit breaker (W 6.9kV).

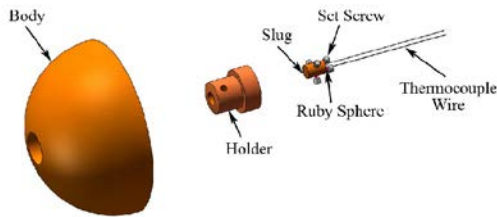


Figure 1. Typical assembly drawing for hemispherical slug calorimeter

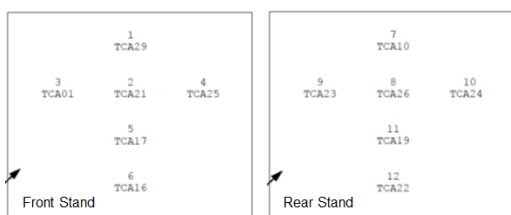


Figure 2. Slug Calorimeter Location

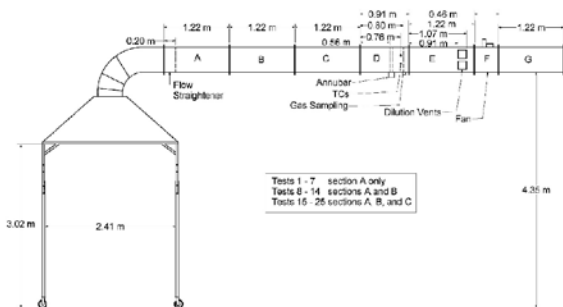


Figure 3. HRR measurement hood and duct



Figure 4. Rear view of breaker

### 3.2 Test Results

OECD/NEA provided the 26 full test results [9]. The test control parameters are nominal voltage, nominal current, event duration and arc location. The measured parameters are heat release rate (HRR), temperature, hear flux, pressure, damage zone, etc.

The HEAF experiments can be broken into two phases, the arcing phase and the post-arcing phase. The post-arcing phase may or may not include an ensuing fire depending on many variables including the arc characteristics, fuel available, and ventilation available.

Figure 4 shows the equipment status of test no. 18 in Table 1. Test no. 18 is performed using the equipment of ④ porcel-line type DHP magnetic air circuit breaker (W 6.9kV). After test, the breaker is severely damaged (right of Figure 4)

In this paper, the test results summary for Korean donated equipment is shown in Table 1. Arc energy in test no. 4~7 shows very low value due to inappropriate arc occurrence in accordance with IEEE C37.20.7 [10].

According to NUREG/CR-6850, App. M, the conservative estimation of arc energy is to multiply the operating voltage of the component (circuit breaker, switch, etc.) by the maximum available fault current, also multiplied by the duration of the energetic event, in that it assumes the arc characteristics remain constant over the duration of the event.

Figure 5 shows the comparison of measured arc energy with estimated arc energy based on nominal values. Estimated arc energy of test no. 17 and 18 is shown the big difference with measured values compared with that of test no.1~3.

Figure 6 shows the comparison of measure arc energy with estimated arc energy based on average values. Estimated arc energy of test no.1, 2, 17 and 18 is lower than that of measure values.

The estimation of arc energy using the methods in NUREG/CR-6850, App. M is very conservative only when the voltage and current are applied as nominal values but the conservativeness cannot be confirmed when the average value is applied.

Therefore it is necessary to reexamine the applicability of arc energy estimation in NUREG/CR-6850, App. M.

Table 1. Test Results Summary

Test No.	Voltage (V)		Current (kA)		Arc Duration (ms)	Max. Plate $\Delta T$ , End of Arc ( $^{\circ}C$ )	Max. Avg. Heat Flux During Arc ( $kW/m^2$ )	Arc Energy (MJ)	Max. HRR Post Arc (kW)	Max. Press. (kPa)
	Nominal	Average	Nominal	Average						
1	480	344	42	34.3	2,115	18	35	29.9	185	31.7
2	480	383	42	26.8	4,124	26	26	47.8	345	35.2
3	480	441	42	36.3	8,138	188	97	87.9	520	-
4	480	-	50	-	9	2	-	-	-	-
5	480	483	50	42.4	312	93	1,167	4.7	35	15.9
6	480	393	50	46.3	321	37	480	4.6	15	33.1
7	480	294	50	57.1	401	17	172	6.6	35	33.1
17	6,900	685	33	43.3	3,084	96	126	82.1	320	31.0
18	6,900	776	33	44.2	3,097	246	322	103.7	325	57.2

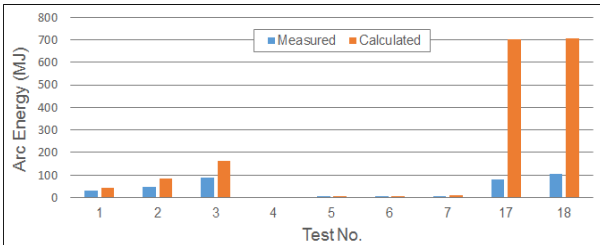


Figure 5. Arc energy calculated with nominal value of Table 1

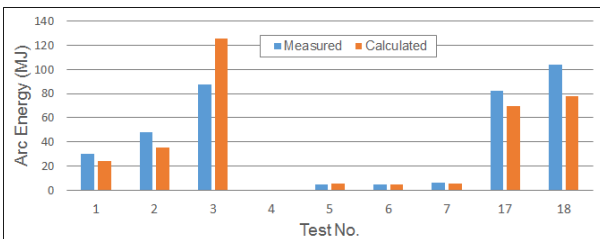


Figure 6. Arc energy calculated with average value of Table 1.

#### 4. Conclusions and Further Study

In this study, HEAF events of foreign nuclear power plant are reviewed and HEAF test results are analyzed.

As stated before, HEAF may cause the significant damage to adjacent equipment as well as the equipment involved.

Estimating the equipment damage, determining the damage area, and predicting the secondary fire after initiating HEAF event are important factors to quantify HEAF effect on the related equipment.

The HEAF experiments can be broken into two phases, the arcing phase and the post-arcing phase. The post-arcing phase may or may not include an ensuing fire.

The results of HEAF test show that the donated equipment from Korean consortium are severely damaged after test.

It is necessary to reexamine the applicability of arc energy estimation in NUREG/CR-6850, App. M because the conservativeness of estimation method could not be confirmed when the average measured value is applied.

The final step of the HEAF impact assessment is to estimate the zone of influence. So further study should be performed for setting the zone of influence using the test data as basic materials.

#### Acknowledgement

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#### REFERENCES

- [1] E.D. Owen, "Arc flash: how extensive is this problem? Part I", Electrical Source, Magazine, pp.33-35, Jan./Feb. 2011.
- [2] OECD/NEA CSNI, "Task on High Energy Arcing Events (HEAF)", CAPS submitted to CSNI/IAGE and to CSNI/PRG, Ver. 9 Oct. 2008 – revised with PRG Chair, Apr. 27, 2009.
- [3] US NRC, "Fire PRA Methodology for Nuclear Power Facilities", App. M of NUREG/CR-6850, Vol. 2, Sept. 2005.
- [4] US NRC, "H.B. Robinson Steam Electric Plant - Augmented Inspection Team Report, 05000261/2010009", ML101830101, July 2, 2010
- [5] M. Hirano, "Safety Research in Nuclear Regulation Authority", US NRC 27<sup>th</sup> Annual Regulatory Information Conference, Mar. 12, 2015
- [6] C. Lopez, et al., "Conceptual Test Plan for High Energy Arcing Faults Experiments", SNL,
- [7] ASTM Standard E457-08: "Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter", Annual Book of ASTM Standards: Space Simulation; Aerospace and Aircraft; Composite Materials. vol. 15, no. 03, 2008.
- [8] T.M. Hightower, R.A. Olivares, D. Philippidis, "Thermal Capacitance (Slug) Calorimeter Theory Including Heat Losses and Other Decaying Processes", NASA/TM-2008-215364, Sept. 2008.
- [9] OECD/NEA, Experimental Results from the Int. HEAF Research Program-Testing Phase 2014 to 2016, NEA/CSNI/R(2016)XX, Dec. 2016
- [10] IEEE C37.20.7, "Guide for testing metal-enclosed switchgear rated up to 38 kV for internal arcing faults, 2007