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Structural Effects Caused by High Energy Arcing Faults at Nuclear Power Plants

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ABSTRACT

The occurence of a High Energy Arcing Fault (HEAF) in a fire area of Nuclear Power Plant (NPP) has a big influence on the safety functions of the NPP. This paper presents the current research status of HEAF which are the oxidation energy of aluminum materials, the relations between arc energy and the secondary fire, the arc travel on bus ducts, and the pressure effects caused by arc. The past research included the experimental HEAF studies of the US Nuclear Regulatiry Commission (NRC), the Japan Nuclear Regulation Authority (NRA), the Central Research Institute of Electric Power Industry (CRIEPI) of Japan, and Nuclear Energy Agency/Committee on the Safety of Nuclear Installations (NEA/CSNI) that were performed to identify HEAF phenomena and clarifty the behavior. One key item identified in the past research was that aluminum oxidation was highly exothermic and the bus bar material of some metal clad switchgear or other electrical power distribution elements can be aluminum rather than the typical copper.

Regarding the oxidation energy of aluminum material such as bus bar during an arc it is estimated to be approximately 12 times of copper material [1]. A major consequence of a HEAF is a secondary fire such as cable fires within the cabinet or externally that are ignited by the arc. The occurance of a secondary internal fire caused by an arc in metal clad switchgear can be defined by a threshold based on the relation between arc electrical energy and secondary fire ignition [2]. Based on past HEAF events and experimental studies HEAF of bus ducts greatly damage the adjacent areas. HEAFs in bus ducts tend to move from the initial arc location and can cause at least two presuure spikes and thermal impacts on the enclosure [3]. Concerning fire protection of NPP, it is most important to ensure the confinement of fire area. Therefore, the external pressures generated by HEAFs should be evaluated for the fire area of NPP. The pressure should be evaluated from two viewpoints. One is the pressure inside of the enclosure such as metal clad switchgear and the other one is the pressure in the room or fire area. The prediction of the internal pressure can be simulated using Computational Fluid Dynamics (CFD) modeling [1]. CFD modeling is expected to be used to evaluate the pressure in fire area from HEAF events in NPP.

INTRODUCTION

Based on event reporting from nuclear utilities worldwide, 11.5% of fire events at NPP from 1979 to 2012 were reported to be HEAF events [4]. According to the 2016 Organisation for Economic Co-operation and Development (OECD) fire database, of the 47 combinations events of the 448 fires reported 24 events were a combination of HEAF and secondary fire [5]. In Japan, the NRA has performed experimental studies and implemented regulatory law amendments [6] after a HEAF event at the Onagawa NPP in the March 2011 Great East Japan Earthquake. HEAF protection measures are being considered by Japanese licensees to be completed within a fixed assessment period. One major counter measure that has been implemented as a safety measure is to reduce the response and interruption time of protective circuits to a time shorter than the time to reach a threshold energy for the HEAF to cause an internal secondary fire. The threshold was determined from the data from HEAF tests in actual equipment [6].

Other safety measures for HEAF at NPP that could be implemented are evaluations of the thermal effects and pressure effects caused by HEAF. In particular, the destruction or damage to fire barriers and fire doors in HEAF events is a major subject for the safety of NPP. The OECD Fire Database 2013 reports two events during 1997 to 2012 where a fire door was damaged by HEAF [4]. NRC also reported fire door damage from a HEAF event in May 2017 at Turkey Point NPP [7]. Therefore, the structural loads caused by the arc pressure spike should be evaluated. The purpose of this study is to investigate the current knowledge base and state of the art of techniques to evaluate the HEAF event influence on external and internal pressure and thermal conditions.

Aluminum oxidization

The aluminum oxidation during an arc is highly exothermic. The bus bar material of metal clad switchgear is typically made by copper but sometimes aluminum is used. The oxidation energy (combustion) of aluminum bus bars was investigated in HEAF tests to reproduce the Onagawa NPP HEAF electrical arc energy and conditions with the same switchgear configuration and internal combustible loads as reported in NUREG / IA – 0470 [3]. The arc electrical energy that caused an internal secondary was calculated from the voltage, current, and arc duration time. The switchgear in the tests had aluminum bus bars and much higher energy was generated than the HEAF arc electrical energy alone [3]. In non-electrical tests a "Rocket Fuel Arc Simulator" (RFAS) with high-energy rocket fuel cast in thin slabs was used to simulate the arc electrical energy and arc duration in the electrical tests with identical switchgears. The tests were inside a large calorimeter to measure the total thermal energy generated by the slabs. The energy in the tests was varied by changing the number of RFAS slabs. The RFAS tests did not ignite a secondary fire at the thermal energy equal to electrical energy in the electrical HEAF tests. The RFAS energy was increased to 3 times the electrical energy that ignited a secondary fire in the electrical HEAF test. The conclusion was the energy to ignite the secondary fire in the electrical tests was 1/3 electrical energy and 2/3 energy from the aluminum oxidation. Based on this it was estimated that oxidation energy of melted, evaporated and oxidized aluminum from damaged bus bars was a major energy contributor in addition to electrical arc energy in the Onagawa NPP HEAF event [3].

The oxidation energy of aluminum is produced from the formation process of aluminum oxide (Al_2O_3). The reaction is:

$$2Al(s) + 3/2O_2(g) \rightarrow Al_2O_3(s) \tag{1}$$

The heat of formation (ΔHf) of Al_2O_3 is the emitted energy during the reaction [3]. The heat of formation (ΔHf) of Al_2O_3 production is 1669.79 KJ/mol (g) or 7.37KJ/g based on the Born-Haber cycle [3] for aluminum dioxide. Based on the formula above, 1.89 g of Al_2O_3 is produced when 1 gram of Al is oxidized. Therefore, 30.9 KJ/g of energy is released when 1 g of aluminum is oxidized [3]. Iwata reports that the generated energy of the vaporized electrode oxidation from the oxidation formula of the electrode materials is estimated as: Copper: 64.9 KJ/mol, Iron: 381 KJ/mol and Aluminum: 772KJ /mol [1]. This indicates that the oxidation energy of the aluminum material is 12 times that of the copper material. Thus, arcs and HEAFs involving aluminum bus bar can cause more damage to the electric cabinet.

Relationships between the arc generation energy and the secondary fire

By evaluating the correlation between the ignition of a secondary fire and the arc electrical energy, it is possible to design the power supply protection system coordination to limit the arc duration and total electrical energy and the associated heat released. A secondary fire occurred with arc electrical energy of more than 58.2 MJ in the test of 6.9 KV medium voltage switchgear as shown in NUREG/IA-0470. In tests of 0.48 KV low voltage switchgear, the secondary fire was ignited with more than 29.6 MJ [3]. In CRIEPI 2017 tests of 7.2V medium voltage, VB type switch gear, the secondary fire occurred at an energy of 27.6 MJ and the case of 0.48 KV low voltage switchgear is 19.8 MJ [8]. Based on these examples other test data the relation between electrical arc energy and secondary fire ignition is established and is independent of the design and type of electrical cabinet. Using this relation, it is possible to change the power supply protection system to reduce the arc duration and the total electrical energy and the associated heat released to below the threshold.

HEAF events in bus ducts

The past HEAF events in NPP show that HEAF of switchgear in NPP fire area can significantly affect the nearby safety equipment and other Structures, Systems and Components (SSC). It was also found from the past events and the experimental studies that HEAF of bus ducts also greatly damage adjacent areas [3]. Thermal flux and pressure from arc flash at the bus duct affects the SSC in the fire area and fire barriers in NPP. If the bus bars and/or bus duct materials are aluminium, the generated arc energy is much larger than the case of copper materials. In the CSNI HEAF 2017 Tests, a bus duct with copper bus bars and aluminum outer duct material was conducted [9]. The aluminum generated very high oxidation energy as the aluminum vaporized and oxidized in the arc flash [9]. Conductive aluminum metal that was not oxidized was ejected by the arc flash and was scattered and deposited on the floor in the test, see Figure 1 [9]. The conductive aluminum metal can cause short circuits and additional arcs or equipment malfunctions.

Figure 1. Bus Duct damage [9]

The other issue is the arc in the bus duct can propagate along the bus bars. In this phenomenon the initial arc can travel to a connection or bend than trigger an additional arc. A Motor Control Center (MCC) HEAF test reported NUREG/IA-0470 shows the arc traveling from the bottom of the cabinet to the upper part of the cabinet. Figure 2 shows how the hot gas and a plasma ball moved in the MCC from the arc starting point at the bottom to a final arc position at the top [3]. Similarly, a Distribution Panel (DP) arc test showed the arc moved downward to the bottom end of the vertical bus bars after the initial ignition [3]. The observations in these tests indicate that there are two pressure spikes in these cases. Similar arc behavior where the arc moves along the bus bar was observed as reported in NEA/CSNI(2017)7 [9]. Partyka et al. said it is possible to analyze arc travel speed along bus bars and to more accurately evaluate the influence of the arc [10].

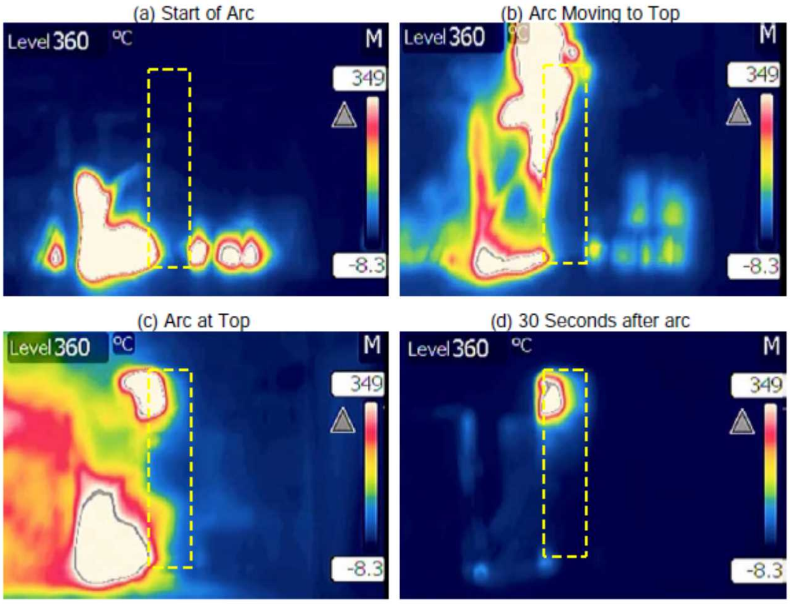

Figure 2. MCC arc test Thermal Images [3]

PRESSURE EFFECT

Concerning fire protection of NPP, it is most important to protect the barriers that separate fire areas and prevent the influence on adjacent fire area. Therefore, the loss of confinement or damage to barriers caused by HEAF must be prevented. But there are cases where fire doors have been damaged by HEAF events so barrier damage is a realistic and important concern. The aforementioned OECD fire database reports two events of fire doors being damaged by HEAF [4]. Figure 3 is a picture of a fire door damaged by HEAF at a German PWR plant [4]. In addition, fire door damage due to HEAF at the US Turkey Point NPP was reported by NRC in May 2017 [7]. In the Turkey Point event, the fire door was located outside the so-called Zone of Influence (ZOI) defined in NUREG 6850 as the distance from the cabinet or component with the HEAF source where damage cannot occur. But the fire door outside the ZOI was damaged in this case indicating that the ZOI based on distance alone may not be adequately conservative for all cases.

Figure 3. Fire door damaged by HEAF (from outside the room) [4]

The ZOI approach focusses on fires and may not be adequate to assess HEAF effects, therefore, the pressure generated by HEAF and its influence on the fire area of NPP must be evaluated. The pressure should be evaluated in two viewpoints. One is the internal pressure of the enclosure such as metal clad switchgear and the other one is the room and fire area pressure.

Iwata et al. performed parametric tests measuring the pressure rise inside enclosures with different arc energies and different materials [1]. The tests were also simulated with SCM and CFD modelling [1]. Pressure rise characteristics inside the container depend on the arc current, electrode material, and container shape. Energy for the pressure rise (E_{pre}) is based on the arc electrical energy (E_{arc}) multiplied by a thermal efficiency coefficient, k_p [1]. The simulation was performed with a three-dimensional distribution of physical quantities (pressure, temperature, density, etc) that were time dependent. The k_p was evaluated based on the electrode material and arc current [1]. The ratio of the pressure increase Δ_{par} for E_{arc} of 150 KJ was Aluminum: Copper: Iron = 3:2:1.

The HEAF energy analysis considered energy consumed by melting and vaporization of the electrode and energy generated by the oxidation reaction of vaporized electrode. The energy balance during the arc flash is expressed by the following equation.

$$E_{pre}=E_{arc} + E_{oxi} - E_{mav} - E_{rad} \quad (2)$$

Where E_{pre} is pressure rise energy, E_{arc} is the arc energy, E_{oxi} is the oxidation energy, E_{mav} is the melting and vaporization energy, and E_{rad} is the radiation energy. Energy generated during the oxidation of the vaporized electrode was calculated as Copper: 64.9KJ/mol, Iron: 81kJ/mol, and Aluminum: 772kJ/mol [1].

Re Li et.al also presented CFD simulations for small cylindrical enclosures (70 cm dia. × 80 cm long) as part of an arc experimental study [11].

These studies indicate that for HEAFs in switchgear or other electrical equipment in the fire area of an NPP, CFD analysis is expected to be required to evaluate the pressure rise in fire area (room) and the effects on the fire doors and other fire barrier structures.

CONCLUSION

HEAF is a serious event affecting SSC of NPP. It is necessary to understand HEAF events and develop predictive methods for the evaluation of HEAF influence. The research items that need be addressed are the (1) the effects of using aluminium material in electrical components because its oxidation energy is much higher than other materials (cooper, iron), (2) the energy required to ignite external secondary fires considering the arc energy that escapes from the electrical component (internal energy to ignite secondary fires is mostly understood), (3) the effects of HEAF on the fire area confinement in NPP by evaluating the pressure effects to barriers and components such as fire doors. For these predictive pressure evaluations, it appears CFD modelling can be used.

The following findings are established from past research: (1) in the case of the material of bus bar is aluminum, the oxidation energy at arc could be as much as 12 times compared with copper [1], (2) the NUREG/IA-0470 HEAF tests show that about 3 times more energy than the arc electrical energy in the Onagawa NPP HEAF event is required to ignite an internal secondary fire [3], (2) the threshold arc electrical energy to ignite a secondary internal fire is established and it is possible to design the power supply protection system to be below this threshold by limiting arc duration and the total heat released, (3) HEAFs in bus ducts generate high energy and severely damages the bus duct enclosure, (3) NUREG / IA 0470 MCC experiments and 2017 NEA / CSNI HEAF tests demonstrate that the initial arc travels along the bus bar and two pressure spikes can occur in bus duct. In addition, bus ducts with aluminum enclosures will be vaporized with high oxidation energy from the arc flash, (4) the influence of arc pressure spike on fire doors can greatly reduce the confinement of the NPP fire area.

Three-dimensional simulation by CFD code is applicable to determine arc effects in an enclosed space [1]. External pressures from HEAF at metal clad switchgear or other components in the fire area of NPP should be evaluated to prevent damage to the confinement barriers of the fire area. CFD modeling should be suitable for this but more research and evaluation are required.

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