UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
OFFICE OF NEW REACTORS
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NRC INFORMATION NOTICE 2017-04: HIGH ENERGY ARCING FAULTS IN ELECTRICAL EQUIPMENT CONTAINING ALUMINUM COMPONENTS

ADDRESSEES

All holders of an operating license or construction permit for a nuclear power reactor under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," except those who have permanently ceased operations and have certified that fuel has been permanently removed from the reactor vessel.

All holders of an operating license for a non-power reactor (research reactor, test reactor, or critical assembly) under 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," except those who have permanently ceased operations.

All holders of and applicants for a combined license under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants."

PURPOSE

The U.S. Nuclear Regulatory Commission (NRC) is issuing this information notice (IN) to inform addressees of operating experience and recent NRC testing results pertaining to the magnitude of arc fault hazards in electrical equipment containing aluminum components. The NRC expects that recipients will review the information for applicability to their facilities and consider actions, as appropriate. The suggestions in this information notice are not NRC requirements; therefore, the NRC requires no specific action or written response.

DESCRIPTION OF CIRCUMSTANCES

NRC-Led International Testing Program Insights

From 2014 to 2016, the Office of Nuclear Regulatory Research (RES) collaborated in a testing program with the Nuclear Energy Agency (NEA), the National Institute of Standards and Technology, and various international partners through the Organization for Economic and Cooperative Development (OECD). The purpose of the testing program was to confirm the zone of influence (ZOI) for high energy arcing fault (HEAF) events that was specified in NUREG/CR-6850 EPRI 1011989 "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Volume 2: Detailed Methodology" (Agencywide Documents Access and Management System (ADAMS) Accession No. ML15167A411). RES initiated the testing program after reviewing international HEAF events documented in the OECD Fire Project – Topical Report No.1, "Analysis of High Energy Arcing Fault (HEAF) Fire Events," published in June 2013 (https://www.oecd-nea.org/nsd/docs/2013/csni-r2013-6.pdf).

The testing protocol initiated the arc by installing a bare copper wire across the three phases of power in accordance with IEEE C37.20.7-2007/Cor 1-2010, “Guide for Testing Metal-Enclosed Switchgear Rated up to 38 kV for Internal Arcing Faults Corrigendum 1.” No accelerants were used to initiate the fault or ensuing fire conditions. The testing was performed using actual electrical equipment from nuclear power plants. There were four primary controlled parameters that were varied as part of the testing program—arc location, fault current, voltage and fault duration:

1. Arc location – operating experience from HEAF events was used to select representative arc locations within the enclosure. Typically the arc locations were across breaker stabs, at enclosure power supply entry locations, or along bolted connections within the enclosure that could be subject to fatigue failures.
2. Fault current – the arc fault currents were selected to replicate fault capacities of typical electrical distribution systems within nuclear power plants.
3. Voltage – The voltages were selected from typical voltages used in nuclear power plants’ power distribution systems. The program tested both low and medium voltage equipment.
4. Arc duration – The duration selected for the HEAF tests was a controlled parameter and based on a review of operating experience where arc duration information was readily available from fault recording devices, or could be determined from post arc fault investigation.

This program has shown that HEAF tests involving aluminum resulted in a significantly larger release of energy than HEAF tests involving copper. This aluminum involvement includes components, subcomponents, or parts that form part of the normal current-carrying pathway (such as bus bars, breaker armatures, contacts, cable, etc.), or components, subcomponents, or parts that could become involved in the fault current pathway as a result of a ground fault (housings, structural framework, adapters, cradles, wireways, conduits, draw-out or racking mechanisms, etc.). In addition to larger energy release during the HEAF event when aluminum is involved, RES staff also observed dispersal of electrically conductive aluminum byproducts throughout the area. This byproduct was conductive and caused short circuiting and grounding of electrical equipment in the area. Through the testing program, RES staff observed that HEAF tests involving aluminum damaged test measurement and recording equipment and the electrical supply of the test facility well beyond the damage limits approximated in NUREG/CR-6850 (EPRI 1011989).

A total of 26 tests were performed, consisting mostly of electrical equipment that contained copper conductors. The equipment with copper components exhibited similar damage states to those postulated in the current methodology presented in NUREG/CR-6850, Appendix M. However, results obtained for equipment containing aluminum components exhibited damage states well beyond current HEAF damage models. These results are summarized as follows:

- Test 23 of the HEAF experimental series consisted of a low-voltage, 480 VAC switchgear cabinet that contained an aluminum bus bar. The test resulted in failure of the cabinet walls such that the plasma created by the arcing fault was expelled a significant distance out of the cabinet. Inconel temperature sensors located approximately 0.9 m (3 ft.) from the enclosure (which is the NUREG/CR-6850 horizontal ZOI limit) were melted and destroyed during the test. The vapor/plasma cloud migrated well beyond the current limit of 0.9 m (3 ft.) horizontal and 1.5 m (5 ft.) vertical distance for the ZOI. In addition to the physical damage caused by the HEAF event, there was a layer of aluminum byproducts that coated structures and components within the test cell.

This aluminum byproduct layer caused shorting problems in the test facility electrical power system and required major repair. This test is an outlier from the other low-voltage tests performed as part of the experimental program. It was the only low voltage experimental test to exhibit a level of damage beyond the NUREG/CR-6850, Appendix M, ZOI methodology. In all other low-voltage tests, the temperature sensors located 0.9 m (3 ft.) horizontally from the cabinet were not damaged, recorded data, and were able to be used in subsequent experimental tests.

- Test 26 of the HEAF experimental series involved a 4.16 kV bus duct section removed from a decommissioned United States nuclear plant. The bus duct section consisted of non-segregated copper bus bars enclosed within an aluminum duct. The bus duct section was secured to the floor of the test enclosure using wooden structural members and the open ends were secured with a sheet of electrically insulating fiber board. This piece of fiber board was installed to create a pressure boundary within the bus duct unit and limit the free release of energy once the fault was initiated. Immediately upon initiating the HEAF event, the hot gas mixture forced the fiber board away, allowing the arc and associated hot gas/plasma mixture to jet out of the bus duct, blowing hot gas/molten metal linearly from the bus duct opening. The hot gases/plasma extended approximately 9 m (30 ft.) horizontally. The instruments associated with temperature and heat flux, located approximately 0.9 m (3 ft.) away from the duct, were damaged. The test facility was coated with an electrically conductive aluminum byproduct and several electrical components in the test cell required replacement.

The increased physical damage to the test specimens, measurement devices, and the testing facility observed during tests 23 and 26 can be attributed to the involvement of aluminum during the HEAF. The presence of aluminum in the components, subcomponents, or parts that form part of the normal current carrying pathway causes a more energetic plasma development when consumed during the arcing process. The increased energetic plasma causes a larger amount of cabinet damage and/or the transport of gaseous high energy particles/plasma farther than previously assumed. These two tests included aluminum components which resulted in exceeding the ZOI documented in NUREG/CR-6850 and its Supplement 1. In both tests, a major impact from the HEAF was a layer of aluminum byproducts that plated out on most surfaces within the test enclosure, including electrical equipment. This aluminum byproduct layer caused shorting problems in the test facility electrical power supply and required a major repair and cleanup activity. The extent of damage observed from tests 23 and 26, which contained aluminum components, far exceeded the damage observed from other tests which did not contain aluminum components.

The OECD/NEA test report is publically available and can be downloaded at https://www.oecd-nea.org/nsd/docs/indexcsni.html "NEA/CSNI/R (2017) 7-Report on the Testing Phase (2014-2016) of the High Energy Arcing Fault Events (HEAF) Project: Experimental Results from the International Energy Arcing Fault Research Programme."

NRC Generic Issue Program

On May 6, 2016, RES submitted a possible generic issue involving an identified vulnerability of electrical equipment containing aluminum components during a HEAF event (ADAMS Accession No. ML16126A091). The issue was entered into the generic issue process on May 12, 2016, (ADAMS Accession No. ML16132A116) and an initial evaluation was performed (ADAMS Accession No. ML16064A250). On May 20, 2016, a generic issue review panel was formed (ADAMS Accession No. ML16209A007). The committee is currently in the screening

phase, in
accordance with the NRC's Management Directive 6.4, "Generic Issues Program" (ADAMS Accession No. ML14245A048).

United States Nuclear Power Plant Operating Experience

Fort Calhoun Station, Unit 1

On June 7, 2011, a switchgear fire occurred at the Fort Calhoun Station while the plant was shut down for a planned refueling outage. The fire resulted in a loss of power to six of nine safety-related 480 VAC electrical distribution buses, one of two safety-related 4160 VAC buses and one of two non-safety related 4160 VAC buses. The event resulted in the loss of the spent fuel pool cooling function and could have resulted in the loss of a safety function or multiple failures in systems used to mitigate a situation had the event occurred at power. Significant unexpected system interactions also occurred. Specifically, combustion products from the fire caused a fault across an open bus-tie breaker on an island bus; as a result a feeder breaker tripped unexpectedly resulting in loss of power to the opposite train bus. Also, the event resulted in grounds on both trains of safety-related direct current (DC) power used for breaker operation and electrical protection.

Fort Calhoun Station originally used General Electric AKD-5 Powermaster Low Voltage Drawout Switchgear, with a welded aluminum bus bar structure that transitioned to copper bus stabs in each breaker cell. The original AK-50 circuit breakers connected directly to the silver-plated areas on the line and load stabs. The new Nuclear Logistics Incorporated/Square-D circuit breaker design was an integrated unit consisting of a circuit breaker and cradle assembly. The cradle assembly converted the internal vertical breaker connectors in the new breaker to top and bottom spring-loaded horizontal finger assemblies which connected to the original switchgear bus stabs.

The fire was caused by the catastrophic failure of the feeder breaker for 480 VAC load center 1B4A in the west switchgear room. A large quantity of soot and smoke was produced by the fire which migrated into the conducting connections associated with the non-segregated bus duct (a metal enclosure containing the bus bars for all three electrical phases) connecting to island bus 1B3A-4A, even though the bus-tie breaker was open. The smoke and soot were sufficiently conductive that arcing occurred between the bus bars such that island bus 1B3A-4A was affected and the other connected train load center, 1B3A, was affected by incorrect breaker sequencing.

The licensee's root cause investigation concluded that the initial fire in the load center was the result of high resistance connections on the line side of the feeder breaker cubicle, which caused overheating and failure of the cradle finger clusters, resulting in bus grounding and phase-to-phase shorting. The investigation also determined that combustion products from the fire caused a fault on the island bus side of the bus-tie breaker (BT-1B4A), which resulted in an overcurrent condition through two breakers (feeder breaker 1B3A and bus tie breaker BT-1B3A). The licensee's initial investigation determined that breaker 1B3A tripped prematurely on a short-time overcurrent fault and concluded that since the breaker protection scheme did not operate as designed, bus 1B3A de-energizing resulted in the loss of multiple electrical power distribution system trains from a single fire. Appropriate breaker coordination was required by the licensee's fire protection program to ensure that the plant could achieve and maintain safe shutdown conditions following a fire.

The maximum conditional core damage probability for the event was estimated to be 3.4×10^{-4}. At the time of the fire, Fort Calhoun Station was experiencing impacts from flooding of the Missouri River and had declared a Notice of Unusual Event on June 6, 2011. Additional information is available in Licensee Event Report (LER) 2011-008, Revision 1, for the Fort Calhoun Station, "Fire in Safety Related 480 Volt Electrical Bus" (ADAMS Accession No. ML113010208), and "Fort Calhoun Station - NRC Special Inspection Report 05000285/2011014; Finding of Preliminary High Safety Significance" (ADAMS Accession No. ML12072A128).

Columbia Generating Station

On August 5, 2009, at 7:49 a.m., while operating at 100 percent rated thermal power, the main generator experienced a differential current lockout. This resulted in a main generator overall differential lockout trip, causing a turbine trip and a fast transfer from the output of the main generator to the startup transformer (normal breakers opened and start up breakers closed). As a result of the turbine trip with reactor power above 30 percent, an automatic reactor scram occurred.

At 7:51 a.m., the control room received a report from the turbine building of a fire in the electrical bus duct above switchgear SM-3. This resulted from a fault on the non-segregated 6900 VAC bus that supplies power from the normal auxiliary transformer to switchgears SH-5 and SH-6. The bus catastrophically failed and vaporized all three phases of the conductor in the location of a flexible bus connection link. The faulted bus section was located above switchgear SM-3.

Operators notified the fire brigade to respond. At 7:53 a.m., operators closed the inboard main steam isolation valves to halt the reactor vessel depressurization and cooldown, however, the technical specification cooldown limit of 100°F was exceeded. Operators called the offsite fire department for assistance due to heavy smoke in the turbine building.

The licensee's root cause evaluation determined that the fault was located on the non-safety-related, non-segregated, 6900 VAC N2/X bus. The bus catastrophically failed, melting all three phases of conductor in the location of a flexible link. The bus bars are completely enclosed in aluminum ducts, with all three phases in the same duct (non-segregated). The bars were a combination of aluminum square hollow tubing and copper connection plates and were mounted on porcelain insulators with spring washers. The bars were assembled together using a series of rigid and flexible connections.

The faulted bus section was located above the medium voltage switchgear SM-3 and damage from the molten metal produced by the fault included another high voltage bus and other cables in the area of switchgears SH-5 and SH-6. The licensee inspected the damage and noted the explosion melted and removed approximately 1.2 m (4 ft.) of each of the three buses and 2.4 m (8 ft.) of the bus duct enclosure. Both the bus and the bus duct enclosure were made of aluminum. This bus duct was located at approximately 4.6 m (15 ft.) above finished floor. The molten aluminum and debris was thrown in the general vicinity. Photographs revealed that a circular pattern of material remained. The licensee evaluation concluded that the fault likely originated on the center flexible link of the bus connection. However, the licensee concluded that the root cause of the failure was indeterminate, because the catastrophic failure of the bus destroyed any evidence that would have provided an indication as to the cause. The remaining bus duct showed signs of high heat exposure. Observed from the ground were smoke streaks

at all metal joints and covers for a distance of 6 m (20 ft.) south and about 3 m (10 ft.) north of the missing section.
The licensee determined that the most probable cause of the event was the relaxation/loosening of a bolted connection on the flexible link from repeated thermal cycles over time. The relaxation/loosening of the bolted connection resulted in degradation and overheating of the connection. The insulation continued to degrade to the point where a short occurred between two phases of the bus. The short destroyed the bus and the surrounding bus enclosure. The molten aluminum and copper splattered nearby switchgear cabinets but did not cause any internal damage. A possible contributor to the non-segregated bus failure was attributed to running the bus near its original rating of 2500 amps. The nominal bus loading at 90 percent capacity was closer to the rating than the other four buses, and, therefore, could have caused higher temperatures and connection degradation. The licensee performed a bus uprate analysis in 1994 and increased the rating to 2806 amps to account for the worst case loading of 2610 amps.

Additional information is available in LER 2009-004-00, for Columbia Generating Station, "6.9 kV Non-Segregated Electrical Bus Failure" (ADAMS Accession No. ML092870468), and "Columbia Generating Station - NRC Special Inspection Report 05000397/2009010" (ADAMS Accession No. ML093280158).

Diablo Canyon Nuclear Power Plant, Unit 1

On May 15, 2000, at 12:25 a.m., at 100 percent power, Diablo Canyon, Unit 1 experienced a turbine/reactor trip. The cause of the unit trip was an electrical phase-to-phase fault on the 12 kV bus in an overhead bus duct supplied by auxiliary transformer 1-1. The switchyard and main generator field breaker opened immediately following the unit trip; however, coast down of the main generator continued to feed the arc fault. The fault and subsequent arcing damaged a 4 kV startup bus duct located immediately above the faulted 12 kV bus. Damage to the 4 kV bus induced a second arcing fault in the 4 kV bus duct resulting in a differential trip of startup transformer 1-2 that occurred 11 seconds after the initial fault. The loss of both offsite sources of power to all 4 kV loads resulted in an undervoltage condition that caused the emergency diesel generators to start and load successfully.

The cause of the bus failure could not be conclusively determined due to the absence of physical evidence. The immediate cause was postulated to be a thermal failure of the bolted connection of the center conductor of the 12 kV bus. The faulted nonsegregated bus duct consisted of three conductors of aluminum in a sealed bus duct enclosure. The bus connections consist of silver-plated splice plates bolted to the silver-plated bus bars and insulated with polyvinyl chloride (PVC) boots or Raychem tape. It is postulated that the PVC boot failed due to the excessive heat and created smoke. The radiant heat from the center conductor caused the insulation to fail on adjacent conductors. The smoke provided an ionized environment for a phase-to-phase arc from the center conductor to the south conductor. Subsequently, there was arcing between all conductors.

Prior to returning Unit 1 to service, the licensee performed extensive inspections, tests, maintenance and repairs, including an effort to increase the capacity by replacing the 12 kV aluminum bus conductors inside the turbine building with copper, from where the bus entered to pass the damaged section. The licensee upgraded buses with little design margin from aluminum to copper and installed large copper splice plates in select locations. Corrective actions included a new preventative maintenance program and upgrades to the 4 kV and 12 kV nonsegregated buses on both units. Additional information is available in LER 1-2000-004-00, "Unit 1 Unusual Event Due to a 12 kV Bus Fault" (ADAMS Accession No. ML003725220).

Zion Nuclear Power Station, Units 1 and 2

On April 3, 1994, at 4:30 a.m., Zion Nuclear Power Station, Unit 1 was synchronized to the electrical distribution system after the completion of refueling outage Z1R13. The unit was stabilized at 25 percent reactor power at 5:11 a.m. At 6:13 a.m., a 3 percent load increase was initiated as required by fuel conditioning guidelines. At 6:18 a.m., a loud noise emanating from the vicinity of the main generator was heard in the control room. Almost simultaneously, a main generator lockout trip and subsequent turbine and reactor trips occurred with the main generator tripping on differential current.

At 6:19 a.m., the operating personnel received a report of a fire emanating from the generator lead box. The station fire alarm was sounded and the fire brigade was dispatched to extinguish the fire. The shift engineer was notified at 6:30 a.m. that the fire brigade could not contain the fire. The plant then requested offsite fire department assistance.

After the termination of the fire, the licensee performed an assessment of the damage to the main generator and associated bus ducts. The A and B phase isophase bus ducts showed signs of excessive arcing. The corners of the 90-degree turns on both phase housings were blown outward, and aluminum spatter covered the general area of the fault. Large amounts of white powder were also found in the A and B phase duct work (later determined to be aluminum oxide). The conductors on both phases were also damaged. The bus duct cooling boundaries for the A and B phases at the insulator penetration on the generator end were blown inward. The retaining clamps for the A and B phase housings, located at the generator end, appeared to have separated. One broken and several damaged stand-off insulators were also found. The C phase bus duct sustained only minor damage in this event. An internal inspection of the C phase bus duct, conducted by the licensee, found an oil film on the first and second standoff insulators from the generator end.

The licensee also inspected the generator lead box and surrounding areas. The licensee determined that the C phase bushing was severely damaged at the isophase shorting plate and internal to the lead box. The A and B phase bushings sustained damage external to the lead box. Molten metal was found in the area where the C phase bushing exits the lead box. The micarta cleats which separate the generator from the lead box were blown upward into the generator. Evidence of arcing between the top flange of the C phase bushing and the structural ribbing of the lead box was discovered. Soot covered the inside of the lead box and appeared to cover the lower third of the generator stator. The licensee also found evidence of arcing on the neutral bus enclosure in the vicinity of the generator lead box.

The licensee determined that the root cause of the electrical fault was a main generator phase C bushing failure. The licensee investigation found that the inner ceramic surface inside the bushing insulator had been contaminated with an oily substance, and this contamination lead to the failure. The high current arc from the C phase to the lead box resulted in the rupture of the bushing internal and external to the lead box. This allowed hydrogen to escape into the atmosphere. The hydrogen was ignited by the flashover and started to burn. The fault currents generated were significant enough in magnitude to cause the fault damage observed on the A phase winding of the west main power transformer. Although this scenario provides an explanation for the high side neutral residual current recorded during the event, the physical damage observed during the internal inspection of the transformer is not of the magnitude seen on other documented failures of this nature.

Samples of molten metal and fire residue obtained from the A and B phase bus ducts and the C phase lead box were analyzed. The intent of this examination was to identify the presence of any conductive foreign material which may have contributed to the flashover of the A and B phases. Nothing out of the ordinary was found in this investigation. The majority of the material examined was identified as aluminum. The white powder found in the ducts was identified as aluminum oxide. The aluminum deposits were a result of the arcing that occurred on the A and B phases, which are fabricated from aluminum. Additional information is available in LER 94-005-01 “Unit 1 Main Reactor Trip and Subsequent Start of 1A Auxiliary Feedwater Pump Following a Generator Fire and Isophase Bus Duct Fault” (Legacy ADAMS Accession No. 9801210070).

Shearon Harris Nuclear Power Plant, Unit 1

On October 9, 1989, at 11:05 p.m., with the plant at full power, a turbine/reactor trip occurred at Shearon Harris Nuclear Power Plant, Unit 1, due to an electrical fault. The reactor was stabilized in hot standby. The licensee determined that the initiating cause of the turbine/reactor trip was multiple ground faults. The ground faults destroyed the neutral grounding bus and caused three fires: (1) an oil fire at the B main power transformer; (2) a hydrogen fire underneath the main generator; and (3) a small oil fire in the generator housing. The licensee declared an alert and the site fire brigade responded to the fires. The site fire brigade was later assisted by offsite fire departments.

The licensee determined that the ground faults were caused by aluminum debris carried down the bus duct by the forced air cooling system. The aluminum debris entered the bus duct as a result of previous damper failures in the bus duct cooling system in 1988 and 1989. Arcing between the conductor and the enclosure occurred over a 15 m (50 ft.) length of the A phase bus immediately upstream of the B main power transformer. Ionization from this arcing reduced the dielectric strength of the cooling air which was carried into the bushing box of the B main power transformer. This caused an A phase to ground flashover in the bushing box, which immediately propagated to the B phase bushing. The fault cracked both low voltage bushings, causing oil to leak from the bushings and ignited the leaking oil.

The fault at the B main power transformer created magnetic forces in the main section of the isolated phase bus that damaged insulators in A and B phase. The 58 cm (23 in.) diameter tubular conductor is suspended in the middle of the 104 cm (41 in.) diameter aluminum enclosure by the ceramic insulators. In the A bus duct, five insulators pulled apart, allowing the conductor to come in contact with the grounded enclosure, creating a phase-to-ground fault.

As part of the corrective actions, the licensee evaluated the design of the isolated phase bus duct bus supports and found it to be adequate. However, the sections in which the conductor supports failed were rotated 180 degrees to place the supports underneath the conductor as a prudent design measure. The licensee also revised the design of the isolated phase bus duct cooling system to preclude debris intrusion into the ducts. The licensee has replaced the damaged duct. Additional information is available in the Shearon Harris Nuclear Power Plant LER 89-017-01, “Electrical Fault on Main Generator Output Bus Causing Plant Trip and Fire Damage in Turbine Building” (Legacy ADAMS Accession No. 8912130259).

Kewaunee Power Station

On July 10, 1987, at 11:43 a.m., with the plant at full power, a reactor/turbine trip occurred due to an undervoltage transient on the 4160-volt electrical buses, which supply the reactor coolant pumps and main feedwater pumps.

The control room operators received an unexpected reactor/turbine trip. Following normal practice, the plant dispatched an equipment operator to verify that the auxiliary feedwater pumps and diesel generators had started and were operating normally. Upon investigation, the equipment operator noticed smoke and fire coming from the vicinity of the electrical bus bar located on the eastern end of the turbine building, and immediately notified the shift supervisor. The bus fire terminated once the transformer was de-energized. A smaller fire occurred on a maintenance cart involving rags and rubber goods ignited by falling aluminum slag. The equipment operator quickly extinguished this fire. At 11:46 a.m., the equipment operator reported to the control room that the fire had been extinguished.

The licensee determined that the event was caused by a phase-to-ground fault which occurred on the bus bar (1.3 cm by 10.2 cm [0.5-inch by 4-inch] flat aluminum bus bar rated at 3000 amps) routed from the main auxiliary transformer to buses 1-3, 1-4, 1-5 and 1-6. The fault caused an undervoltage condition resulting in a reactor trip and subsequent turbine trip. The bus undervoltage reactor trip is set at less than 77 percent of the rated bus voltage for greater than 0.1 second. Plant systems performed as designed. The fast transfer prevented the reactor coolant pumps from tripping on the undervoltage condition because of the time delay of approximately 5 seconds in the pump breaker trip logic. A time delay relay of approximately 5 seconds is designed in the reactor coolant pump logic to prevent tripping of the pumps before fast transfer to an offsite power supply.

The licensee determined that the root cause of the event was an insulation failure on the bus bar compounded by accumulation of particulate debris. The bus bar runs perpendicular to turbine building ventilation fans mounted in the turbine building exterior wall. Suction from the fan pulled dust-filled air through the bus duct. Dust and metallic powder debris collected on the outside of the bus bar insulation. The insulation failure combined with the accumulated dirt provided a tracking path from phase to ground. The phase-to-ground fault progressed to a phase-to-phase fault which accounted for the extensive bus damage. The event damaged a 9 meter (30 ft.) section of the bus bar from the main auxiliary transformer to buses 1-3, 1-4, 1-5 and 1-6. The equipment operator quickly extinguished the related fire. There was no other equipment damage as a result of this event.

The damaged section of bus bar was isolated. The bus bar and main auxiliary transformer were inspected to determine the extent of damage, and a temporary change request was implemented to supply electrical buses 1-3 and 1-4 from the reserve auxiliary transformer. The main auxiliary transformer supplied buses 1-1 and 1-2. Safeguards buses 1-5 and 1-6 remained in their normal lineup. In addition to the immediate corrective actions taken to replace damaged components, the licensee inspected and cleaned various sections of the bus bar ducting. The licensee implemented a triennial inspection procedure covering all bus bar ducting. Additional information is available in LER 87-009-00, "Electrical Bus Bar Failure Causes Undervoltage on RXCP Buses and Reactor Trip" (ADAMS Accession No. ML111661536).

BACKGROUND

HEAF events have occurred in both United States and foreign nuclear power plants. HEAFs are energetic and explosive faults in electrical equipment characterized by a rapid release of energy in the form of heat, light, vaporized metal, and pressure increase due to high current arcs between energized electrical conductors or energized conductors and ground or neutral. HEAFs have the potential to cause extensive damage to the failed electrical components and distribution systems along with adjacent equipment and cables. Furthermore, the significant energy released during a HEAF event can act as an ignition source of nearby combustibles resulting in an ensuing fire, which could potentially affect the performance of nearby structures, systems, and components (SSCs) important to safety.

The current method for estimating the damage from a HEAF for electrical enclosures is contained in an industry/NRC fire probabilistic risk assessment methodology document, EPRI 1011989/NUREG/CR-6850 Appendix M. This method is based on a single well-documented event that occurred at San Onofre Unit 3 in 2001. NUREG/CR-6850 Supplement 1 FAQ 07-0035 provides the current methodology for estimating damage specific to bus duct failures. Recent international HEAF testing has been performed to better characterize the damage potential and modes of failure. RES initiated this testing project after investigating international HEAF events documented in the OECD Fire Project – Topical Report No.1, "Analysis of High Energy Arcing Fault (HEAF) Fire Events," NEA/CSNI/R (2013) published in June 2013 (https://www.oecd-nea.org/nsd/docs/2013/csni-r2013-6.pdf). The experimental test program identified that the presence of aluminum can cause a more energetic plasma arc and subsequent metal fire. Under some circumstances this may cause a larger amount of cabinet damage and/or cause the transport of conductive aluminum byproducts further than previously assumed.

Each operating nuclear power plant is required to have a fire protection plan that satisfies General Design Criteria (GDC) 3 in Appendix A of 10 CFR Part 50. This is to ensure that SSCs important to safety are designed and located to minimize the probability and effects of fires and explosions. Licensees who have chosen to voluntarily adopt a risk-informed, performance-based fire protection program in accordance with 10 CFR 50.48(c) have typically evaluated the hazard posed by HEAF events through the use of the EPRI/NRC-RES fire Probabilistic Risk Assessment document, EPRI 1011989/NUREG/CR-6850. Licensees adhering to a deterministic fire protection program either meet the prescriptive requirements of Section III.G in Appendix R of 10.CFR 50.48(b) (or corresponding NRC staff guidance in NUREG-0800) and approved exemptions, or have a NRC staff-approved safety evaluation report on the fire protection program.

Related NRC Generic Communications and Documents:

The following NRC generic communications contains additional operating experience addressing general electrical distribution equipment complications (non-aluminum related):

- IN 1999-13, "Insights from NRC Inspections of Low- and Medium-Voltage Circuit Breaker Maintenance Programs,"dated April 29, 1999 (ADAMS Accession No. ML031040447).

- IN 2000-14, "Non-Vital Bus Fault Leads to Fire and Loss of Offsite Power," dated September 27, 2000 (ADAMS Accession No. ML003748744).

- IN 2002-01, “Metalclad Switchgear Failures and Consequent Losses of Offsite Power,” dated January 8, 2002 (ADAMS Accession No. ML013540193).

- IN 2002-27, “Recent Fires at Commercial Nuclear Power Plants in the United States,” dated September 20, 2002 (ADAMS Accession No. ML022630147).

- IN 2005-21, “Plant Trip and Loss of Preferred AC Power from Inadequate Switchyard Maintenance,” dated July 21, 2005 (ADAMS Accession No. ML051740051).

- IN 2005-15, “Three-Unit Trip and Loss of Offsite Power at Palo Verde Nuclear Generating Station,” dated June 1, 2005 (ADAMS Accession No. ML050490364).

- IN 2006-18, Supplement 1, “Significant Loss of Safety-Related Electrical Power at Forsmark Unit 1 in Sweden,” August 10, 2007 (ADAMS Accession No. ML071900368).

- IN 2006-31, “Inadequate Fault Interrupting Rating of Breakers,” dated December 26, 2006 (ADAMS Accession No. ML063000104).

- IN 2007-14, “Loss of Offsite Power and Dual-Unit Trip at Catawba Nuclear Generating Station,” dated March 30, 2007(ADAMS Accession No. ML070610424).

- NUREG/IA-0470, Volume 1 “Nuclear Regulatory Authority Experimental Program to Characterize and Understand High Energy Arcing Fault (HEAF) Phenomena,” dated August 2016 (ADAMS Accession No. ML16235A163).

DISCUSSION

Title 10 CFR Part 50, Appendix A, GDC 3, “Fire Protection” states, in part, “Structures, systems and components important to safety shall be designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions…”

Improper operation and maintenance practices represent the most significant contributors to HEAF events. Additional contributing causes include the use of improper tools and equipment during maintenance, introduction of conductive foreign material, insulation breakdown due to aging, failure of tripping mechanisms, loose bolted connections due to vibrations or inadequate maintenance practices, corrosion, improper work practices due to inadequate training, and a lack of preventative maintenance. Any of these contributors could lead to the development of a low resistance path between conductors or between conductors and ground, creating a HEAF event.

For plants that have transitioned to a performance-based fire protection program under 10 CFR 50.48(c) and National Fire Protection Association Standard 805, HEAF events constitute some of the high-risk scenarios. Recent testing suggests HEAFs involving aluminum components may exceed the ZOI methodology presented in NUREG/CR-6850.

For plants that have not transitioned to a performance-based fire protection program, fire hazard analyses performed to satisfy 10 CFR Part 50, Appendix A, GDC 3, may not have considered HEAFs as potential failure modes, including explosions or the dispersion of aluminum byproducts. These regulations include 10 CFR 50.48(a) and (b) and Appendix R to 10 CFR Part 50, Section III.G (or corresponding NRC staff guidance in NUREG-0800) and/or exemptions/deviations from these requirements granted in accordance with 10 CFR 50.12 or established in the licensing basis.

The operating experience and recent testing presented in this information notice demonstrates that the hazards from a HEAF may be substantially greater for electrical equipment that contains aluminum components than for those with copper components. Additionally, the operating experience and testing highlights the spread of an electrically conductive coating of aluminum byproducts which could lead to additional failures. A summary of the aluminum impact from operational experience is stated below:

- The Fort Calhoun event illustrates the adverse effects caused by large quantities of conductive aluminum byproducts in the smoke produced by HEAF events involving aluminum which can adversely affect adjacent equipment. The event further resulted in significant unexpected system interactions. Specifically, loss of power to both train A and train B buses occurred. Also, the event resulted in grounds on both trains of safety-related DC power used for breaker operation and electrical protection.

- The Columbia event involved aluminum bus bars completely enclosed in aluminum ducts. The event vaporized approximately 1.2 m (4 ft.) of each of the three buses and 2.4 m (8 ft.) of the bus duct enclosure and smoke and heat effects were observed at all metal joints and covers for a distance of 6 m (20 ft.) south, and about 3 m (10 ft.) north of the missing section.

- The Diablo Canyon HEAF event damaged both the 12 kV bus duct and the 4 kV bus duct. Both bus duct conductors were made of aluminum. The event led to the loss of both offsite electrical sources and the reliance on emergency diesel generators.

- The Zion HEAF event initiated a fire that the onsite fire brigade could not control. The bus duct was made of aluminum and the A and B phase isophase bus ducts showed signs of excessive arcing. The licensee found extensive aluminum spatter in the general area of the fault as well as large amounts of white powder that were later determined to be aluminum oxide. Additionally, the licensee stated that the physical damage observed during inspections was greater than other documented failures of this nature.

- The Shearon Harris event damaged over a 15.2 m (50 ft.) section of the phase A bus. The bus duct enclosure was made of aluminum. The event also destroyed the neutral grounding bus and caused three fires: (1) an oil fire at the B main power transformer, (2) a hydrogen fire underneath the main generator, and (3) a third small oil fire in the generator housing.

- The Kewaunee Power Station HEAF event damaged a 9.1 m (30 ft.) section of the bus bar and the licensee observed the spread of a metallic dust. The bus bar conductor was made of aluminum.

As previously discussed, the NRC has entered the issue of high-energy arc faults involving aluminum into the generic issue process. As part of this process, the NRC staff will obtain additional data and will perform additional evaluations to inform future agency actions, as appropriate. As described in a memorandum dated March 4, 2016, the NRC staff had also performed an initial evaluation and determined that there was no immediate safety concern (ADAMS Accession No. ML16064A250).

Although not explicitly required, the NRC encourages addressees to review the information in this information notice for applicability and consider actions, as appropriate. Suggestions contained in this information notice are not NRC requirements; therefore, the agency requires no specific action or written response.

CONTACTS

Please direct any questions about this matter to the technical contact(s) listed below or the appropriate Office of Nuclear Reactor Regulation (NRR) or Office of New Reactors (NRO) project manager.

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NRC INFORMATION NOTICE 2017-04, "HIGH ENERGY ARCING FAULTS IN ELECTRICAL EQUIPMENT CONTAINING ALUMINUM COMPONENTS," DATE: August 21, 2017

ADAMS Accession No.: ML17058A343 **TAC No. MF9285**

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