U.S. NRC Fire Safety Research Activities

N. Melly, G. Taylor, and D. Stroup
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission, USA

Paper presented at
OECD/NEA/CSNI/WGRISK International Workshop on Fire PRA
Garching, Germany
April 28-30, 2014

Abstract

The NRC is actively pursuing a number of research activities in the area of fire safety. One of the objectives of the fire research branch is to improve the agency's knowledge in areas where uncertainty exists in support of regulatory decisions for existing or new designs and technologies with respect to fire safety. This paper will provide details related to high priority test programs such as the Electrical Enclosure Heat Release Rate test program, the Joint Analysis of Arc Faults (Joan of Arc) Organization for Economic Co-Operation and Development (OECD) International Testing Program for High Energy Arc Faults and the Evaluation of Incipient Fire Detection System Performance for Fire Probabilistic Risk Assessment. The paper will also discuss current data and techniques used in NUREG/CR-6850 EPRI TR-1011989 "Fire PRA Methodology for Nuclear Power Facilities" and areas that are being improved with the current programs.

U.S. NRC Fire Safety Research Activities

N. Melly, G. Taylor, and D. Stroup
U.S. Nuclear Regulatory Commission
Washington DC, 20555
Nicholas.Melly@nrc.gov
Gabriel.Taylor@nrc.gov
David.Stroup@nrc.gov

ABSTRACT[1]

The NRC is actively pursuing a number of research activities in the area of fire safety. One of the objectives of the fire research branch is to improve the agency's knowledge in areas where uncertainty exists in support of regulatory decisions for existing or new designs and technologies with respect to fire safety. This paper will provide details related to high priority test programs such as the Electrical Enclosure Heat Release Rate test program, the Joint Analysis of Arc Faults (Joan of Arc) Organization for Economic Co-Operation and Development (OECD) International Testing Program for High Energy Arc Faults and the Evaluation of Incipient Fire Detection System Performance for Fire Probabilistic Risk Assessment. The paper will also discuss current data and techniques used in NUREG/CR-6850 EPRI TR-1011989 "Fire PRA Methodology for Nuclear Power Facilities" and areas that are being improved with the current programs.

1. Electrical Enclosure Heat Release Rate

1.1 Purpose

In 2005, the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) jointly published NUREG/CR-6850 (EPRI 1011989), "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities [1]." This report documented methods, tools, and data for conducting fire probabilistic risk assessments (PRAs) in commercial nuclear power plant (NPP) applications. The NUREG/CR-6850 (EPRI 1011989) fire PRA methodology consists of 16 separate tasks with multiple steps for each task. In addition, there are two "support tasks" and a number of appendices with supplemental information required for each task. Using a significant body of previous research on material combustibility characteristics , the authors of NUREG/CR-6850 (EPRI 1011989) established a list of recommended heat release rates (HRR) for a variety of potential fuel types including electrical cables, electrical cabinets, flammable liquids, and transient combustibles. The HRR is a measure of the rate at which a burning item releases chemical energy and has often been characterized as the single most important variable in understanding a fire hazard [2].

1 This paper was prepared (in part) by employees of the United States Nuclear Regulatory Commission. It presents information related to NRC upcoming testing programs. NRC has neither approved nor disapproved its technical content. This paper does not establish an NRC technical position.

While NUREG/CR-6850 (EPRI 1011989) is a guidance document for fire PRA in NPPs, the HRR information is useful for both fire PRAs and fire hazard analysis (FHA). Over the last several years, the NRC has been working to improve and refine the HRR values presented in NUREG/CR-6850 (EPRI 1011989). Recently completed work to characterize the HRR, flame spread and ignition of electrical cables has been conducted under NRC sponsorship [3]. The current project is focused on better characterizing the peak HRR and fire growth model for electrical enclosures.

Electrical enclosures[2] are found throughout NPPs. These enclosures are typically constructed of metal on the order of 16 gauge steel (1.5 millimeters (mm) or 0.06 inches (in). The geometries range from small wall-mounted cabinets, to large vertical electrical enclosures of multiple sections with various ventilation configurations. Electrical components (wires, relays, circuit breakers, transformers, etc.) are installed inside the enclosures and vary in physical size, function, and electrical specifications. Junction boxes, pull boxes, and similar smaller enclosures are not considered in this study.

Fire in electrical enclosures has been identified as a significant contributor to fire risk in NPPs. During an Advisory Committee on Reactor Safeguards (ACRS) subcommittee meeting on November 16, 2010, EPRI identified electrical panel fires as a very significant risk driver (see Figure 1) for the licensees making the transition to National Fire Protection Association (NFPA) 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants (2001)" under Title 10 of the Code of Federal Regulations (10 CFR) 50.48(c). The combination of combustible materials and electrical energy within the electrical enclosure can lead to fires and possibly High Energy Arcing Faults (HEAFs). These fires have the potential to disrupt electrical power, instrumentation, and control in the plant. To gain a comprehensive understanding of the fire phenomena within electrical enclosures, the effects of enclosure size, openings, cabinet function, and quantity of combustible material is being examined.

This test program is confirmatory research based on fire physics to quantify the rate of energy release and spread of fires within electrical enclosures. The testing phase of this project will evaluate the potential HRR and fire growth rates for electrical enclosures typically found in NPP. The test data will be used to support the development of improved guidance for understanding and modeling electrical enclosure fires.

[2] "Enclosure" is defined in IEEE 100, *The Authoritative Dictionary of IEEE Standard Terms*, as a surrounding case or housing to protect the contained equipment against external conditions and to prevent personnel from accidentally contacting energized parts. "Cabinet" is defined as an enclosure designed either for surface or flush mounting, provided with a frame, mat, or trim in which a swinging door or doors are or may be hung, and housing modules, backplane(s), I/O connector assemblies, internal cables, and other electronic, mechanical, and thermal devices.

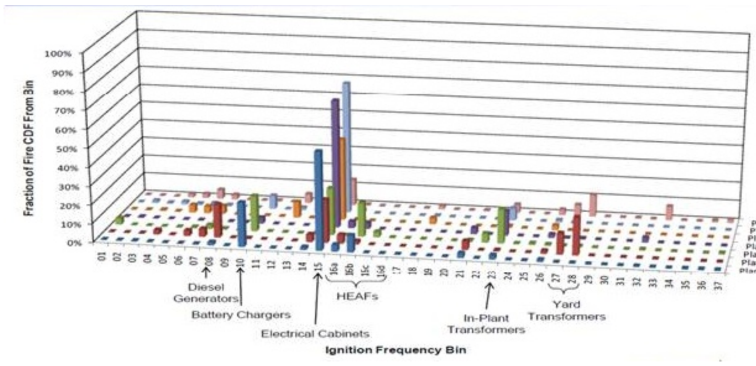

Figure 1 – Fire CDF contribution by ignition source

1.2 Background

The HRR has typically been characterized as the single most important variable in FHA [2]. HRR is a measure of the rate at which a burning item releases chemical energy. HRR is used as input to a computer fire model, and informs fire size, fire growth rate, available egress time, and suppression system impact when all parameters affecting HRR are known [4].

Classically there are two broad categories of methods for estimating the potential impact of burning materials on occupants and structures— risk-based and hazard-based. Both types of methods estimate the potential consequences of possible events. Risk-based methods also analyze the likelihood of scenarios occurring while hazard-based methods typically do not [4]. In a FHA, the impact of fire exposure on people and structures is evaluated based on one or more assumed fire scenarios. The HRR of the burning items is a key element of each fire scenario and defines the “size” of the fire exposure [5].

If the heat of combustion of a material is known, the HRR of a burning item can be determined by measuring the item’s mass loss rate during combustion (i.e., the mass burning rate). Alternatively, the HRR can be determined directly from measurements of the product of combustion gases collected in an exhaust hood. Laboratory calorimeters can provide useful information concerning HRR using small material specimens. However, these calorimeters may not represent the actual performance of a material when used in the actual built environment. Laboratory calorimeters do not usually test the same size materials as found in most fire scenarios and the laboratory results can be influenced by the relative closeness of the material edges to the center of the flame zone. There is also little or no geometry consideration included in small-scale tests. Intermediate and large-scale calorimeters attempt to provide a more realistic method for understanding actual materials HRR.

In general, combustible materials in NPPs can be divided into four broad categories, including the following [6]:

(1) transient solid and liquid fuels
(2) in situ combustibles consisting of both solid and liquid fuels
(3) liquid fuels used in NPP equipment
(4) explosive and flammable gases

Solid transient fuels include general trash, paper waste, wood, plastics, cloth, and construction materials. Liquid transient fuels commonly include cleaning solvents, paints, and lubricants being used for maintenance of plant equipment. These fuels are generally found in small quantities in most NPP areas at any given time. The most common category of potential fuels found in NPPs is that of in situ solid fuel elements. Of these, the largest single potential fuel source is electrical cable insulation and jacketing materials. These "cables" vary widely in size and location, most commonly installed in open cable trays where they present a hazard as an exposed combustible. Liquid fuels include lubricating and cooling oils, cleaning solvents, and diesel fuels. Finally, explosive and flammable gases can be present in NPPs with hydrogen being the most abundant.

The electrical enclosure HRR project will be to conduct experiments on actual electrical enclosures that are commonly installed in NPPs and were selected according to size and ventilation type to cover a range of plant configurations. The enclosures will be "mocked up" with cabling and components to simulate combustible loading configurations for electrical enclosures identified during the plant site visits conducted by the NRC staff. The ignition conditions necessary to obtain established burning within the enclosures will be examined. The time history of the HRR and the extent of the fire within the electrical enclosures will be measured and documented.

The experimental data obtained will be used to re-evaluate the HRR information contained in NUREG/CR-6850 (EPRI 1011989) and the 2012 EPRI guidance document [7]. Specifically, a joint working group consisting of EPRI and NRC sponsored experts will be assembled to review the available information and develop revisions where appropriate to NUREG/CR-6850 (EPRI 1011989). The NRC expects to use an expert elicitation for portions of this work. The panel will focus efforts on examining cabinet configurations, refining the electrical cabinet frequency bin to reflect plant experience, evaluating the potential to develop a fire hazard model for electric cabinets, and use the electrical enclosure HRR and fire growth information to develop revised HRR distributions for use in PRA applications. A technical report will be issued upon completion of the working group efforts documenting the outcome and associated peer review of the experts' analysis and conclusions.

1.3 Technical Approach

Staff from the National Institute of Standards and Technology (NIST) and NRC performed site visits to several commercial NPP facilities. These sites included: Bellefonte, Three Mile Island, and Zion. During these visits, site staff members were able to open numerous electrical enclosures to allow the NIST and NRC staff to take photographs and document general characteristics of the enclosures including amount of combustibles and ventilation conditions. From these site visits, the NIST and NRC staffs were able to gain an understanding in the variations between the types of electrical enclosures used in NPPs. The NPP electrical enclosure pictures will be used to inform and develop combustible loadings for the "mocked up" cabinets that are representative of those found in NPPs.

The cabinets will be modified to represent various enclosure configurations that were identified during the plant walkdowns. The combustible loading, i.e., bundles of electrical wire and cables, will typically be described in terms of total mass per unit length, total length, number of conductors, plastic and cooper mass ratio, and whether the cables are used with or without the jacket. The final report will document the relationship between a test cabinet mock-up and the associated actual plant configuration (see Figure 2). The subsequent working group will also use this information to develop guidance for quantify combustible loading.

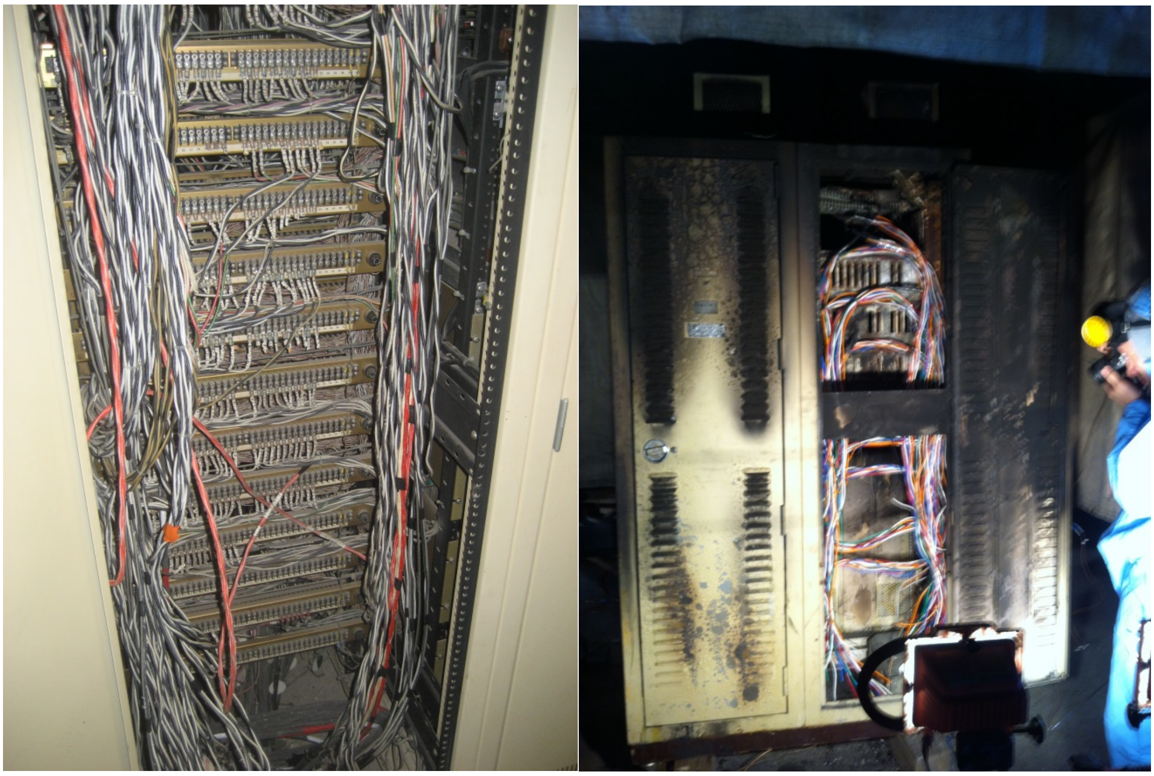

Figure 2 – Actual plant loading example (left), Thermoplastic unjacketed “mock up” (right)

The primary measurement of the testing is the HRR of the burning electrical enclosures. This measurement is to be achieved by way of oxygen consumption calorimetry. Infrared and conventional video cameras provided by NIST will also be positioned outside of the enclosures. All fire development information such as; time to ignition, steady state, time to peak HRR, decay phase and time to self-extinguishment will all be documented in the final experimental report. Thermocouples are to be positioned inside the enclosure 0.15 meters (m), (6 in) below the ceiling and at 0.3 m (1 foot (ft)) intervals. These thermocouples will be monitored during the tests to indicate if the fire spreads beyond its origin. Combustible load measurements of the cables will be evaluated in terms of length, weight and combustible load based on information obtained though small scale cone calorimetry insights.

Previous testing conducted at Sandia National Laboratories[8][9][10], VTT Technical Research Centre of Finland [11], used either a propane burner or a “transient” ignition source[3] yielding between approximately 1 to 30 kilowatts (kW) to ignite the cable fuels. Based on review of the fire event database, the testing requirements for qualified cable, and preliminary test results, several ignition scenarios have been identified. The ignition scenarios consist of various combinations of a propane burner and a small pan of acetone. The ignition source will simulate a range of ignition energies 1kW—30kW (Figure 3). Ignition will be done in such a way that fires achieve established burning condition and then will be allowed to burn out naturally. After established burning has been achieved the ignition source will be removed allowing for unaided combustion to continue.

A liquid acetone fuel source will be used to simulate the larger ignition energy events (>10 kW) because of safety issues associated with using a propane gas burner in the electrical enclosure which is defined as, a confined space. Acetone will also be used for cabinet preheating purposes because of the cold conditions of the laboratory space during this program. Preheating was necessary because the majority of testing was performed in the winter of 2013 when the unheated ambient laboratory conditions were below freezing. Researchers selected acetone to provide a constant HRR source that is easily reproducible throughout the series of test experiments. The goal was to simulate the electrical enclosures at their operating temperature range when the test starts. The burning rate of acetone has been well established by various research studies and is a function of the surface area available for combustion. The HRR and burning duration can be controlled by selection of an appropriately sized container and quantity of acetone. The HRR ignition profiles selected are comparable to ignition methods used in other ASTM standardized fire test procedures such as ASTM E1537, Standard Test Method for Fire Testing of Upholstered Furniture, (propane burner 19.7 kW) and ASTM E1822, and Standard Test Method for Fire Testing of Stacked Chairs, (propane burner 17.8 kW).

[3] The “transient” ignition source consisted of a 9.5 L polyethylene bucket, with an open 0.5 kg box of Kimwipes, and 0.946 L of acetone in the bucket (NUREG/CR-4527, An Experimental Investigation of Internally Ignited Fires in NPP Control Cabinets, Volume 1: Cabinet Effects Tests, April 1987).

Figure 3 – Ignition methods: 1-2kW propane burner (left), 10kW propane burner (middle), 20kW acetone pan (right)

1.4 Test Results and Fire Model Improvement

After completion of the testing program the NRC will establish a balanced “working group” of experts who will use lessons learned from the application of NUREG/CR-6850 (EPRI 1011989), insights from the testing and their own experience to enhance the guidance currently found in NUREG/CR-6850 (EPRI 1011989). An expert elicitation may be conducted to evaluate all available test data to re-quantify electrical enclosure HRR distributions. These distributions will be developed such that they can be used to enhance Fire PRA guidance. To improve these distributions, the panel will focus on what it believes to be first order parameters impacting HRR such as; fuel load, ventilation, fire growth profiles, fire elevations and fire location within a cabinet.

As a whole, these experts will possess collective expertise in fire testing, fire modeling and fire PRA application. EPRI participation in the working group will provide a balance between the regulator (i.e., two or three members from the NRC and National Laboratories) and EPRI (i.e., two or three members from EPRI/nuclear power industry/consultants). The panel will use test results, previous research, expert judgment and operating experience to develop a new approach to determining electrical enclosure HRR distributions.

2. JOINT ANALYSIS OF ARC FAULTS (Joan of ARC) OECD INTERNATIONAL TESTING PROGRAM FOR HIGH ENERGY ARC FAULTS

2.1 Purpose

NUREG/CR-6850 Appendix M delineates a High Energy Arc Fault (HEAF) event into two phases: an energetic phase and an ensuing fire. One of the key components in addressing a HEAF event is characterizing the damage during the energetic phase of the event. The enclosure or cabinet in which a HEAF event occurs may be breached by the explosive release of energy. This factor greatly influences the immediate heat flux to

which nearby objects are exposed. The ensuing fire is also of interest, as it can be the cause for fire spread and failure of additional components and adjacent equipment that was not damaged by the initial heat released during the HEAF event. One of the major limitations to Appendix M is that it presents a “one size fits all” model. That is, as long as a component meets the criteria for inclusion as a HEAF source, there is no further distinction made based on the characteristics of the specific initiating component (e.g., voltage or current level, device type, etc.) nor those of the component’s enclosure (e.g., robustness of the surrounding cabinet).

This project was identified as part of the OECD fire events database program. Catastrophic failures of energized electrical equipment, referred to as HEAF, have occurred in NPP components throughout the world. HEAF’s typically occur in 480 volt (V) and higher electrical equipment and cause large pressure and temperature increases in the component cabinets, which could ultimately lead to serious equipment failure and secondary fires posing a NPP risk. Most recently the United States has experienced events at Palo Verde in 2013, H.B. Robinson in 2010 and Columbia in 2009. Discussions at the OECD Fire Incidents records exchange meetings indicate similar HEAF events have recently occurred in Canada, France, Germany and most recently at Japan’s Onagawa NPP during the earthquake and tsunami of 2011. OECD Fire Project – Topical Report No.1 “Analysis of High Energy Arcing Fault (HEAF) Fire Events, NEA/CSNI/R[13] published June 2013 documents these international events.

HEAFs have the potential to cause extensive damage to the failed electrical component and distribution system along with adjacent equipment and cables within the zone of influence (ZOI). The significant electrical energy released during a HEAF event can act as an ignition source to other components. HEAF phenomena have been identified as a risk driver and represent a unique challenge for PRA practitioners and fire modelers.

The primary objective of this project is to perform experiments to obtain scientific fire data on the HEAF phenomenon known to occur in NPPs through experiments. The goal is to use the data from these experiments and past events to develop a mechanistic model to account for the failure modes and consequence portions of HEAFs. These experiments are expected to improve the state of knowledge and provide better characterization of HEAF in the fire probabilistic risk assessment (PRA) and support National Fire Protection Association (NFPA) 805 license amendment request applications and regulatory reviews.

Researchers will examine the initial impact of the arc to primary equipment and the subsequent damage created by the initiation of an arc in the ZOI (e.g., secondary fires). To meet the goals of this test program, experiments will be conducted to explore the basic configurations and effects of HEAF events. The equipment to be tested in this study primarily consists of switchgears and bussing components.

This project will be operated as part of a larger international OECD/NEA effort. The NRC will be leading the physical testing and instrumentation of equipment at the designated test laboratory. International member countries participating in the project will provide equipment to be tested as well as technical expertise. Figure 4 depicts a 480 V load

center undergoing HEAF testing as part of the recent Japanese test program to investigate HEAF events in context of the Onagawa event.

Figure 4 – 480 V load center undergoing HEAF Testing: before arcing (left) after arcing (right)

2.2 Background

As defined by the Institute of Electrical and Electronic Engineers (IEEE), switchgear components are classified as low, medium, and high voltage which corresponds to less than 1 kV, 1 to 100 kV, and greater than 100 kV, respectively. The majority of the testing of these components has focused on exposure to personnel and worker safety. The testing to be conducted in this project is driven by a need to better understand the HEAF phenomenon within an NPP systems framework, the effects on secondary combustibles ZOI, and how to quantify and model these fire risks.

The initial HEAF impacts are important in understanding the structural integrity of the component during overpressure as well as the potential for catastrophic equipment failure. Understanding the heat exposure effects can further define the ZOI. Quantifying this ZOI from a HEAF is particularly important when analyzing the arc effects on secondary combustible materials (e.g., transient combustibles, adjacent equipment, exposed electrical cabling). This provides the basis for subsequent damage, which may result from an ensuing fire. This ZOI approach can create fire scenarios with extensive target sets resulting in high conditional core damage probabilities (CCDP) and little to no solutions for risk mitigation and has been identified as a high priority for future research.

Currently, NUREG/CR-6850, Appendix M discusses the analysis of HEAF and surrounding combustibles as well as the relevant assumptions applied during the analysis. The assumptions were developed from analysis of NPP incidents, previous studies and expert judgment. The majority of the events occurred in 4160 V switchgear/bussing equipment; however, some failures have occurred in 480 V and 6900 V. For the more intense arcing incidents, adjacent cabinets and secondary combustibles (e.g., cables) were impacted by the HEAF. The ZOI for HEAF events is intended to capture the

damage generated during the energetic phase. The following is a summary list of the current assumptions from Appendix M of NUREG/CR-6850.

- The initial arcing fault will cause destructive and unrecoverable failure of the faulting device
- The next upstream over-current protection device will trip open
- The release of copper plasma and/or mechanical shock will cause the next directly adjoining/adjacent switchgear and/or load center cubicles within the same bank to fault
- Subsequent fires will burn consistent with a fire intensity and severity consistent with the methodology presented in Appendix G of NUREG/CR-6850
- Unprotected cables that drop into the cabinet will ignite
- Any unprotected cables in the first overhead cable tray will be ignited concurrent with the initial arcing event provided that the tray is within 1.5 m vertical distance of the top of the cabinet
    - Fire will spread to other trays consistent with the treatment of cable tray fires described in the methodology
    - This assumption also applied to trays located 0.3 m in any horizontal direction of the impacted cabinet or duct
    - Cables in fire wrap or conduit are considered protected
- Any vulnerable component within 0.9 m horizontally in front or in the rear of the cabinet will suffer physical damage and functional failure
    - This includes operable structural elements like fire dampers and fire doors, equipment such as cables and transformers, and oil feed lines less than 1” diameter
    - This excludes structural elements such as walls and floors as well as large components and purely mechanical components such as pumps and valves

2.3 Technical Approach

To meet the goals of this test program, experiments will be conducted to explore the basic configurations, failure modes, and effects of HEAF events at the KEMA power test facility in Chalfont, Pennsylvania USA. The equipment to be tested in this study primarily consists of switchgears and bussing components. The HEAF will be initiated inside of the electrical equipment according to IEEE Standard C37.20.7-2007 “Testing Metal-Enclosed Switchgear Rated Up to 38 kV for Internal Arcing Faults”. General characteristics of the arc may be obtained for the different initial voltages (i.e., 480, 4160, and 6900 V). For low voltage equipment, the arc will be initiated by means of a copper wire 2.6 mm in diameter (10 AWG). For medium voltage equipment, a 0.5 mm in diameter (24 AWG) copper wire will be used. (See Figure 5)

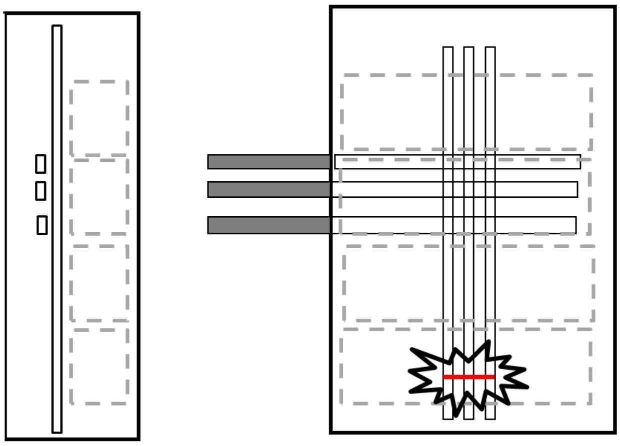

Figure 5 – Initial arc location

High speed video and instrumentation will be used to best capture relevant information related to the release of energy created during the arcing event. Both active and passive gauges to measure temperature and pressure have been evaluated during an exploratory test program with Sandia National Laboratories [13]. Instrumented cable trays and cables will be placed above the cabinet and evaluated for ZOI damage conditions. It is expected that cables located on cable trays above the location of the HEAF will ignite and support an enduring fire. Where possible, oxygen consumption calorimetry will be used to estimate the heat released from such post-HEAF fire. This testing will use a portable oxygen consumption calorimetry hood developed as part of the Electrical Enclosure HRR testing program by NIST.

2.4 Test Results and Fire Model Improvement

This research program is intended to improve the realism in the current state of the art in fire PRA methodology and will be targeting different types of equipment and different voltage levels to better characterize the ZOI for HEAF events. The data collected will support further classification of risk relevant targets and improve the understanding of HEAF susceptible enclosures. This program is being conducted in collaboration with the OECD.

The current equipment list includes contributions from the Central Research Institute of Electric Power (CRIEPI) Japan, the Japanese Nuclear Energy Safety Organisation (JNES)(now a part of Japan Nuclear Regulator Authority (NRA)), the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Germany the Korean Institute of Nuclear Safety (KINS), Korea (Republic of) and The Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France. Testing will be performed in 2014 and a final report is expected to be published in 2015.

3. INCIPIENT FIRE DETECTION

3.1 Purpose

Incipient fire detection (IFD) has been used in the telecommunications industries for years to meet prescriptive requirements described in NFPA 76, "Fire Protection of Telecommunication Facilities." These IFD systems have gained wide acceptance in the telecommunication industry due to the high air change rate in telecommunication facilities which results in high levels of smoke dilution rendering conventional spot type smoke detectors ineffective. Since the mid-1990's the use of these systems have begun their introduction in Canadian and U.S. NPPs as a very early warning fire detection (VEWFD) systems. Air sampling detection (ASD) type smoke detectors are commonly used to meet the Very Early Warning sensitivity and transport time requirements per NFPA 76. These systems have the potential to detect low-energy fires at an early stage, allowing for additional time for operators to response to possible fire threats. However, information regarding the performance of these systems in non-telecommunication type facilities is limited and quantification of the characteristics and benefits of these systems for the application within the PRA has been highly uncertain.

NUREG/CR-6850 provides an empirical fire growth model for electrical cabinet fires that is based, in part, on testing conducted by Sandia National Laboratories, VTT Technical Research Center of Finland, and the empirical "t-squared" fire growth model developed by the NIST fire growth model. However these testing programs have provided scarce data on the incipient growth stages of an electrical panel fire and other postulated events or phenomena. This is largely due to the uncertainty and randomness of the incipient phase of fires. Additionally there is a lack of adequate guidance related to PRA treatment to reflect this improvement in plant safety when using these systems. To assist in resolving this issue, the NRC has initiated a confirmatory test program that will analyze the incipient phase of the fire growth stage in electrical panel fires and evaluate both the human behavioral response and detection system performance.

This program includes some consideration for the root cause and fire growth characteristics in cabinets during the incipient fire stage. NRC is also considering the development of a model that would characterize the incipient phase of the fire growth stage based on the information gained during this program.

3.2 Background

ASD systems mechanically draw air samples from the protected area (room or electrical enclosure) and assess these samples for the presence of smoke particles. This allows for the use of filters to remove dirt and dust particles, a common source of false alarms for ordinary nonaspirating smoke detectors [14]. The filtering allows for the detector to have a higher sensitivity than conventional spot detection. These high sensitivity detectors can be used to detect the earliest traces of airborne particles or aerosols released caused by the overheating of materials. As these systems have the potential to provide numerous advantages over conventional systems, there exists the possibility of challenge in adequately implementing this technology to take full effect of the advantage.

For example, differences in human interaction, response, system design, installation, maintenance, reliability, and testing need to be taken into consideration to ensure the potential advantages are utilized.

Air aspirated VEWFDS have been used in some U.S. NPPs for over a decade to qualitatively reduce fire risk contributors identified during the Individual Plant Evaluations of External Events (IPEEEs) or for prompt detection to support exemptions. However, only recently has there been an interest in using these systems in the regulatory context to document quantitatively risk reductions per fire PRA methodologies and the NFPA Standard 805, “Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants”, 2001 Edition.

In September 2010, the NRC and EPRI issued Supplement 1 to NUREG/CR-6850 / EPRI 1019259 entitled, “Fire Probabilistic Risk Assessment Methods Enhancements” [12]. This report provides interim guidance on questions raised by the pilot plants during their transition to NFPA 805. Section 13 entitled, “Incipient Fire Detection Systems,” provides an NRC staff interim position for determining the probability of non-suppression in fire areas that have installed incipient fire detection systems[4]. Because of the lack of information and test data, the interim position limited the applicability of VEWFDS with regard to crediting these systems for fire risk reduction. Several requirements are provided in the FAQ 08-0046, including:

- Smoke detection system shall be an ASD installed as a very early warning fire detection system (VEWFD SYSTEMS) per the requirements of NFPA 76 (2009 version)
    - Per NFPA 76, VEWFD SYSTEMS shall meet two sensitivity criteria;
        - alert threshold of at least 0.2 percent obscuration per foot, and
        - alarm threshold of 1.0 percent obscuration per foot
- ASD shall be installed to monitor component degradation in electrical cabinets
- Cabinet component voltages shall have less than or equal to 250 Volts
- Proper cabinet ventilation must exist to allow ASD VEWFD SYSTEMS to function (systems do not function properly in tightly sealed cabinets)
- No credit should be taken for using ASD VEWFD SYSTEMS to protect rotating equipment or cabinets containing voltage greater than 250 volts
- The ASD VEWFD SYSTEMS shall be designed and installed by technicians who are trained and qualified to apply NFPA 76 following appropriate vendor guidance, tested in accordance with an appropriate standard including appropriate vendor requirements, and maintained in accordance with manufactures code requirements.
- No credit shall be provided for operator success in identifying ASD VEWFD SYSTEMS alert source and removing power from it during incipient stage

[4] As a matter of clarification, the term *incipient fire detection system* will not be used in this test plan, instead the term very early warning fire detection systems (VEWFDS) will be used. The use of the term VEWFDS is to reduce any confusion with regard to regulatory applications where licensees have installed conventional non-VEWFDS spot detectors in cabinets or other areas and classified these detectors as incipient detection in licensing documentation.

Based on these recommendations the NRC decided to perform confirmatory testing to evaluate the following aspects of incipient detection systems:

- effectiveness of area wide versus in-cabinet VEWFDS applications, including effects of in-cabinet VEWFDS layout and design on system response
- comparison between conventional fire-detection systems currently used in NPPs and VEWFDS, including VEWFDS fire signature response to products of combustion from common combustibles found in NPPs
- human Reliability Analysis (HRA) response and effectiveness of equipment used to locate pre-fire source
- system reliability
- a scientific evaluation to determine and characterize the root cause and nature of pertinent postulated or observed phenomena and an argument for how VEWFDS may detect and discriminate such phenomena
- a discussion of the intended or anticipated outcome and benefit of the application of VEWFDS in NPPs

3.3 Technical Approach

Following a literature review, staff from NIST and NRC performed several site visits to operating NPPs in the United States and Canada, along with visits to non-nuclear facilities. These site visits provided two benefits. First, it was realized early on that the literature review and testing alone would not able to provide answers to all of the program's objectives. With regard to this aspect, the site visits provided information on system availability, reliability and human interaction per plant procedure review and operator interviews. Second, the site visits provided information on the system layout and design being used in plants, which enabled a test plan to be developed that adequately represented the design and use of these systems in plants.

The testing phase included small scale laboratory testing to evaluate system response to various smoke signatures. Researchers selected eleven different materials to represent realistic plant materials and heated at three different heating rates to simulate an incipient fire sources under differing conditions. The full scale testing focused on the impact that room size and ventilation would have on parameters of interest; including in-cabinet detection, area wide detection, and air-return grills. This test program also will evaluate the human response impact for VEWFD's systems since the proposed systems use human intervention as the primary means of mitigating an impending fire. This research program is intended to improve the realism in the current state of the art in fire PRA methodology and provide supplemental guidance for the treatment of VEWFD systems in a PRA model.

References

[1] Electric Power Research Institute and U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "Fire Probabilistic Risk Assessment Methods Enhancements: Supplement 1 to NUREG/CR-6850 and EPRI 1011989," EPRI 1019259 and NUREG/CR-6850 Supplement 1, Electric Power Research Institute (EPRI), Palo Alto, CA and U.S. Nuclear Regulatory Commission, Washington, DC, 2009.

[2] Babrauskas, V., and R.D. Peacock, "Heat Release Rate: The Single Most Important Variable in Fire Hazard," Fire Safety Journal, 18, pp. 255-272, 1992.

[3] McGrattan, K., et al., "Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) – Phase 1: Horizontal Trays," NUREG/CR-7010 Vol. 1, US Nuclear Regulatory Commission, Washington, DC 20555, 2012.

[4] Madrzykowski, D., and D.W. Stroup, "Flammability Hazard of Materials," Section 2, Chapter 3, Fire Protection Handbook, National Fire Protection Association, Quincy, MA, pg. 2-31, 2008.

[5] Hurley, M.J., and R.W. Bukowski, "Fire Hazard Analysis Techniques," Section 3, Chapter 7, Fire Protection Handbook, National Fire Protection Association, Quincy, MA, pg. 3-121, 2008.

[6] Iqbal, N. and M. Salley (2004) Fire Dynamics Tools, NUREG-1805, U.S. Nuclear Regulatory Commission, Washington, DC.

[7] Electric Power Research Institute, Evaluation of Peak Heat Release Rates in Electrical Cabinet Fires, Technical Report-1022993, February 2012 Palo Alto, CA

[8] Chavez, J.M. (1987). An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets: Part I: Cabinet Effects Tests, NUREG/CR-4527/V1, US Nuclear Regulatory Commission, Washington, DC.

[9] Chavez, J.M. and S.P. Nowlen (1988). An Experimental Investigation of Internally Ignited Fires in Nuclear Power Plant Control Cabinets: Part II: Room Effects Tests, NUREG/CR-4527/V2, US Nuclear Regulatory Commission, Washington, DC.

[10] Nowlen, S.P. (1989) A Summary of Nuclear Power Plant Fire Safety Research at Sandia National Laboratories, 1975-1987, NUREG/CR-5384, SAND89-1359, Sandia National Laboratories, Albuquerque, New Mexico.

[11] Mangs, J., J. Paananen and O. Keski-Rahkonen (2003) "Calorimetric fire experiments on electronic cabinets," Fire Safety Journal, 38: 165-186.

[12] Electric Power Research Institute and U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, "EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities," EPRI 1011989 and NUREG/CR-6850, Electric Power Research Institute (EPRI), Palo Alto, CA and U.S. Nuclear Regulatory Commission, Washington, DC, 2005.

[13] Lopez, Carlos, "Evaluation of Heat and Pressure Gauges for High Energy Arcing Fault Tests: A Test Report," U.S. NRC Project N6981, Sandia National Laboratories (SNL), February 2013.

[14] Custer, Richard L.P.et al. 2002, Design of Detection Systems, SFPE Handbook of Fire Protection Engineering, 3rd Ed., NFPA, Quincy (MA), USA, ISBN: 087765-451-4.