Very Early Warning Fire Detection of Incipient Sources in Nuclear Power Plant Applications

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This paper[a] presents several outcomes of an experimental study conducted to evaluate the performance of aspirating smoke detection (ASD) systems configured for very early warning fire detection (VEWFD) for use in nuclear power plant (NPP) applications. The needs, objectives, approach, and results of the experimental program are presented herein.

Overview

Recent interest in quantifying the performance of VEWFD systems in risk applications is a result of many U.S. NPPs transitioning to performance-based fire protection programs (FPPs) per the National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition." The objective for using these systems is to provide earlier notification to plant personnel that may allow additional time for human or automatic intervention prior to fire conditions developing that threaten the ability to achieve and maintain the nuclear fuel in a safe and stable condition. Insights from preliminary fire PRA developments[1] indicate that electrical enclosure such as control/relay cabinets, switchgear, and motor control centers represent some of the highest potential fire initiators.

In 2009, the NRC issued an interim staff position on the use of VEWFD systems in risk assessment. The position was developed based on NRC staff understanding of the VEWFD equipment, as well as how NPP electrical and electronic equipment typically fails.[2] At the time of issuance, there was very little applicable data available that was representative of the applications sought. To address this, the NRC initiated a confirmatory research program to evaluate the performance of various smoke detection systems, and provide a fire risk scoping study focusing on these systems performance. The results of the research program are currently in the review and publication process.

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[a] This paper was prepared (in part) by an employee of the United States Nuclear Regulatory Commission (USNRC). The USNRC has neither approved nor disapproved its technical content. This paper does not establish a USNRC technical position.

Testing Objectives and Approach to Support Risk Quantification

The objectives of the testing were to (1) evaluate the effectiveness of various smoke detection systems to detect incipient fire sources; (2) provide performance comparisons between VEWFD and conventional spot-type detectors; (3) evaluate smoke detection system response to common products of combustion; and (4) evaluate the electrical enclosure layout and design attributes that affect performance.

Experimental Approach

The experimental study focused on evaluating the performance of several ASD and spot-type VEWFD, as well as conventional ionization and photoelectric spot-type detectors' ability to respond to the incipient (non-flaming) stage, and to detect overheating electrical components contained in NPP electrical enclosures. The scope of the experimental approach was limited to only the pre-flaming incipient stage, and did not attempt to evaluate the flaming pre-growth stage.

Since a test procedure exists to achieve the objectives of this testing, an aerosol-generating method was developed to simulate the non-flaming incipient stage of an overheating component. Variations in cabinet and room size, as well as ventilation conditions were evaluated. The times and temperatures at various alarm set points were recorded. Aerosol measurements in small-scale laboratory tests were also taken.

Smoke Source

Electrical fires are often preceded by some form of arcing or joule heating of electrical components. A pre-flaming smoke source was developed to mimic these slow overheat conditions to degrade polymeric electrical and electronic materials. The source consists of a copper bus bar block with an axial cylindrical hole where a 500W cartridge heater is mounted. Polymeric materials, such as insulated electrical conductors, phenolic terminal blocks, and printed circuit boards representative of those found in NPP electrical enclosures, are attached to the external surface of the bus bar along with a single thermocouple to allow for temperature feedback control. The cartridge heater raises the surface temperature of the copper bus bar block from ambient to a maximum temperature of 485 °C, using one of three linear heating rate periods (HRPs), namely, 15 minutes, 1 hour and 4 hours. Heat from the copper block is transmitted down the stranded conductors, and elevates the temperature of the conductor insulation. Based on thermal imaging camera data (see Figure 1), elevating the copper block temperature to 485 °C results in surface conductor insulation temperatures at or above the piloted ignition temperatures for the materials tested.[3] Although the experimental approach was not intended to ignite the source materials, literature and ad hoc ignition tests demonstrate that the materials were elevated to temperatures at which piloted and sustained ignition could be supported. Since electrical enclosures contain components that are energized, potential ignition sources are typically present. Figure 1 shows the smoke source with insulated conductors attached.

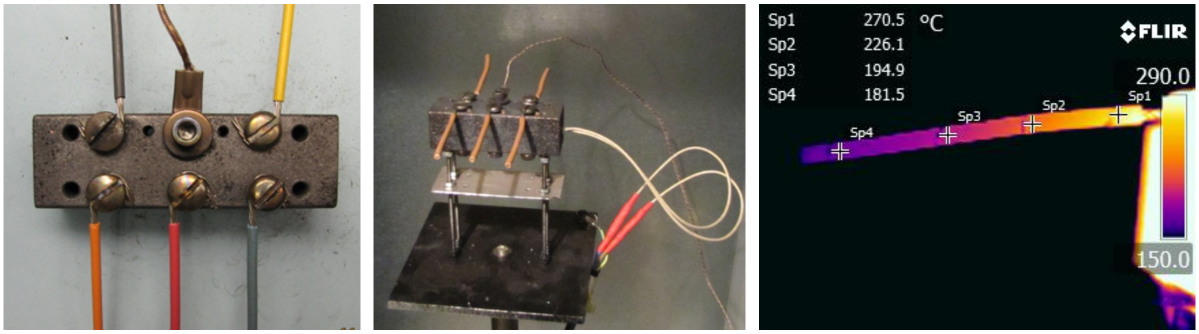

Figure 1. Photographs of pre-flaming smoke source with insulated conductors attached (thermocouple connection shown top center). Left photo shows plan view, center photo shows assembly installed in cabinet with heater cartridge installed, right photo shows thermal image of attached insulated conductor with temperature measurements at specific locations.

Scales of Testing

Three scales of testing were performed using cabinets of the dimensions shown in Table 1. Laboratory scale testing consisted of small and large cabinets located within slightly larger enclosures used to contain and evacuate the gases from the test space. The small-room facility consisted of a 2.5m high ceiling and a 38m^2 floor area, while a large-room facility had a ceiling height of 3m and a 100m^2 floor area. All cabinets were ventilated at or near the top of the enclosures with front, rear, and bottom vents to allow air into the electrical enclosure (see Figure 2).

Table 1. Cabinet Dimensions

Test Series	Cabinet Dimensions
Laboratory Scale – small	0.56 m by 0.61 m by 1.32 m tall
Laboratory Scale – large	0.61 m by 0.61 m by 2.13 m tall
Small Room	0.61 m by 0.61 m by 1.78 m tall Single, 4- and 5-cabinet banks
Large Room	0.74 m by 0.91 m by 2.11 m tall Single and 3-cabinet banks

Smoke Detectors Evaluated

Two types of VEWFD detectors were tested, aspirated and spot-type. ASD systems from three different manufacturers were tested using two different detection technologies, namely, light-scattering and cloud chamber. A spot-type, light-scattering detector capable of achieving VEWFD sensitivities, was also included and is referred to as the sensitive spot (SS). Conventional ionization (ION) and photoelectric (PHOTO) spot-type smoke detectors were also tested. NFPA 76, "Standard for the Fire Protection of Telecommunications Facilities," provides sampling port sensitivity in %/ft obscuration (obsc.) to meet VEWFD requirements.[4] The tested light-scattering-based VEWFD systems were configured to meet the 0.2%/ft obsc. (the "alert" setpoint) and those data will be used in this paper as the first response of VEWFD systems. The cloud chamber ASD is not configurable to %/ft obsc.; therefore, the vendor-recommended settings for the specific application were used (~1.0E+06 particles per cm^3 at the sampling port). The conventional ION spot-type "alarm" setpoint was set to 1.0%/ft obsc., while the PHOTO was set to 2.0%/ft obsc. The spot detectors, ASD sampling port, and ventilation locations for the small-scale laboratory experiments are presented in Figure 2.

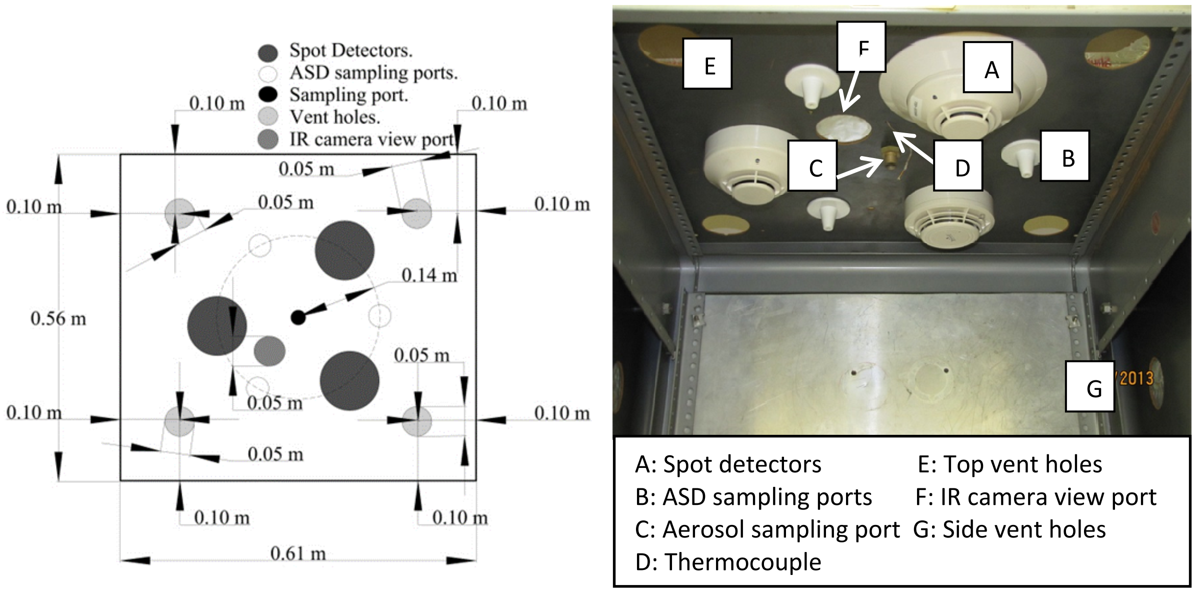

Figure 2. Illustration and photograph of in-cabinet smoke detection layout

Test Procedure

In all tests, the copper block smoke source was located within the electrical enclosure. Typical placement was on or near the floor of the electrical enclosure, with a few tests placing the source at approximately 2/3 height of the electrical enclosure. All smoke detectors were included in the small laboratory-scale and small room tests. In the large laboratory-scaleand the large-room tests, only one of the two light-scattering type ASDs was included.

An electrical low pressure impactor (ELPI) was used to monitor the aerosol concentration and size distribution at the electrical enclosure ceiling near the in-cabinet smoke detectors and ASD sampling ports. The ELPI provided measurements of mass concentration, mass mean diameter (MMD) and arithmetic mean diameter (AMD). The small laboratory-scale tests were used to evaluate the aerosol characteristics generated by numerous materials.

The AMD and MMD both varied by a factor of three from polytetrafluoroethylene (PFTE) to chlorosulfonated polyethylene (CSPE) insulated conductors. Based on these results, the later tests reduced the number of materials tested to Polyvinyl chloride (PVC), cross-linked polyethylene (XLPE) and CSPE which represented the smallest, medium and largest particle sizes tested, respectively.

Test Results

ELPI results for XLPE wire, using a 15-min heating ramp, are shown in Figure 3. The mass concentration is plotted along with MMD and AMD. Prior to 500 seconds of heating, the ELPI was recording primarily background room aerosol. After 500 seconds, the mass concentration started to increase and the AMD and MMD were attributed to primarily pyrolysis particles. The estimated relative uncertainties of the ELPI results were ± 20% for MMD, AMD, and mass concentration, primarily due to uncertainty in the aerosol density.

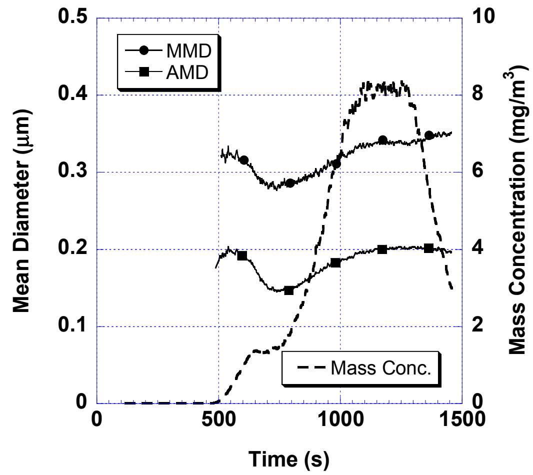

Figure 3. Mass mean diameter (MMD), arithmetic mean diameter (AMD) and mass concentration for XLPE wire and a 15-min heating ramp, with estimated combined relative uncertainties of ± 20% for MMD, AMD, and mass concentration.

Alert or alarm times for XLPE, PVC (2) and CSPE wire samples subject to one-hour heating ramps, and six-cabinet experimental conditions, are shown in Figure 4. The six conditions were as follows: (1) an isolated cabinet with the source at the bottom (1C);(2) a group of four cabinets and two sampling port locations with the source at the bottom (4C); (3) a group of five cabinets with three sampling port locations with the source at the bottom (5C); (4) configuration 5C with the source elevated 2/3 from the bottom of the cabinet (5 ES); (5) configuration 5C with room ventilation (5 RV); (6) and configuration 5C with cabinet ventilation (5 CV). For the XLPE and PVC (2), ASD 2 was the first to alert for all experiments, while for CSPE, ASD 3 was the first to alert. Increasing and decreasing alert or alarm time trends were observed for the 1C, 4C and 5C configurations, and the three materials.

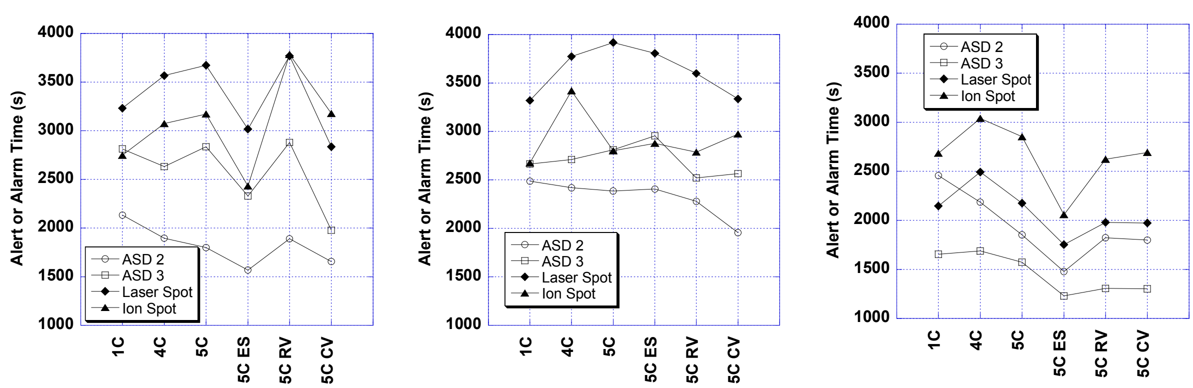

Figure 4. Alert and Alarm times for various full-scale experimental configurations for XLPE (left), PVC (center) and CSPE (right)

A comparison of the in-cabinet data showing the relationship between VEWFD 'alert' response, and ION spot-type 'alarm' response for a given experiment, are presented in Figure 5 as a histogram for the 1-hour HRP data. The histogram indicates the variances in performance between several VEWFD systems and ION spot-type detection.

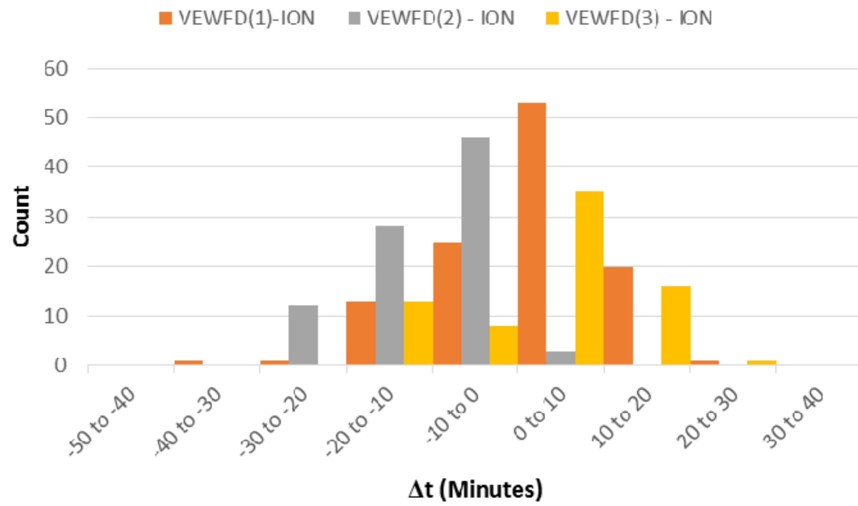

Figure 5. Histogram of Δt (ION – VEW) for several different VEWFD systems

System effectiveness is evaluated based on the assumption that the smoke source is elevating the attached materials to a temperature at which piloted ignition can occur. Thus, the experimental procedure is assumed to present a potential fire hazard, were an ignition source present (i.e., electrical energy). The detector's response during the experiment is modeled as a binomial case, with the HRP representative of a surrogate to the incipient stage duration. The system effectiveness is presented in Figure 6 as a 3-D column plot.

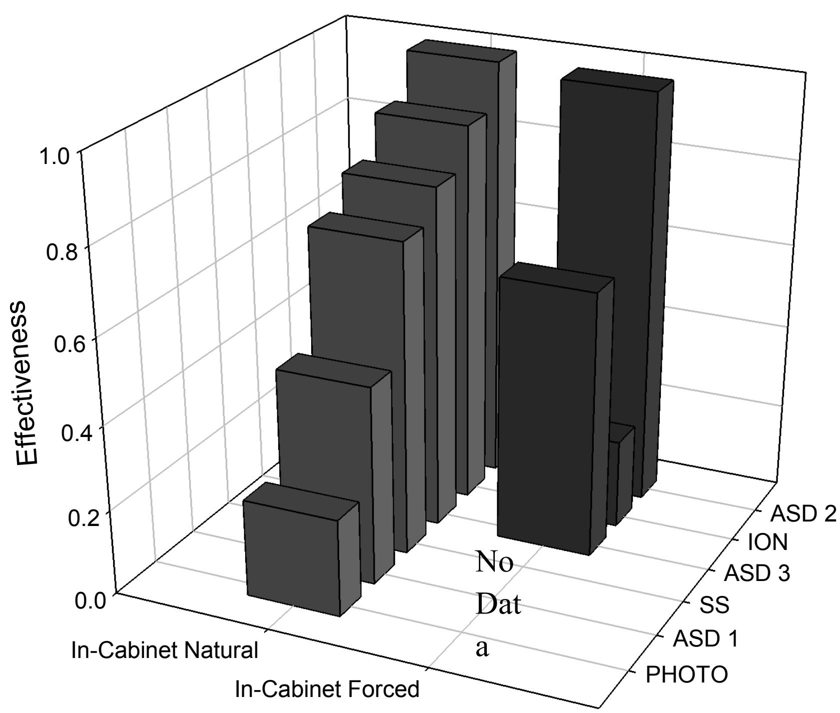

Figure 6. System Effectiveness by detector and application

CONCLUSIONS

A smoke source that mimics the slow overheat conditions during degradation of polymeric electrical insulating materials commonly found in NPP electrical enclosures was developed. The source was sufficiently repeatable to use in follow-on system performance testing. Insulated electrical conductors, with insulation materials representative of a range of chemical compositions of materials producing smoke during incipient fires, were studied. Measurements of detector alert or activation and smoke aerosol properties were made. Full scale performance tests were conducted based on results of laboratory small-scale testing.

It was observed that material, heating rate, sample location, electrical enclosure and air sampling port configuration, electrical enclosure ventilation, and room ventilation, factor into the order of alert or alarm times for the various detectors examined. In experiments conducted in the instrument cabinet, some wire samples did not produce enough smoke to initiate alerts or alarms in some of the detectors. ASD 2 alerted first for all materials except CSPE, for which ASD 3 alerted first. Similar relative response characteristics were observed between ION and PHOTO spot-type detectors, with the PHOTO responding sooner to the CSPE material. In the full-scale experiments, the two ASD's tended to outperform the ION spot alarm with ASD 2 typically alerting several hundred seconds before the ION spot alarm. The SS pre-alarmed after the ION spot with XLPE and PVC (2) wire samples, but before the ION spot with CSPE wire samples.

These test results indicate a wide variance of system performance for the materials and the modes of degradation tested to evaluate smoke detection system response to the "incipient stage" of potentially-threatening fire conditions. Smoke detection systems configured as VEWFD responded both sooner and later than ION spot-type smoke detectors used for in-cabinet applications. The amount of advanced warning is dependent on the materials involved, mode of degradation or combustion, environmental conditions within the protected enclosure and the detection technology used.

A draft report containing all of the details from this testing series along with a scoping risk study will be published in the near future. The draft report will be available for public comment and revised where needed prior to final publications of the report.

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