U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

NUREG-2180

Determining the Effectiveness, Limitations, and Operator Response for Very Early Warning Fire Detection Systems in Nuclear Facilities (DELORES-VEWFIRE)

Draft Report for Comment

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Library at www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources.

1. **The Superintendent of Documents**
   U.S. Government Publishing Office
   Mail Stop IDCC
   Washington, DC 20402-0001
   Internet: bookstore.gpo.gov
   Telephone: (202) 512-1800
   Fax: (202) 512-2104

2. **The National Technical Information Service**
   5301 Shawnee Rd., Alexandria, VA 22312-0002
   www.ntis.gov
   1-800-553-6847 or, locally, (703) 605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: **U.S. Nuclear Regulatory Commission**
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: distribution.resource@nrc.gov
Facsimile: (301) 415-2289

Some publications in the NUREG series that are posted at NRC's Web site address www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
www.ansi.org
(212) 642-4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractorprepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-2180

Determining the Effectiveness, Limitations, and Operator Response for Very Early Warning Fire Detection Systems in Nuclear Facilities (DELORES-VEWFIRE)

Draft Report for Comment

Manuscript Completed: October 2014
Date Published: June 2015

Prepared by:
G. Taylor[1], S. Cooper[1], A. D'Agostino[1], N. Melly[1], and T. Cleary[2]

[1]U.S. Nuclear Regulatory Commission
[2]National Institute of Standards and Technology

Office of Nuclear Regulatory Research

COMMENTS ON DRAFT REPORT

Any interested party may submit comments on this report for consideration by the staff of the U.S. Nuclear Regulatory Commission (NRC). Comments may be accompanied by additional relevant information or supporting data. Please specify the report number **NUREG-2180** in your comments, and send them by the end of the comment period specified in the *Federal Register* notice announcing the availability of this report.

Specific areas of this draft report where comments and additional relevant information or supporting data are sought include:

1. System availability, including system down time and surveillance test interval for the aspirated smoke detection systems used in nuclear and non-nuclear facilities.

2. Time duration between a very early warning fire detection system "alert" condition and the commencement of flaming conditions. Alternatively, the time duration of the incipient stage, from start of component degradation to flaming conditions.

Addresses: You may submit comments by any one of the following methods. Please include Docket ID **NRC-2015-0112** in the subject line of your comments. Comments submitted in writing or in electronic form will be posted on the NRC Web site and on the Federal rulemaking Web site http://www.regulations.gov.

Federal Rulemaking Web Site: Go to http://www.regulations.gov and search for documents filed under Docket ID **NRC-2015-0112**. Address questions about NRC dockets to Carol Gallagher at 301-415-3463 or by e-mail at Carol.Gallagher@nrc.gov.

Mail comments to: Cindy Bladey, Chief, Rules, Announcements, and Directives Branch (RADB), Division of Administrative Services, Office of Administration, Mail Stop: OWFN-12-H08, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001.

For any questions about the material in this report, please contact: Gabriel Taylor, Senior Fire Protection Engineer, 301-251-7576 or by e-mail at Gabriel.Taylor@nrc.gov.
Please be aware that any comments that you submit to the NRC will be considered a public record and entered into the Agencywide Documents Access and Management System. Do not provide information you would not want to be publicly available.

ABSTRACT

Aspirated smoke detection systems have been available on the commercial market for more than four decades as an alternative technology to spot-type smoke detection for detecting products of combustion. In the United States, several nuclear power plants (NPPs) have installed these systems as early as the mid-1990s as an alternative method to conventional fire detection systems with the idea to provide advanced warning of potential fire threats. Recently, there has been indication that numerous licensees of NPPs transitioning to a performance-based fire protection program intend to install these types of systems configured as very early warning fire detection (VEWFD). In many, but not all cases, the choice to install these systems is based on the expectation that these systems may reduce the estimated fire risk in a fire probabilistic risk assessment (PRA).

In 2008, the U.S. Nuclear Regulatory Commission (NRC) issued a staff interim position documented in a National Fire Protection Association (NFPA) Standard 805 Frequently Asked Question (FAQ) 08-0046, “Incipient Fire Detection Systems.” This staff interim position provides guidance on the use of these systems and the associated fire PRA quantification for in-cabinet applications. At that time, there was limited test data and PRA experience available for those applications and as such a confirmatory research program was needed. Research was also needed to advance the state of knowledge related to the performance of these systems. This report documents the results and findings from the confirmatory research program.

This program provides an evaluation of VEWFD and conventional spot-type smoke detection system performance, operating experience, and fire PRA quantification for applications in NPPs where these systems are expected to detect fires in their incipient (pre-flaming) stage. The results of this report show there is a wide variance in performance for both spot-type and VEWFD systems. It has been shown that variables in NPPs such as ventilation, fuel type, system application/design, and operator response play a significant role in the performance of these systems to detect low-energy fires.

Ultimately, this research has shown that (1) the state of knowledge regarding the duration of an incipient stage for electrical components found in NPPs, and the associated failure modes with regard to fire development of such components is low (uncertain and highly variable), (2) in-cabinet smoke detection used to protect electrical enclosures provides the most effective and earliest notification of potential fire threats (3) for areawide applications the aspirated smoke detection systems when configured as VEWFD can potentially notify plant personnel of potential fire threats sooner than conventional spot-type smoke detection systems, and (4) plant personnel responsible for responding to smoke detection systems must be properly trained, follow plant procedures suitable for response to these systems, and ensure that every smoke detection system notification has adequate response time and necessary urgency. This report concludes with an updated approach to quantify the performance of these systems in Fire PRA for in-cabinet and areawide applications in non-continuously occupied NPP areas.

TABLE OF CONTENTS

Section **Page**

Section **Page**

LIST OF FIGURES

Figure **Page**

Figure		**Page**

LIST OF TABLES

Table **Page**

EXECUTIVE SUMMARY

The purpose of this research is to evaluate the relative performance of smoke detection systems when configured for very early warning fire detection (VEWFD) applications, to conventional spot-type detection systems for use in nuclear power plant (NPP) applications. There has been recent interest in quantifying potential risk enhancement associated with these systems to support fire probabilistic risk assessments (PRAs) developed for NPPs transitioning to performance-based fire protection programs per National Fire Protection Association (NFPA) Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition." The performance objective for using these systems is to provide earlier warning to plant personnel that may allow for additional time for human intervention before fire conditions that threaten the ability to achieve safe shutdown conditions.

The need for this research is a result of limited test data and understanding of the performance of these systems in NPP applications to detect low energy pre-flaming (incipient) fire conditions typically originating in electrical enclosures. The availability of applicable empirical data is scarce and operating experience in NPP applications for detection of electrical enclosures fires are limited. Specifically, data on the detection of slowly developing, incipient stage, pre-flaming conditions is not available. The focus of the research presented in this report is to better understand these systems performance, operating experience, and their potential risk benefits via a risk scoping study. Specific needs included evaluation of the effectiveness of using VEWFD systems for in-cabinet and areawide applications, response to representative products of combustion, system design aspects, comparison to conventional spot-type smoke detection, and operator response.

The focus of this research is related to the use of these systems as potential fire risk reduction measures, associated with electrical enclosures fire hazards by providing enhanced warning of pre-flaming (incipient) fire conditions to support fire probabilistic risk assessments. A common failure mode of electrical enclosures occurs as a result of slow overheating followed by electrical component thermal decomposition (pyrolysis) that may eventually lead to flaming fire conditions, if sufficient heat and ignition conditions exist.

This research includes a literature review, a review of available operating experience, several scales of testing, and an evaluation of human performance. All of these elements taken together support the risk scoping study. A literature review was conducted early on in the project to understand the availability of information to support the risk analysis and test plan development. The literature review concluded that, in general, there has been substantial research supporting the use of aspirating smoke detection (ASD) VEWFD systems in special applications, such as telecommunication facilities, warehouses, atria, and as a reference tool to support evaluation of model prediction of conventional spot-type detector activation. However, most of the available information was developed to acquire specific data needed to support specific applications. Where applicable to NPP scenarios, these data have been used to support the risk scoping study documented in this report. In addition to test data, several sources have provided valuable information on the characteristics of smoke, and the parameters that affect smoke aging and detector response associated with electrical enclosure fires.

Concurrently, operating experience was obtained as related to VEWFD systems, by conducting site visits, interviews with plant operating staff, procedure review and assessing the historical fire events in NPP electrical enclosures. The operating experience supported the human

performance evaluation by providing an understanding of common plant personnel response and an understanding of where and how operators interface with VEWFD systems and associated fire alarm annunciator response. Observations made during the site visits also supported test development to ensure testing was representative of their use in NPPs. Though not found in direct support of the research objectives, other valuable information was obtained during the site visits, and is also documented in this report to allow communication of lessons learned from using these systems.

Following the operating experience and literature review, actual VEWFD system testing was conducted. The testing evaluated three single-port ASD and two multi-port ASDs from three different vendors, all configured to VEWFD. One spot-type VEWFD detector and two types of conventional spot-type detectors, and three scales of testing were completed. Laboratory scale tests evaluated detector response to a variety of material in a small instrument cabinet and in reactor protection system cabinets procured from an unfinished NPP. The next scale of testing evaluated both in-cabinet and areawide detector response is a small room. This testing included variations in both cabinet and room ventilation conditions. The final large-scale testing again evaluated the in-cabinet and areawide detector response, but also included testing VEWFD system performance in an air return grill application. The test results provide a wealth of information regarding the performance of these systems to support a better understanding of their risk benefit of detecting low energy pre-flaming fire conditions.

<u>Objectives Supported by Testing</u>

Testing and the analysis of the results provided insights that supported several objectives of this project. The first objective supported was the evaluation of the effectiveness of in-cabinet and areawide VEWFD system applications. The results confirmed that in-cabinet smoke detection provides the earliest notification of low-energy incipient fires originating in the cabinet. This is because of the close proximity of ASD sampling ports and spot-type smoke detectors in to protected equipment that could exhibit an incipient stage. Phenomena such as dilution and stratification are minimized as compared to areawide applications. The data indicated that cabinet ventilation can have a negative effect on smoke detection system performance when high air velocities within the electrical enclosure are encountered. This negatively impacts both conventional spot-type and ASD VEWFD systems. In an areawide application, the ASD VEWFD systems are also more effective in detecting low-energy incipient fire sources than conventional spot-type detectors. ASD VEWFD show improved protection in areawide applications with high-airflow room ventilation conditions, as compared to conventional ceiling mounted spot-type detectors. A test result comparison between air return grill and ceiling mounted ASD applications showed marginally increased effectiveness in the air return grill application for the limited experimental conditions. However, competing parameters such as ceiling height and ventilation will influence the performance of ceiling versus air return ASD VEWFD application effectiveness.

Contrasting the performance of conventional detection devices to VEWFD systems, the following insights were identified. The amount of additional time will vary based on the failure mechanism of the degrading component and the associated length of its incipient stage. In an effort to capture an estimate on the range of additional warning time provided by ASD VEWFD systems over conventional spot detectors a wide variety of materials, range of heating rates, and space configurations were explored. For areawide applications, all ASD VEWFD systems performed better, on average, than the conventional spot type detectors when responding to low-energy smoke sources. In-cabinet application showed mixed results based upon detection technology. The experimental tests show for in-cabinet applications, a conventional ionization (ION) spot type detector performed better, on average, than three of the five ASD VEWFD

systems tested. For fast developing fires the amount of additional warning between these two systems is marginal, regardless of application (in-cabinet vs. areawide).

VEWFD system response to common products of combustion encountered in NPP electrical enclosures was also evaluated. Laboratory scale tests evaluated the characteristics of the products of combustion generated from the selected components expected to be found in NPP electrical enclosures, and allowed for a reduction of the materials tested in large-scale testing. The mean diameters of smoke particles were measured and shown to vary by a factor of three for the materials tested. This particle characteristic information was used to down select the number of materials used in subsequent testing to bound the range of particle characteristics.

Literature and testing supported an evaluation of several parameters that affect in-cabinet VEWFD system layout and design characteristics with regard to system response. The following findings were made with regard to this objective:

- Cabinet design, loading, and ventilation effects can have an influence on the performance of ASD VEWFD systems, as well as conventional spot-type detectors installed inside electrical cabinets. Mechanical (forced) cabinet ventilation is a primary influence factor on detector response, especially with high rates of cabinet air exchange. As cabinet ventilation rates increase, so does smoke dilution. High ventilation conditions affect both time to detection and the effectiveness of the VEWFD systems to detect low-energy incipient stage fires. However, in the empty ventilated cabinet tests in which lower rates of cabinet ventilation were used, the ASD VEWFD response marginally improved relative to the naturally ventilated cabinet case.

- For in-cabinet applications, the presence of openings, or lack of partitions between adjacent cabinet sections having ASD sampling ports, enhances the time to detection. This is because of the cumulative effect of drawing samples from multiple sampling ports. The full-scale, small room, in-cabinet tests indicated that ASD response to a single cabinet with no openings to adjacent cabinets, was slowest, compared to multi-section cabinets without cabinet partitions.

- Source location inside the electrical cabinet also has an effect on VEWFD response. In the full-scale small room tests where the source was elevated off the cabinet floor approximately two-thirds of the height of the cabinet, the ASDs responded approximately 9 percent faster than when the sources were located on the floor.

- Other parameters not explicitly explored in this program, but covered in the literature, relate to soot deposition and loss of aerosol thorough ventilation. Soot deposition internal to the electrical cabinet will be influenced by the obstructions (impactation), thermal gradients (thermophoresis), and electric fields (electrophoresis). Cabinets with a large surface area of ventilation, such as louvered vents compounded by thermophoresis, could result in a fraction of aerosol being lost through these vents. These phenomena would cause less aerosol to transport to the ASD sampling ports or spot-type detectors located at the ceiling of the electrical cabinet, resulting in a delay in detection, as compared to the data in this report, and a decrease in effectiveness in the detection of low-energy fire during the incipient stage.

Objective Supported by Human Performance

The human factors were also evaluated to foster a broader understanding of both types of tasks required by plant personnel, and the factors that affect human performance. A tabletop analysis was developed to present main control room, field operator, and technician response to VEWFD system alarms. Factors identified as affecting human performance include, the use of special equipment, such as portable ASDs, or thermal imaging cameras; human-system interface; procedures; training; staffing; communications; complexity; and perceived workload, pressure, and stress.

Information obtained from operating experience, literature review, and the tabletop analysis, supported a human reliability analysis. Based on the expected operational response and timing estimate developed from operating experience and test results, and the overall strategy that parallels post-initiator operator actions, a human reliability analysis was conducted. The results of this HRA analysis indicate that human error probabilities vary with the number of protected electrical cabinets and range from 5×10^{-4} for main control room, to 5×10^{-1} for field operator/technician response to a 10-cabinet bank, protected by a single zone of a light-scattering ASD VEWFD system.

Risk Scoping Study Objectives

A model to quantify the non-suppression probability for use in fire PRAs is presented. The model uses the best available test data, operating experience, and expected operator responses. It has been shown that a dominant contributor to the risk quantification is the estimation of the fraction of *potentially challenging or greater fires* which exhibit an incipient fire stage of sufficient duration to allow for successful operator response. Since fire PRAs only quantify those fires that initiate and can potentially grow to a damaging state, the majority of smoking events are not modeled (i.e., included as a fire initiator). The previous methods to estimate this fraction were mostly subjective, lacked supporting data relevant to the types of fires postulated in fire PRAs and could not be confirmed based on the evaluation of the operating experience.

Evaluation of ASD VEWFD system reliability and availability confirmed the reliability estimate from the Electric Power Research Institute (EPRI) in its EPRI 1016735 “Fire PRA Methods Enhancements: Additions, Clarification, and Refinements to EPRI 1019189.” Based on the information collected during the site visits, a wide variance of system downtime was observed. It was noted that system availability improved for facilities that had these systems installed and operating for a substantial period of time. Facilities that were using ASD VEWFD systems for the first time indicated longer system downtime likely because of the lack of understanding of the system start-up and maintenance requirements to ensure proper operation. This early downtime was not included in the unavailability estimates. For areawide air return grill applications, the reliability and availability of the ventilation system need to be modeled into the risk quantification as the air return grill application requires forced ventilation to perform as intended.

The risk benefit for using these systems varies by application with in-cabinet detection being the optimal approach for detecting low-energy incipient sources early enough to allow for enhanced suppression capabilities and avoidance of damage to multiple components within the electrical cabinet or to targets outside of the electrical cabinet. Areawide applications also provide some risk benefit; however, they are usually slower to detect low-energy fires when compared to in-cabinet applications because of a number of contributing factors, which are identified above. Overall, the approach and information presented in this report provides the best available information on VEWFD system performance and PRA application.

ACKNOWLEDGMENTS

The authors acknowledge and appreciate the many people who contributed to this project. First, we acknowledge the contributions of the staff at the National Institutes of Standards and Technology, who not only supported the testing program, but evaluated and documented the results. In particular, the assistance from Mariousz Zarzecki and Mike Selepak is greatly appreciated. The authors would like to thank all of the individuals who supported site visits, meetings and phone interviews, including;

Keenan Dodson, NASA Goddard Space Flight Center
Chip Wellington, NASA Goddard Space Flight Center
Edward O'Connell, NASA Goddard Space Flight Center
Grant Cherkas, Canadian Nuclear Safety Commission
Joelle DeJoseph, Duke Energy
Jeff Ertman, Duke Energy
Ashley Lindeman, Electric Power Research Institute
Sean Taylor, Exelon
Wayne Aho, Xtralis
Ron Robertson, Safe Fire Detection
Robert Robertson, Safe Fire Detection
Scot Robertson, Safe Fire Detection
Jim Lloyd, Safe Fire Detection
Nick Gomez, System Sensor

The authors would also like to thank Montgomery County Public Service Training Academy for use of their facilities. U.S. Nuclear Regulatory Commission (NRC) staff members also supporting this research include Tammie Pennywell, David Stroup and Nathan Siu, and their support is greatly appreciated. Additionally, Eric Knowles and Woody Machalek must be acknowledged for several of the high quality graphics presented in this report.

Acknowledgements must also be made to those individuals who provided feedback and constructive comments on the early draft versions of this report, including Christine LaFleur (Sandia National Laboratories); Harrold Barrett, Daniel Frumkin, Raymond Gallucci, Brian Metzger, of the NRC staff; and individuals from the Southwest Research Center under contract to the NRC. Finally, our special thanks to Anita Aikins-Afful at the NRC for her technical editing of this entire report.

ACRONYMS AND ABBREVIATIONS

ACH	air changes per hour
ADAMS	Agencywide Documents Access and Management System
AHJ	authority having jurisdiction
AHU	air handling unit
AMD	arithmetic mass diameter
APCSB	Auxiliary and Power Conversion Systems Branch
ARP	alarm response procedure
ASD	aspirating smoke detection (or detector)
ASD-CC	cloud chamber aspirating smoke detector
ASD-LS	light-scattering aspirating smoke detector
ASIC	application specific integrated circuit
ASME	American Society of Mechanical Engineers
AUO	auxiliary unit operator
AW	areawide
AWG	American wire gauge
BS	British Standard
BSI	British Standard Institution
BTP	branch technical position
CBDTM	cause based decision tree method
cd	candela
CDF	Core damage frequency
CFR	Code of Federal Regulations
CPT	control power transformer
CSA	Canadian Standards Association
CSPE	chlorosulfonated polyethylene
CVPC	chlorinated polyvinyl chloride
DCRDR	detailed control room design review
DI&C	digital instrumentation and controls
EDG	emergency diesel generator
ELPI	electrical low pressure impactor
EOP	emergency operating procedure
EOT	end of test
EPRI	Electric Power Research Institute
EWFD	early warning fire detection
FACP	fire alarm control panel
FAQ	frequently asked question
FCC	Federal Communications Commission
FIA	Fire Institute Association
FM	Factory Mutual
FO	field operator
GL	generic letter

HCR/ORE	human cognitive reliability/operator reliability experiments
HEAF	high-energy arc fault
HEP	human error probability
HEPA	high efficiency particulate air
HF	human factors
HFE	human failure event
HRA	human reliability analysis
HRP	heating ramp period
HSI	human-system interface
HVAC	heating, ventilation, and air conditioning
I&C	instrumentation and controls
ID	inside diameter
IEEE	Institute of Electrical and Electronic Engineers
IN	information notice
ION	ionization detector
IPEEE	individual plant evaluations of external events
IR	infrared radiation
IST	in-service testing
IT	information technology
LCS	local control station
LED	light emitting diode
LER	licensee event report
LQ	lower quartile
MCC	motor control center
MCR	main control room
MMD	mass mean diameter
MOU	memorandum of understanding
NASA	National Aeronautics and Space Administration
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PCB	printed circuit board
PHOTO	photoelectric detector
PPE	personal protective equipment
PRA	probabilistic risk assessment
PVC	polyvinyl chloride
QA	quality assurance
RA	return air
RES	Office of Nuclear Regulatory Research
RoHS	restriction of hazardous substances
RTGB	reactor turbine generator board

SDP	significance determination process
SIS	synthetic insulated switchboard
SPAR-H	standardized plant analysis risk human reliability analysis
SRO	senior reactor operator
SS	sensitive spot detector
SSC	systems, structures, and components
STA	shift technician advisor
TB	terminal block
THERP	technique for human error rate prediction
THT	total heating time
UL	Underwriters Laboratories
ULC	Underwriters Laboratories Canada
UQ	upper quartile
VEWFD	very early warning fire detection
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin insulated

1. INTRODUCTION

1.1 Overview

This report describes an evaluation of the performance of smoke detection systems configured as either conventional or very early warning, including aspirating smoke detection (ASD)[1] systems, for use in nuclear power plant (NPP) applications. In addition to this evaluation, general information applicable to NPP installation is presented. This research is confirmatory in nature, such that its primary purpose is to evaluate the technical adequacy of a U.S. Nuclear Regulatory Commission (NRC) interim staff position documented in a National Fire Protection Association (NFPA) Standard 805 Frequently Asked Question (FAQ) 08-0046, “Incipient Fire Detection Systems.” FAQ 08-0046 provides an interim staff position on the use of ASD systems configured as very early warning fire detection (VEWFD) to protect electrical enclosures[2] containing low voltage control components found in U.S. NPPs. This research was funded and managed by the NRC Office of Nuclear Regulatory Research (RES). Testing was performed by the National Institute of Standards and Technology (NIST). In addition to the testing, staff from the NRC supported this project by conducting site visits, reviewing literature, and evaluating human performance and smoke detection system performance for fire probabilistic risk assessment applications.

The report is broken into three parts. Part I presents information gathered to develop a knowledge base for this project. Information contained in Part I includes presentation of fundamental smoke detection terminology and theory; a summary of operating experience and literature review; the experimental approach, basis and results. Part II evaluates the performance of smoke detection technologies in quantitative terms. This includes an overview of a fire risk scoping study, estimation of parameters used, timing analysis, human performance assessment, and an evaluation of the results for common NPP applications and comparisons to the interim staff position. Part III concludes the report and provides a summary, conclusions and future research recommendations, along with supporting information such as definitions of key terms and a list of references.

1.2 Need for Confirmatory Research

On March 31, 2008, FAQ 08-0046 “Incipient Fire Detection Systems” was proposed by the Nuclear Energy Institute (NEI) NFPA 805 Task Force to describe the treatment of VEWFD systems in a fire probabilistic risk assessment (PRA), because guidance for the treatment of such a system with respect to hardware failure rates and its relationship with the EPRI TR-1011989 (NUREG/CR-6850) Appendix P treatment of fire suppression was insufficient (Ref. 1). In an addendum on fire risk under its memorandum of understanding (MOU), the NRC-RES and the Electric Power Research Institute (EPRI) began developing guidance for determining the effect on the probability of non-suppression in fire areas that have these VEWFD systems installed. Before the conclusion of this work, EPRI published an interim report TR 1016735 titled, “Fire PRA Methods Enhancements (Additions, Clarifications, and Refinements to EPRI 1011989),” in December 2008. The EPRI report presented an interim methodology and

[1] Definitions are presented in Section 15.

[2] “Electrical enclosure,” “electrical cabinet,” and “electrical panel” are used synonymously in this report to mean a surrounding case or housing used to protect the contained equipment or prevent personnel from accidentally contacting live parts.

guidance for fire PRA, including re-evaluation of fire ignition frequency, a framework for quantifying incipient-fire detection systems in fire PRA, and treatment of large oil fires caused by main feed water pumps. Chapter 3 and Appendix C contain information pertaining to incipient detection systems. Although, EPRI was working with NRC-RES on many of these issues, the methods presented in the interim report were never endorsed by NRC.

To improve accuracy and realism, and in an effort to close out FAQ 08-0046, the NRC staff took the EPRI approach and modified it to address several issues and conditions, and to develop an acceptable approach to evaluate the performance of ASD VEWFD systems in fire PRA applications. On June 24, 2009, the NRC released a draft interim position on FAQ 08-0046, regarding the use of VEWFD systems for use in NFPA 805 applications, on which the staff requested comments. The NRC staff reviewed all comments received on the draft interim position, and on November 30, 2009, closed out the FAQ as the final interim staff position, which was later incorporated into NUREG/CR-6850, Supplement 1, "Fire Probabilistic Risk Assessment Methods Enhancements," dated September 2010.

Given the number of comments received on the draft interim position and the authors' discussions with knowledgeable individuals from both the industry and the regulatory arenas/sides, vastly differing views regarding these systems' performance, and suitable application in fire PRA, were apparent. Notably, both empirical data and operating experience in NPP applications are scarce; additionally, terminology is commonly used inconsistently. Because of these difficulties, the NRC identified a need to obtain a better understanding of these systems' performance and their operating experience(s). Thus, the NRC began a confirmatory research program to address the objectives identified below.

1.3 Purpose and Objectives

The research completed by NRC and NIST staff as documented in this report provides an assessment on the use of smoke detection systems in NPP applications. This research focuses on the use of these systems in risk-informed performance-based applications.

The objectives of this report are as follows:

A. To evaluate the effectiveness of smoke detection systems

   o This evaluation includes an evaluation of in-cabinet and areawide applications.

B. To compare the performance of common smoke detection systems currently used in NPPs to VEWFD systems

C. To evaluate the response and effectiveness of equipment used to locate a pre-fire source(s) through the use of human reliability analysis (HRA)

D. To evaluate smoke detection system availability and reliability

E. To evaluate smoke detection system response to common products of combustion applicable to NPPs

F. To evaluate electrical cabinet layout and design effect on smoke detection system response

G. To evaluate the performance of smoke detection technologies in various applications, including in-cabinet and areawide

- o The evaluation should support fire PRA applications and provide a technical basis and approach for updating the interim approach described in FAQ 08-0046, “Incipient Fire Detection Systems.”

1.4 Project Planning and General Approach

This confirmatory research is broken down into three distinct tasks: operating experience, review of literature, and testing. Each area has its own sub-tasks, as shown in Figure 1-1. In addition to these tasks supporting the risk scoping study, the tasks also supported the human performance evaluation. Early in the project, staff from NIST reviewed available literature on ASD VEWFD systems to support development of a test plan. Following the literature review, staff from NIST and the NRC performed several site visits to operating NPPs in the United States and Canada, as well as visits to non-nuclear facilities. These site visits provided two benefits. First, it was realized early during the literature review that testing alone would not be able to provide answers to all of the project objectives. Second, the site visits provided information on system layout and designs being used in plants, such that a test plan could be developed that adequately represented the design and use of these systems in NPP applications.

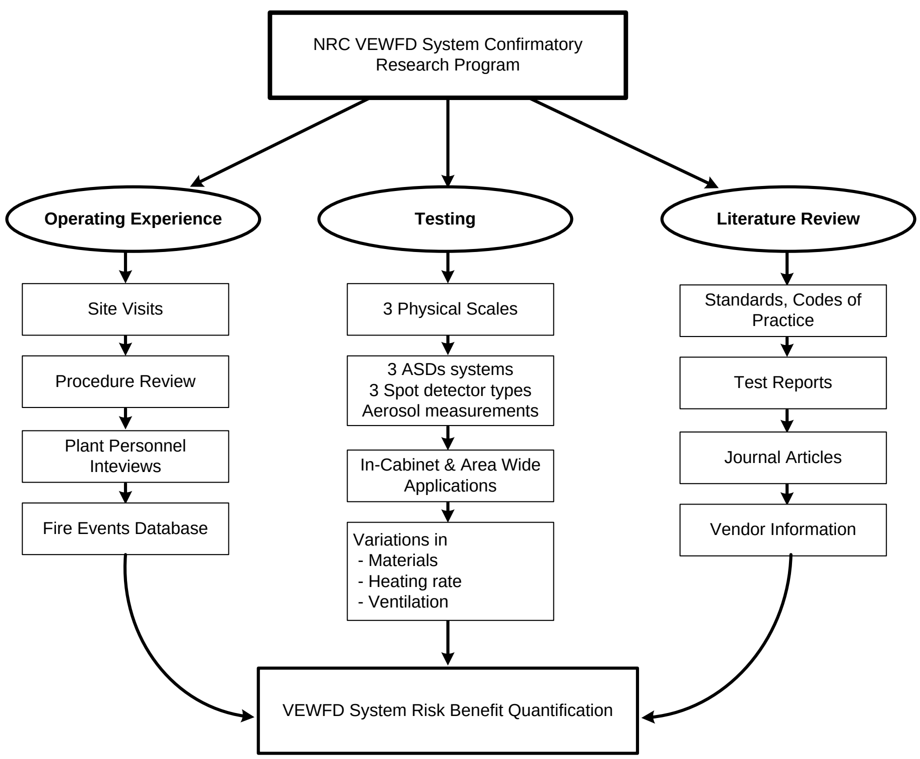


Figure 1-1. Illustration of VEWFD System Confirmatory Research Project

Once the literature review and the majority of the site visits were complete, NIST developed a draft test plan that focused on providing data to address objectives A, B, E, and F. A draft version of the test plan was reviewed by several NRC staff members, and shared with EPRI under the NRC-RES/EPRI MOU Fire Risk Addendum. Additionally, the draft test plan was shared with the ASD VEWFD system vendors whose equipment was selected for testing. Comments were received from all parties and the test plan was modified, as needed. Upon finalizing the test plan, systems and materials were procured and testing commenced.

During the course of this project, two non-public meetings were held with external parties. The first meeting occurred on May 16, 2013 between the NRC staff and vendors of ASD VEWFD systems equipment being tested. The second meeting occurred on July 24, 2013, between the NRC and EPRI. Both meetings were considered information exchanges, and were used to receive additional feedback on the project approach, specifically testing. The NRC presentations are available electronically from the NRC's Agencywide Documents Access and Management System (ADAMS), Accession No ML14356A581.

Once the literature review, test data, operator response characteristics, and operating experience were understood, that information was used to evaluate how the effect of these systems performance in fire PRA applications.

1.5 Scope of this Report

This report provides information on ASD and spot-type systems configured for VEWFD and conventional spot-type smoke detector performance in various NPP applications, with a focus on their response to low-energy fires during the early stages (pre-flaming). The potential risk benefits from using these systems and associated operator response characteristics are also provided. The focus on these two types of systems was directed by the regulatory need and doesn't represent any determination that these are the only fire detection methods suitable for NPP applications. Additionally, this report doesn't explore negative impact from using ASD systems such as whether single failure potential is increased, configurations where other detections systems perform better, or any significant risks associated with inappropriate equipment de-energization.

This report specifically focuses on evaluating ASD VEWFD systems' ability to detect electrical enclosure fires during low-energy fire conditions. Electrical enclosures are defined as items such as switchgears; motor control centers; direct current (dc) distribution panels; relay cabinets; control and switch panels, (excluding panels that are part of machinery); fire protection panels, etc. Voltages in electrical enclosures vary from low voltage to 6.9kV switchgear. Although other types of equipment found in NPPs are likely to have equipment failure modes which exhibit an incipient stage of sufficient duration to allow for enhanced operator response, this report does not provide an evaluation of ASD VEWFD performance to protect those other types of equipment.

1.6 Report Organization and How to Use This Report

This report is broken into three parts. Part I contains a collection of supporting information associated with smoke characteristics, detection technologies, operating experience and presentation of the experimental program approach and results. Part II presents a refined method for quantifying the performance of smoke detection in fire PRA applications. Part III

provides report summary, conclusions, definitions and references. Each part is organized as follows:

PART I

- **Section 2** provides general background information on fire dynamics; smoke detection principles; system performance measures; and the importance of quality assurance and inspection and testing; and maintenance programs.

- **Section 3** presents a review of operating experience associated with VEWFD systems, NPP use of these systems, and information obtained during site visits. An overview of national consensus standards, listing and approval standards and information found in codes of practice is also provided. A literature review summary is also presented.

- **Section 4** describes the experimental approach taken to address the objectives of this project. Included in this section are descriptions of the detectors, incipient fire source, instrumentation, test facilities, test protocols and experimental design.

- **Section 5** documents the test results obtained and presents them graphically. Characteristics of the incipient fire source with regard to heat conduction and ignition potential are also presented. The last subsection presents the results in a format to support the scoping risk study documented in Part II.

PART II

- **Section 6** presents a summary of previous efforts used to quantify the performance of ASD VEWFD systems in fire PRA. An overview of the model used in this project is also presented.

- **Sections 7–11** provides a basis for estimating the parameters of the model presented in Section 6.

- **Section 12** presents illustrative examples using the model and parameters developed in this project to quantify the performance of various smoke detection technologies.

PART III

- **Section 13** presents a summary from the findings of this project and conclusions.

- **Section 14 i**dentifies recommendations for future research

- **Appendices A–E** contain supporting information including; view graphs from meetings with vendors, experimental data, human performance, operating experience, and literature reviewed.

PART I

Knowledge Base

2. FUNDAMENTALS OF SMOKE GENERATION AND FIRE DETECTION TECHNOLOGIES

Success in limiting or even preventing fire damage is dependent on the rate of fire development. The earlier a fire is detected the sooner fire suppression activities can be initiated to reduce the likelihood of damage to equipment. This section provides an overview of the fundamental fire science underlying the performance of fire detection systems and key definitions of the fire stages used throughout this report. Included in this discussion are a generalized representation of fire growth and fire classification, fire byproduct generation and the principles of smoke detection. The fundamental information presented here supports assessing smoke detection system performance and quantifying the use of these systems in fire probabilistic risk assessments.

2.1 Background

Very early warning fire detection (VEWFD) is defined in National Fire Protection Association (NFPA) Standard 76, “Fire Protection of Telecommunication Facilities,” as *systems that detect low-energy fires before the fire conditions threaten telecommunications service*. VEWFD systems are used extensively in the telecommunications industry in areawide applications to meet the intent of NFPA 76, protect high value or mission critical contents and limit interruption of services. Their extensive use in mission critical and telecommunications industries is a result of smoke damage being the biggest risk to electrical equipment, not fire. Telecommunications facilities also find VEWFD systems useful because of the high air exchange rates needed to cool electronic equipment, whereas conventional spot-type smoke detector performance is degraded because of smoke dilution. Most Canadian and some U.S. nuclear power plants (NPPs) also use some form of air aspirated VEWFD systems to reduce risk and provide advanced warning of fire conditions. In general, VEWFD systems are finding wide applications in a variety of other industries, especially in performance-based design.

Air aspirated (sampling-type) smoke detectors are commonly used to meet the NFPA 76 requirements for VEWFD systems. These ASD VEWFD systems actively sample air from the protected space and transport the air samples through a smooth bore piping network back to a centralized detector unit where the air samples are monitored for combustion-based products (in accordance with either light-scattering or cloud chamber smoke detection principles). An illustration of such a system is shown in Figure 2-1. These systems have the potential to provide numerous advantages over conventional systems. However, their difference from conventional spot-type detectors presents several challenges to successful implementation and proper quantification of any risk improvements in fire PRA.

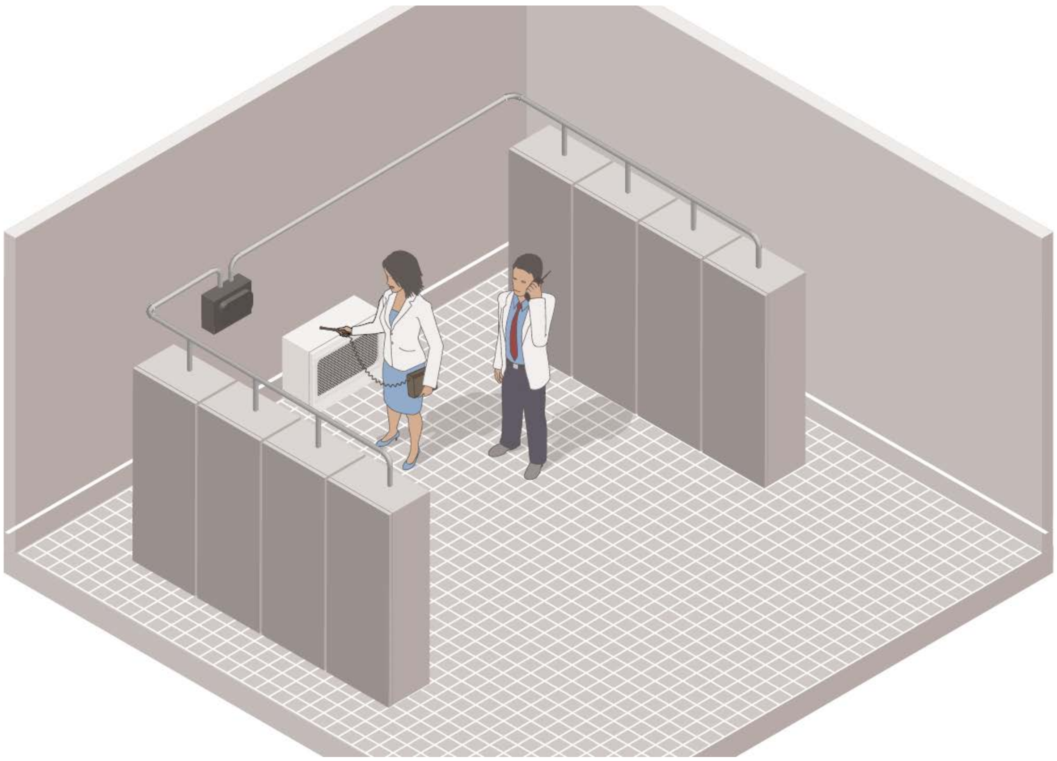


Figure 2-1. Illustration of ASD system in an in-cabinet application

ASD VEWFD systems have been used at several U.S. NPPs (e.g., Three Mile Island, Robinson) for over a decade as a measure to reduce fire risk contributors identified during the individual plant examinations of external events (IPEEEs) or for enhanced fire detection means to support exemptions (Ref. 2 and 3). However, only recently has there been an interest to use these systems in the regulatory context in fire PRAs, to support the application of NFPA Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2001 Edition." The performance objective for using these VEWFD systems is to provide earlier notification to plant personnel that may allow for additional time for human intervention before fire conditions that threaten reactor safety. However, these initiating devices could also be used to initiate heating, ventilation, and air conditioning (HVAC) changes or to automatically initiate a suppression system. Hypothetically, these systems could even be used to automatically de-energize the electrical equipment which they are protecting, reducing the likelihood of any potential fire threat, without human intervention.

NFPA-805 Frequently Asked Question (FAQ) 08-0046 (Ref. 4), was later incorporated into Supplement 1 to NUREG/CR-6850/EPRI 1019259. NFPA-805 FAQ 08-0046 provided an interim staff position on questions raised by the pilot plants during their transition to NFPA 805. Section 13 of Supplement 1 titled, "Incipient Fire Detection Systems," provides an interim position for determining the non-suppression probability for fire scenarios that have installed *incipient fire detection systems*[3] *installed*. Because of the lack of information and test data, the

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

interim staff position limited the applicability of VEWFD systems with regard to quantifying these systems in fire PRA.

Following the issuance of FAQ 08-0046, "Incipient Fire Detection Systems," the U.S. Nuclear Regulatory Commission (NRC) initiated a research program along with confirmatory testing at NIST to ensure the interim position is technically adequate. This report documents that research.

2.1.1 Fire protection defense-in-depth

A fundamental understanding of the concept of defense-in-depth will be important later when evaluating the entire fire protection safety performance objectives. Fire protection programs at U.S. NPPs must ensure that both the probability of occurrence and consequences of fire and explosions are minimized. To achieve the required level of fire safety, licensees use the concept of defense-in-depth to provide echelons of protection from fire effects. This concept was first introduced in NRC Branch Technical Position, Auxiliary and Power Conversion Systems Branch 9.5-1 (BTP APCSB 9.5-1) as a result of Browns Ferry Special Review Group recommendations (NRC IN 92-46, Attachment 1). Subsequently, defense-in-depth for fire protection is a design concept applicable to deterministic [Sections 50.48(a) and (b) of Title 10 of the *Code of Federal Regulations* (10 CFR)] and performance-based [10 CFR 50.48(c)] fire protection plans. The three echelons of defense-in-depth related to fire protection are:

a. Preventing fires from starting.

b. Detecting fires quickly, suppressing those fires that occur, putting them out quickly and limiting their damage.

c. Designing plant safety systems such that if a fire does get started in spite of the fire prevention program, and burns for a considerable time, in spite of fire protection activities, it will not prevent essential plant safety functions from being performed.

VEWFD systems partially support the second echelon by providing a means of quickly detecting fires. Because VEWFD systems support defense-in-depth, there have been differing views on the role of VEWFD systems in performance-based fire protection programs, leading to complexity in the evaluation of these systems' performance in a fire PRA.

2.2 Dynamics of Fire Stages

A fire development profile is typically discussed in terms of "fire stages." These are commonly referred to as the "incipient," "growth," "steady-state," and "decay" stages as illustrated in Figure 2-1 (Ref. 5). This idealized representation provides a foundation for understanding the various fire stages; however, the shape and, more importantly, the duration and transition point of each stage are scenario dependent. Having a clear definition and understanding of the incipient stage and transition point as it relates to performance-based methods, is paramount to the research performed under this project.

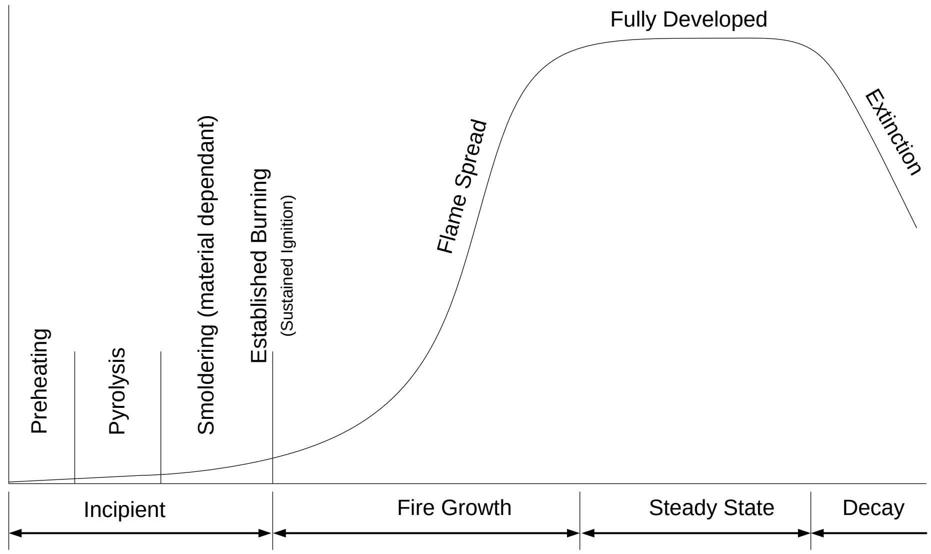


Figure 2-2. Fire stages

The incipient stage includes the preheating, gasification and smoldering phases, which are all stages before flaming combustion. The preheating phase is the process of heating combustible materials to a point where gasification begins. As combustible material continues to heat up, it is decomposed, or broken down into more simple molecular compounds; this stage is known as pyrolysis. Smoldering is a slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel (Ref. 6). True self-sustaining smoldering conditions will not occur for many of the materials of interest in electrical enclosures (Ref. 7).

A common fire scenario includes an initial pre-heat phase, typically followed by a pyrolysis phase, then followed by a transition to either smoldering or flaming conditions. In electrical enclosures, the preheating phase could start as a result of circuit, component, or inter-connecting electrical conductor failure, or by some other mode. Regardless of how the initial degradation begins, a source of energy to cause the preheating is needed to initiate the potential fire scenario. Once sufficient concentrations of combustible material are present during the gasification phase, electrical energy within the electrical enclosures provides the potential ignition source to end the incipient stage.

There are also variations on this prototypical fire scenario. The degradation mechanism may not continue to progress in severity. For example, the pyrolysis phase may be reached, but sufficient vapor may not be evolved to support combustion, or an ignition source may not be present at a physical location where flammable concentrations are present. Another example would be an instance in which the component degradation begins to decrease in severity before the ignition and fire growth stage. Although these cases may produce considerable combustion products, the heat output could be relatively low, and thus, not all situations involving an incipient stage actually result in a fire.

For the purposes of this report, "ignition" will be defined as the point where "self-sustained flaming combustion is initiated." This definition of ignition corresponds to the start of the growth phase as depicted in NUREG/CR-6850. The logic for using this definition will become apparent later on when the risk scoping study structure is presented, showing the dependency between

fire-initiating events that are risk-significant and are counted in the fire initiating frequency, and the fraction of those fires which exhibit an incipient stage of sufficient duration to support enhanced suppression capabilities.

In addition to underscoring/highlighting the stages of a fire, it should also be emphasized that different fire growth profiles have been defined. Figure 2-3 illustrates common fire growth profiles across various electrical enclosure heat release rate categories, as found in performance-based designs, such as the slow, medium, fast and ultrafast growth profiles as presented in fire protection literature (Ref. 5 and 8) and NUREG/CR-6850 Appendix G. Notably, the growth profiles of actual fires that occur in NPPs will vary, and are functions of the component failure mode and configuration of combustibles; simply, just as the fire growth profiles are variable, the incipient stage duration can vary dramatically as well (Ref. 9).

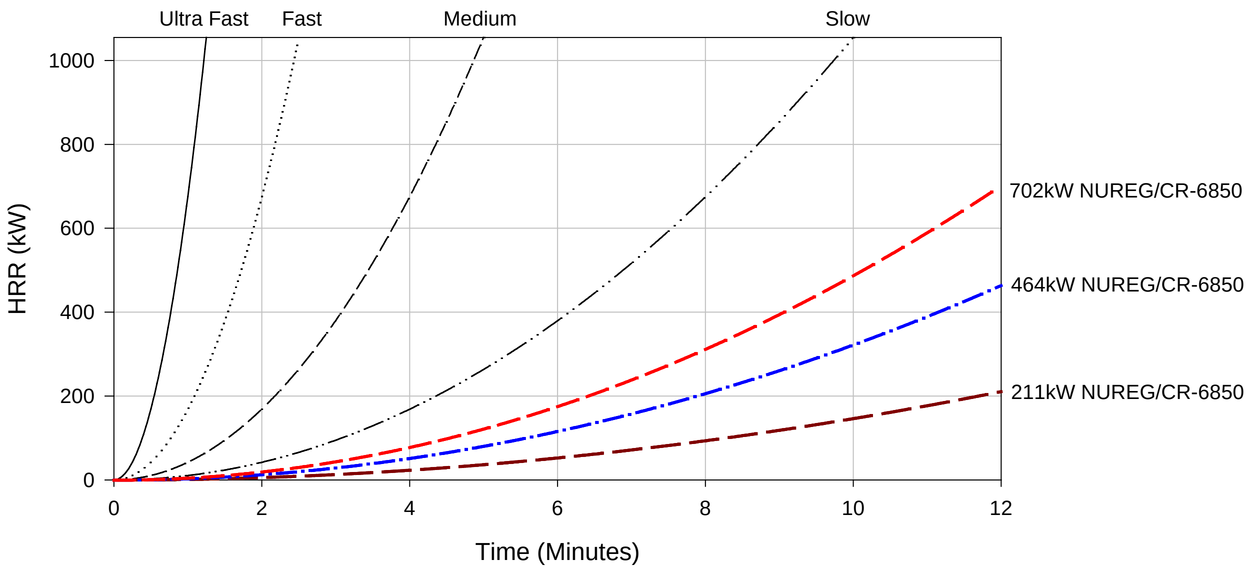


Figure 2-3. Illustration of several performance-based t-squared fire growth profiles

Alternative definitions

For completeness, it should also be mentioned that there are alternative definitions of an incipient stage. For instance, Heskestad and Yao define three fire stages for solid materials with an input heat source of relatively low energy (Ref. 10). The three phases included “incipient,” “smoldering,” and “flaming” stages of a fire. Here, Heskestad and Yao identified ignition as the point where smoldering combustion starts. Therefore, they did not consider smoldering combustion to be included in the incipient stage.

Even within the same reference material, definitions differ; for example, the NFPA Fire Protection Handbook commonly cites an incipient fire as one that can be extinguished by portable fire suppression equipment (Ref. 5). If this definition were used to classify fires that have occurred in NPP, all but a very small fraction of fires would be classified as incipient fires. In the same NFPA reference, in the section discussing smoke detection, the incipient fire is defined as a stage when there is smoldering, but insufficient flaming to achieve established burning. For this project, the latter definition is used, because it has a stronger physical

connection to the observed fire phenomena, and is not based solely on the success of human intervention to suppress fires.

2.3 Aerosol Generation

Fire signature response

From its inception, fire produces a variety of changes to the ambient conditions within the fire environment. These changes are referred to as “fire signatures” and have the potential to be measured by detection systems. Examples of the fire signatures include aerosol (commonly referred to as smoke), energy release, gas, and transport fire signatures. For a specific fire signature to be of value, a measurable change in ambient condition is required, and that magnitude change (“the signal”) must be greater than the normal background variations (“the noise”). Thus, the preferred fire signature for a specific application will be that which generates the highest signal-to-noise ratio in the earliest period of fire development (Ref. 11). Proper application of fire detection technologies requires an understanding of the fire conditions for which detection system response is required.

Aerosols are the type of fire signatures that can be detectable by smoke detectors, and will be studied exclusively for the purpose of this research. Smoke is defined as, “*the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass”* (Ref. 6). Some ASD vendors do sell components for their systems that have the capability of detecting gas signatures; the performance of ASDs used in the latter application will not be evaluated in this report.

Aerosols are classified as solid and liquid particles ranging in size from 5×10^{-4} to 10 micrometers (µm) and suspended in air. The characteristics of the aerosol are a function of the source material (source composition), combustion stage (incipient, smoldering or flaming), and amount of dilution with air, coagulation from Brownian motion, and surface deposition. These factors play an important role in determining the chemical composition, refractive index, particle size distribution, and concentration. The characteristics of the aerosol play an important role in the response of the detector because specific characteristics will affect sensing technologies differently. For instance, flaming fires tend to produce smokes that have a large fraction of sub-micron particles that tend to absorb a greater fraction of incident light than the fraction scattered, while smokes from smoldering fires tend to have a larger fraction of particles micrometer sized or greater, and they tend to scatter more incident light that the fraction absorbed. Based primarily on these factors, an ionization type detector is better suited for detecting flaming fires and a photoelectric type detector is better suited for detecting smoldering fires. Because of these differences, combination detectors have been developed and are available on the commercial market (Ref. 12).

2.4 Smoke Detection Principles

Reliable fire detection is an essential part of the fire protection program in NPPs. The use of smoke detectors is common because they typically detect fires before heat detectors and sprinkler activation. The NFPA Glossary of Terms defines the following types of smoke detectors (Ref. 13):

Cloud Chamber Smoke Detection:

The principle of using an air sample drawn from the protected area into a high-humidity chamber combined with a lowering of chamber pressure to create an environment in which the resultant moisture in the air condenses on any smoke particles present, forming a cloud. The cloud density is then measured by a photoelectric principle. The density signal is processed and used to convey an alarm condition when it meets preset criteria.

Ionization Smoke Detection:

The principle of using a small amount of radioactive material to ionize the air between two differentially charged electrodes to sense the presence of smoke particles. Smoke particles entering the ionization volume decrease the conductance of the air by reducing ion mobility. The reduced conductance signal is processed and used to convey an alarm condition when it meets preset criteria.

Photoelectric Light Obscuration Smoke Detection:

The principle of using a light source and a photosensitive sensor onto which the principal portion of the source emissions is focused. When smoke particles enter the light path, some of the light is scattered and some is absorbed, thereby reducing the light reaching the receiving sensor. The light reduction signal is processed and used to convey an alarm condition when it meets preset criteria.

Photoelectric Light-Scattering Smoke Detection:

The principle of using a light source and a photosensitive sensor arranged so that the rays from the light source do not fall (as normal) onto the photosensitive sensor. When smoke particles enter the light path, some of the light is scattered by reflection and refraction onto the sensor. The light signal is processed and used to convey an alarm condition when it meets preset criteria.

Video Image Smoke Detection:

The principle of using automatic analysis of real-time video images to detect the presence of smoke.

In NPP applications, smoke detectors have traditionally been considered best-suited for fire detection in spaces with physical barriers where rapid heat generation and smoke confinement can be expected in the event of a fire. The purpose of these systems is to provide early warning to building occupants, and rapid notification of the fire brigade. Some detection devices will also perform the function of automatically actuating suppression systems, and interfacing with other building systems such as HVAC. Advancements in electronics have aided in the improvement of the smoke detector signal processing, allowing for algorithms to be developed to reduce nuisance alarms from non-fire combustion products.

For room fire detection, smoke detectors have typically been placed in the uppermost space of the protected area. This placement assumes a growing or high-energy (steady-state) fire in which the energy released causes a strong buoyant plume to force the products of combustion upward and outward along the horizontal ceiling where the detectors are located. For low-energy fires, characterized by low temperatures and relatively small amounts of combustion products, the plume strength may not be sufficient to transport the products of combustion to the uppermost level where the detectors are located. In addition, if the room has a vertical temperature gradient (on the order of a few degrees Celsius) such a weak plume could result in stratification of the smoke (Ref. 14).

2.4.1 Smoke characteristics

Smoke production of a given fuel will vary with the type of fuel; mode of combustion; size of fuel package; arrangement; physical configuration; material moisture content; and ignition input energy. The earliest indication of a fire occurrence usually involves the heating of materials during the pre-ignition (incipient) stages, which produces submicron particles ranging in size from 5×10^{-4} to 1×10^{-3} micrometers. Under ambient conditions, particles of this size are normally found in concentrations from several thousand per cubic centimeter to several hundred thousand per cubic centimeter. Incipient stage conditions can raise the sub-micrometer particle concentration sufficiently above the background levels (noise) to be used as a fire detection signal. As a reference point, a match flame can produce ten million particles per cubic centimeter (Ref. 15).

The size of the particle produced by diffusion flame[4] combustion also varies with the heating of the air and the development of the fire progressing to flaming combustion. Large particles are formed by coagulation, with the particle size distribution varying between 0.1 micrometer and 4.0 micrometers. The smaller particles below 0.1 micrometer tend to disappear as a result of the formation of larger particles by coagulation, while the larger particles tend to settle out through the process of sedimentation (Ref. 15). Both of these properties contribute to smoke aging.

The performance of ASD systems exposed to smoke is dependent on the particular ASD technology (i.e., light-scattering vs. cloud chamber), because the ASD technologies respond differently to varying particle sizes and particle concentrations. For instance, cloud chamber technology is more sensitive to particle concentration and less sensitive to particle size. This is because the particles act as a condensation nucleus when the cloud is formed, and the response of the system is similar whether 100 large particles or 100 small particles are present. Light-scattering ASD technology requires the particles to be of sufficient size to scatter light. In this sense, the system response would differ between 100 large particles (more light-scattering occurs) and 100 small particles (less light-scattering occurs). Smoke detector response depends on detector type and accumulation of smoke particulate within the sensing chamber. In addition to the differences among detector technology, the performance within a technology may differ because of the design and characteristics of the detector. For instance, light-scattering based technologies may use forward scattering, back scattering or a combination, along with employing different wavelengths of light sources. These design variations result in variable performance levels. Consequently, the motivation for choosing one ASD technology over another for use in NPP applications is not clear. The test results documented in this report confirm this statement (see Section 5).

2.4.2 Smoke properties

The Lambert-Beer Law (also known as Bouguer's law) provides an expression for the light intensity reduction caused by smoke. The Lambert-Beer Law is shown mathematically as:

$$I = I_0 \exp(-\kappa C L)$$

where: I = intensity of transmitted monochromatic light (cd)
I_0 = initial intensity of monochromatic light (cd)

[4] Diffusion flame combustion refers to a mode of combustion where fuel and air mix or diffuse together at the region of combustion.

κ = extinction coefficient, (m^2/g)
C = mass concentration of smoke particles, (g/m^3) and
L = pathlength of the optical beam passing through smoke (m).

The use of this law allows for the development of a parameter known as optical density,

$$D_e = -10 log_e \left(\frac{I}{I_0}\right) = \kappa C L$$

Obscuration is the effect that smoke has on reducing visibility. Higher smoke concentrations result in higher obscuration, which results in lower visibility. Light obscuration is defined as:

$$\frac{I_0 - I}{I_0} x100$$

Obscuration is the standard definition of smoke detector sensitivity in the fire protection industry today. Detector sensitivity is reported in units of percent obscuration per unit length (e.g., %/ft obscuration or %/m obscuration). Percent obscuration per unit of length (meter or foot) is shown mathematically as:

$$\left[1 - \left(\frac{I}{I_0}\right)^{\frac{1}{d}}\right] \cdot 100$$

2.4.3 Spot-type detectors

Most of the devices associated with conventional fire detection are typically located near the ceiling surfaces of NPP compartments. In the event of a fire, hot gases in the buoyancy-driven fire plume rise directly above the burning fuel, and impinge upon the ceiling. The ceiling surface causes the flow to turn and move horizontally beneath the ceiling, to other areas of the room, located some distance from the fire. The response of detection devices installed below the ceiling, submerged in this hot flow of combustible products, provides the basis for the construction of active fire detection features.

The response of conventional spot-type (also referred to as “point type”) detectors like those shown in Figure 2-4, are influenced by several parameters. Smoke characteristics, smoke transport and detector characteristics are the predominant factors that influence detector response. The performance of spot-type smoke detectors is also dependent on fire-induced flow velocities near the detector. Typically, spot-type smoke detectors operate on two types of detection principle: ionization or photoelectric.

Figure 2-4. Image of conventional spot-type detectors

Conventional photoelectric spots, laser spots and the non-cloud chamber ASDs all sense scattered light. In the photoelectric spot the beam is an infrared radiation (IR) diode, in the laser spot it's a diode laser, and in ASDs it could be either. All have a detector located at some fixed angle from the beam. PHOTO will be used throughout this report when referring to the conventional spot-type photoelectric detector. ION will be used throughout this report when referring to the conventional spot-type ionization detector. SS will be used throughout this report to when referring to the sensitive spot-type detector used in testing that was configured to the VEWFD sensitivities of NFPA 76.

2.4.4 Aspirating smoke detectors

ASDs, also known as air sampling-type detectors, provide a means of smoke detection that actively draws air samples from the protected space through a network of sampling pipes into a centrally located smoke detector unit. Figure 2-5 and Figure 2-6 provide illustrations of an ASD in-cabinet and areawide application, respectively. These figures show the detector unit, smooth bore pipe network with two zone and sample ports.

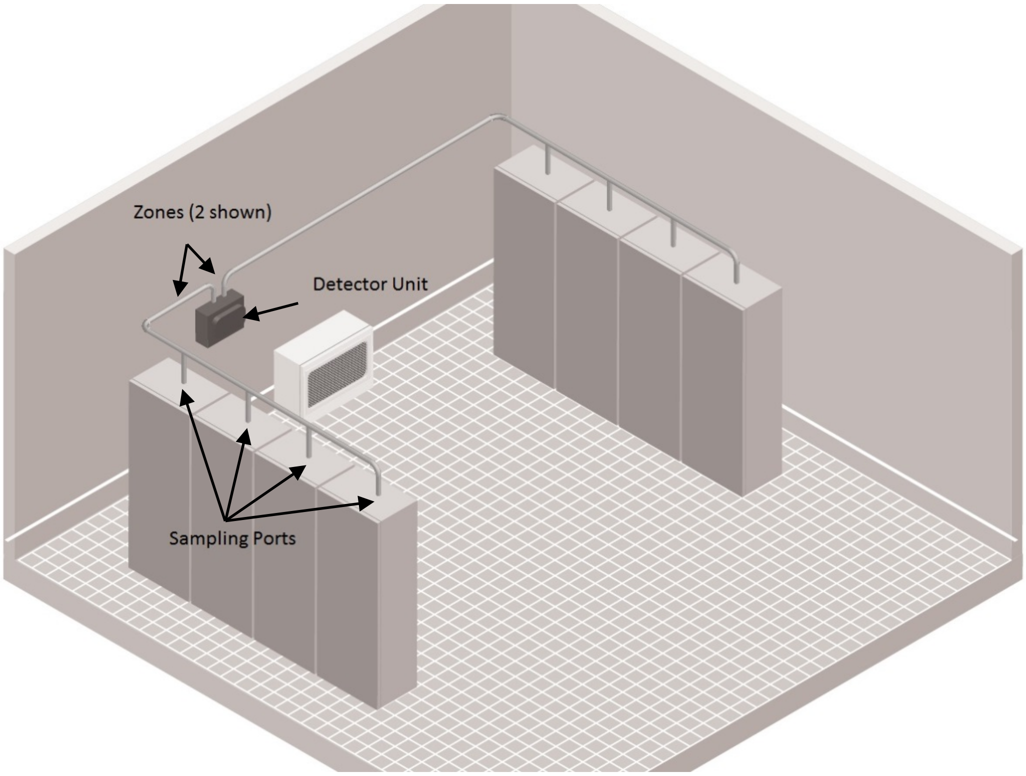


Figure 2-5. Illustration of ASD in-cabinet application

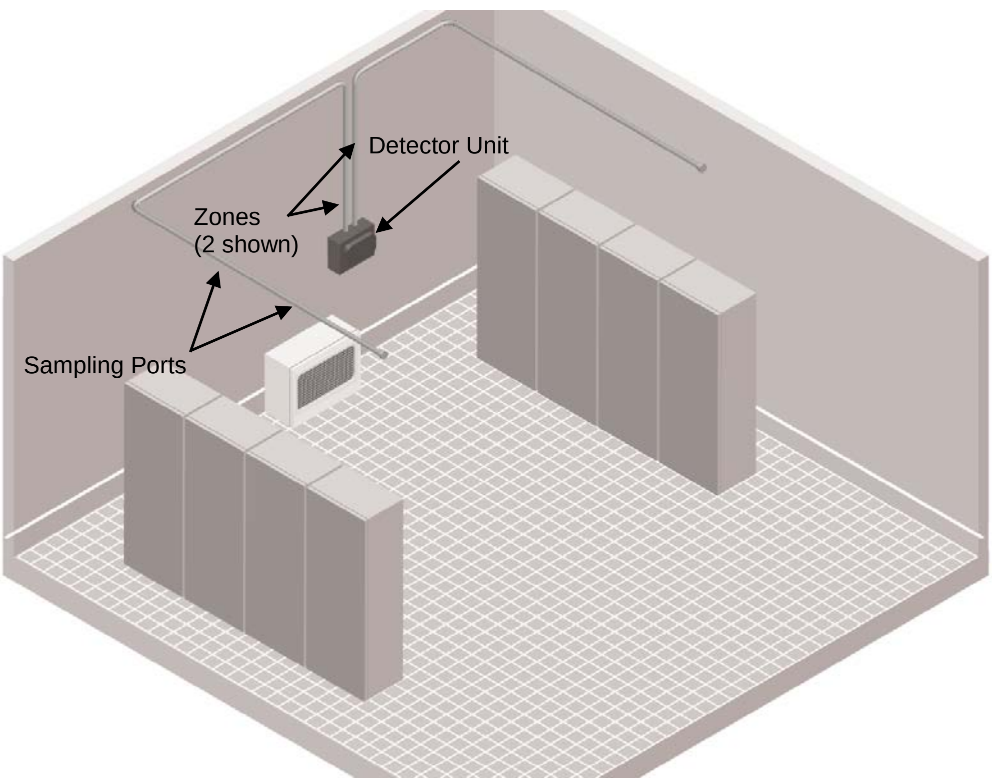


Figure 2-6. Illustration of an ASD areawide application

Two types of detector unit technology are commonly used; one is based on the light-scattering principle, while the other uses cloud chamber technology. The light scattering-type ASDs detect smoke particles using the same principles as photoelectric spot detectors, but typically have an improved detection unit that is more immune to external light sources that can affect conventional photoelectric spot detectors. The cloud chamber detector places the air sample in a humidifier where distilled water is used to bring the relative humidity to nearly 100 percent. Then, a vacuum pump reduces the chamber pressure to cause supersaturated conditions (i.e., relative humidity above 100 percent). When this occurs, any smoke particles present will act as condensation nuclei for water droplets to form on, resulting in the formation of a cloud in the sensing chamber. The particle concentration (cloud density) is measured by light-scattering detector principles, which provide an output that is proportional to the number of droplets. Either of the detector technologies will respond when a pre-programmed threshold is exceeded (Ref. 5).

The ability to mechanically transport air to the detector allows for the use of filters to remove dust. Physical filters remove large dust particles from the air sample, before it being analyzed. The filters can minimize unwanted alarms and contamination of the detector. Filter placement and designs vary by manufacturer, but typically are built or fused into the ASD detector unit or installed in the pipe network.

ASD systems typically have multiple alarm thresholds that are determined by the performance objectives of the application and the pipe network design. Per NFPA 76, for an ASD to be classified as a VEWFD system, the following <u>minimum</u> sensitivity setting above ambient air borne levels must be achieved:

Alert condition: 0.2 percent obscuration per foot (effective sensitivity at each sampling port)

Alarm condition: 1.0 percent obscuration per foot (effective sensitivity at each sampling port)

Alert and alarm threshold settings more sensitive than these may be achievable in an application and will provide for an enhancement over these minimum requirements. However, the ability to use more sensitive settings will be dependent on a number of variables, including operational transients on background aerosol noise levels. Thus, most vendors recommend at least a two week burn-in period, (sometimes referred to an auto learn cycle), during which the detector monitors background noise variations, such that an optimum alert and alarm threshold can be chosen, which enables a sensitive system with few unwanted nuisance alarms. Additionally, per NFPA 76 to be classified as VEWFD a maximum transport time from the most remote port to the detection unit of an air-sampling system <u>shall not exceed 60 seconds.</u>

It is important to point out that the sensitivity of a detector unit is not equivalent to the sensitivity at the sampling port. The sensitivity of each sampling port is a function of “detector unit” sensitivity and the number of sampling holes in a sampling zone. Most ASD VEWFD systems require multiple sampling ports per zone. The smoke entering the air sampling port network will be diluted by air entering the network from other ports that does not contain smoke. Thus, for an ASD system to be able to detect a specific smoke concentration, the detector must have greater sensitivity than at the air sampling port for which the system is designed. For example, assume a 2,000 square feet (ft^2) room is protected by an areawide ASD system consisting of a single zone piping network located at the ceiling, having 10 sampling ports, spaced per NFPA

76 requirements, and all sampling ports have been calculated to have an equivalent sensitivity (i.e., balanced). If the design requires each sampling port to have a sensitivity of 1.0 percent per foot obscuration, the detector sensitivity would be required to be set at 0.1 %/ft obscuration. This estimation method is applicable to a balanced system; however, it is typically not sufficient to ensure the performance of the ASD VEWFD system. Such assurance can only be given through product testing and approvals. Vendors of ASD systems have software tools to assist in designing an ASD system pipe network and calculating detector unit sensitivity threshold setting to achieve the required sampling port sensitivities. As discussed in the literature and confirmed in this project's test results (Section 5), ASD VEWFD systems may have varying response times if they are from different vendors; use identical piping networks; are set to the same sampling port sensitivities; and are exposed to the same smoke sources. Given the different technologies and processing algorithms, it is reasonable to expect differences in response.

It is important to understand the difference because much of the literature reports the detector unit sensitivity, and not the various sensitivities at the sampling ports, which are not equivalent, and will differ by design. The use of a single piping zone sampling from multiple ports also has an effect on the performance of the system. For instance, in areawide applications, the phenomenon known as cumulative air sampling may improve the performance of ASD systems, and allow for earlier detection by permitting smoke sampled from multiple ports to contribute to the total smoke particulate being sampled at the detector from a protected space. Sample port spacing has a direct correlation to the cumulative air sampling effect. As the spacing of sampling ports is reduced, there is a greater possibility for smoke particles from a single source to enter into more than one sampling port, thus improving detector response. Theoretically, the concept of cumulative air sampling can be understood; however, there are many variables that influence the effect of this phenomenon, and unless specific validation testing is performed for the scenario under evaluation, it is a difficult phenomenon to quantify. Thus, standards such as NFPA 76 specify minimum port sensitivity (above background) for each sampling port.

Spot-type air sampling detectors are also available on the market. These detectors combine the spot-type light-scattering smoke detector with filtered aspirating features. Typical applications are heated stables, paper plants, cotton and textile mills, commercial laundries, food processing areas, and other applications where very dusty conditions exist. Performance of these types of detectors is not evaluated in this research.

2.4.5 Ambient conditions affecting detector response

Ambient environmental conditions influence the performance of smoke detection technologies. The improper selection of detector type and location can lead to problems ranging from false or delayed alarms, to, in some cases, no alarms when fire conditions exist. Issues to consider when selecting and locating detectors/sampling ports include, but are not limited to:

- Background noise
  - Detectors responding to invisible aerosol fire signatures are prone to detecting signals from cigarette smoke and automobile exhaust fumes. Thus, placement of a smoke detection system which responds to invisible aerosol fire signatures in proximity to an emergency diesel generator (EDG) should be evaluated to ensure that the frequent operation of the EDG does not result in numerous nuisance alarms.

- Routine maintenance of plant structures, systems and components may increase the background noise level above the alarm threshold for detection systems set up to signal very early warnings.

- HVAC effects
  - Ventilation conditions within rooms and electrical enclosures are important to understand, because detecting/sampling port location without considering the air movement and thermal effects within the room, especially for low-energy incipient fires, may slow the detection systems' response(s), and could result in the detection system missing the fire signal completely. Areas of low air flow or stagnation should be considered and avoided when designing the detection system layout.
  - ASD systems may be prone to pressure change within a room because of periodic changes in HVAC operational state.
- Humidity
  - High relative humidity of the air space affects the smoke transport to detectors or sampling ports located at the ceiling such that a high relative humidity will enhance the agglomeration of smoke particles. Depending on room conditions, the moist smoke laden air may not be transported to the elevations where detectors and sampling ports are located.
- Radiation
  - Ion type detectors are not suitable for use in applications in which high radioactivity levels are to be expected; the radiation causes a reduced sensitivity of ion type detectors.

2.5 Quality Assurance Program

Each licensed NPP is required to have a quality assurance (QA) program that provides reasonable assurance that the requirements for design, procurement, installation, testing and administrative controls for the fire protection program are satisfied. Licensees typically meet the fire protection QA program criteria by (1) implementing those fire protection QA criteria as part of their QA program under 10 CFR Part 50 Appendix B, or by (2) providing for NRC review a description of the fire protection QA program and the measures for implementing the program. Commitments made by licensees regarding fire protection quality assurance are applicable to both deterministic [10 CFR 50.48 (b)], and performance-based [10 CFR 50.48(c)] fire protection plans.

In 1977, a letter sent to each licensee titled, "Nuclear Power Fire Protection Functional Responsibilities, Administrative Controls, and Quality Assurance," provided NRC supplemental guidance on the quality assurance necessary to assure an effective fire protection program, which was reiterated in Generic Letter (GL) 82-21, "Technical Specifications for Fire Protection Audits." These documents provided supplemental guidance on the 10 fire protection QA program criteria, which included:

1. design control and procurement document control
2. installations, procedures, and drawings
3. control of purchased material, equipment, and services
4. inspection
5. test and test control
6. inspection, test and operating status
7. non-conforming items

8. corrective action
9. records
10. audits

All 10 of these criteria have application to the QA of VEWFD systems. However, because of the fact that ASD VEWFD systems are engineered systems, several of these QA criteria can have a high impact on assuring the adequate performance of VEWFD systems. Some of these criteria are discussed in detail below.

Design Control and Procurement Document Control

a. Control of design and procurement documents changes—including field changes and design deviations are subject to the same level of controls, reviews, and approvals that were acceptable to the original document—is controlled.

The sensitivity of the ASD at the sampling port is dependent on the size and number of sampling port holes on an individual zone. Any deviations or field changes (sometimes referred to as “as-built”) from the original engineered design of the system (as-designed) will have a direct impact on the performance of the system. Depending on the differences between the as-built and the as-designed system this may improve or degrade the performance of the system.

b. Quality standards are specified in the design documents such as appropriate fire protection codes and standards, and deviations and changes from these quality standards are controlled.

c. New designs and plant modifications, including fire protection systems, are reviewed by qualified personnel to assure inclusion of appropriate fire protection requirements.

Installations, Procedures, and Drawings

a. Configuration control activities such as design, installation, inspection, test, maintenance, and modification of fire protection systems are prescribed and accomplished in accordance with documented instructions, procedures, and drawings.

b. Instructions and procedures for design, installation, inspection, test, maintenance, modification and administrative controls are reviewed to assure that proper inclusion of fire protection requirements.

Clear and coherent procedures ensure that installation, inspection, testing, maintenance, and modifications are completed with a high certainty of success. Procedures also support maintaining the system with a high reliability of proper operation under conditions requiring their response.

Inspection

A program for independent inspection of activities affecting fire protection should be established and executed by, or for the organization performing the activity to verify conformance to documented installation drawings and test procedures for accomplishing activities. The independent inspectors should be knowledgeable in the design and installation requirements of the structures, systems and components (SSCs) being inspected and follow appropriate

procedures, instructions and checklists to perform a comprehensive inspection. For ASD VEWFD systems, these inspections and, the applicable code requirements should be followed and could include, but are not limited to, the following:

- Verify that sampling ports or points are not obstructed.
  - If drop-down flexible capillary tubing is used, this should include a verification that no blockage has occurred at the sampling end of the capillary or at the junction of where the capillary connects to the rigid smooth bore piping.
- Verify that filters are clean and have been changed per manufacturer's recommendations, plant procedure, or code requirements.
- Visually verify that sampling piping has been permanently installed per design requirements, or as-built if calculations based on as-built configurations, fittings appear air tight, and piping is clearly identified.
- Verify that the system sensitivity settings are consistent with any code requirements or regulatory commitments.
- Verify that the system sensitivity calculations are adequate and correct.
- Verify that system testing has been completed per code, plant, or regulatory requirements.

<u>Test and Test Control</u>

A test program should be established and implemented to ensure that testing is performed and verified by inspection and audit to demonstrate conformance with design and system requirements. Following construction, modification, repair or replacement, sufficient testing (referred to as "installation testing" or "start-up testing") is performed to demonstrate that the detection system will perform satisfactorily when it is placed in service and that all design criteria are met. Written test procedures for installation tests incorporate the requirements and acceptance limits contained in applicable design documents. Periodic testing (referred to as "in-service testing" or IST) should be conducted on a pre-defined schedule to assure that the system will properly function and continue to meet the design criteria. For example, testing should be conducted with smoke or other acceptable product per manufacturers' recommendations and instructions. Testing should be conducted at the farthest end sampling port or test port in each piping run (zone). Airflow through all ports on each piping run should also be verified. Additionally, sensitivity testing should be conducted to ensure detector operability per design requirements.

<u>Records</u>

Records should be prepared and maintained to furnish evidence that the criteria enumerated above are being met for activities affecting fire protection systems. Records should include results of inspections, tests, reviews, and audits; non-conformance and corrective action reports; and construction, maintenance and modification records and certified manufacturers' data. Records can also be an important part of documenting the trending system performance

or aging management; such records could support advancement to PRA modeling of any such system.

Audits

Audits should be conducted and demonstrated to verify compliance with design and procurement documents, instructions, procedures, and drawings and inspection and test activities. Audits should follow written procedures, and be conducted by knowledgeable personnel not directly responsible for the area being audited. Audit results should be documented, and follow-up actions should be taken by responsible management to correct any deficiencies identified.

2.6 System Performance Measures

As with any system, there are attributes that affect the systems performance. Performance of a specific detector will be dependent on the as-built system configuration[5], manufacturing procedures, quality and reliability control procedures, and the training and supervision of the persons who install, use, and maintain the system. Quality assurance programs for fire protection are maintained at each U.S. NPP and provide a level of assurance that fire protection systems are designed, fabricated, erected, tested, maintained, and operated so that they will function as intended (Ref. 16). Although no QA program will be able to identify all deficiencies, the application of the fire protection defense-in-depth concepts provide added assurance that if system deficiencies are not identified other echelons of protection are available to ensure safety. Additionally, NFPA 805 requires procedures be established for inspection, testing, and maintenance for fire protection features credited by the fire protection program.

This subsection provides a high-level overview of some of the system performance measure associated with smoke detection systems. Several of these system performance measures will be used to quantify the performance of smoke detection systems in Section 7.2. In addition, the NFPA 805 standard requires monitoring programs to be established with methods to monitor system effectiveness measures such as availability, reliability, and performance[6].

2.6.1 Reliability

Reliability is an important aspect to consider when quantifying the usefulness of a detection system. Reliability relates to the ability of the system and each individual component to be in proper working condition at all times ready to perform its intended function (Ref. 17). The complement to reliability is ***unreliability***, which is commonly used in PRA and is defined in the ASME/ANS PRA Standard as the *probability that a system or component will not perform its specified function under given conditions upon demand or for a prescribed time*.

2.6.2 Availability

Availability is defined by NFPA Std. 805 as *the probability that a system, structure or component of interest is functional at a given point in time* (Ref. 18). In PRA terms, the complement to

[5] ASD VEWFD systems are engineered systems, and any deviations between as-built and as-designed configurations will have an effect on system performance.

[6] See Paragraph 2.6 of the 2001 edition of NFPA Std. 805, "Performance-Based Standard for Fire Protection of Light Water Reactor Electric Generating Plants."

availability is *unavailability*, which is an attribute that may affect a plants response to an initiating event. Unavailability is defined in the ASME/ANS PRA Standard as the probability that a system or component is not capable of supporting its function including, but not limited to, the time it is disabled for test or maintenance.

2.6.3 Effectiveness

System effectiveness is a measure of how well a design solution will perform or operate given anticipated operational scenarios (Ref. 19). Effectiveness estimates for smoke detection systems are influenced by the several parameters including detector technology; fire combustion type; smoke generation material; smoke characteristics (particle size, concentration, and transport length); ventilation configurations; and stratification effects. For ASD systems, the as-built system configuration with regard to the application, layout, and sensitivities is also important with regard to system effectiveness. Thus, the design of the smoke detection system should be suited for the systems and components being protected. Effectiveness provides a measure of how well a particular design solution will perform in meeting its design objectives.

2.6.4 Maintainability

The maintainability of detection units varies directly according to the complexity of the design (Ref. 17). Detection systems should be maintained to ensure that performance deficiencies as a result of outside influences such as dust, insects, requiring periodic maintenance include the detector, filters and piping.

Smoke detectors are typically designed for a life expectancy of 10 years or more. Extended use beyond 10 years should be evaluated, and, for systems expected to perform in excess of 10 years, detectors should be replaced or sent out for re-calibration to ensure proper functionality. In addition, in-field calibrations such as re-baselining the alert and alarm thresholds, drift compensation, or any other methods that could reduce the sensitivity of the system to slowly developing fires, should provide evidence that such calibrations do not compromise the early detection function of the system. Any reductions in sensitivity will affect system performance, and the fire PRA quantification should be modified as a reduction in the system's effectiveness (Ref. 20). Vendor recommendations should be followed regarding calibration requirements.

Filters can be used for different purposes depending on the design of the system, but are commonly used to remove dust particles from the air sample. High-efficiency particulate air (HEPA) filters may be used on some ASDs as part of a dual air filtering design where the HEPA filtered air is used to protect and isolate the detector optics from the actual air sample (non-HEPA filtered) being analyzed. Protecting the detector optics can extend the life of the detector and reduce the likelihood of detector soiling. Soiling of detector optics over time will reduce the sensitivity of the system. The non-HEPA type filters are used to remove dust particles from the sampled source but allow smaller particles of combustion to pass through into the sampling chamber of the detector unit. These filters may be found inside the detector unit or in the sampling manifold external to the detector unit. Depending on the environment where air samples are taken, the rate of filter loading will vary, and periodic maintenance based on vendor recommendations or field operating experience should be factored into determining the filter replacement period.

The ASD smooth bore piping network must be maintained to ensure sampling points are not blocked because of accumulation of dust or other foreign materials. Although the detector units

are capable of annunciating a trouble alarm because of low- or high-flow conditions, they are not sensitive enough to alert when only one air sampling point is blocked. Gottuk and McKenna reported that ASD system supervisory trouble alarms did not provide a low air flow warning until 76 percent of the total air flow was blocked on one sampling line for the system they use in testing (Ref. 21). Operating experience has identified at least one instance in which systems were commissioned, but not all sampling points were verified to be open and able to sample from the protected space. Thus, for an extended period of time, the system was partially nonfunctional. Operating experience from Canadian NPPs has also identified that collection of dust balls within the ASD piping having degraded system performance. This has resulted in the development of internal cleaning methods using compressed air and condenser balls to pass through the ASD piping network to push out and clear any obstructions.

Ensuring sampling point functionality (ability to sample at each sampling point within a zone) is important when the ASD VEWFD systems are installed for in-cabinet applications. Because cleanliness of the air being sampled will vary among applications and plants, an increased surveillance beyond the vendors' recommended surveillance period may be warranted to ensure proper system function. In addition to using compressed air or vacuum cleaning methods (depending upon vendor recommendations), a verification of openness of ASD sampling points should be conducted, especially for in-cabinet applications. Although a blocked sampling point in an areawide ceiling-mounted ASD type application will degrade the systems performance, the blockage in the zone will result in increased flow in the other sampling points. In addition to ensuring the ASD piping is clear and clean of any foreign materials and accumulation of dust particles, the ASD piping network must also be periodically inspected to ensure that no portions of the pipe have become dislodged or broken from other plant activities. Any openings in the pipe will reduce the VEWFD system effectiveness, because the system is no longer balanced as designed and the volume of air from the sampling points is both reduced and diluted by the air flowing through the pipe opening.

2.6.5 Stability

The stability of a detector relates to its ability to sense fires over extended periods of time with no change of sensitivity (Ref. 17). Stability is sometimes also referred to as detector sensitivity drift. For ionization spot-type detectors, the accumulation of dust within the sensing chamber over time can interfere with the detectors' sensitivity rendering them more sensitive, and hence more prone to spurious nuisance alarms. The same effect occurs in photoelectric detectors where by the accumulation of dust in the sensing chamber results in increased internal reflectance and detector sensitivity, and makes the detector more prone to spurious nuisance alarms (Ref. 5). However, light-scattering detectors become less sensitive as light intensity is decreased because of the accumulation of dust and film (Ref. 15).

Detector sensitivity drift is a uni-directional gradual shift in the range of combustion products that will activate the smoke detector. Background noise is the short time variation of the detector signal. Most smoke detector use some form of drift compensation to counter this effect.

Figure 2-7 provides an illustration of noise and drift. Noise is considered to be the high frequency peak-to-peak fluctuations. Background noise levels may fluctuate throughout the day, or as a result of changing environmental conditions (e.g., HVAC changes, maintenance, housekeeping, etc.). During commissioning of ASD VEWFD systems, background noise levels are typically monitored for an extended period of time (up to 90 days) before making the system operational, such that the relative sensitivities for the alert and alarm set points have a background reference point that will minimize nuisance alarms.

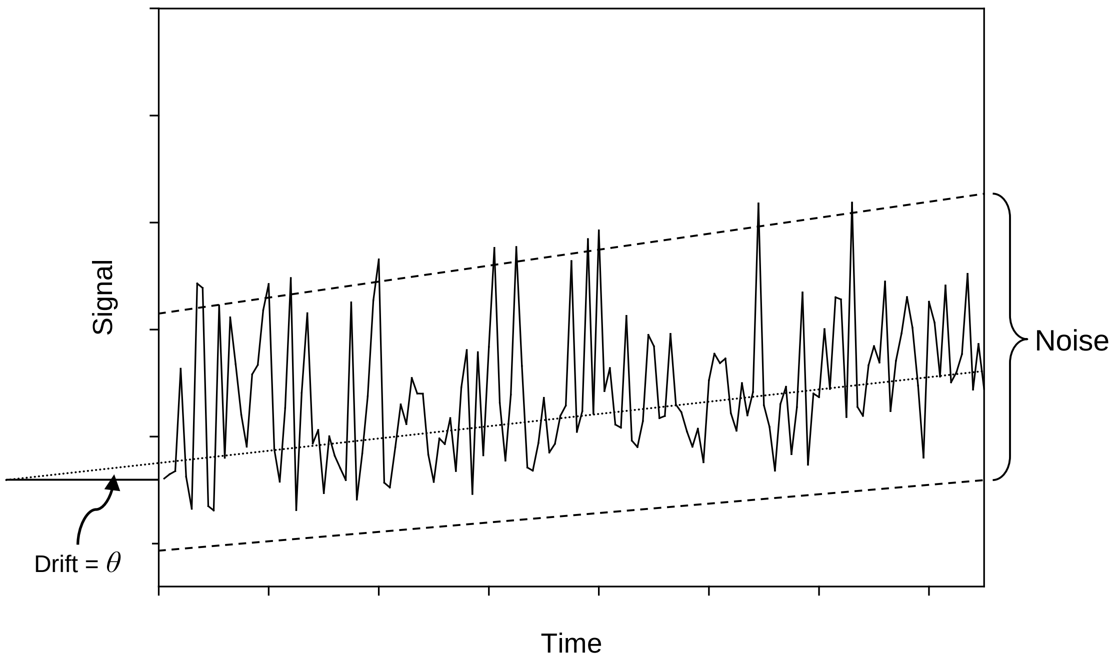


Figure 2-7. Illustration of detector signal background noise and drift

2.6.6 Serviceability

The ease of which a system can be repaired is referred to as serviceability, and can be a desirable aspect from a cost perspective (Ref. 21). Serviceability is a characteristic of the system's design and is usually evaluated in the design stage. It is difficult to measure on a numerical scale, and typically is evaluated by comparing various alternatives and assigning, a ranking to each system in terms of its ease of serviceability.

For smoke detection systems in NPPs, numerous system design aspects should be considered when evaluating serviceability. For instance, detection systems require periodic inspection, testing and maintenance. The purpose of periodic inspection, testing and maintenance is to ensure operational integrity of the system. Equipment performance can be affected by building modifications; environmental changes; physical obstructions; physical damage; configuration issues related to as-built and as-designed differences; improper installation; improper system startup testing; degree of cleanliness; and other problems that may not be readily apparent. The accessibility of the detection systems to support visual inspections and functionality and sensitivity testing should be evaluated. In many areas of an NPP, obstructions in the upper volume of the compartment can negatively impact the ease of performing periodic inspections and testing. In some instances, the amount of obstructions (cable trays in particular), can make it difficult or impossible to view the detector from floor level. On some occasions, scaffolding would need to be constructed to support inspection and testing of detection systems. Depending on the number of detectors or sampling ports in a room requiring scaffolding to be erected, there could be a negative impact on the cost of performing such inspections and testing, along with potentially increasing the risks to plant worker safety and NPP operational continuity.

2.6.7 Nuisance alarms

Nuisance alarms (also known as *unwanted alarms*) are associated with non-fire conditions that produce ambient conditions which mimic fire signatures and can cause a smoke detector to go into an alarm condition. The detector sensitivity is frequently tailored to the particular application to achieve the performance capability desired without being susceptible to nuisance alarms.

2.7 Inspection, Testing and Maintenance of Smoke Detection Systems

The use of performance-based approaches places greater dependence on fire detection system success as a foundation of the fire protection strategy. The use of ASD VEWFD systems in fire PRA as a risk reduction method requires the ASD systems to achieve a high level of performance. With the increased reliance on ASD VEWFD systems to improve plant fire safety, an increased importance on maintaining the predictability of these types of systems is required. The required high level of performance necessitates the use and implementation of an effective inspection, testing and maintenance program. The use of an ASD VEWFD system results in the use of a single detector unit to cover a large area (up to 20,000 square feet) where traditionally a large number of single spot-type detectors would have been needed. Simply, an ASD VEWFD system detector unit failure (loss of protection in an entire area), causes further consequences than spot-type detector failures in which the additional number of detectors provides redundancy. Thus, use of ASD systems necessitates a high level of performance be maintained to achieve the performance-based objectives and assumptions used in the quantification of these systems. This section provides an overview of the types of inspections, testing, and maintenance that support ensuring a high level of performance for ASD VEWFD systems.

The performance of any fire detection system is dependent on system elements such as design, installation, equipment, and maintenance (Ref. 5). An adequate inspection, testing, and maintenance program allows for a method to reduce deficiencies in these elements. For instance, room ventilation conditions may not allow for smoke to be transported to the location where smoke detector sampling points are located. Initial inspection and testing of the system should identify any problems that are designed into the system so that they can be fixed before the system being accepted and placed into operation. Unlike spot-type detectors, ASD systems are engineered systems. That is, these systems can be designed to meet a wide variety of performance goals and objectives. As such, any deviations in the system from as-designed to as-built, will affect the ASD's performance. Depending on the deviation, the "as-built" system could be performing better or worse than expected. Thus, a thorough initial inspection and testing of the system should be conducted to identify any deviations and then it should be evaluated to ensure adequate system performance. Periodic maintenance and inspection programs also provide assurance that statistical failures of the electronic components and mechanical blockage or breakages of the smooth bore piping network are promptly identified and properly corrected.

The inspection, testing and maintenance methods of smoke detection systems are designed to ensure that smoke can enter the sensing chamber of the detector; the detection system achieves an alarm state at the smoke concentrations for which the detection system was designed; and the detector alarm signal is received and processed by the fire alarm control panel. Inspection, testing, and maintenance methods are typically specified by the vendor for

ASD systems. The test methods must verify that all of the air-sampling ports operate at their designed flow rates and that the detector unit, including the sampling fan, operates within the parameters established by the listing. This implies a sensitivity measurement similar to that required by all of the other detector types (Ref. 5).

The telecommunications industry consensus standard NFPA 76 on the use of these systems in performance-based applications requires installation, testing and maintenance in accordance with NFPA 72 (Ref. 22). NFPA 72 provides methods and schedules for inspection, testing, and maintenance of fire detection systems. With regard to air sampling-type initiating devices, the NFPA 72 standard recommends following vendor guidance for testing detector alarm response (functionality) and verifying air flow through all sampling ports (Ref. 8). It also provides the frequency for conducting the recommended inspections, testing and maintenance.

Based on the available information and the need to ensure a highly reliable system through proper inspection, testing and maintenance, it is recommended that, for NPP applications, the requirements of NFPA 72 and vendor-recommended practices be followed. The fire risk scoping study described in Part II is based on the assumption that these practices are followed at a minimum.

3. OPERATING EXPERIENCE, STANDARDS, AND LITERATURE REVIEW OF VEWFD SYSTEMS

3.1 Review of VEWFD System Operating Experience

Early on, the project team determined that testing alone would not provide all of the information needed to quantify the performance of very early warning fire detection (VEWFD) systems in fire probabilistic risk assessment (PRA) applications. Project objective Item C, "human reliability analysis"; Item D "system availability and reliability"; and in part, Item E "system response to common products of combustion applicable to NPP," could not be adequately addressed by testing alone. Consequently, the project team coordinated several site visits and expanded the team with human reliability and human factor experts. The human factors and HRA aspects of this project are presented in Section 9 and 10, respectively. This section describes how the site visits and actual operating experience were used to gain a better understanding of these systems applications, and their reliability, availability, and general operating experience.

3.1.1 Site visits

The National Institute of Standards and Technology (NIST) and U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES) staff conducted several site visits to nuclear and non-nuclear facilities to gather information and operating experience for aspirating smoke detection (ASD) applications. These site visits provided two benefits. First, observing how the systems were used in the field allowed the planning of the testing to be conducted in a manner that reflected actual use. Second, the team gathered information on the operating experience (e.g., reliability and availability) of these systems to address project objectives. Site visits were conducted at the following facilities;

- NASA Goddard Space Flight Center (Maryland)
- Shearon Harris Nuclear Power Plant (North Carolina)
- H.B. Robinson Nuclear Generating Station (South Carolina)
- Bruce Nuclear Generating Station (Ontario, Canada)
- Darlington Nuclear Generating Station (Ontario, Canada)
- Pickering Nuclear Generating Station (Ontario, Canada)
- Three Mile Island Nuclear Station (Pennsylvania)
- Operator response questionnaire (through the Electric Power Research Institute)

To facilitate a structured, consistent, and thorough exchange of information during these site visits, a checklist of questions was developed and used. Topics included system performance objectives, system design, installation and maintenance, operator interface, and actual system performance. A summary of the insights obtained during these visits is provided herein.

3.1.1.1 U.S. nuclear facilities

For the U.S. nuclear facilities visited, licensees indicated that VEWFD systems were installed as risk reduction measures to support risk quantification studies, or to support an exemption from deterministic fire protection requirements. The VEWFD systems used were of the ASD type.

Deterministic Applications

The use of ASD systems has been in support of exemptions from NRC requirements. At Three Mile Island, ASD systems are used to enhance the second echelon of fire protection, defense-in-depth, by providing early warning to complement the passive fire protection features and other fire protection measures, such as zero combustibility zones. In this instance, an ASD system was used in areawide configurations. The system has been in use since 1998 and consists of two multi-zone detectors protecting battery rooms, battery/inverter rooms and a switchgear room. For this application, the licensee chose to install the system to provide early detection as an alternative to upgrading other passive fire protection features within the protected rooms. Room sizes varied from 600 feet squared to 1,200 feet squared, with an average room height of 18 feet. Typically, the sampling ports were within 2 feet of the ceiling, and each room had two sampling ports on a single zone. One additional application was protecting an office type space adjacent to a switchgear room, which was previously classified as the Technical Support Center. Ceiling height in this space was approximately 8 feet (Ref. 2).

Operating experience obtained during interviews (with fire protection staff regarding the successes from these systems), included a case in which a potential fire from an air-handling unit (AHU) fan motor failure was detected by this ASD system and operators responding to the alarm were able to identify the failing component and isolate it before any fire conditions. It was indicated that the early detection and response to this event possibly prevented a plant trip. Other events detected by these systems, but not directly related to reactor safety, include detecting hot work in a battery room and burned popcorn from a microwave oven. Documentation of success cases can play an important role in understanding and quantifying the reliability of operator response to ASD system notifications. Unfortunately, these cases were not documented.

Risk Applications

The use of VEWFD ASD systems and the associated risk reductions were either prompted by risk insights obtained from the results of Generic Letter 88-20, "Individual Plant Examination of External Events (IPEEE) for Severe Accident Vulnerabilities;" or to meet the risk metric as directed by National Fire Protection Association (NFPA) 805.

In an IPEEE case, the licensee postulated a fire scenario in a control room reactor turbine generator board (RTGB) contributing to a core damage frequency (CDF) of 4.47×10^{-5} per year. Installing the in-cabinet ASD VEWFD system resulted in an increased time period between fire detection and mitigation, which the IPEEE states a drop in the overall CDF for the postulated fire scenario to 6.86 E-6 per reactor year (Ref. 23).

The use of ASD VEWFD systems in fire PRA for plants transitioning to NFPA 805 typically followed the interim staff position method described in Supplement 1 to NUREG/CR-6850, Frequently Asked Question (FAQ) 08-0046 titled, "Incipient Fire Detection Systems." In one scenario, several installations of the VEWFD systems were used as defense-in-depth measures only and were not quantified in fire PRA.

For the risk analysis applications, ASD VEWFD systems were exclusively used for in-cabinet (within electrical enclosures) applications in non-continuously occupied areas and in most cases, are complemented by conventional NFPA 72 standard areawide spot detectors within the same room. The installation of ASD VEWFD in-cabinet detection either replaced conventional in-cabinet spot detectors, or provided new detection within the electrical enclosure. The electrical enclosures protected by ASD VEWFD systems contain safe shutdown system function and components. Within these enclosures vital electronic circuitry, instrumentation and

control devices are found along with electrical cable and wiring used by these systems. Ventilation flow rates were not known, but all electrical enclosures that used VEWFD systems were of a vented design. There were no applications identified at the sites visited where VEWFD systems were used to detect smoke entering the return air ducts of the compartment ventilation system.

NFPA 72, "National Fire Alarm and Signaling Code," was used[7] as the code of record for these systems and in one case the response time of 60 seconds found in NFPA 76, "Standard for the Fire Protection of Telecommunications Facilities" was adopted over the 120-second maximum response time specified in NFPA 72. Section 8.5 of NFPA 76 states several requirements for VEWFD and early warning fire detection (EWFD) systems, such as the maximum coverage area per port; minimum sensitivity settings for alert and alarm conditions; and the maximum transport time from the most remote sensing port to the detector (Ref. 22). Section 3.2 of this report provides more detail on smoke detection standards.

Two types of ASD technologies were found to be in use at the sites visited. One site used a laser-based detection technology that had been in use for over 14 years. The other site used a cloud chamber detector technology that had been in service since 2010 (about 20 months of operation at the time of the site visit). Both systems were ASD VEWFD, Underwriters Laboratories (UL) listed, and installed by certified installers. In all cases, the detector unit was located within the same room as the electrical enclosures that were being protected. The distance the detector is located away from the cabinets was dependent on meeting the NFPA response time criteria. One unit consisted of a single zone with five sampling ports, whereas the other system was capable of sequentially sampling multiple zones (up to four) connected to the detector. In the latter case, the cycle time to complete sampling of all four zones was one minute.

The systems were installed by plant craft (instrumentation and control, electrical maintenance, or electrical craft personnel). Once installed, plant operations, engineering, system certifying officials, and the VEWFD system vendor technical representative performed the initial system configuration and testing. The VEWFD systems were initially configured with sensitivity settings consistent with the vendors experience in similar monitoring locations and environments. For one site using a cloud chamber detector, the sensitivity settings were set to a gain of 7 or 8 out of 10, with 10 being the most sensitive range. The specific sensitivity settings within this gain setting were set to vendor predetermined values (30 percent, 50 percent, 70 percent, and 90 percent). Acceptance testing followed, which, depending on the VEWFD systems included the following:

- validation of detector response to smoke source
  - (small element heat gun) provided by the vendor for generation of particles of combustion
  - British Standard (BS) 6266 annex tests
  - test gas/aerosol

- validation of transport times (detector response times)

- placing the detector in fault by restricting air flow

[7] One licensee used the 1996 edition of NFPA 72, while the other used the 2007 edition as the code of reference.

- placing the backup batteries in fault condition
- placing the air separator in a fault condition
- putting the alternating current (ac) power in a fault condition
- confirming proper alarms on detector panel, local interface panel, and fire alarm console in control room.

Following this initial setup, the systems were allowed to operate with this configuration over a period of several weeks to validate set points and lack of nuisance alarms. Upon completion of these activities, the systems were commissioned and placed into operation. Site operators test the systems per their plant procedures, either quarterly or semi-annually and annually. Instrumentation and control technicians maintain and repair the systems with vendor support when needed. As required by the VEWFD system vendor, plant technicians who install and service the detector systems received initial classroom training on the detectors and associated software. Plant operators were also provided classroom and hands-on training for operation of the detector system software and were required to show proficiency with the software to gain qualification. Additionally, teaching aids were provided to the site's training department for continued training.

Availability of these systems varied among the two sites visited. In one instance, the systems were down for semi-annual and annual testing, trouble alarms and for any cases in which the systems were intentionally turned off because of hot work, or other activities that would cause unwanted alarms. Any time the system is off, fire watches are in place. Testing alone could account for up to 8 hours per device per year of downtime. Trouble alerts/alarms received included lower water level; vacuum fault (cloud chamber failure); airflow exceed set point (out of set point tolerance, but within system range); and transport time faults. Most of these troubleshooting alerts/alarms required vendor input to resolve. The other site experienced roughly the same down time for testing, but also experienced several weeks of outage time because of hardware failure. At this site, the system was out for 27 days in 2002 for a panel replacement. The lengthy interruption resulted from not having a replacement panel on site, nor the lead time to acquire a replacement from non-domestic sources. The second outage occurred in 2007 and lasted for 20 days. In this instance, staff initially thought that another panel failure had occurred. This time there was a replacement panel on site, but upon installation, it was determined that the replacement panel experienced an infant mortality failure. The site ultimately determined that the root cause of the initial panel failure was the need for a battery replacement. Upon battery replacement in the initial panel, the system was returned to operation. In all cases, trouble alarms were received from the system and the site instrumentation and controls technicians promptly began their investigation. The sites corrective measure to avoid future excessive downtime was to have spare parts available on site.

No fire, even in its earliest pre-flaming phase, occurred in the areas where the VEWFD systems were installed at either site. In other words, there were no opportunities for these systems to respond to actual incipient fire conditions. However, there were several cases in which the systems generated nuisance alarms because of hot work, grinding and operation of a floor buffer. None of these instances resulted in fires, but this information does provide some quantitative information on the sensitivity of these systems. In response to future unwanted alarms, the utility intends to turn off the VEWFD systems and station fire watches while the

activity/work is completed (that may cause these systems to generate unwanted alarms), and then return the systems to service. From the end users' point of view, the VEWFD systems reacted as designed because of the presence of pre-combustion products being present, and both sites found that the installed VEWFD systems met performance expectations.

As identified by the users, a drawback to these systems was that the required quarterly and annual surveillances were time-consuming and expensive. The sites identified that the systems were complicated and required significant vender interface to ensure proper operation. Lastly, one of the sites ran into an issue with receiving replacement parts in a timely manner, which resulted in an extended outage of the system. Their recommendation was for end users to determine the timeliness of acquiring replacement parts, and to, wherever possible, have spare units on site to reduce extended outage times.

Operator actions in response to system alert/alarm conditions are important to understand in characterizing the failure probability of operators trying to complete specific actions. During the site visits, several questions were asked focusing on how operators would respond to notification from the installed VEWFD systems. The operator responses were slightly different between the facility that used the ASD for fire PRA applications and the one that used it for IPEEE risk reduction.

For the fire PRA case, when an "alert" (pre-alarm) notification is received in the main control room (MCR), an auxiliary unit operator (AUO) and technician are dispatched to the detector zone electrical enclosure(s) to look for source of the notification. The technician is responsible for bringing along a portable ASD, that he/she is trained and qualified to operate. The AUO uses his/her human senses (sight and smell) to try to identify the source of the notification, while the technician uses the portable device. Meanwhile, in the control room, the VEWFD systems software is monitored from the shift technical advisor (STA) desk. If the ASD goes into an alarm state, the fire brigade is activated and sent to the area where the detector is located with necessary equipment for fighting any potential fires.

In the non-fire PRA case, it is important to note that the ASD VEWFD system is installed in the RTGB located in the MCR. The RTBG is located in the front of the MCR, visible to the operators. Both the VEWFD system detector and fire alarm panel are located within the MCR. Upon detector alarm, the response procedure prescribes than an operator is to investigate the five sections of the RTGB for smoke, charring, or overheating components. In addition to a visual inspection, thermography equipment can be used to further investigate the source of the alarm. Upon identification of the component causing the detector alarm condition, shutdown and repair of the affected component are initiated. If necessary, the fire brigade is to be activated. If no source component can be located, then the operator is to attempt to reset the detector. If detector resetting doesn't clear the alarm, a fire watch is to be started, and preparations should be made to activate the fire brigade. If an additional alarm on an opposite zone is received, then the fire brigade is to be activated and the ventilation fans are to be secured.

In all U.S. sites visited, any changes to the ASD VEWFD system sensitivity set points would require an engineering change evaluation. If such changes were deemed appropriate, personnel trained and qualified in the use of VEWFD system software for the installed detectors were to make the approved changes. At the site with the longest operating experience (more than 14 years), the sensitivity has never been changed.

3.1.1.2 Non-U.S. nuclear facilities

The non-U.S. facilities visited use ASD VEWFD systems because at the time of installation (mid-1990s to mid-2000s), they were thought to be the best available detection technology to protect critical areas of the plant that house critical control equipment. In addition, these systems were installed in areas where spot detectors were difficult to install, inspect, test and maintain. Currently, a regulatory design basis standard CSA N293-07, “Fire Protection for Nuclear Power Plants” requires the installation of ASD VEWFD systems that meet the requirements of NFPA 76 where redundant safe shutdown systems are located within the same fire compartment. This standard also has a “control room complex” requirement to detect fires at their incipient stages. In addition, some sites identified the use of standard Underwriters Laboratories Canada (ULC) 536, “Fire Alarm Verification.” Some respondents identified using a 0.1 factor in their fire PRAs for detection using ASD VEWFD system in non-continuously occupied cases. No basis for this estimate was provided.

The VEWFD systems were installed in areawide configurations protecting critical electrical control and instrumentation equipment. VEWFD systems were used to protect control equipment and instrumentation rooms that contained critical reactor control and shutdown equipment. These rooms included the main control room (four unit), control equipment rooms, digital control computer rooms, and cable spreading rooms. The ASD VEWFD systems were typically employed in areas where highly congested overhead components existed, making routine maintenance and testing difficult for conventional spot detection heads, or multi-sensor spot detectors. The ASD VEWFD systems complemented, replaced, or provided new detection to the areas being protected.

Laser-based ASD VEWFD systems, which were used exclusively, operate on a light-scattering principle and use dual photoelectric sensors. The multi-zone detector was the most commonly used design, but there were a few instances in which single-zone detectors were used to protect small rooms. As a pre-requisite for procurement, all detectors had to be ULC listed. Additionally, the systems used also contained listings from UL and Factory Mutual (FM).

The detector units are typically located within the protected zone to minimize any pressure differential effects. The ASD air sample is exhausted into the protected space to ensure that smoke or airborne radioactive particles are not inadvertently propagated to other areas. The detector sampling port coverage is typically 50-75 ft^2, which is less than that required by NFPA 76 (200 ft^2). However, there are several areas near but still below the 200 ft^2 coverage area required by NFPA 76. Ventilation conditions in rooms using ASD ranged from 2.5 to 4.5 air changes per hour[8]. A third party installed the piping network and detectors, while an independent certified engineering firm verified the installation. Commissioning of the system was completed by a trained and qualified entity. Acceptance testing included verifying parameter setup; determining alarm set points; verifying relay/wiring configurations; taking flow; pressure and transport time measurements from each sample hole, conducting heated wire testing, and third party verification.

The systems are maintained by the station control maintenance technicians who received week-long training on the ASD system, the operation, detection panel and software. Annual preventive maintenance accounts for 2-3 hours per detector, per year; monthly maintenance accounted for approximately 12 hours of system down time per detector per year. With the large population of ASD in use at the sites, the typical down time from system failure or trouble

[8] These values are representative of air changes in rooms other than the control room.

is approximately 2–3 hours. As time progressed from initial installation to current conditions, the maintenance staff understanding of the systems operation and failure modes has greatly reduced the down time from random failures or system trouble alarms. Types of trouble alarms received from the devices include: laser problems, filter fault, major/minor flow trouble, and detector failure. One of the sites identified that the typical frequency of trouble alarms from the two-dozen detectors on site was approximately six times per year. When the ASD system is out of service, the site implements continuous fire watches and restricts work activities in the associated protected area.

Operator Interface

Before commissioning the systems, they are placed into an "auto-learn" operating state in which background conditions are monitored to determine the baseline ambient conditions. Following this typically 2-week auto-learn state, the detector sensitivities are set to meet NFPA 76 sensitivity requirements. Temporary changes may be made following the plants temporary configuration change process for cases in which heavy smog or wildfires are found to cause nuisance alarms. Permanent changes to detector sensitivity settings cannot be changed without a design change, as well as the approval of the detection system's responsible design engineer and system engineer.

When pre-alarm conditions are detected, operators attempt to clear the pre-alarm. If unsuccessful, an operator initiates an alert and requests emergency response technician support. When detector alarm conditions are met, operators consult the fireworks computer and data gathering panels for fire alarm message information. In an alarm condition, Operations staff sound the emergency response tones for fire alarm response, which results in the response of the fire brigade. Upon entry into the protected area, staff uses thermal imaging cameras to detect incipient fires.

System Performance

Operating experience identified several system notifications from potential fire sources, including smoke from grinding and welding activities within the protected room; however no opportunities presented themselves for detection of incipient fires that progressed to a flaming state. Air handling unit belt and cork isolator fires were detected. In one instance, a series of alarms was received from an ASD system during commissioning of the reactor's safety system during restart. It was concluded that overheating/charring wire insulation was the cause of the alarms.

Early on during the use of these systems, several nuisance alarms were received. Over the years of use, some of these systems' set points have been offset to account for the environmental conditions, which as a result, have reduced the number of nuisance alarms. The causes of these nuisance alarms include airborne charcoal dust from charcoal filters, fumes from floor stripping, nitrogen purging, dust accumulation within the air sampling ports, but, in some cases, are unknown. The most common cause of nuisance alarms was related to work activities in the protected area when the system was not bypassed for such activities. Also, during the summer immediately following the installation, heavy smog and wildfires in the adjacent province resulted in higher than normal background conditions and resulted in nuisance alarms.

Some final qualitative insights from the non-U.S. nuclear facilities visited included issues with maintenance and sensitivity settings. For maintaining the systems, the users found that it is very difficult to perform any maintenance outside of what is identified by the manufacturer. For instance, if issues with flow, pressure, or transport time measurements are observed at the test

point, it may be required to test the individual sample holes. This can be difficult, time consuming, and may potentially have a negative impact on safety because of the complexity of accessing the sampling pipes and ports in very sensitive areas. In addition, foreign particles or dust may accumulate in the air piping, and in several cases it has been found that the manufacturer's recommended practice of using compressed air is not effective. Alternative actions were required to restore system operations. This specific problem occurred in a ¾-inch diameter piping network. Regarding sensitivity, both operations and control maintenance have indicated that the system is overly sensitive to dust and smog. It was also emphasized that plant personnel are pleased with the ASD VEWFD systems and they work well for small rooms, but in several cases in-duct, non-ASD type detectors were preferred for protecting larger rooms.

3.1.1.3 Other U.S. facilities (non-nuclear)

Non-nuclear U.S. facilities used VEWFD systems because they were specified in their safety standards for fire protection in mission-critical areas.

NASA employed VEWFD systems in mission-critical applications for asset protection. They have over 100 ASD systems designed as VEWFD systems at the site visited, and have a similar number of systems at other major installations. All systems are laser-based; cloud chamber type systems were used for a short period of time, but none remain. The vast majority of ASD systems used were from a single manufacturer. They are also considering or have plans to install video smoke detection and wide-area, beam-type smoke detection in high bay applications.

The basis for using VEWFD systems as specified in NASA-STD-8719.11 Revision A, Safety Standard for Fire Protection (Ref. 24). The standard refers to very early smoke detection, or automatic smoke detection equipment capable of early warning, and references NFPA 72 and NFPA 75. There is no reference to VEWFD systems specifically, nor is NFPA 76 referenced.

All new constructions are required to have VEWFD systems installed. In retrofits, spot detectors remain and are maintained. Applications include clean rooms (tents), high bays, and computer rooms, and all are general area systems; no in-cabinet monitoring using ASD is employed. VEWFD systems are used for duct detection in protected spaces (installed on returns). The layout is designed to meet the time requirements for detection, stated as 60 second–plus delays. There are pipe length restrictions, which can be relaxed if the system is engineered, (i.e., pipe flow software).

Systems are installed by factory-certified contractors, and are serviced in-house by factory trained technicians, who are certified (Level II) by the National Institute for Certification in Engineering Technologies. There is a 30-day burn-in period after installation, and commissioning includes formal acceptance testing. The performance test procedure was not specified, but is most likely handled by the contractor to industry specifications; the assumption is that they follow the test procedures outlined in NFPA 76 Appendix B.

The NASA experience with VEWFD systems includes the following observations:

1. Fewer nuisance alarms were installed than spot detectors.

2. Issues arose from flow imbalances tripping airflow trouble alerts. The fix usually involves piping the exhaust back to the protected space.

3. One system sensitivity adjustment was made (lowered) because of picking up a circuit board "fry," which is not unusual in areas with instrumentation assembly.

4. Nuisance alarms occurred because of vacuum dust.

5. Fire was recently picked up in a lab space.

The technicians check all pre-alert and trouble signals; (response is not time sensitive) Fire I level does not evacuate the building; however, Fire II results in fire department response. Sensitivity set to an equivalent 3 %/ft obscuration at sampling locations.

3.1.2 Other sources of operating experience information

<u>Conference Proceedings</u>
Forell and Einarsson identified one weakness in the fire detection systems evaluated in German NPP units associated with the battery system (Ref. 25). Fire detection systems are connected to the emergency power supply and equipped with an additional battery, making the fire detection systems' power supply both reliable and redundant. However, in one reportable case it was identified that the emergency power supply failed, the fire detection system properly functioned on the backup battery supply until its energy was depleted. It wasn't until sometime later (not reported) that operators identified the failure, leaving portions of the plant unprotected for an extended period of time. Although the fire detection system backup power supply performed as designed, human error, in not recognizing that the primary power supply had failed, resulted in unavailability of the system.

Forell and Einarsson also reported that the primary cause of failures in ASD systems can be attributed to flow changes caused by clogging of inlets and leaks in the pipework. The use of ASD systems in German NPP units is a result of changes to Insurance Europe (formally the Comite Europeen des Assurances) and the European Standard EN 54 Part 20. Because of the clogging and pipe leakage issue, the new specifications require an increased tolerance of changes in ASD air volume flow from ±50 percent to ±20 percent (Ref. 25).

3.1.3 Experience within other industries

<u>Telecommunications</u>

The Network Reliability Council of the Federal Communications Commission (FCC) identified fire protection challenges related to the network reliability of public telecommunications. Their focus on a need to improve reliability in protecting the network from fire effects was largely a result of a main switching room fire that occurred in the Hinsdale Central Office of the Illinois Bell Telephone Company on May 8, 1988.

At the time, the Hinsdale Central Office was one of the largest switching systems in the state of Illinois; the facility processed more than 3.5 million calls per day, including calls from numerous hospitals, as well as the communications between Chicago's O'Hare and Midway Airports. As the Hinsdale Central Office was not continually occupied, after receiving fire and power failure alarms at the Alarm Reporting Center, it took nearly an hour before a technician arrived at the facility. Upon arrival it was determined that the fire had become large enough to require fire department response, and had knocked out much of the region's telephone service, requiring the responding technician to drive to the fire department to initiate their response. Battling the fire involved additional complications in that the uninterruptible electrical power

supply associated with the fire area was still live, and the lack of telephone services meant that the local power company could not be contacted to remove power. Two hours were lost while firefighters manually removed all fuses from the power feeds to the building. In addition, toxic fumes from fiber optic equipment required the response of hazardous materials experts and evaluation of civilians living within five blocks of the Central Office. All told, the fire lasted for more than six hours, and it took nearly two weeks to completely restore service (Ref. 26). Although the Hinsdale event is described in detail, there have been numerous other catastrophic fires in telecommunications facilities, including one that occurred only one month before the Browns Ferry Fire of 1975, in a New York City Telephone Exchange.

As a result of the recurrence of severe fire events in telecommunication facilities, and the need to maintain high reliability and business continuity for these types of installations, the telecommunications industry developed NFPA 76, "Standard for Fire Protection of Telecommunications Facilities." This standard provides the minimum level of fire protection in telecommunications facilities to protect equipment and service continuity where services such as telephone (landline, wireless), data, internet, voice-over internet protocol and video transmission are rendered to the public. Details on this standard are provided in Section 3.2.

As a result of this standard, the telecommunications industry has extensively used ASD technology in certain applications to provide advanced warning. Part of the reasoning for using ASD technologies are employed in telecommunication facilities, in part, as a result of difficulties in implementing conventional spot-type smoke detection in environments with high air ventilation rates and numerous complex physical configurations. Common telecommunication challenges to detecting fires in information technology (IT) server room environments include the following (Ref. 27):

1) varying fuel loads and ignition sources
   - large number and concentration of electronic devices generate excessive amounts of heat

2) obstructions that interfere with movements of smoke toward detection points
   - server enclosures

3) high airflow
   - smoke dilution

<u>U.S. Navy</u>

Engineers at the Naval Sea Systems Command indicated that they were unaware of any U.S. Navy ships that employ these types of systems. Spot-type smoke, heat and flame detectors are commonly used on surface ships. Because of the large size and number of compartments aboard, the increased cost and installation difficulties make using ASD systems challenging. However, future ship designs are expected to use ASD systems (not configured as VEWFD) in a limited number of special applications, because of unique overhead structures (Ref. 28).

3.2 Standards, Listings, Approvals and Codes of Practice

Standards, listings, and approvals provide a means to demonstrate that a product meets a minimum level of performance. Applicable standards for air sampling smoke detection systems include NFPA 72, "National Fire Alarm and Signaling Code," and NFPA 76, "Standard for the

Fire Protection of Telecommunications Facilities." BS 6266, "Fire Protection of Electronic Equipment Installations – Code of Practice," also provides useful information on the use of ASD systems. Listings and approvals provide a structured and inspectable process to ensure that equipment, materials, and services meet identified standards, or have been tested and found suitable for a specific purpose. Listings and approvals are provided by organizations that are acceptable to the authority having jurisdiction (AHJ), such as UL or FM.

The remainder of this subsection provides a brief overview of the associated standards and listings. For specifics on these standards, the reader may reference the applicable standard(s).

NFPA Standards

NFPA 72 establishes the minimum required level of performance for the application, installation, location, performance, inspection, testing and maintenance of fire alarm systems. It provides installation guidance for air sampling-type smoke detectors, but doesn't identify any requirements for VEWFD or EWFD systems. The guidance provided includes maximum transport time, each sampling port to be treated as a spot-type detector, air flow trouble signal, pipe labeling and a requirement the sampling pipe networks be designed and supported by fluid dynamic principles.

NFPA 76 provides installation requirements for VEWFD systems used in telecommunication facilities. The requirements of NFPA 76 detail the maximum coverage area; requirements for monitoring air return ventilation from protected space; minimum sensitivity settings for alert and alarm conditions; and the maximum transport time of the system. Although NFPA 76 provides requirements for protection of telecommunications facilities, there is no other U.S. consensus standard that is available for these systems, and as such, most U.S. NPP utilities reference NFPA 76 as the standard applicable to their VEWFD system.

In addition to specifying the performance requirements of VEWFD systems, Annex B of NFPA 76 also provides performance test procedures. Two types of tests are presented in the annex. One uses a heated wire, while the other uses chemicals. Both tests are designed to simulate small amounts of visible smoke that would be present in the early stages of a fire in a telecommunications equipment area. The intent of the tests is to provide a quick, easy, and repeatable functionality test (quantity, temperature, and color of smoke), while minimizing the potential hazard to the facility and health of personnel in the test area. These test methods are not intended to serve as a calibration of the ASD detection unit.

Listings and Approvals

UL provides a URXG product category listing that covers smoke-automatic fire detectors, including air sampling types, employing a special construction different from conventional detectors and designed to detect products of combustion in a specific location. Detectors with this listing are installed in accordance with manufacturer installation instructions, in a manner acceptable to the AHJ, and in accordance with NFPA 72. The basic standard used to investigate products in this category is UL 268, "Smoke Detectors for Fire Alarm Signaling System."

UL 268 covers smoke detectors defined as "*an assembly of electrical components arranged to detect one or more products of combustion*." It provides a standard set of requirements for smoke detectors employed in ordinary indoor locations, in accordance with NFPA 72. These include assembly and component requirements, evaluation of detector performance under

numerous conditions, manufacturing and production requirements, along with required markings and installation instructions. The standard evaluates detector performance by conducting numerous types of tests, including detector sensitivity, fire, temperature, humidity, and endurance, among others. Because ASD VEWFD sensitivities can be outside the sensitivity test range of 0.5 to 4.0 %/ft obscuration, specified under Section 30, the UL URXG product category uses the sensitivities recorded during the fire test for the detector listing. The standard also requires a means for measuring or indicating the nominal sensitivity or sensitivity range of the detector after it has been installed as intended. This is to verify that the sensitivity of the detector is within its marked range (UL 268, Section 6.2 & 30). The sensitivity testing can be conducted using the typical United States sensitivity smoke test chamber as described in Annex B of UL 268, and a smoldering cotton lamp wick, or an aerosol generator, either of which will produce gray smoke.

FM provides independent testing and approval of smoke actuated detectors, including any aspirating-type detectors for indoor locations, per its Class Number 3230 "Approval Standard for Smoke Actuated Detectors for Automatic Alarm Signaling." FM approval criteria include performance and marking requirements, manufacturing facility examinations, quality assurance procedure audits, and a followup program. Performance requirements include air flow, transport time, sensitivity, and fire tests, per UL 268 Section 39 guidance.

Codes of Practice

British Standards Institution (BSI) publication BS 6266, "Fire Protection of Electronic Equipment Installations—Code of Practice," provides recommendations for the protection of electronic equipment from fire. It identifies electronic equipment such as computer servers, communications systems, design, manufacturing and distribution equipment. Because the scope of this standard is for the protection of electronic equipment, it covers a variety of fire protection topics, including separation, construction, building services, detection, suppression, smoke control, and management. BSI 6266 indicates that all ASD systems should conform to BS EN 54-20, "Fire Detection and Fire Alarm Systems. Aspirating Smoke Detectors," and be used in accordance with the Fire Industry Association (FIA) Code of Practice. For the interests of this report, the information on detection, along with the material presented in Annex A on spacing and location, are useful.

Annex A of BSI 6266 provides recommendations for the spacing and location of aspirating sampling holes. For return air vent applications, it is recommended that each sampling port have a maximum 0.4 square meter (m^2) area of coverage, be a Class A system per EN 54-20, and that manufacturers' recommendations should be followed. For ceiling applications (including floor or ceiling voids), a nominal effective sampling hole coverage area of 25 m^2 is specified. The Annex then identifies that the coverage area can be increased or reduced depending on various room attributes (e.g., air flow velocity, air conditioning state, detector class, or layered detection configuration). For in-cabinet applications, the Annex recommends that the sampling hole be placed where the ventilation exits the electrical enclosure, or within the top 10 percent of a cabinet with no ventilation (sealed). There are also provisions for using multiple sampling points within the same cabinet that has large vents. Annexes B through H describe the various performance tests, including smoke pellet; paper; overheated enamel wire; polyvinyl chloride/low smoke and fume (PVC/LSF) wire; PVC coated wire; resistor; polyurethane mat; and potassium chlorate/lactose chemical test.

The FIA (England) has also developed a code of practice document titled, "Design, Installation, Commissioning and Maintenance of Aspirating Smoke Detector (ASD) Systems" (Ref. 29).

This document defines three sensitivity classes (Class A, B, C),with Class A being described as "Very High Sensitivity" applicable for in-cabinet application with high risk, as well as five ASD sampling methods, including in-cabinet applications. It also explains that when operating as a Class A or Class B system, the source of the alarm may not be readily visible and special training should be provided to acquaint responders with the performance of these systems. With regard to in-cabinet detection, the code of practice recommends that a sample point in each cabinet be installed, and specifies preferred locations of sampling within the cabinet for cabinet ventilation configuration (sealed, natural or forced). The in-cabinet application section also provides recommended limits on the number of cabinets protected by various classes of systems. In general, the FIA document provides fundamental design guidance of ASD systems for various applications and supports the use of vendor experts to ensure that the design will meet the intended design goals.

3.3 Literature Review

A literature review was conducted to better understand the information available on the use of ASD VEWFD systems. Literature was collected from publically available sources, academia, Internet, vendor Web sites, and journal articles. The collected literature was reviewed and evaluated for its applicability in developing the test plan and to better advice regarding the capabilities of this technology. Appendix E provides a summary of relevant literature reviewed.

In general, there has been substantial work in supporting the use of ASD VEWFD systems in special applications, such as telecommunications facilities, warehouse, atria, and as a reference tool to support evaluation of model prediction of conventional spot-type detector activation. Unfortunately, most of the available test programs were developed to acquire data needed to support a specific application.

4. EXPERIMENTAL APPROACH

The purpose of the experiments conducted in this program was to provide a quality data set to allow for the evaluation of the responsiveness and effectiveness of aspirating smoke detection (ASD) very early warning fire detection (VEWFD) systems and make comparisons to conventional spot-type detectors. The experiments were focused on evaluating the responsiveness of detectors to aerosols generated from the degradation of polymer components commonly found in NPP electrical enclosures. Experiments were conducted at three different facilities, a laboratory space at NIST; a 38 m^2 floor area, 90 m^3 volume fire test room (small room) located at the Montgomery County Public Service Training Academy in Rockville, MD; and a 93 m^2 floor area, 283 m^3 fire test room (large room) at Hughes Associates Inc., located in Arbutus, MD.

Experimental configurations were selected to represent a limited range of possible in-cabinet and areawide arrangements and incipient fire scenarios, and as such, the results alone do not represent a complete performance assessment. The experimental designs for the different size scales were developed to assess performance of specific smoke sources; and variations in the location of sources; detectors; sampling ports; and ventilation (in-cabinet and areawide). Each set of experiments added to the overall performance assessment of ASDs in VEWFD applications.

4.1 Detectors

There are currently several vendors that offer air-aspirated VEWFD systems and many vendors that offer conventional spot detectors. It was not the intent of this research to perform a product comparison or evaluation of specific vendor products, but rather, to provide information on the performance of VEWFD systems with regard to the objectives listed in Section 1.3. As such, several different air-aspirated VEWFD systems were procured, and are generically identified in Table 4-1 as ASD1-ASD5. The sensing technologies of these ASDs included both light-scattering and cloud chamber based. Single-zone ASDs have a single sampling pipe directed to the detector, thus all sampling locations are incorporated into the air flow being monitored by the detector. Multi-zone ASDs have more than one sampling pipe directed to the detector and a selection valve cycles between different incoming pipes, thus more than one zone can be monitored by an individual multi-zone detector. Conventional spot detectors were procured to provide representative spot-type technology comparisons. The following three types of spot detectors were included: PHOTO, ION and SS that can be used in a VEWFD system.

Table 4-1. Smoke Detection Technologies Generic Identification System

Detector ID	Technology	Application
ASD1	Single-zone, air-aspirated, light-scattering	VEWFD
ASD2	Single-zone, air-aspirated, cloud chamber	VEWFD
ASD3	Single-zone, air-aspirated, light-scattering	VEWFD
ASD4	Multi-zone, air-aspirated, cloud chamber	VEWFD
ASD5	Multi-zone, air-aspirated, light-scattering	VEWFD
SS	Spot detector head, sensitive photoelectric	VEWFD*
PHOTO	Spot detector head, photoelectric	Conventional
ION	Spot detector head, ionization	Conventional

* For areawide installations, VEWFDS sensitivity settings were used, but coverage was the same as the conventional spot detectors.

The aspirated detector systems ASD1-ASD5 are stand alone, while the spot detectors are interfaced to a fire alarm control panel (FACP). Because the spot detectors interfaced to the FACP were addressable, the individual detector response times were identifiable.

The intent of this research was to examine the gross differences between VEWFD systems and conventional detectors, and the expected performance from a range of VEWFD system implementations. Because National Fire Protection Association (NFPA) 76 specifies the minimum sensitivity settings above ambient background levels for VEWFD systems as an **Alert** level of 0.2 %/ft obscuration at each port (or sensitive spot detector), and an **Alarm** level of 1.0 %/ft obscuration, these were the target sensitivities for ASDs and the sensitive spot detector. In addition to **Alert** and **Alarm** settings, ASDs typically have additional adjustable settings. Thus, a **Pre-alert** setting, more sensitive than the **Alert** setting, may be considered to instigate a non-emergency investigation. Conventional photoelectric and ionization detector sensitivities were set to the factory default settings. The specific photoelectric and ionization detectors were individually addressable and had the feature of two sensitivity settings, a **Pre-alarm** and an **Alarm** threshold. Per NFPA 72, 13^{th} Ed., an alarm condition poses immediate threat to life, property or mission, while a pre-alarm condition poses a potential threat but time is available for investigation. For the testing completed, the pre-alarm setting is more sensitive than an alarm setting, but still within the listing of the detectors used.

There was an issue identified concerning sensitivity settings for the procured cloud chamber ASDs, which was not fully resolved. These ASDs do not report detector sensitivity in terms of ANSI/UL 268 standard engineering units of percentage of obscuration per foot, but, in terms of numeric (dimensionless) settings. That being said, for the testing performed to support this research, the dimensionless units were converted to a nominal particle number concentration obtained from the cloud chamber ASD software. An assumption was made that the number concentration is a linear function of the obscuration, as would be the case with low concentrations of the same smoke particles. The cloud chamber ASD sensitivity settings were selected to represent **Alert** and **Alarm** settings that covered a range. These settings were not fixed, but may have changed for different experimental configurations. The exception was the last series of experiments with the multi-zone cloud chamber ASD, in which the vendor commissioned the system, and provided the sensitivity settings.

The terms **Alert** and **Pre-alarm** are synonymous. Both intended to present a condition where a potential threat is posed and sometime of unknown duration is available for investigation. However, this report will use the terms consistent with the associated NFPA standards. That is, **Alert** will be used exclusively for VEWFD systems per NFPA 76 and **Pre-alarm** will be used exclusively for the conventional spot-type detectors per NFPA 72.

4.2 Incipient Fire Sources

A key to the assessment of any detection system is identifying challenging scenarios that need to be detected, then evaluating detection systems against surrogate test conditions that represent those scenarios. For example, the performance requirements for residential smoke alarms were developed from relevant household fire scenarios, while the performance requirements for VEWFD systems in telecommunications facilities were developed from scenarios deemed to be appropriate for that application. For NPP in-cabinet and areawide applications, there were no documented, challenging incipient fire scenarios that could have formed the basis for surrogate test conditions. Thus, a major task in this research was to

develop surrogate test conditions that were plausible, and challenging for both in-cabinet and areawide applications.

It is assumed that the most probable, slowly developing incipient fire sources of the type that a VEWFD system would be used to detect, would be electrically initiated. That is, electrical power is the energy source used to produce the heat needed for the incipient source. Electrically initiated fires are often preceded by some form of arcing or joule heating of electrical components. The literature lists various ways electrical fires may be initiated including arcing, overloads, poor connections and corrosion (Ref. 30, 31, 32). Regardless of the failure mechanism, heat is typically conducted from a metallic electrical conductor to an insulating polymeric material. Upon heating, insulating polymeric materials degrade, and pyrolysis products can condense into smoke particles, which in sufficient concentration, can be detected. Therefore, to assess the performance of VEWFD systems, smoke sources were developed that mimic slow overheat conditions which degrade polymeric insulating materials and produce smoke before flaming combustion.

The smoke sources were designed to mimic smoke evolution from a particular scenario likely to be experienced in various electrical fires. A current overload, a high-resistance connection, or combination of both produces joule heating that conducts heat to polymeric insulating material, here, wire insulation, a printed circuit board, or terminal block insulation. As the material heats up, it starts to thermally degrade, gases are released, and a fraction forms pyrolysis smoke particles. The temperature at which particles are formed, the amount, and particle size depends in part on the specific material, including the base polymer and additives.

The goal was to produce sufficient smoke to initiate alert and alarm conditions in some or all detectors during a test. No attempt was made to achieve a flaming combustion transition as a test end point. It is not necessary to have flaming ignition to provide a relative comparison between detector technologies. It is, however, useful to specify a condition indicative of imminent hazard for performance analysis purposes. In the data analysis, the end of test is specified as an imminent hazard based on the heating source end temperature, and the extent of thermal damage to the materials being heated. The rationale for choosing the final heat source temperature achieved at the end of the test as an imminent hazard given the ignition potential of the materials studied is detailed below

Transition to flaming requires an ignition event which would be scenario specific and frequently a stochastic event. The ignition event could be piloted or non-piloted. A piloted ignition would occur when a flammable mixture of the pyrolysis gases and air encounter an electrical arc or spark whereas it ignites and a flame is established. A non-piloted ignition would occur when the temperature of the degrading material is such that the reaction of the pyrolysis gases and air spontaneously ignites and establishes a flame. For solids, piloted ignition is often characterized by a piloted ignition temperature specific to a material, while non-piloted ignition is characterized by a non-piloted ignition or auto-ignition temperature specific to a material. Piloted ignition temperatures are lower than auto-ignition temperatures. Babrauskas tabulated a range of ignition temperatures of plastics obtained by various literature sources based on broad polymer property classes for both piloted ignition and auto-ignition experiments (Ref. 33). The classes in the table represent a range of electrical insulation materials. The tabulated values are shown in **Error! Reference source not found.** below.

Table 4-2. Ignition Temperatures for Plastics Grouped by Polymer Properties (Ref. 33)

Polymer Property Class	Piloted Ignition Temperature	Auto-ignition Temperature ˚C
Thermoplastic	369 ± 73 ˚C	457 ± 63 ˚C
Thermoset	441 ± 100 ˚C	514 ± 92 ˚C
Elastomer	318 ± 42 ˚C	353 ± 56 ˚C
Halogenated	382 ± 70 ˚C	469 ± 79 ˚C

One can imagine three scenarios influencing the probability of ignition. In the first scenario, an ignition source of sufficient strength is available at the onset of material heating. The material must be heated to a point where the necessary gaseous pyrolysis fuel and air form a flammable mixture. At that time, the gases ignite and establish a flame. This would be piloted ignition at the lowest possible material temperature. An example would be continuous arcing that provides sufficient heating to form a flammable mixture, with the arc itself acting as the ignition source.

In the second scenario, no piloted ignition source is available, and the material must be heated to its auto-ignition temperature, whereas the material ignites. Whereas the auto-ignition temperature is higher than piloted ignition temperature, these two temperatures bound the minimum temperatures for ignition, below the minimum piloted ignition temperature the necessary conditions do not exist for ignition, and at or above the auto-ignition temperature both necessary and sufficient conditions exist and ignition will occur.

The third scenario involves an intermediate temperature range above the minimum piloted ignition temperature and below the auto-ignition temperature. This scenario would involve the introduction of an ignition source at some time when the material is in the intermediate temperature range. The introduction of an ignition source would be a stochastic ignition event involving a shorting spark, a wire breaking spark, a tracking arc, or a glowing hot surface either of which at the right location and of sufficient energy to ignite the material. For a current overload condition, or a high resistance connection, it is plausible to assume that the probability of any stochastic ignition event described above would increase as the heating time increased because of the level of local damage to the insulating material.

Given the smoke sources developed for the VEWFD experiments, the ignition scenario above is an appropriate assumption to make, where some stochastic ignition event occurs before auto-ignition of the material being heated. The end of test heating source temperature was initially selected as 450 degrees C, for scoping experiments conducted in the laboratory at NIST, and subsequently raised to 485 degrees C to produce more smoke at the end of the test for full-scale experiments. Given the tabulated values of the piloted and auto-ignition temperature ranges above, the end of test was specified as a condition of imminent hazard because the end of test heat source temperature is in the range of auto-ignition temperatures and the materials being heated appear to be above piloted ignition temperatures based on temperature measurements detailed in Section 5.8. Also, ignitability experiments in Section 5.8 show that piloted ignition is achievable at heating source temperatures well below the end of test value for three down-selected materials. A more detailed analysis of ignition scenarios or ignition probability is not within the scope of this research.

A range of polymeric materials was initially selected for research, including electrically insulated materials, representing polymers found in nuclear power plants (Ref 31), and other electrical insulating materials. It is important to note here that such materials are not virgin polymers, but a mixture of polymeric material and additives necessary for processing, electrical characteristics, flame retardancy, etc. The first 11 materials listed in Table 4-3 were used in the incipient smoke source experiments. Other materials included in this research, which were not considered slowly developing incipient sources, were overheated resistors and capacitors, an insulated wire used in standard tests (British Standard BS 6266), and smoldering, shredded copy paper. These materials were used to provide challenging, but short-lived smoke sources for in-cabinet experiments with resistors and capacitors; a non-polymeric smoldering source for areawide experiments; and a standardized source to assess areawide system design. The materials used in the in-cabinet and areawide experiments are described in Table 4-3. The material names and ID numbers are short-hand descriptions used in the report; wire descriptions refer to conductor size using the American Wire Gauge (AWG) nomenclature. The RoHS descriptor refers to materials that pass the European Union “Restriction of Hazardous Substances Directive”.

Table 4-3. Materials Used in Experiments

ID #	Name	Description of Material*
1	PVC1	Polyvinyl chloride insulated, 18 AWG wire, RoHS lead-free
2	PVC2	Polyvinyl chloride insulated, 14 AWG wire, RoHS lead-free
3	Silicone	Silicone insulated , 18 AWG wire, RoHS lead-free
4	PTFE wire	Polytetrafluoroethylene insulated, 14 AWG wire, lead free
5	XLPO1	Cross-linked polyolefin insulated, 12 AWG wire, RoHS lead free
6	XLPO2	Cross-linked polyolefin insulated, 12 AWG wire, lead free
7	XLPE	Cross-linked polyethylene insulated, 12 AWG wire, lead free (Synthetic Insulated Switchboard, SIS wire)
8	CSPE	Chlorosulfonated polyethylene insulated, 10 AWG wire , lead free
9	PCB	FR4, glass-reinforced epoxy laminate circuit board
10	TB	Phenolic barrier terminal block
11	Cable Bundle	NPP cable XLPE jacket, XLPO insulation 7 wire, 12 AWG wire
12	Resistor	12 ohm, ¼ W, carbon film resistor
13	Capacitor	Small electrolytic can type
14	BS 6266 Wire	PVC, BS 6266 test wire
15	Shredded Paper	Copy paper run through paper shredder, ignited with a smouldering wick

* Wires 4, 6, 7, and 11 were classified as qualified per IEEE 383, “IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices and Connections for Nuclear Power Generating Stations.”

Other materials included in this study as implemented which were not considered slowly developing incipient sources included overheated resistors and capacitors, an insulated wire used in standard tests (British Standard BS 6266), and smoldering shredded copy paper (materials 12-15 in Table 4.2). The scenarios developed were challenging, but short-lived smoke sources in the cases of in-cabinet experiments with resistors and capacitors, a

nonpolymeric smoldering source for areawide experiments, and a standardized source to assess areawide system design. Experiments with these sources were included as reference sources and were not considered in any analysis of VEWFDS effectiveness in this report.

4.2.1 Bus bar heat source (insulated conductors, terminal block and printed circuit board)

The first 10 materials were degraded by conduction of heat from a copper block bus bar whose temperature was ramped from ambient to 450 ºC or 485 ºC. The bus bar was 9.84 cm long and 3.2 cm square with a 9.5 mm hole drilled out along the long axis to accommodate a 500 watt electric cartridge heater. Figure 4-1 is a schematic of the bus bar.

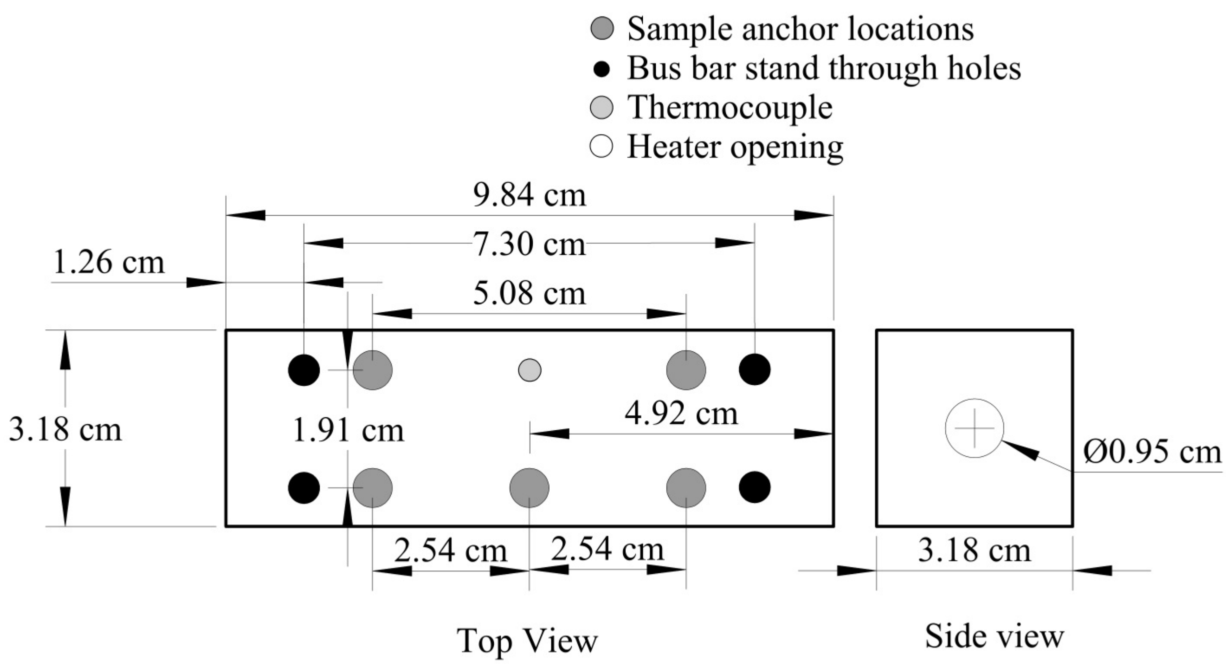


Figure 4-1. Schematic of the bus bar

Wire samples were cut to 10.0 cm lengths, with 3.0 cm of insulation stripped from one end. Up to five samples of the same wire type were attached to the bus bar by wrapping the stripped wire end around a machine-head screw that passed through the bus bar and was held in place with a nut. The screw was tightened to the bus bar with a torque wrench to 110 ± 5 N-m. Wires were mounted such that a 5-mm length of stripped wire separated the bus bar from the insulated wire and 7 cm of insulated wire extended horizontally from the bus bar. An example of a prepared assembly before heating is shown in Figure 4-2. (Smoke production from wire sources was adjustable based on the number of wires attached to the bus bar. Early scoping experiments were conducted with fewer than five wires, but it was observed that the best chances for conventional alarm response were realized with the five-wire arrangement.)

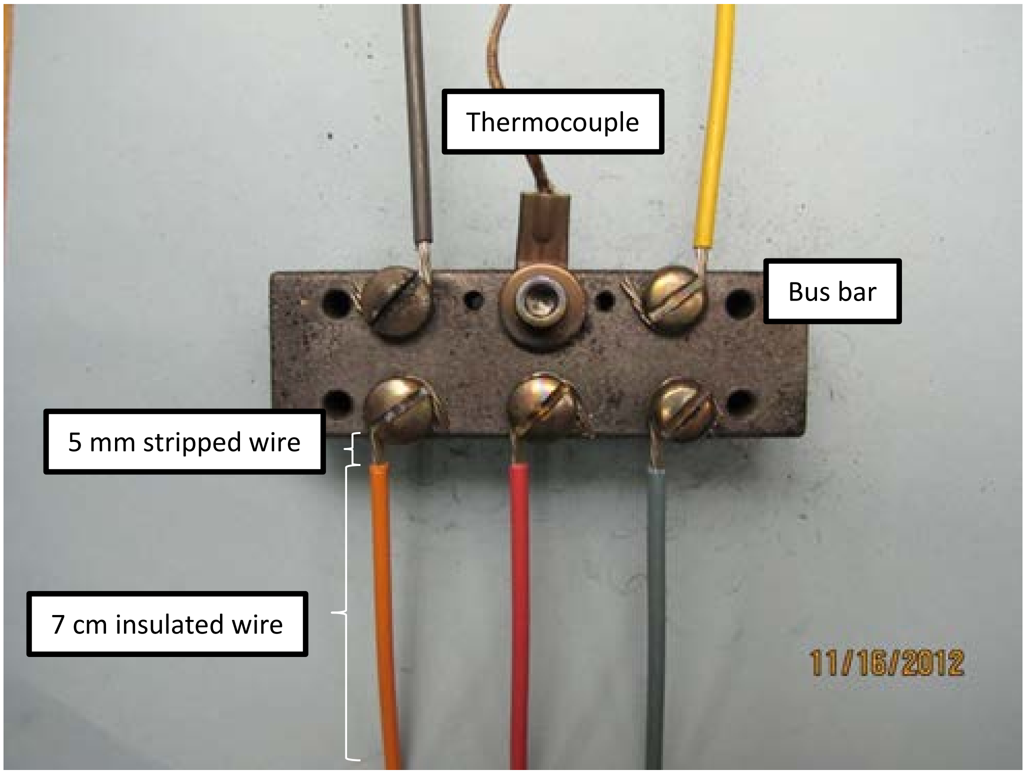


Figure 4-2. XLPO2 wire mounted to the bus bar

The bus bar was mounted on a stand such that the wires were located 13 cm above the ground. The stand had four posts that fit inside the bus bar through holes. The stand provided a stable platform, and thermally insulates the copper block from the floor to some extent. The bus bar with wire samples attached and placed on the holder, can be seen in Figure 4-3. The assembly was then placed inside a cabinet or on the floor for areawide experiments. A cartridge heater was inserted into the bus bar, a ground wire was attached to the stand, and the thermocouple was connected to the temperature controller.

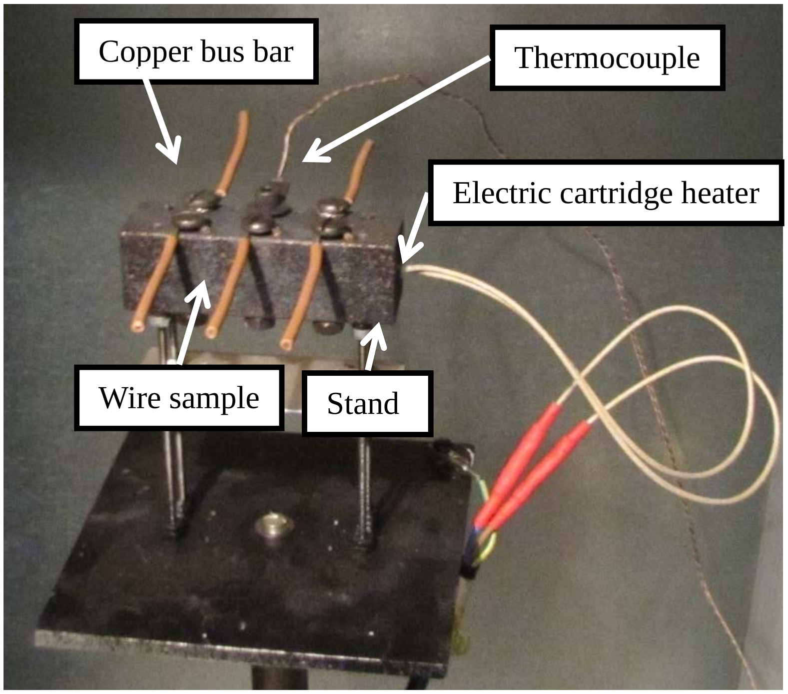


Figure 4-3. The bus bar mounted on the stand inside a cabinet

Six heating profiles were specified using three set point heating ramp periods (HRPs) and two final set point ending temperatures. The first set of preliminary experiments were conducted with three heating profiles: a 15 minute set point ramp from ambient to 450ºC with a 5 minute soak period where the set point remained at 450ºC, a 60 minute ramp to 450ºC with a 5 minute soak, and a 240 minute ramp to 450ºC with a 5 minute soak. Subsequent experiments were conducted using three set point ramps to 485ºC, keeping the same slope as the first set, which extended the HRPs to 16.3, 65, and 260 minutes, and maintaining the 5 minute soak period for total heating times (THTs) of 21.3, 70, and 265 minutes, respectively. Set points read back from the controller and bus bar temperatures were recorded in a heater log file for all experiments.

The three heating profiles of nominally 15-, 60-, and 240 minute heating duration represent a factor of four increase from the first to the second, and the second to the third heating duration, and heating rates of 28.33ºC/min, 7.08ºC/min, and 1.77ºC/min, respectively.

Actual failure mechanisms that cause heating of polymeric insulating materials could present other than linear heating profiles in the incipient phase that could be increasingly faster or slower than a linear heating ramp. Linear heating ramps were chosen since actual heating profiles are unknown, and the three linear heating ramps cover a wide range of heating rates.

Figure 4-4 shows set point ramps for 15-, 60-, and 240 minute HRPs along with two bounding heating profiles, a logarithmic and exponential increase in the heating profiles ending at 485 degrees Celsius (C) after 1 hour. The three linear ramp slopes are bound by the logarithmic profile from 265 degrees C to 412 degrees C, and the exponential profile from 41 degrees C to 446 degrees C which covers a temperature range where degradation is detectable by the ASDs.

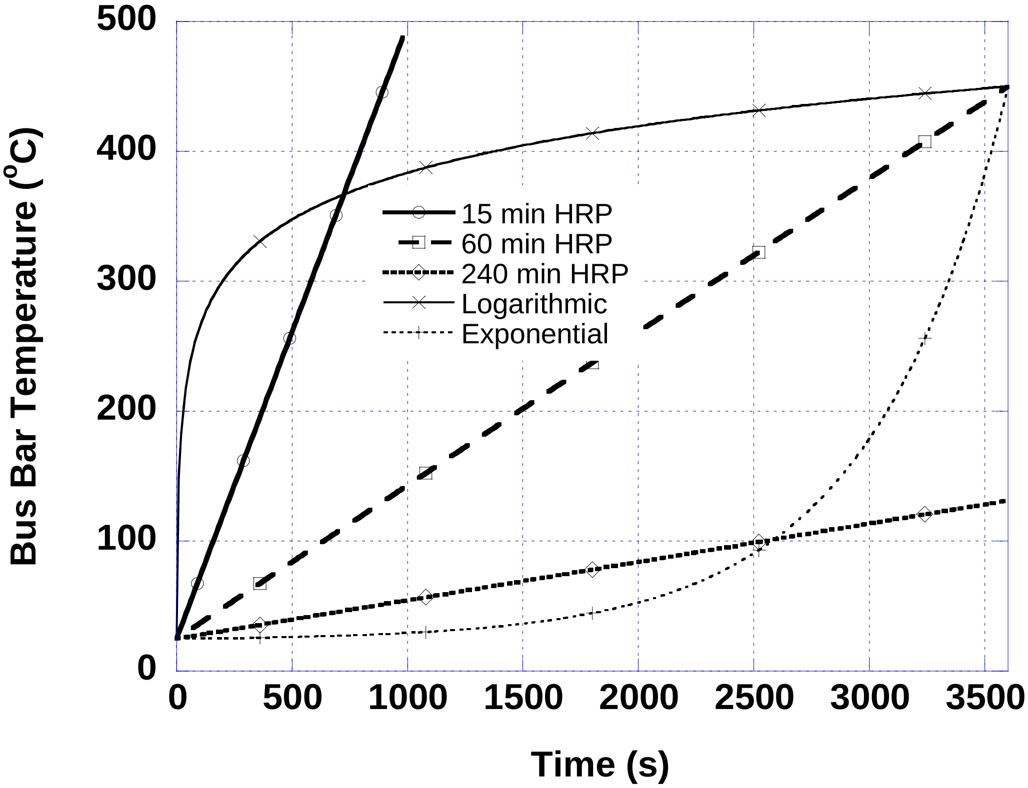


Figure 4-4. Heating ramp profiles for 15, 60, and 240 minute HRPs, with logarithmic and exponential bounding profiles that reach 485 °C in 60 minutes

A load cell was used to weight the wire samples before and after each test. The expanded combined uncertainty of the mass measurement was 5 mg. Other test samples were not weighed.

In addition to the wire samples, printed circuit board (PCB, 10.1 cm by 10.2 cm by 0.1 cm thick) and phenolic resin terminal block (TB, 5.5 cm by 1.8 cm by 0.6 cm thick) samples were also used in experiments. The PCB was clamped between two 25 mm by 10 mm by 6 mm thick copper plates, with the bolts tightened using a torque screwdriver to 110 ± 5 N-m. Because the degradation was localized to the side being heated, a PCB could be reused for an additional experiment. The terminal block was mounted to a copper plate (2.5 cm by 10 cm by 0.3 cm thick) with two screws, with the plate then bolted to the bus bar. A mounted PCB and terminal block can be seen in Figure 4-5 and Figure 4-6, respectively.

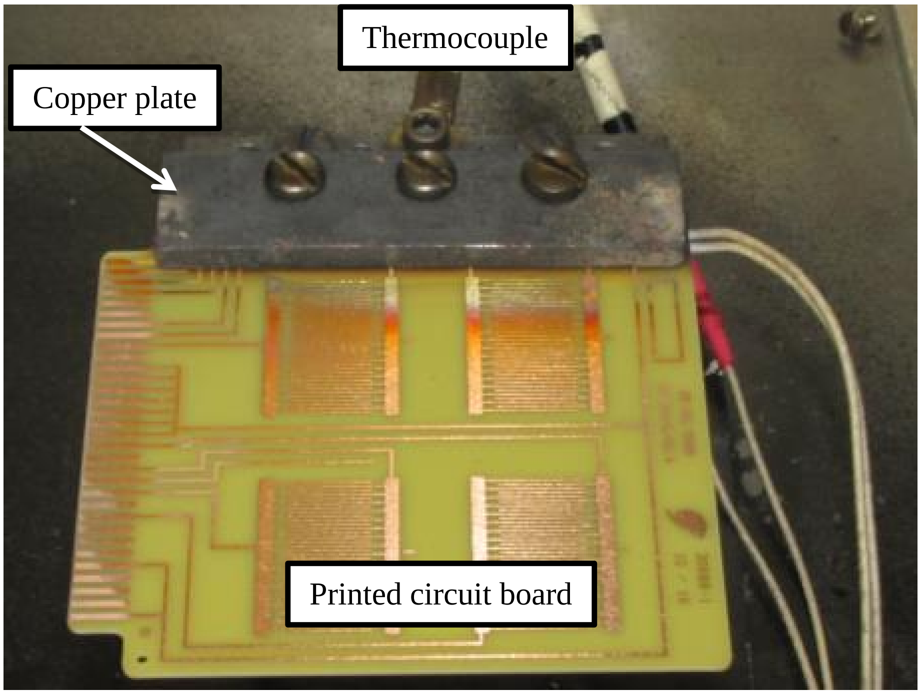


Figure 4-5. Printed circuit board (PCB) mounted to the bus bar

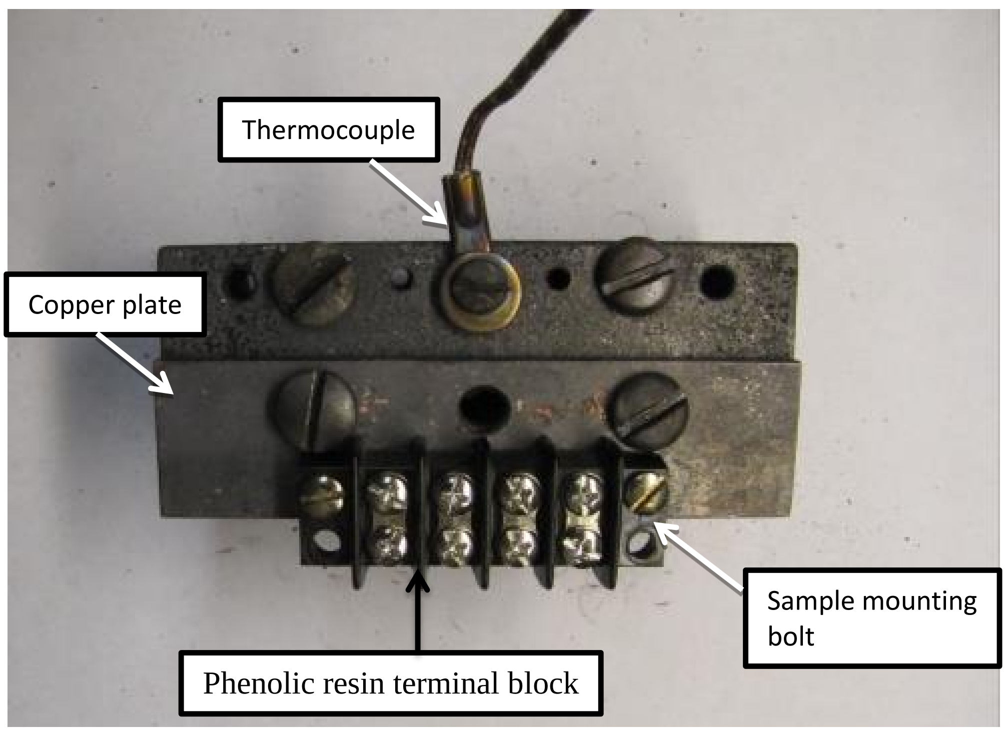


Figure 4-6. Terminal block (TB) mounted to the bus bar

4.2.2 Cable bundle sample preparation

The cable bundle source was a 7-wire bundle of 12 AWG cross-linked polyolefin insulated (XLPO) insulated wires with an outside jacket of cross-linked polyethylene (XLPE). The cable diameter was 13 mm. Six 12 cm long pieces were attached to a 15.2 mm long, 12.7 mm OD, 11.1 mm ID copper tube. The cable sections were held firmly to the tube by three nickel-chromium wires wrapped tightly around the cables. A thermocouple was clamped to one end of the copper tube (away from the cable sections) for temperature control, and was attached to the same temperature controller used for the bus bar block. A 15 cm long 9.5 mm diameter 400 W heater cartridge was inserted inside the cooper tube as seen in Figure 4-7. The 400W heater replaced the 500W heater because the extra power was not needed to elevate the surface of the cable material to the 485 degrees C and the 400W heater was longer, allowing for more contact with the cable samples. Three HRPs were specified for these experiments: 16.3, 65.0, and 260.0 minutes, and THTs to 21.3, 70.0, and 265.0 minutes, respectively. The cable bundle rested on ceramic insulating paper on top of an aluminum foil-covered piece of gypsum wallboard. Because the cartridge heater did not fit tightly inside the copper tube, but would tend to rest on the bottom of the tube, the inner tube may have experienced temperature non-uniformities. However, the relatively high thermal conductivity of the cooper tube will tend to reduce any exterior temperature non-uniformity. Because of the limited number of experiments with the cable bundle, repeatability of the source was not evaluated.

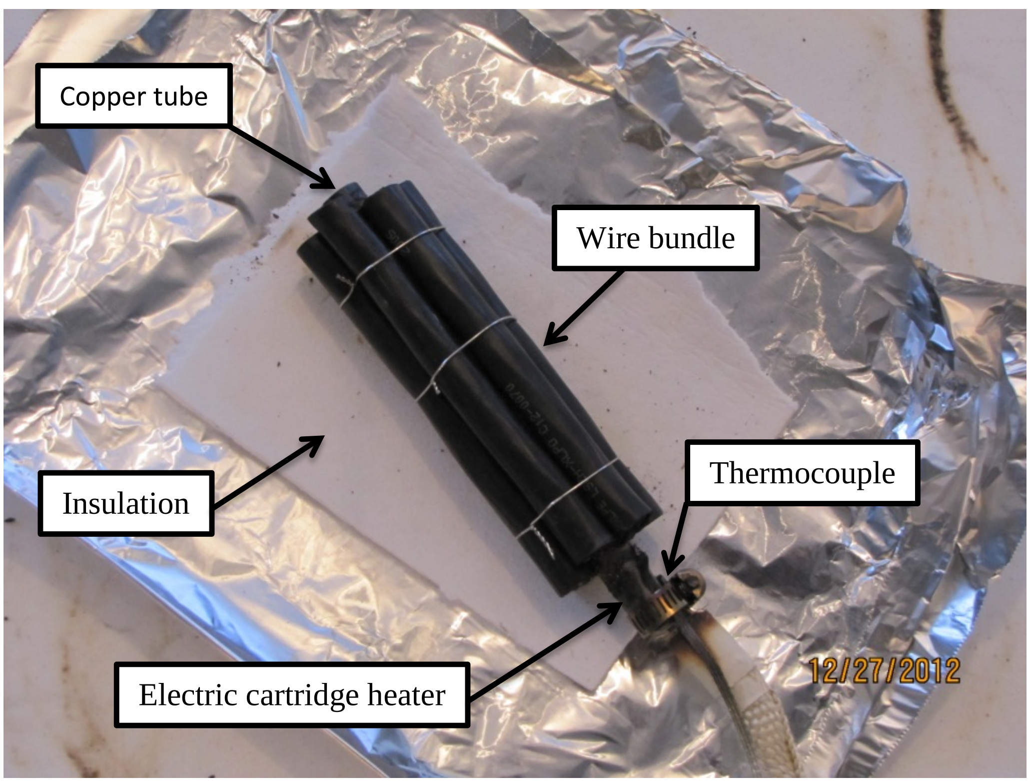


Figure 4-7. The cable bundle sample

4.2.3 BS 6266 PVC wire test

A series of heated wire tests were performed, following the performance test procedures in Annex B of NFPA 76, 2012 Ed., and based on British Standard BS 6266. A 1 m long polyvinyl

chloride (PVC) insulated wire was heated for 60 seconds by passing a current through it from a power supply capable of generating current up to 30 amps at 6 VAC. Additional tests were based on a modified BS 6266 test which involves replacing the single wire with two 1 m wires in parallel. Wire samples were placed on electrically and thermally insulated ceramic paper on top of gypsum wallboard**.** An example of a single wire configuration can be seen in Figure 4-8. The current causes significant resistive heating that subsequently cooks off the PVC insulation. A pass/fail criterion of detection system response (any sensitivity) was used within 120 seconds after the end of the electrical power application for the single wire source or **Alert** for two parallel wire tests for VEWFD systems.

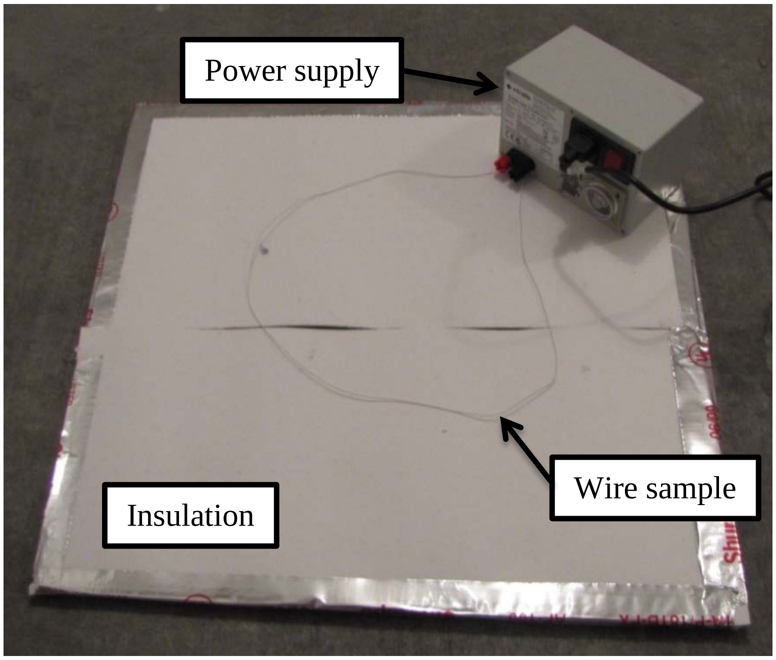


Figure 4-8. A single wire test was setup following the British Standard 6266

Experiments were conducted by exposing resistors and capacitors to excessive voltage. The methodology closely followed the Fire Industry Association's ***Code of Practice for Design, Installation, Commissioning, and Maintenance of Aspirating Smoke Detection (ASD) Systems*** using resistors. A set of three 12 Ohm, 0.5 Watt resistors were wired in parallel. The BS 6266 6 VAC power supply was used as the power source. The power supply timer was set to 90 seconds and turned on. After 90 seconds the power supply automatically turns off. Detectors were monitored for an additional 300 seconds. Similarly, two capacitors were mounted in parallel. The power supply timer was set to 30 s. After the power was shut off, the alarms were monitored for an additional 300 s. The setup for the resistor and capacitor tests can be seen in Figure 4-9, and Figure 4-10, respectively. A 15 cm diameter plastic dome with holes drilled through it (Figure 4-11) was placed on top of the setup during experiments to contain debris, in case of any material expulsion, but allow for smoke to escape.

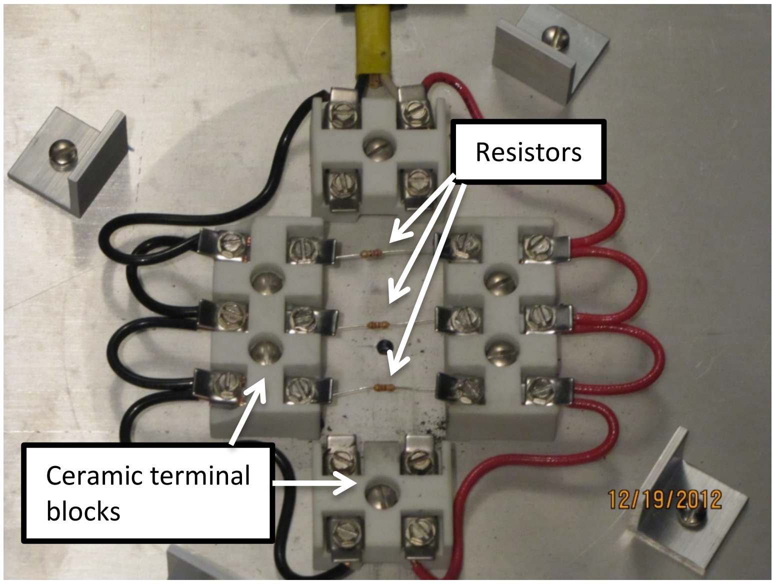


Figure 4-9. A set of three resistors wired in parallel.

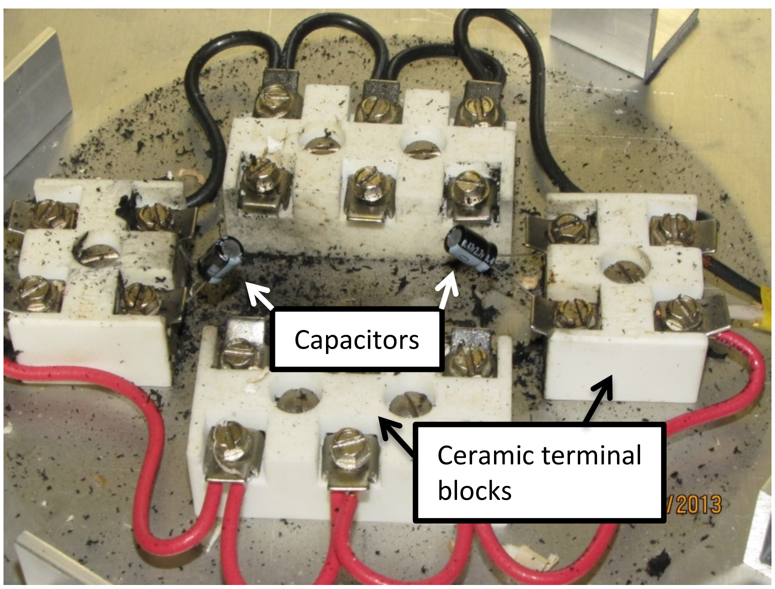


Figure 4-10. A pair of capacitors wired in parallel

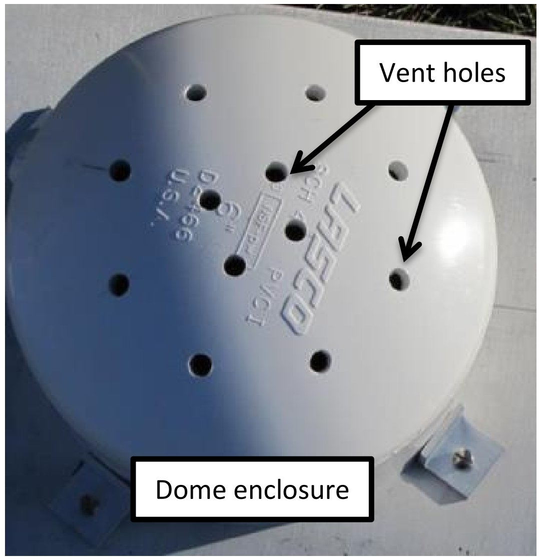


Figure 4-11. Dome enclosure for the resistor and capacitor tests

4.2.4 Shredded paper smoldering source

Two experiments were conducted with a smoldering paper source. The purpose of introducing this source was to evaluate detector response to smoldering conditions. Two cotton wicks (same used in UL smoke box) were inserted into a clean one gallon can, filled with shredded paper. Approximately two handfuls of shredded copy paper were used. The wicks were ignited before they were placed inside the can. The test began when the sample was placed in the center of the test room, and concluded when the fire transitioned to flaming combustion. The test generated a substantial amount of visible smoke during the smoldering process before it transitioned to flaming combustion. An example of the smoldering paper can be seen in Figure 4-12.

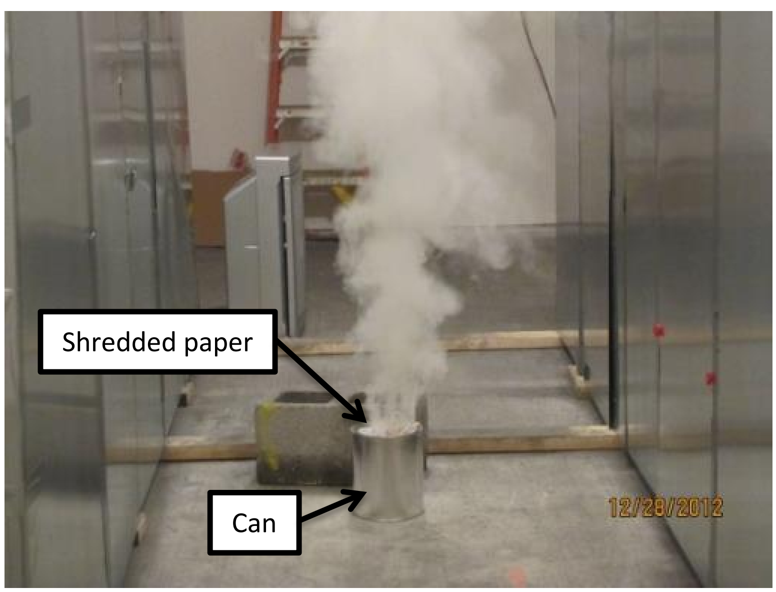


Figure 4-12. Shredded paper test

4.3 Measurement and Control Instrumentation

Data acquisition and control of the bus bar or cable bundle heater were accomplished by a program running on a PC. Details of the programs are given in the Appendix.

A humidity probe with a built-in thermistor was used to record the relative humidity and air temperature during the experiments. For the small room, areawide setup the center room vertical temperature profile was recorded. A thermocouple tree was placed in the center of the room, with seven Type-K thermocouples respectively placed 2.54 cm, 5.08 cm, 7.62 cm, 0.31 m, 0.61 m, 0.914 m and 2.13 m below the ceiling. A set of four more thermocouples was placed on the ceiling in the center of each quadrant of the room.

4.3.1 Temperature controls

The front panel of the main program had a button to open and start the temperature controller program. The ramp slope was fixed by the final set point temperature and the heating rate period. About every 30 seconds, the program sends the temperature controller a new set point. During the update, the power to the heater is disabled for about 5 seconds. This latency produced little lag in the rate of block temperature rise. The soak period was specified by a 5.0 minute heating period at the final set point temperature. During the soak period, the program stops updating the controller, thus the power is not disabled during the 5 minute soak period.

Preliminary tests identified a problem of potential contamination of the bus bar or cartridge heater during handling, leading to particle generation upon heating of a bus bar with no wires attached. Thus, after every experiment, the bus bar previously used was heated by itself in a separate location for a cleaning cycle. This would remove residue from the previous experiment or handling. The reheating took about 20 minutes, which includes a 15 minute heating ramp period and a 5 minute soak period. A total of three bus bars were used during the experiments and were regularly rotated during testing; after an experiment the bus bar was put through its cleaning cycle, while a prepared test sample bus bar was readied for the next experiment and a clean bus bar cooled, waiting for sample preparation.

4.3.2 Smoke detector monitoring

The ASD VEWFD response times were recorded by monitoring the state of the ASD relay switches on digital inputs of the data acquisition card. The FACP detector response times were obtained by monitoring the data stream that typically is sent to a printer or other output device. The ASCII text data was parsed by the program automatically to light program indicator buttons and log the pre-alarm and alarm times of all detectors; up to 16 detectors were monitored during these experiments.

4.3.3 Aerosol instrumentation

Selected aerosol measurement instrumentation was used to gather particle size and aerosol concentration data at the ASD sampling locations for laboratory in-cabinet experiments. An electrical low pressure impactor (ELPI) measured the aerosol size distribution during most small cabinet experiments to help characterize the smoke sources. Additional experiments were conducted with three instruments that recorded the particle number concentration (zero-th moment of the size distribution), mass concentration (third moment of the size distribution), and

the total aerosol length, (a measure of the first moment of the size distribution). These measurements complement the ELPI data. The aerosol data is detailed in Appendix B.

4.3.4 Ambient environment measurements

Measurements were taken at all locations to monitor the ambient environment before, during and after each test. For small-scale tests, ambient temperature was monitored near the top and bottom of the cabinet. In most laboratory experiments, the particle concentration was also being recorded. The large-scale tests in the 38 m^2 room had its room temperature monitored at various heights in the center of the room. A portable particle counter was used to monitor the ambient particle concentrations. Humidity was monitored at all the test locations for the duration of all tests. Background information was taken for up to 120 seconds.

4.3.5 Thermal imaging

Some small-scale, in-cabinet experiment setup used an infrared camera to monitor the temperature of the heat source and degrading samples. The camera was placed 1 meter above the sample, on the outside of the test cabinet. An IR window was installed between the camera and the sample. A series of top view, thermal images were taken using an FLIR E30 infrared camera. Twenty images were taken for each heating rate. The time intervals between the images were 1, 3 and 10 minutes for 15, 60 and 240 minute ramps, respectively.

The emissivity of the bus bar was taken to be 0.78, that of oxidized copper, and was kept constant for all the tests. The transmissivity of the IR window was taken to be 0.5. The camera was controlled remotely from the computer via a USB cable. The settings on the camera, such as emissivity and transmissivity, could be changed after the test by using the accompanying software. The camera was limited to measuring temperatures up to 370ºC. An example of a temperature profile measured using the thermal camera can be seen in Figure 4-13. All images for the monitored experiments are given in the Appendix.

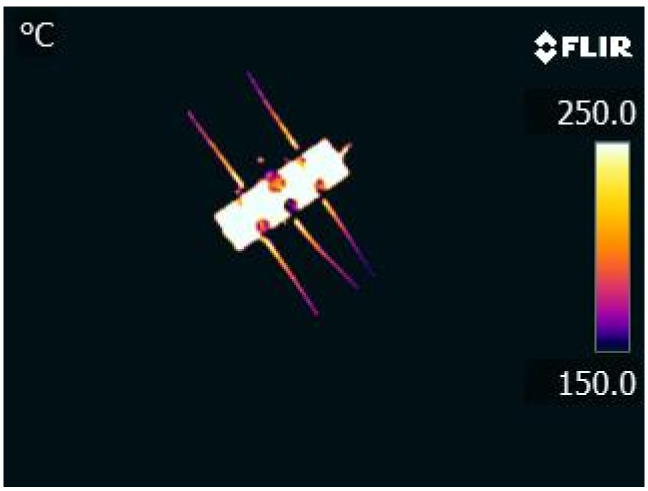
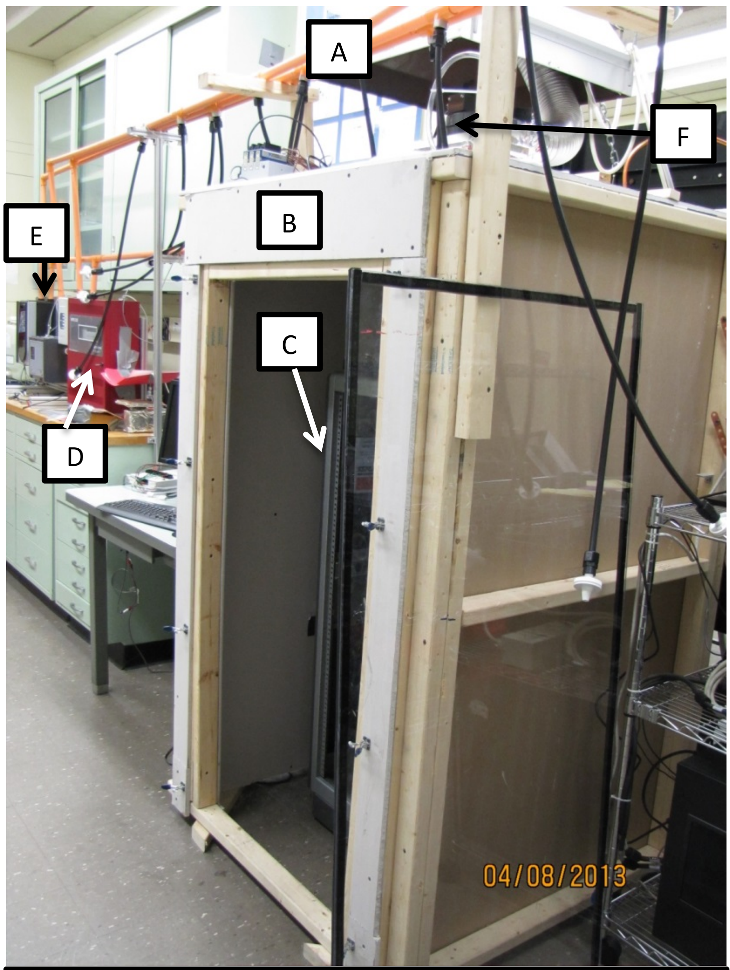


Figure 4-13. Thermal image of XLPE wires following a 60.0 minute heating ramp and a 5.0 minute soak period

4.4 Experimental Configurations

4.4.1 Laboratory, instrument cabinet configuration

A laboratory space was used for the small cabinet experiments. The cabinet was an empty instrumentation cabinet with dimensions of 0.56 m by 0.61 m by 1.32 m tall. While the height of this cabinet is shorter than those commonly encountered in NPP facilities, it is a reasonable surrogate to represent an upper portion of an NPP cabinet. The cabinet was placed inside a ventilated enclosure. The laboratory instrument cabinet experimental configuration can be seen in Figure 4-14.

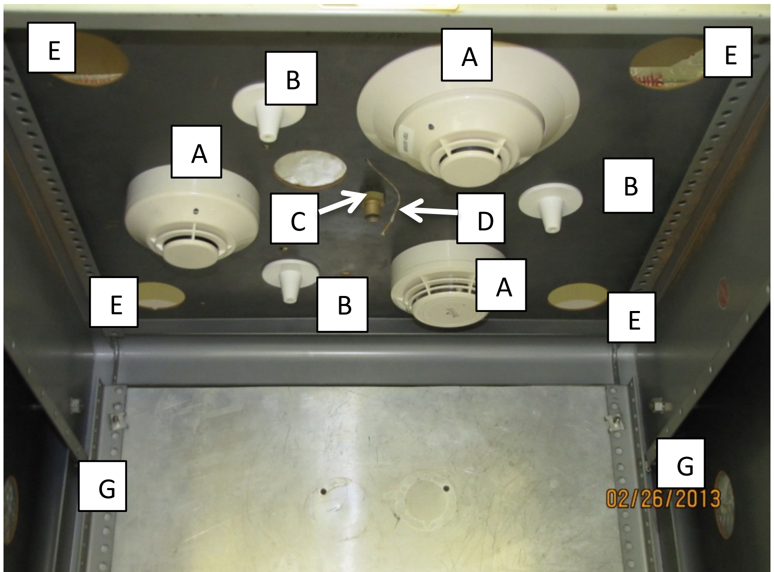


A: ASD piping	D: Fire alarm control panel
B: Ventilated enclosure	E: ASD systems
C: Instrument cabinet	F: Blower motor

Figure 4-14. Laboratory instrument cabinet experimental configuration

The instrument cabinet had spot detectors and air-sampling detector ports installed on its ceiling. Figure 4-15 shows how they were mounted inside the cabinet, and a schematic of the top plate hole pattern is shown in Figure 4-16. The ASD detector units were located outside the

cabinet and individual but identical piping networks were used to transport air samples from within the cabinet to the detector units. The pipe used was a 1.91 cm inside diameter (ID) chlorinated polyvinyl chloride pipe (CPVC). Flexible tubing, 1.24 cm ID, was used to connect the sampling port to the CPVC piping. The ASD piping layout can be seen in Figure 4-17. Each detector had four sampling ports, one routed to the inside of the cabinet and three sampling laboratory-space ambient air. The sampling port diameters were 3.2 mm.



A: Spot detectors
B: ASD sampling ports
C: Aerosol sampling port
D: Thermocouple
E: Top vent holes
F: IR camera view port
G: Side vent holes

Figure 4-15. Instrument cabinet ceiling view

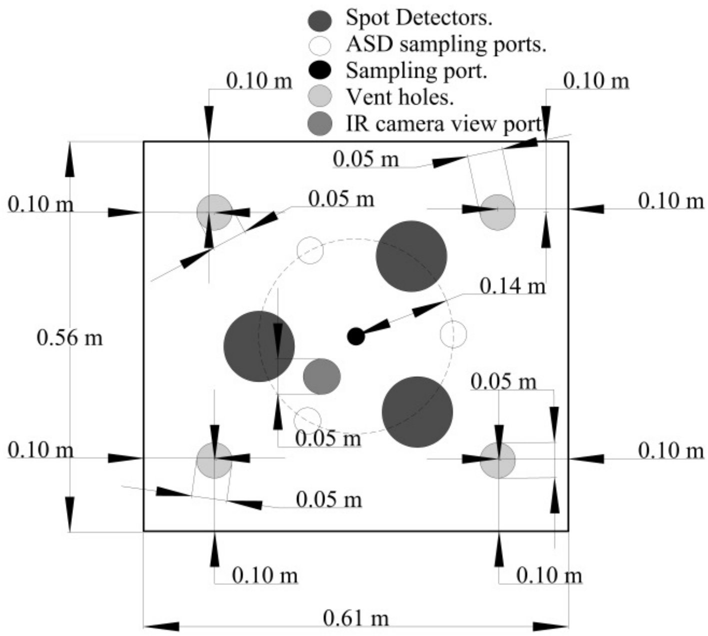


Figure 4-16. Instrument cabinet top plate hole pattern

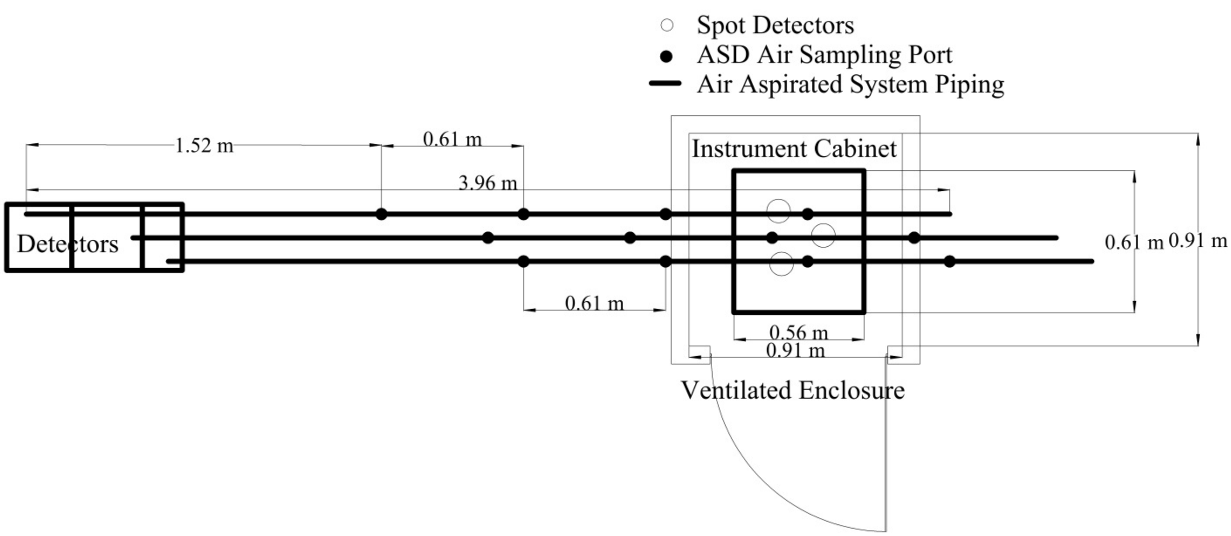


Figure 4-17. ASD pipe layout for the instrument cabinet experimental setup

The cabinet had two sets of vent holes, four through the ceiling and three each on the left and right sides. The locations of the top vent holes and some of the side vent holes can be seen in Figure 4-16. The top vent hole configuration consisted of four 5.08 cm holes, while the side vent configuration had six. The side vent holes, consisting of three holes separated by 0.18 m, were placed on left and the right sides 0.2 m from the top of the cabinet. Each test had either the top or side vents opened, but in no test were both open.

The cabinet was located inside a ventilated enclosure to contain and evacuate the smoke. The ventilated enclosure was 0.91 m by 0.91 m and 1.75 m tall. A blower motor installed on top of the enclosure provided the ventilation to exhaust smoke fumes through the top of the cabinet, and into the laboratory fume hood. A 3.8 cm gap between the bottom of the enclosure and the floor, allowed fresh air to enter the enclosure. Inside the test cabinet the air was quiescent, except for the thermal plume generated by the heat source. A close-up of the cabinet inside the ventilated enclosure can be seen in Figure 4-18.

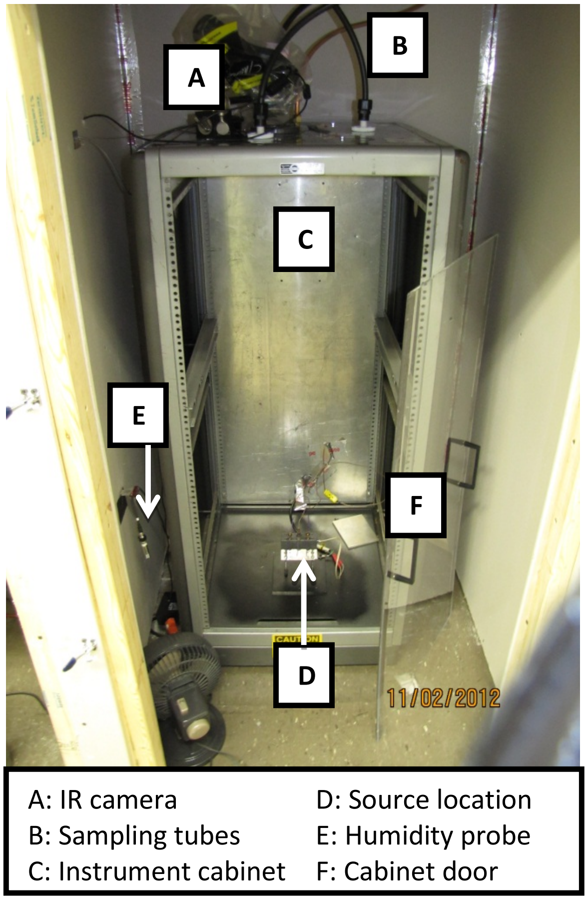
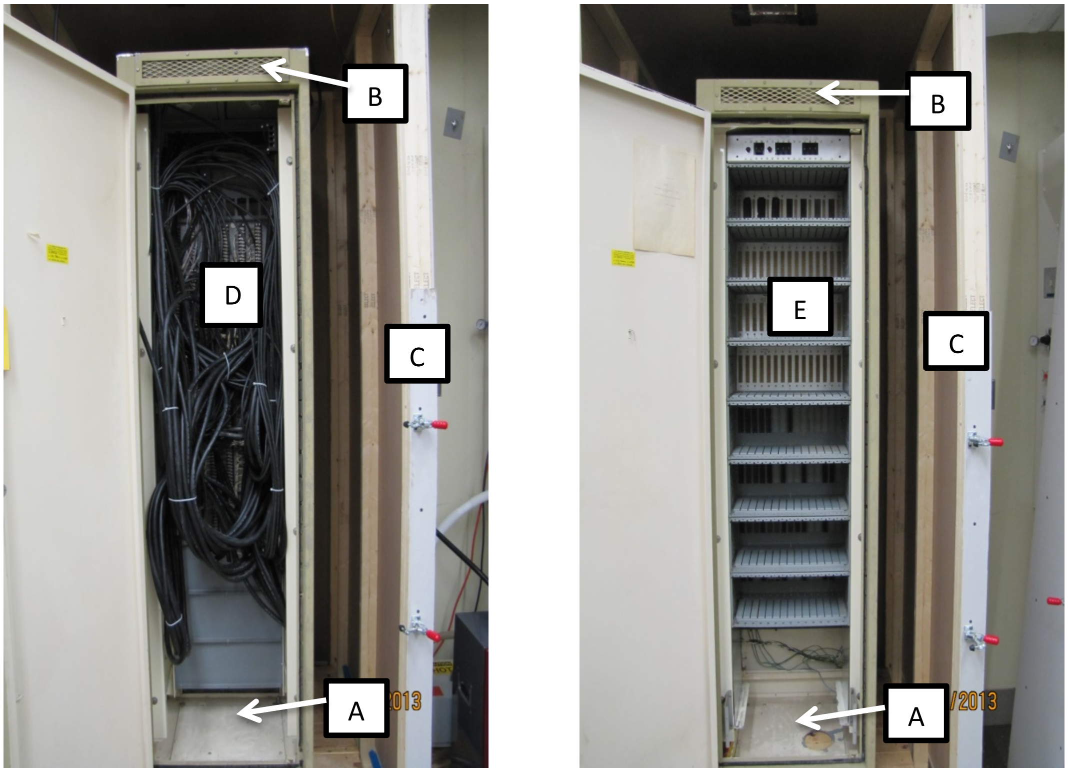


Figure 4-18. Instrument cabinet inside NIST laboratory

4.4.2 Laboratory, large NPP cabinet configurations

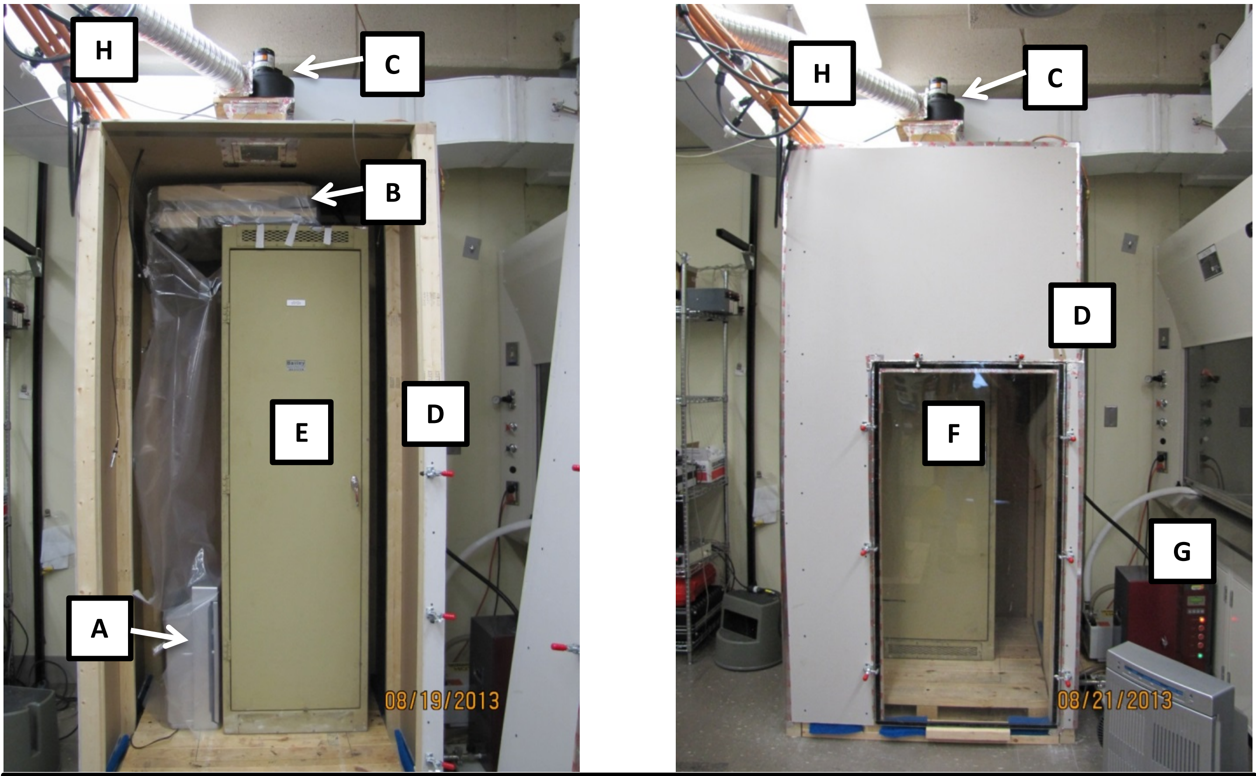
These experiments used two surplus NPP electrical cabinets, which can be seen in Figure 4-19. The cabinets were 0.61 m by 0.61 m by 2.13 m tall. The cabinet on the left had cable bundles hanging from the back wall and was naturally ventilated. The cabinet on the right was a compartment with multiple shelves with circuit card slots in them; no circuit cards were in place. A piece of sheet metal covered the front opening simulating a compartment with all the circuit cards in place. Each cabinet was placed inside the ventilated enclosure for experimentation, which can be seen in Figure 4-20. Spot smoke detectors and ASD sampling ports were installed inside at the top of each cabinet, as shown in Figure 4-21. Only ASD2 and ASD3 were installed during these experiments. SS and ION spot detectors were installed inside the

naturally ventilated cabinet, while the force-ventilated cabinet only had space for the ION spot detector.



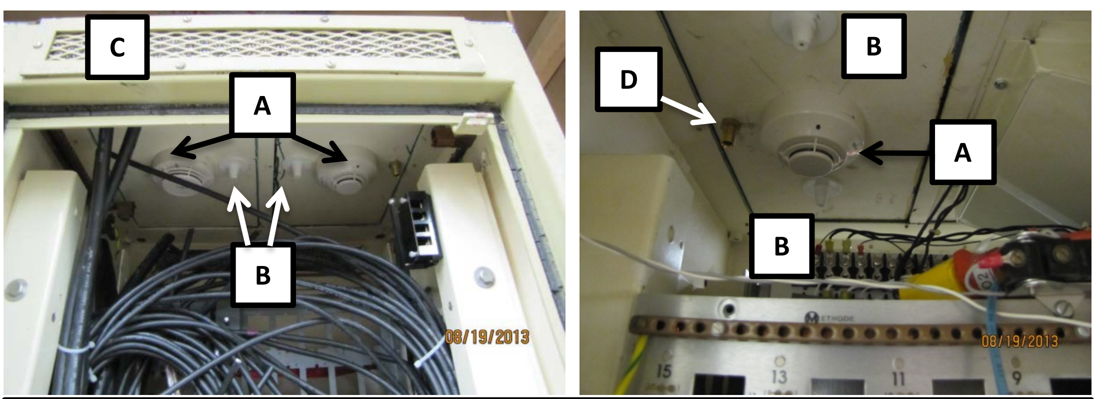
A: Source location
B: Air vents
C: Cabinet enclosure
D: Naturally ventilated cabinet
E: Force ventilated cabinet

Figure 4-19. NPP cabinets used in large cabinet experiments



A: Air purifier
B: Cabinet cooling fan
C: Exhaust fan
D: Cabinet enclosure
E: Force ventilated cabinet
F: Naturally ventilated cabinet
G: Particle counter
H: ASD piping

Figure 4-20. Large cabinet installation and enclosure detail



A: Spot detectors
B: ASD sampling ports
C: Air vent
D: Aerosol sampling port

Figure 4-21. View of sampling ports and spot detectors installed inside the naturally ventilated (left) and force ventilated (right) NPP large cabinets

Cabinet 2 had a blower installed on top that was used for cooling of the circuit cards. The blower forced air down through a series of vents and across the circuit card slots, then back up to the top of the cabinet. To limit the effects of air recirculation in the cabinet enclosure, air to the blower was sampled from the bottom of the enclosure into a plastic shroud containing a heap-filter air cleaner. A close-up of the top of the cabinet with and without the blower can be seen in Figure 4-22. This configuration was meant to simulate a large compartment with abundance of clean air, such that the air being sucked into the cabinet would be clean air. ASD1 was used to monitor the air entering the cabinet.

Figure 4-22. The ventilation configuration of the forced ventilation cabinet

4.4.3 In-cabinet, small room, cabinet mock-up configurations

The single-zone experiments were conducted at the Montgomery County Public Safety Training Academy, in the Burn Prop building. A space on the lower floor was used to configure an 8.2 m x 4.6 m room containing electrical cabinet mock-ups. The ceiling height was 2.4 m. A forced-air ventilation scheme could be implemented in the room using a variable-speed blower and ducting to direct air flow to wall registers, which exhaust air grills vented to the outside of the building. The cabinet mock-ups were constructed to simulate naturally ventilated, or forced-air ventilated electrical equipment cabinets. Individual cabinets were 0.61 m wide by 0.61 m deep and 1.78 m tall. Figure 4-23 shows the small room experimental space layout. Photographs of the setup can be seen in Figure 4-24 and Figure 4-25.

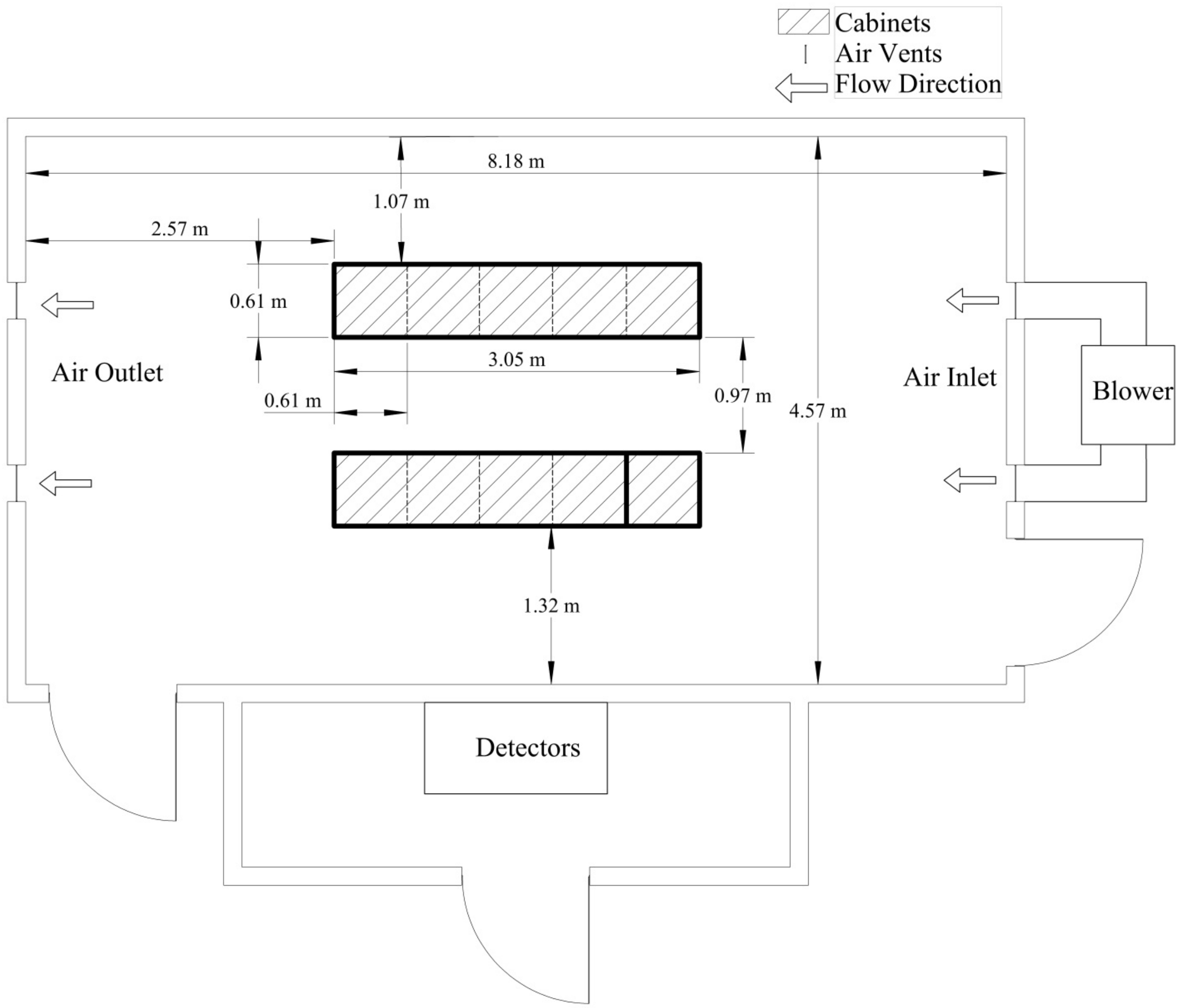
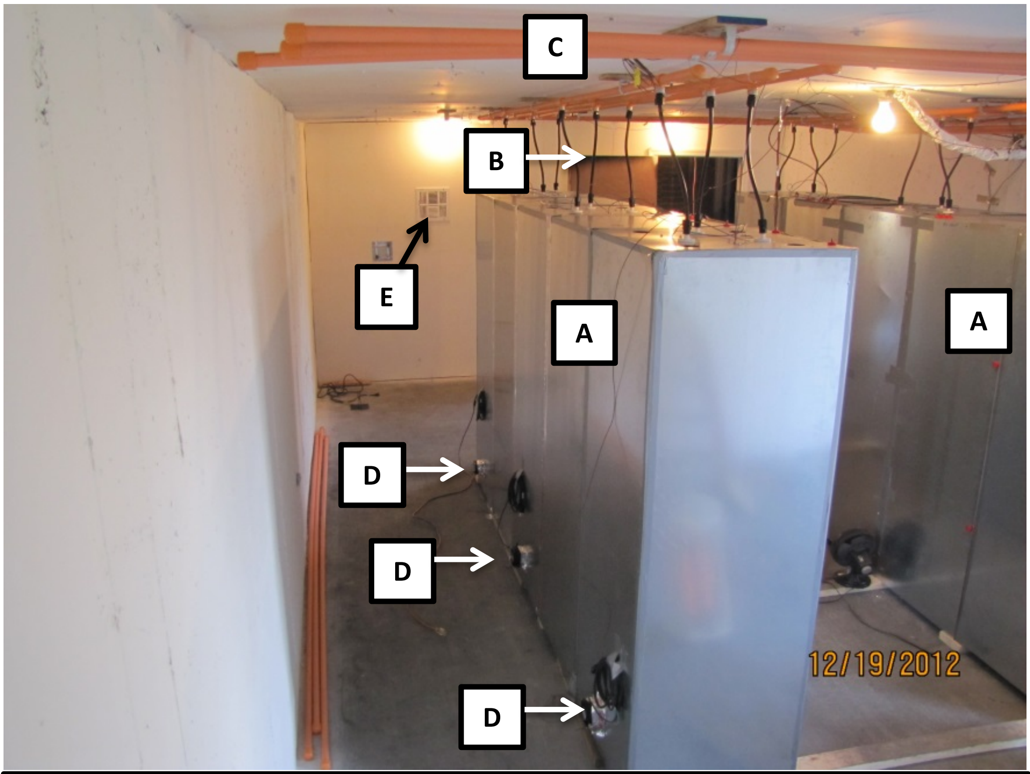


Figure 4-23. Small room full-scale experiment space layout



A: Cabinet mock-ups
B: Sampling tubes
C: ASD pipes
D: Cabinet ventilation fans
E: Room ventilation air inlet

Figure 4-24. View of the small room experimental space

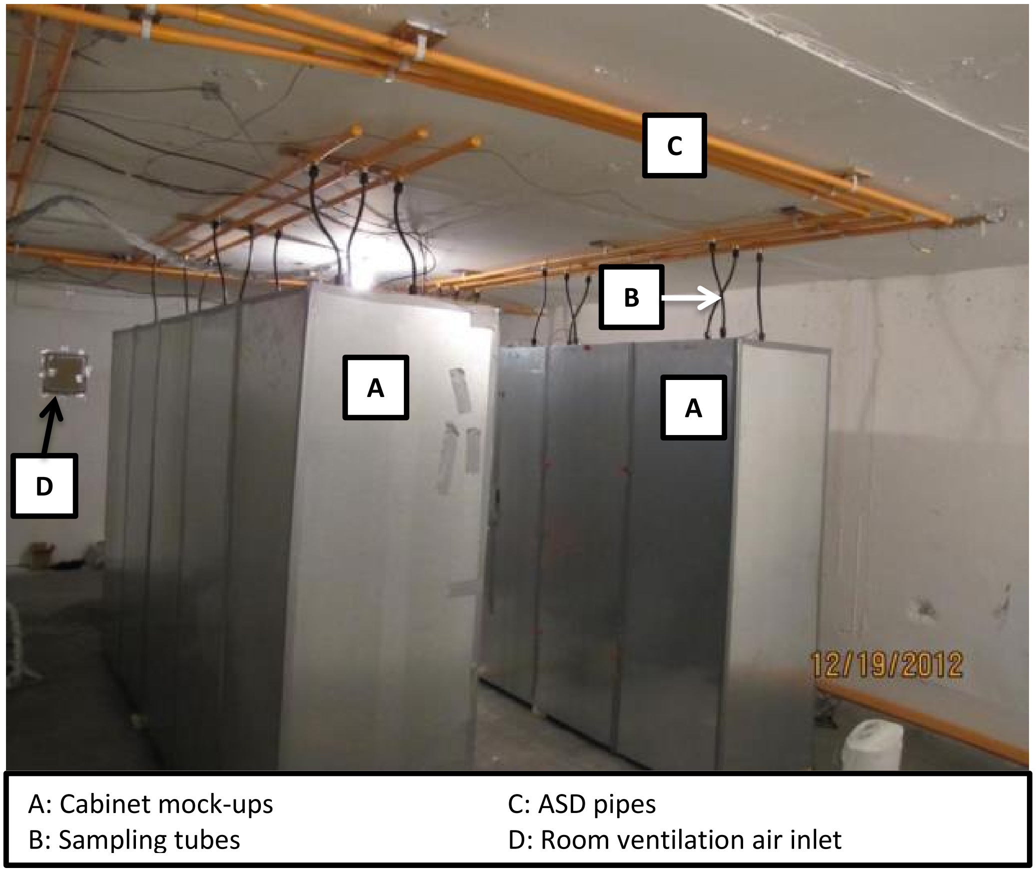


Figure 4-25. View of the small room full-scale experimental space ceiling

Experiments were conducted with ASD1, ASD2, and ASD3 running simultaneously. The in-cabinet configurations had spot detectors installed in a similar fashion to the small-scale setup. The aspirated smoke detectors had ports installed into the top of selected cabinets, which directed the sampled air to the piping connected to each ASD VEWFD system. Single-cabinet and multiple open-side cabinet designs were constructed in a row with top ventilation. The following (three) cabinet configurations were tested: single cabinet with ASD ports and spot detectors; a 4-cabinet arrangement where two cabinets had ASD ports and spot detectors; and a 5-cabinet arrangement where three cabinets had ASD ports and spot detectors. Figure 4-26 shows the alarm layout inside the 5-cabinet configuration. The cabinets were raised 5.08 cm above the ground to allow air to enter.

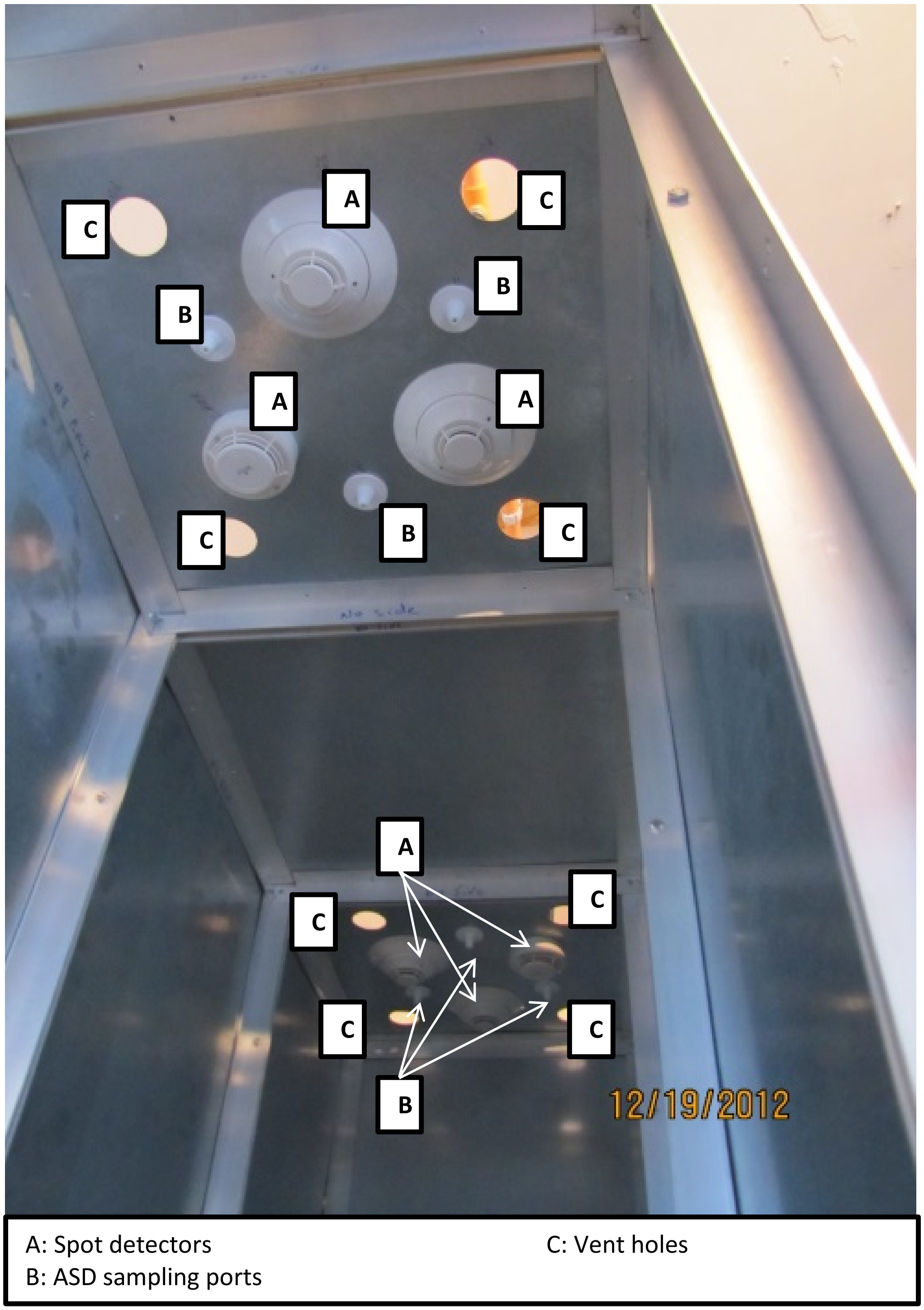


Figure 4-26. Five-cabinet spot detector and ASD sampling port configurations

Figure 4-27 shows the ASD piping layout for in-cabinet sampling configuration. The four- and five-cabinet arrangements had ceiling ventilation holes with ASD ports and spot detectors, and no internal side wall partitions.

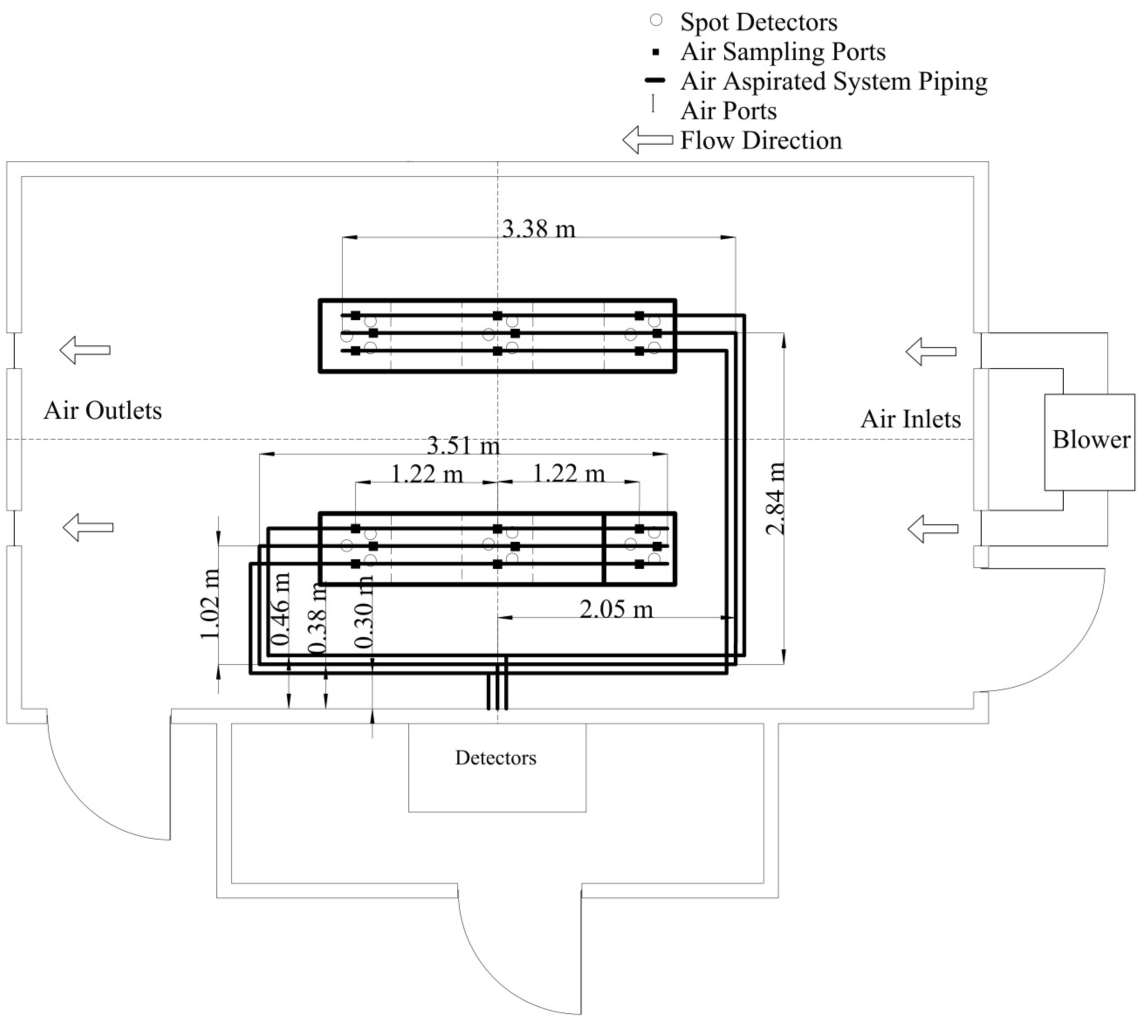


Figure 4-27. In-cabinet ASD pipe layout

Three small muffin fans provided forced ventilation during some experiments. They were installed in the first, third, and fifth cabinets (in each) of the 5-cabinet configurations, on the back wall along the central axis, and 30.5 cm above the cabinet floor. The fans were installed in the cabinets that had the spot alarms and the ASD sampling ports. Unlike the previous tests, the openings on the bottoms of the cabinets were covered to prevent air entrainment. The fans can be seen in Figure 4-24.

Figure 4-28 shows in-cabinet and areawide source locations. The samples were placed in cabinets 1, 2 and 7 for the single cabinet, 4-cabinet and 5-cabinet experiments, respectively.

The spot alarms and ASD sampling ports were located in cabinets 1, 3, 5, 6, 8, and 10. The in-cabinet layout for the spot detectors, the ASD sampling ports and the vent holes can be seen in Figure 4-27.

For areawide ASD experiments, the samples were placed in either cabinet 7, the center of the room or one of the room quadrants.

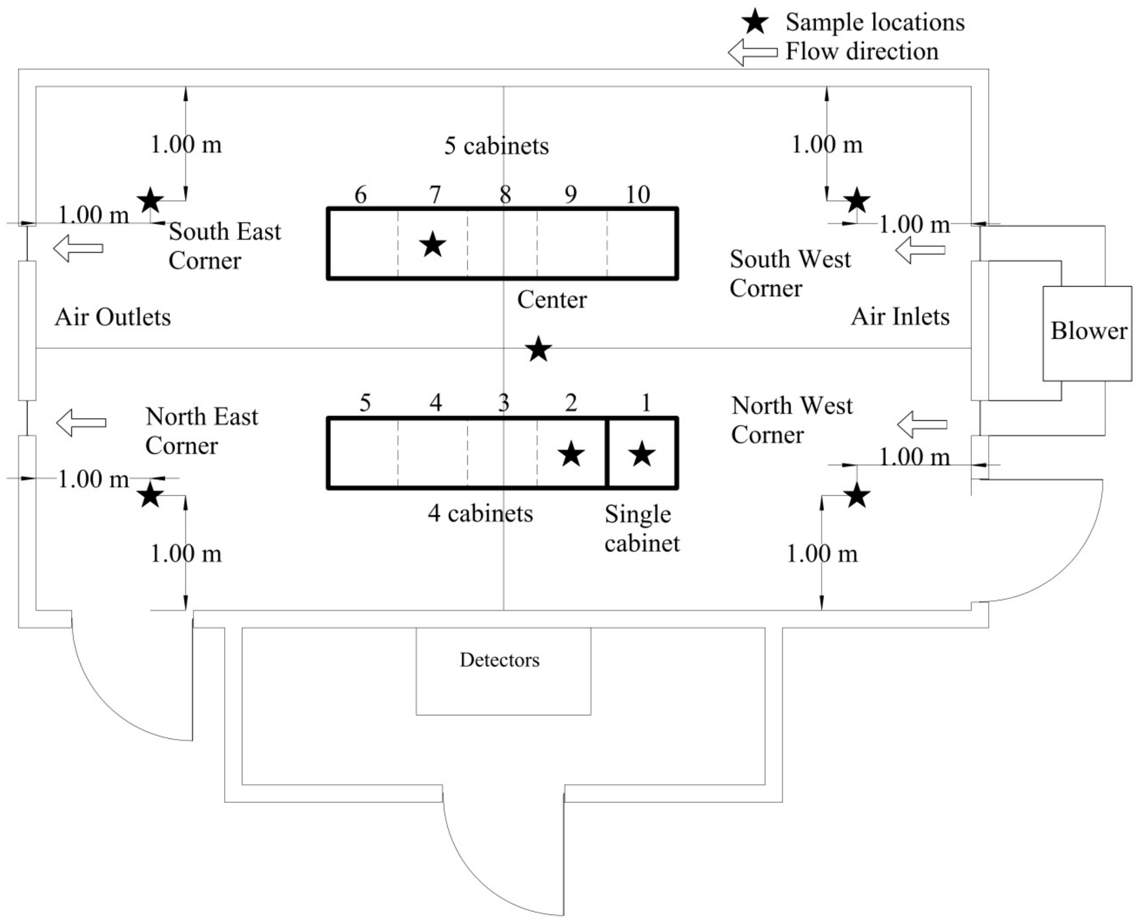


Figure 4-28. Smoke source sample locations

4.4.4 Areawide, small room configuration

The areawide ASD configuration had spot detectors on the ceiling of the room. The piping system for the aspirated smoke detectors was modified for this configuration. Areawide piping and detector locations can be seen in Figure 4-29. The areawide piping had 3.2 mm holes (DIA) drilled into it to serve as sampling ports. There were four sampling holes in total for each detector.

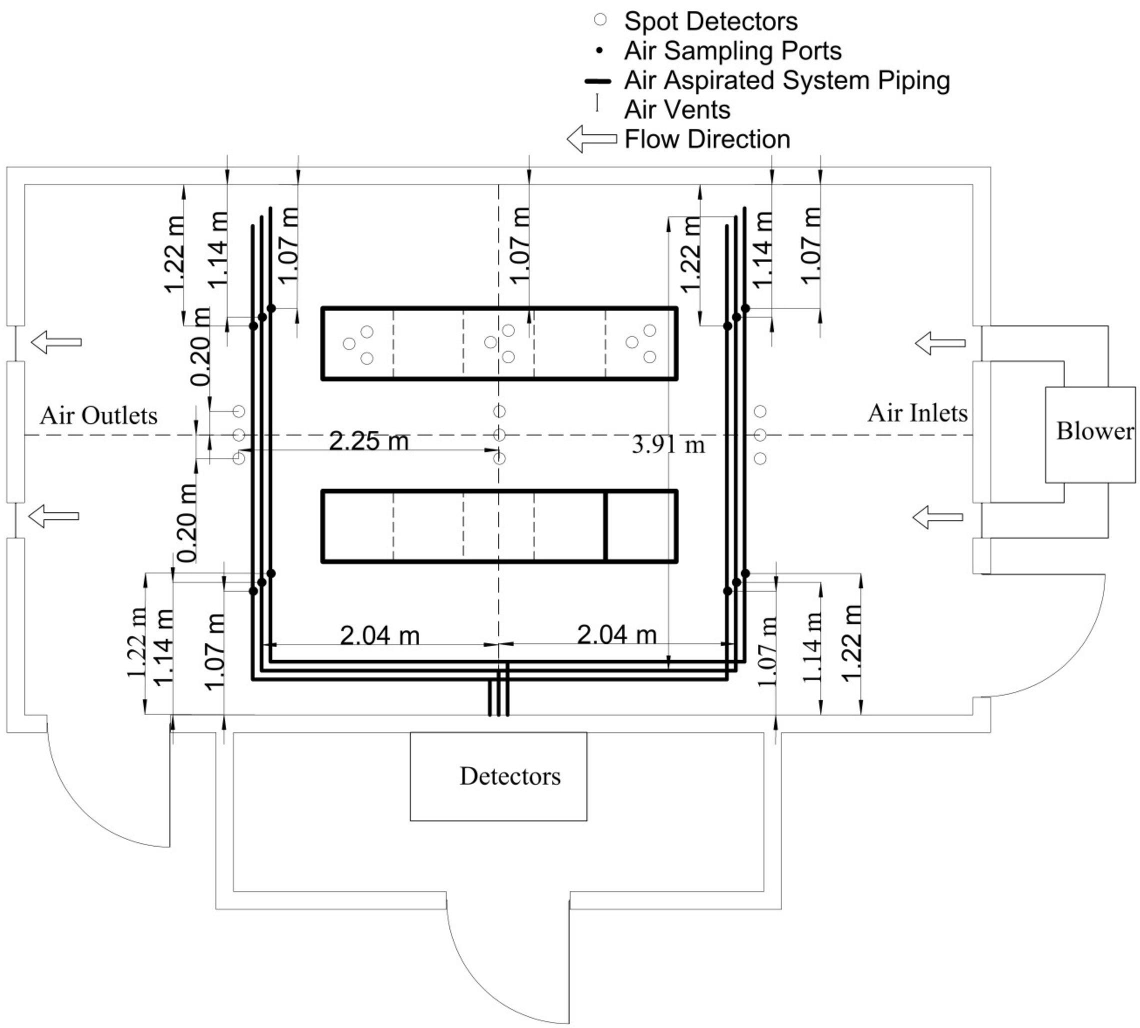


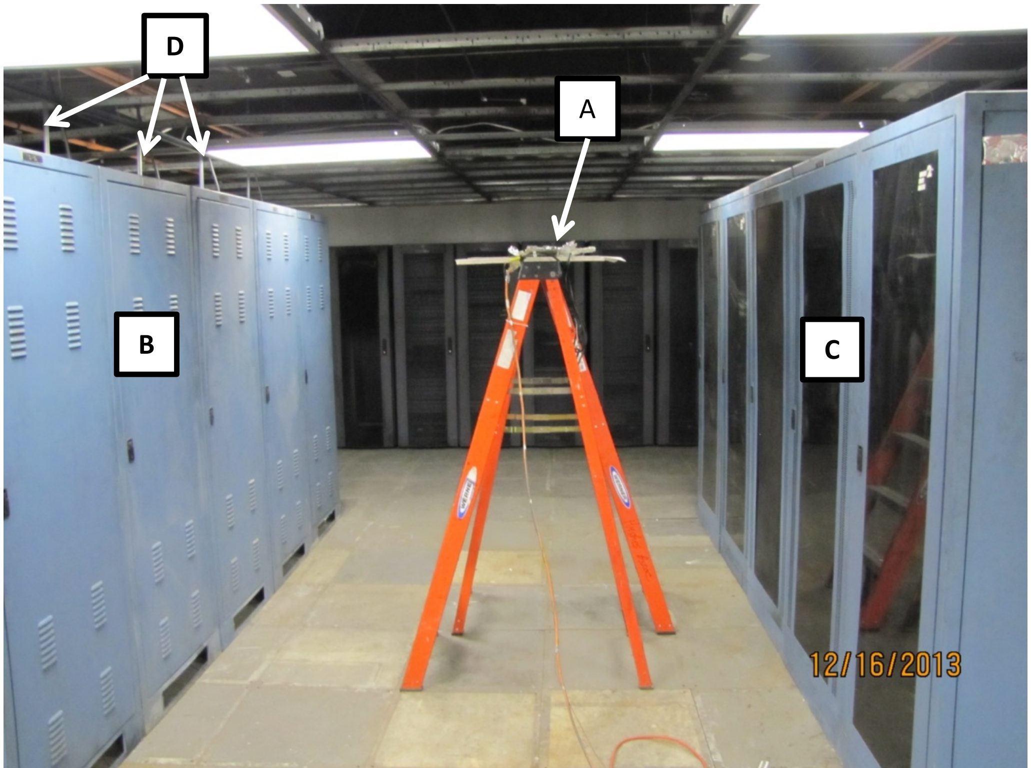
Figure 4-29. Areawide ASD pipe layout

4.4.5 In-cabinet, large room, electrical cabinet configurations

The experimental space for the large-room, full-scale experiments was 10 m x 10 m x 3 m high ceiling with a variable speed ventilation fan. The facility can be seen in Figure 4-30 and Figure 4-31, and the complete layout can be seen in Figure 4-32. With access doors closed, air was pulled through two openings located on the ceiling in the rear of the room, and exhausted at the front through a 76.2 cm high by 61.0 cm wide louver with a 49.5 cm by 54.6 cm opening behind it with the center of the louver located in the center of the wall.

A: Source location	D: In-Cabinet ASD Sampling Lines
B: Test Cabinets, Instrumented	E: Area-wide ASD piping
C: Test Cabinets, Not instrumented	F: Area-wide sampling port

Figure 4-30. Off angle view of 100 m^2 facility



A: Source location, Wire bundle | C: Test Cabinets, Not Instrumented
B: Test Cabinets, Instrumented | D: In-Cabinet ASD Sampling Lines

Figure 4-31. Front view of the 100 m² facility

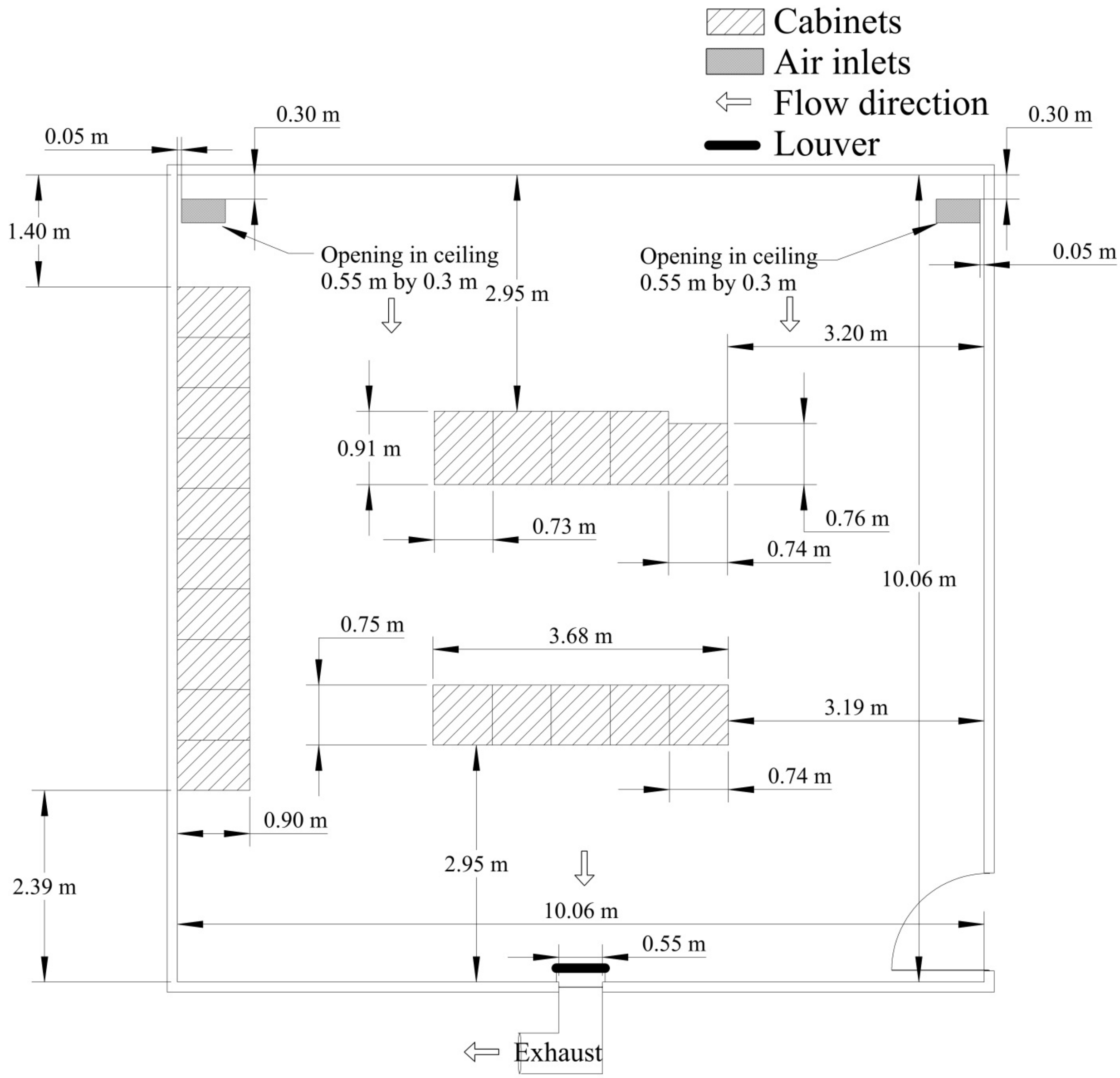


Figure 4-32. Large room testing facility layout

Experiments were conducted with single-port ASD VEWFD systems for in-cabinet coverage and multi-port ASD VEWFD systems for in-cabinet and areawide coverage. Figure 4-33 shows the ceiling-mounted and in-cabinet spot detector locations. Ceiling mounted detectors included photoelectric, ionization, and sensitive spot detectors, while in-cabinet detectors included ionization and sensitive spot detectors.

Figure 4-34 shows the detector layout inside the cabinet and the ventilation hole pattern, and Figure 4-35 gives the locations on the ceiling plate. Figure 4-36 shows the detector layout, ASD sampling pipe vertical entrance, and ventilation configuration between cabinets in the three-cabinet bank.

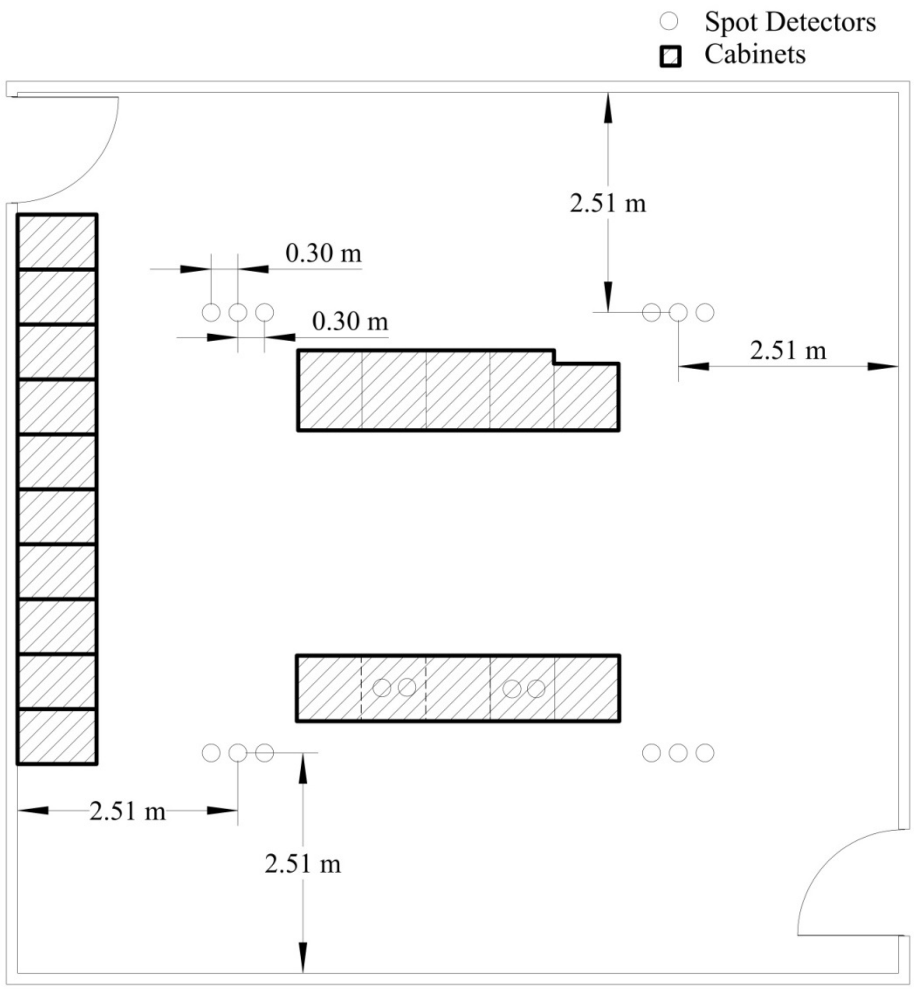
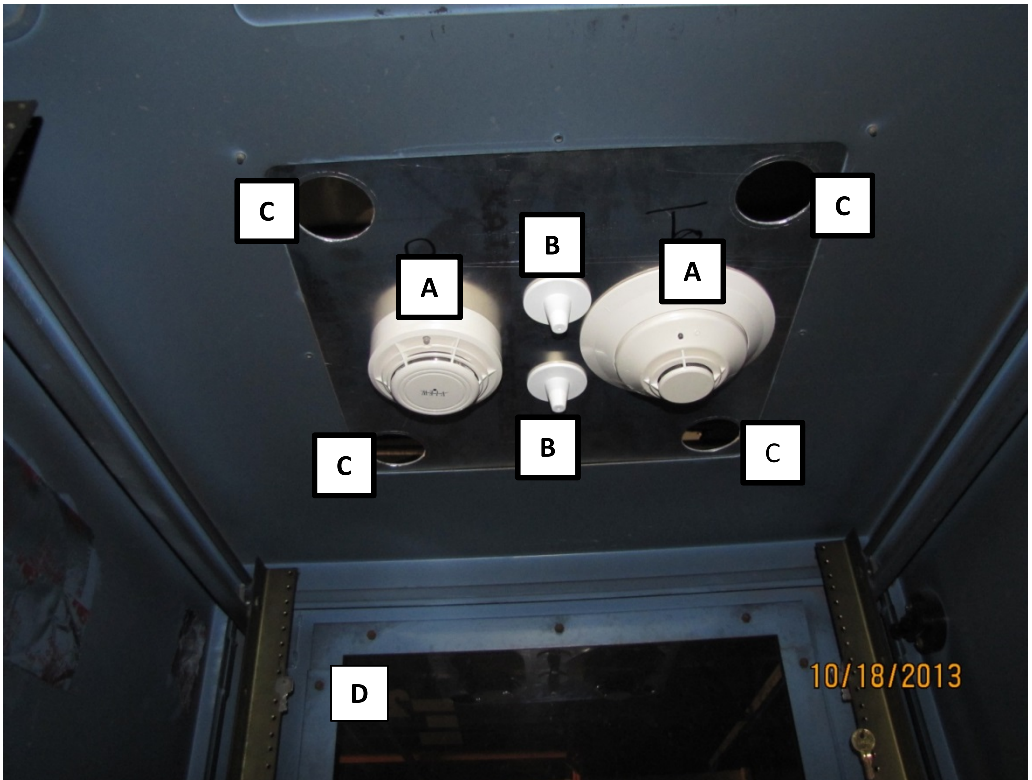


Figure 4-33. Spot detectors layout inside 100 m^2 facility



A: Spot detectors | C: Vent holes
B: ASD sampling ports | D: Cabinet door

Figure 4-34. Detector and sampling port locations for single-zone experiments

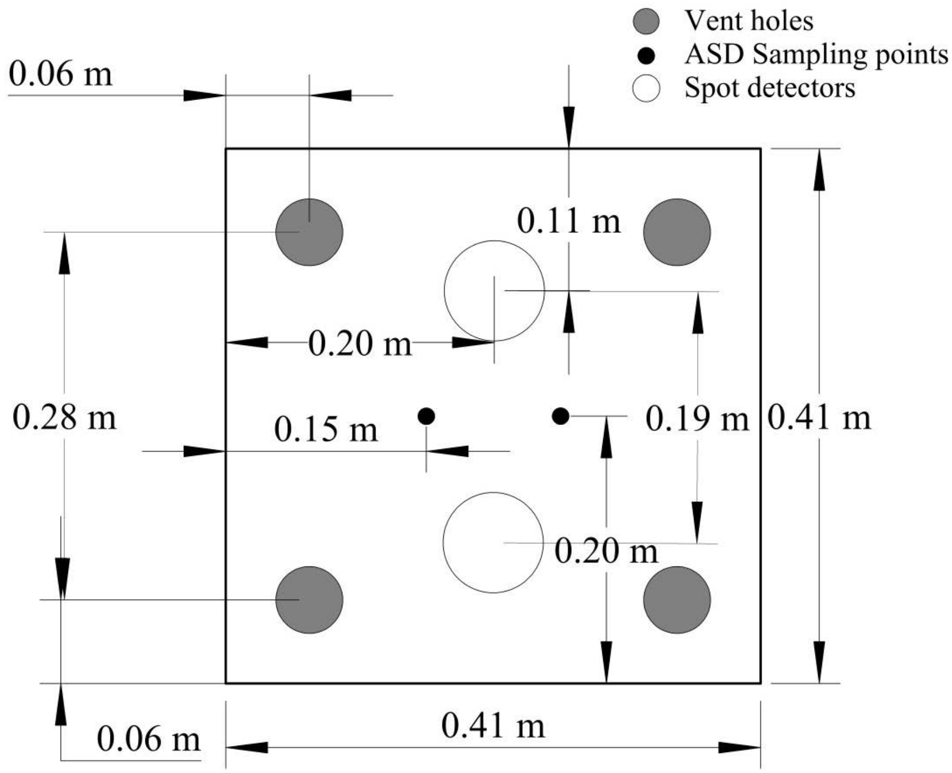
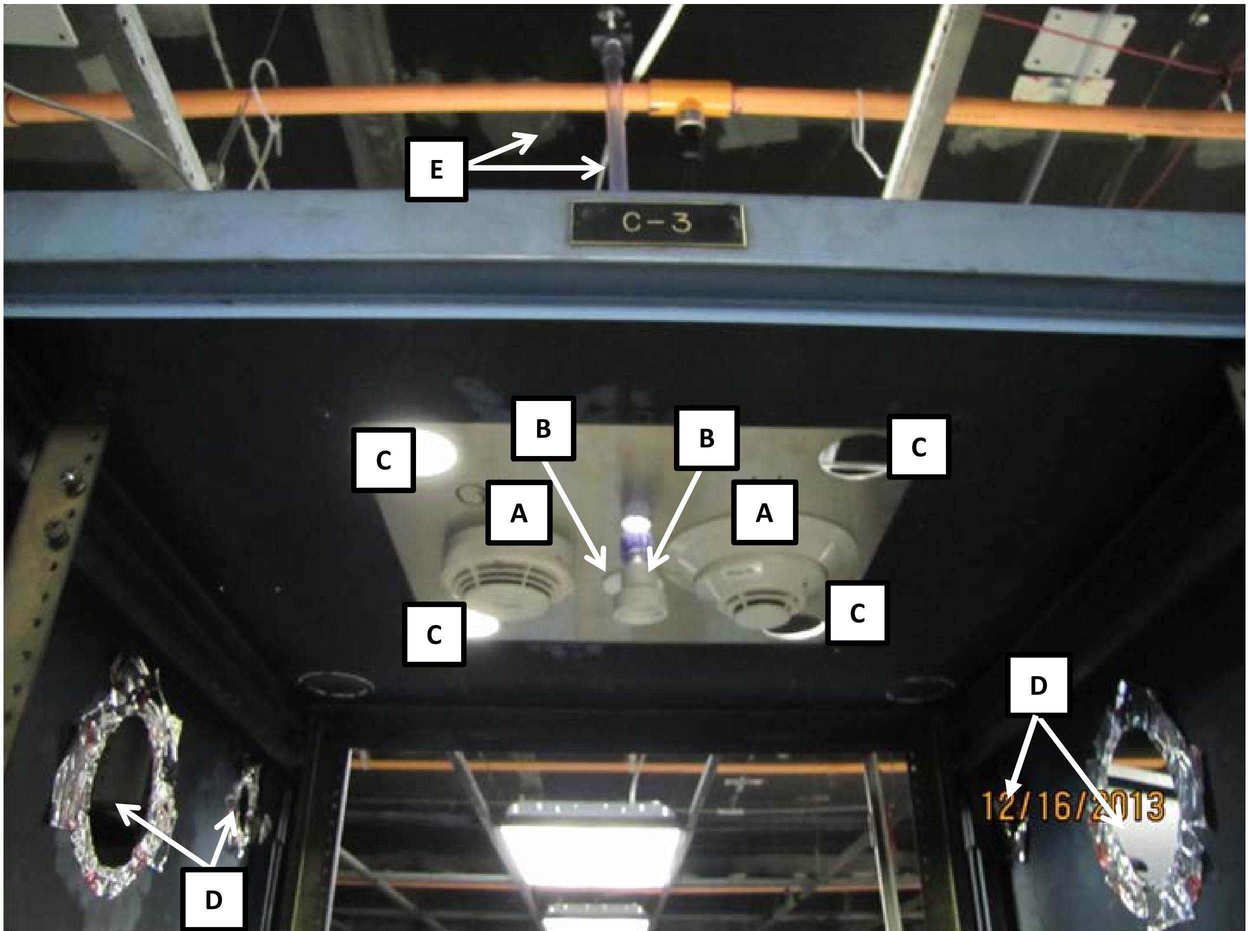


Figure 4-35. Detectors, sampling ports, and vent hole locations for in-cabinet experiments



A: Spot detectors
B: ASD sampling ports
C: Top vents
D: Side vents
E: ASD piping

Figure 4-36. Detector layout and side vent location

Figure 4-37 shows the piping diagram for the single-zone, in-cabinet experiments. Separate piping with a single port in four cabinets was directed to either ASD2 or ASD3. One cabinet was isolated from adjacent cabinets by sealing the side wall opening. Figure 4-37 and Figure 4-38 show details of ASD4 (cloud chamber type) configuration where individual pressure regulators were installed in piping. These allowed for flow adjustments.

Figure 4-40 and Figure 4-41 show the details of the openings between the three-cabinet configurations. Figure 4-42 shows the source locations.

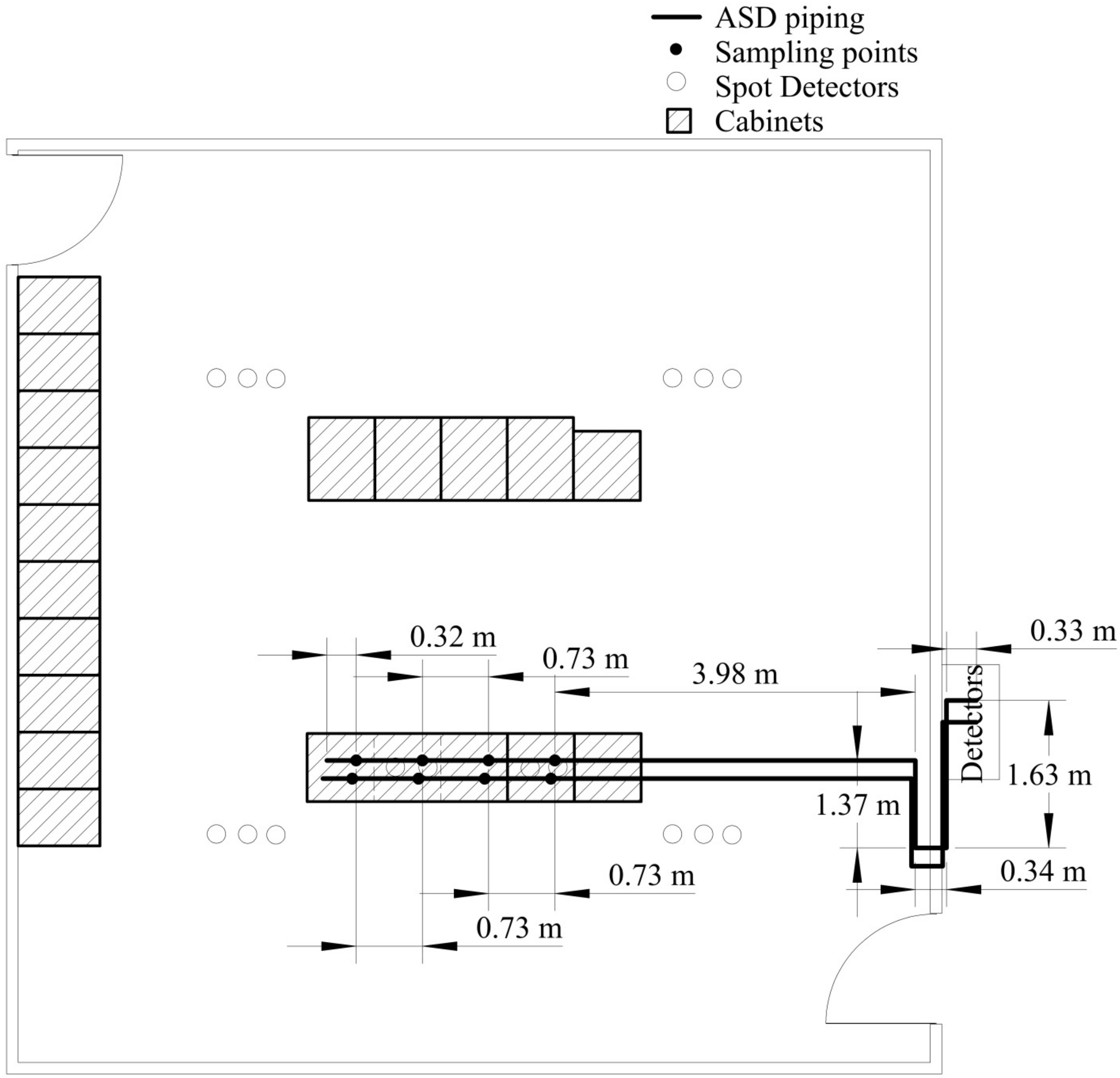


Figure 4-37. Single zone piping configuration for ASD2 and ASD3

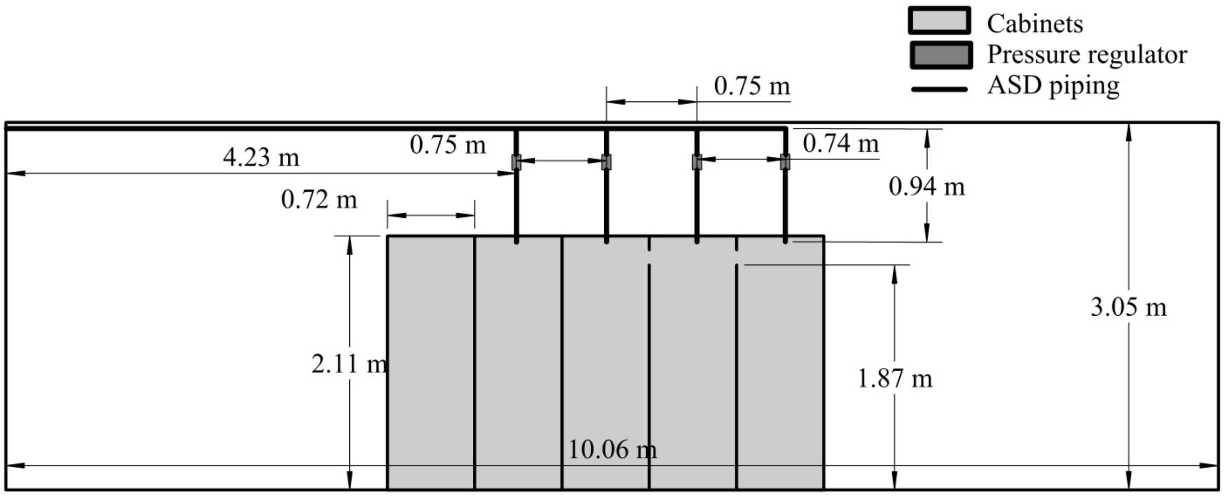


Figure 4-38. Front view of the ASD4 piping setup for the in-cabinet sampling

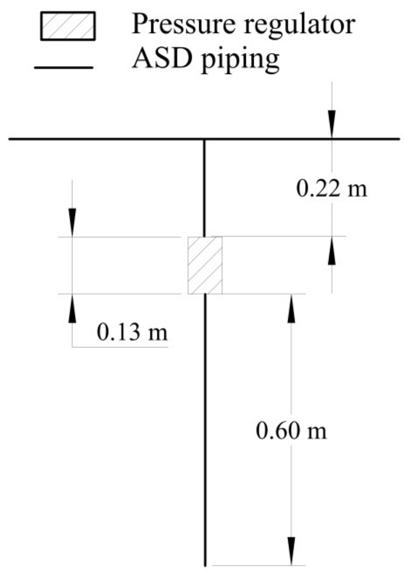


Figure 4-39. Pressure regulator located above each sampling port for ASD4

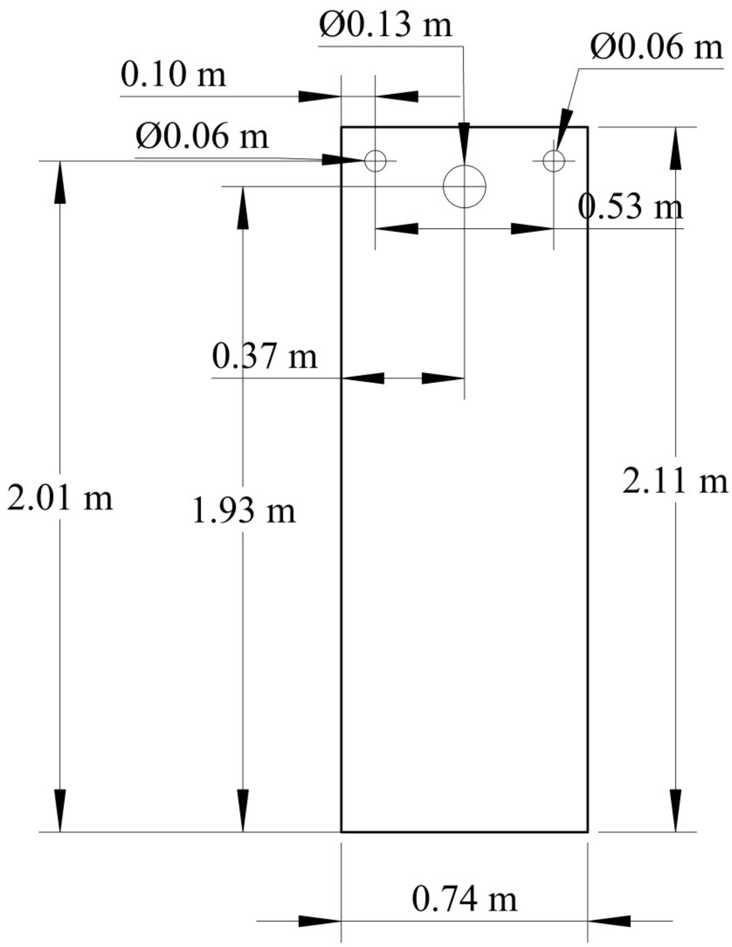


Figure 4-40. Side view of a cabinet, showing the location of the side vents

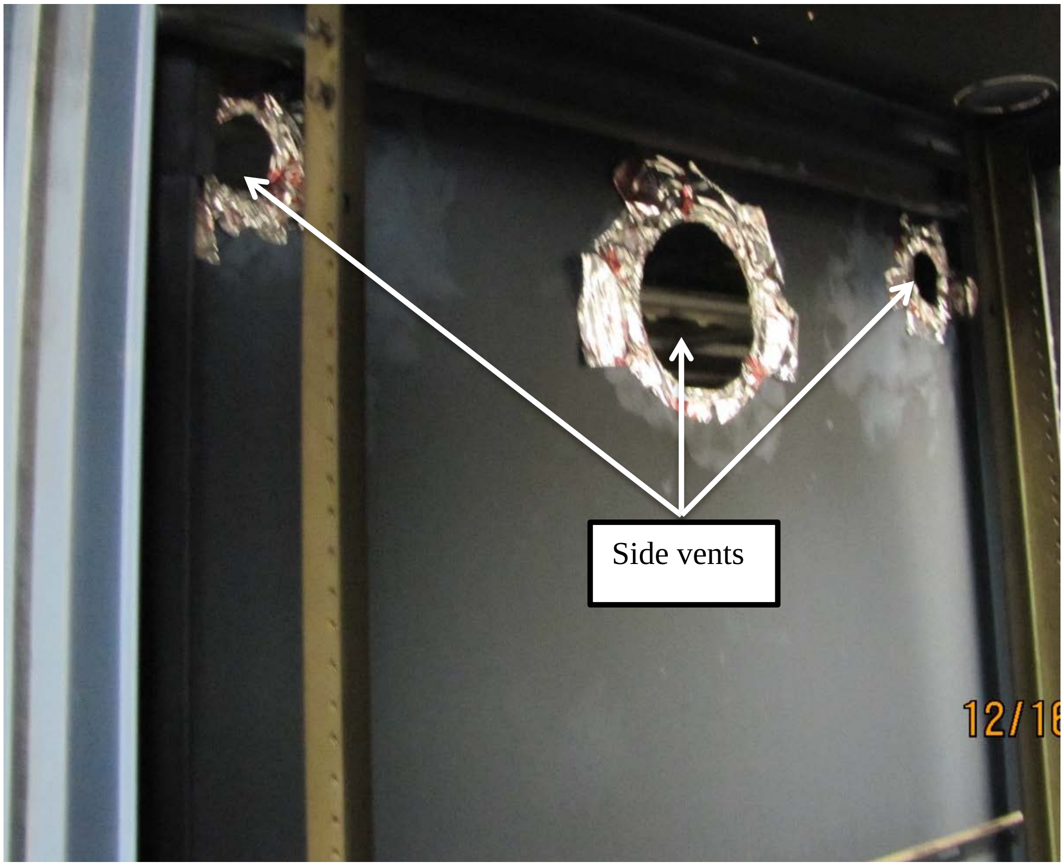


Figure 4-41. Side vents allowing flow between three cabinets with ASD sampling

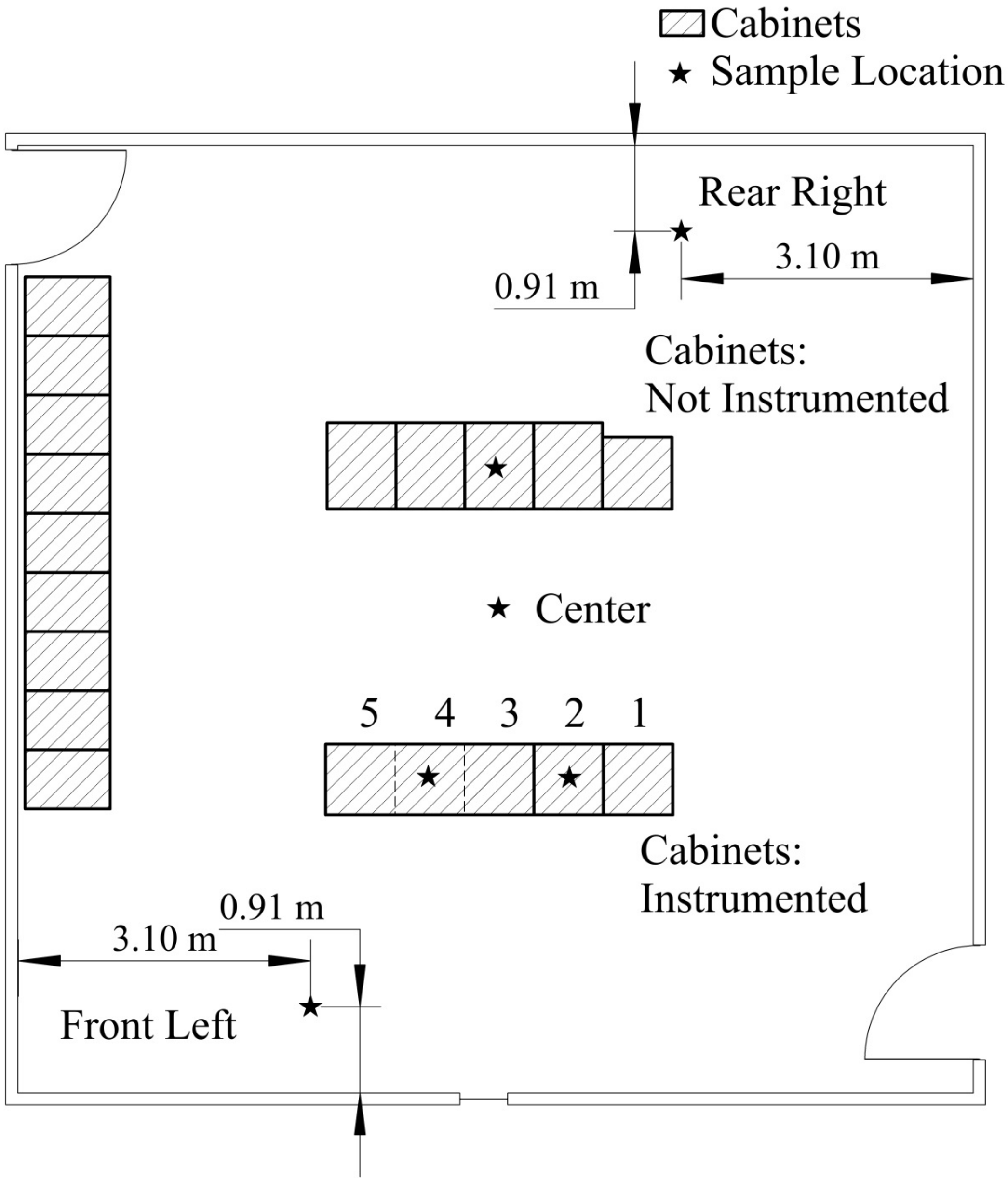


Figure 4-42. Sample locations in the experiments performed

4.4.6 Areawide, large room configurations

In the multi-zone ASD VEWFD experiments, two areawide smoke detection zones were covered, (i.e., the return air grill, and the ceiling). A separate zone monitored the four-cabinet that were monitored during the single-zone experiments. Figure 4-43 and Figure 4-44 show a plan view of the piping network layout for the return air grill, and the cabinets for ASD4 and ASD5. Figure 4-45 and Figure 4-46 show elevation views of the return air grill piping network layouts. Figure 4-47 shows a picture of the return air grill and the piping for the two ASDs. Figure 4-48 and Figure 4-49 show the plan view of the areawide ceiling ASD piping networks.

For conventional detection, per NFPA 72, no return air monitoring is required. The use of duct detectors were not able to be installed at the facility where the testing was being performed.

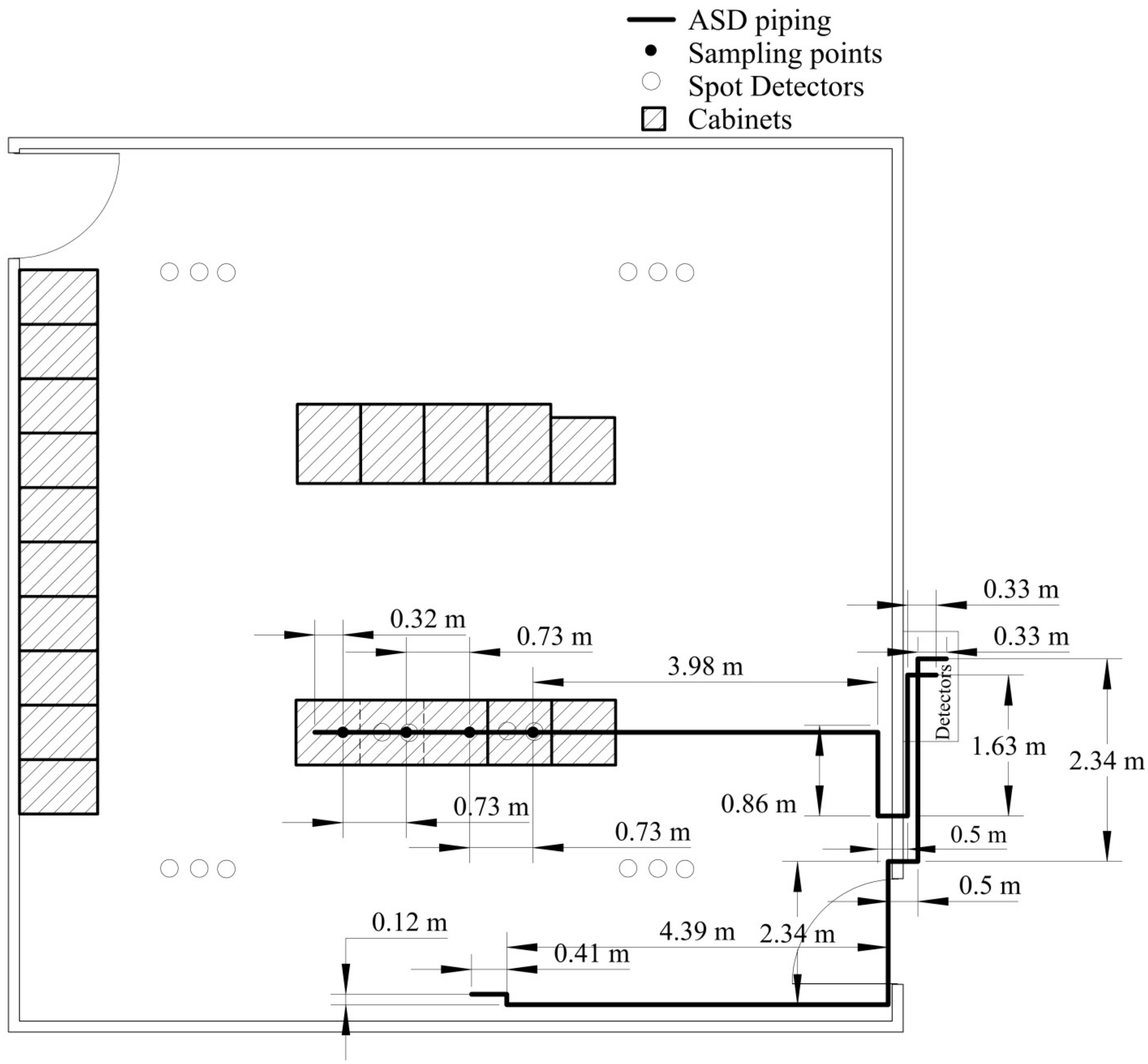


Figure 4-43. ASD4 piping layout for the in-cabinet and HVAC inlet sampling

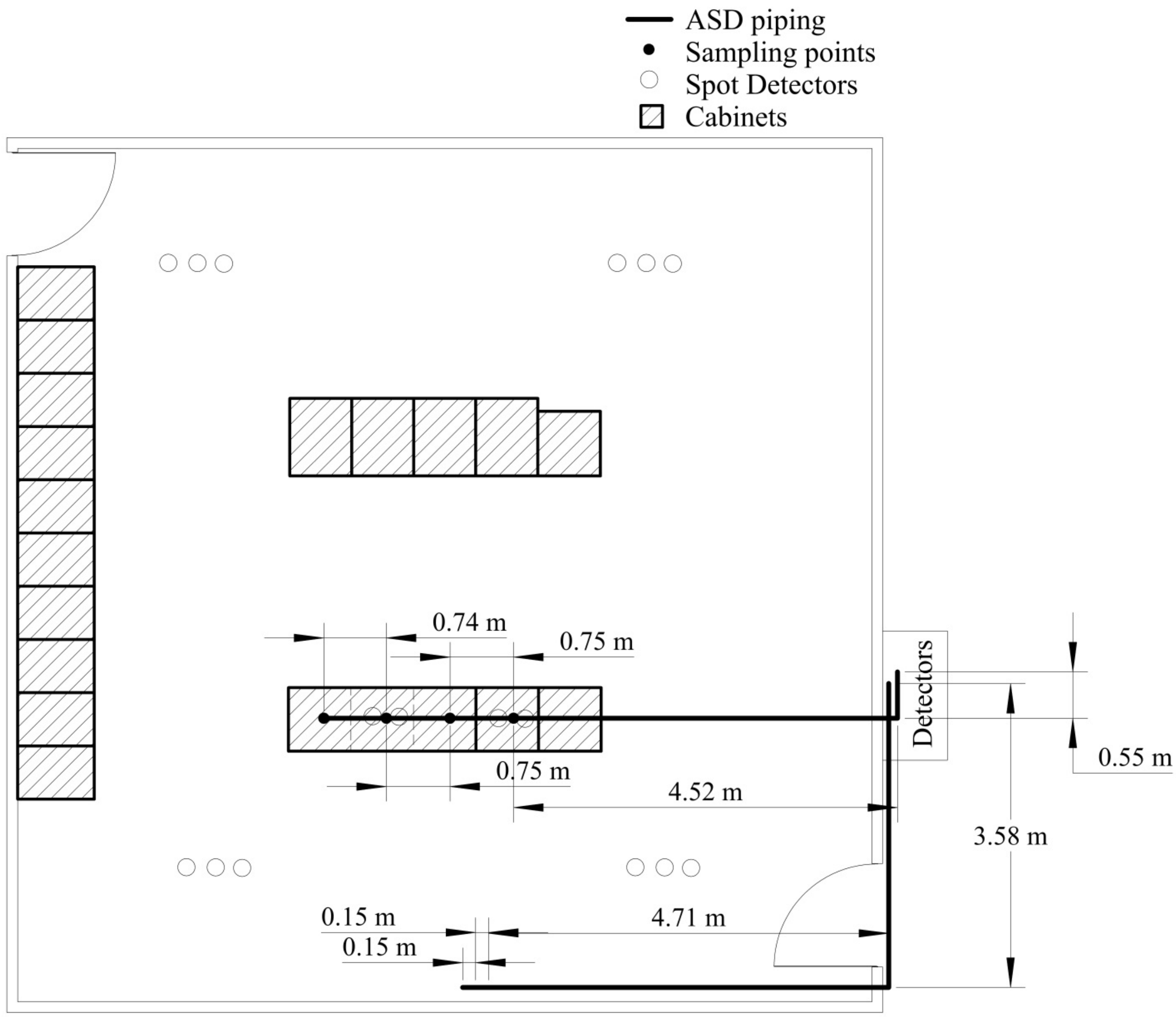


Figure 4-44. ASD5 piping layout for the in-cabinet and HVAC inlet sampling

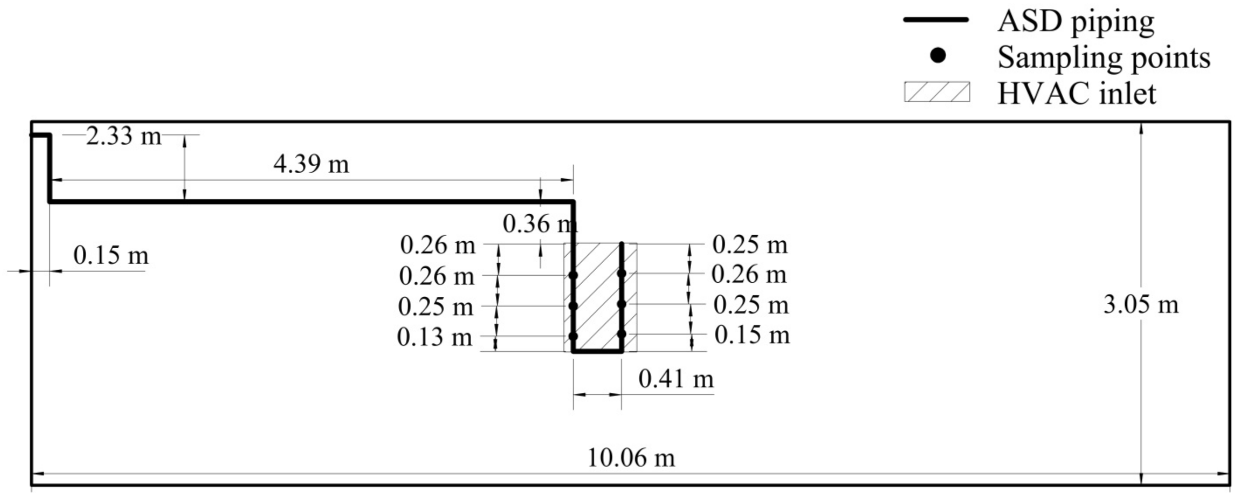


Figure 4-45. ASD5 piping layout, with sampling locations located at the HVAC exhaust

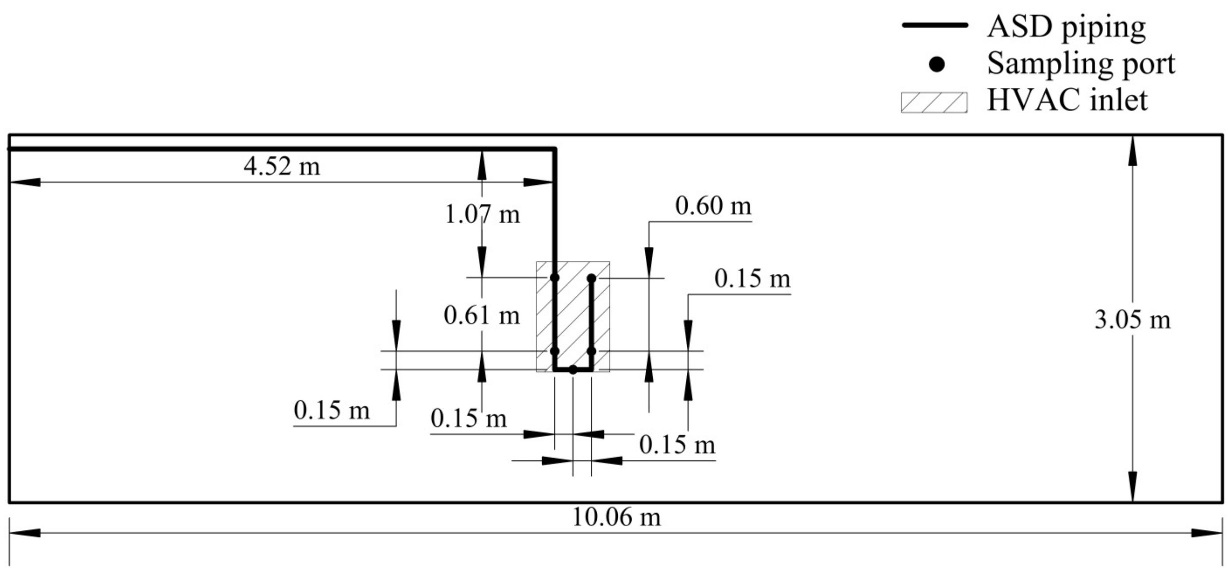
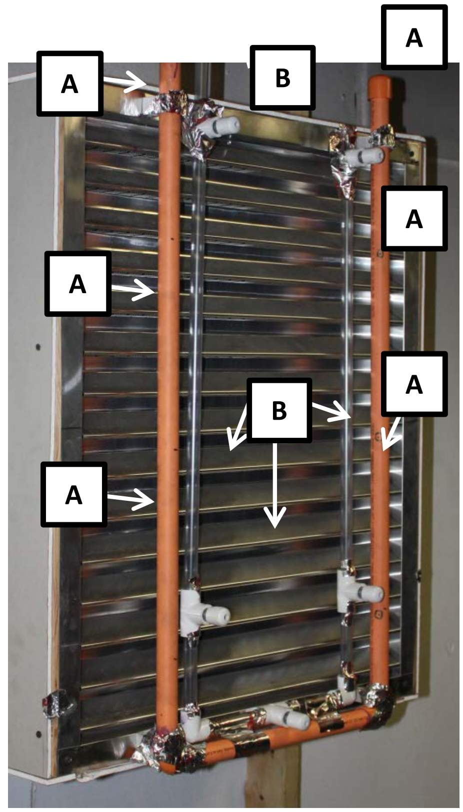


Figure 4-46. ASD4 piping layout, with sampling location located at the HVAC exhaust



A: ASD 5 B: ASD 4

Figure 4-47. Return air grill protected with ASD piping

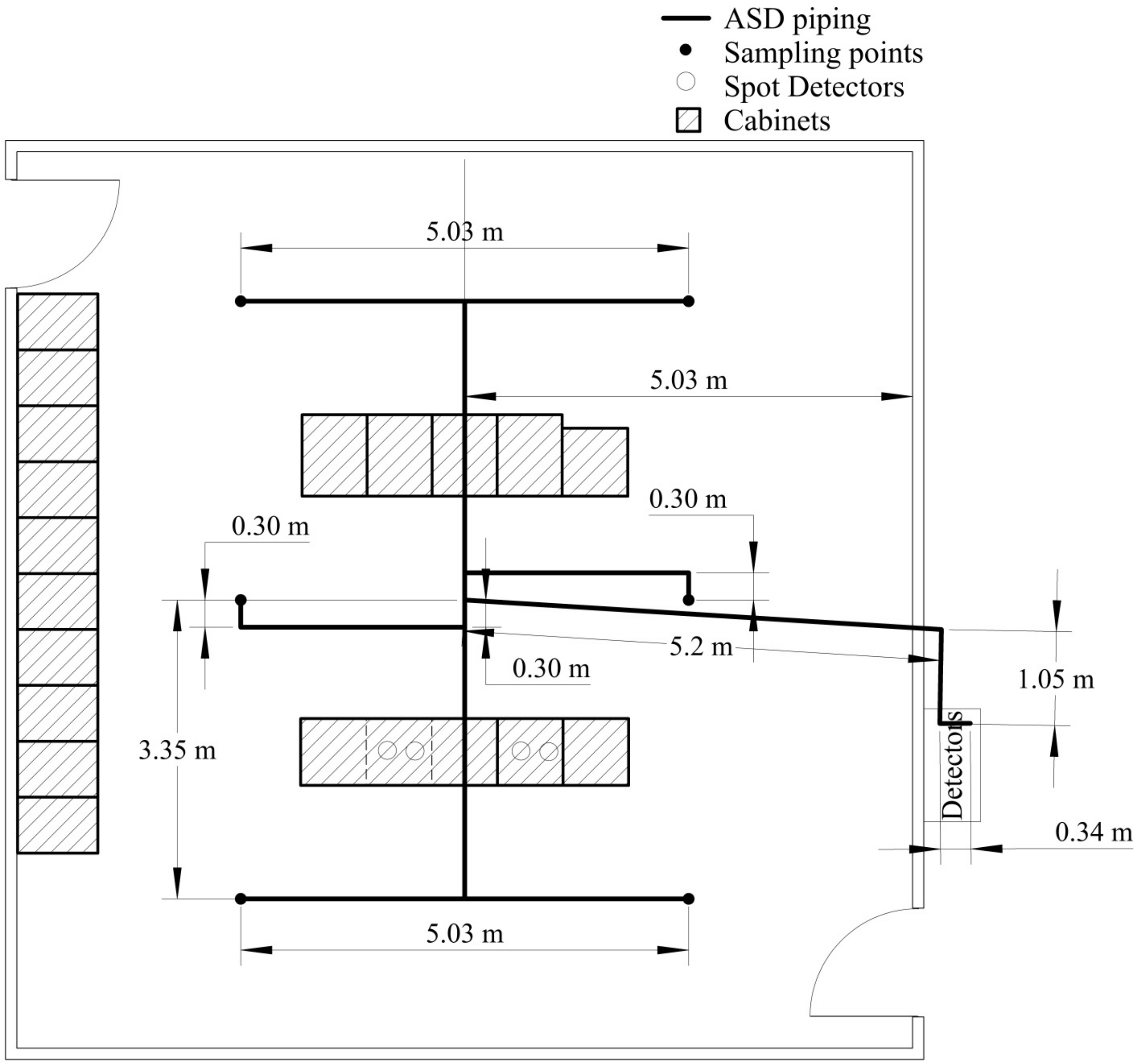


Figure 4-48. Areawide ASD4, piping layout

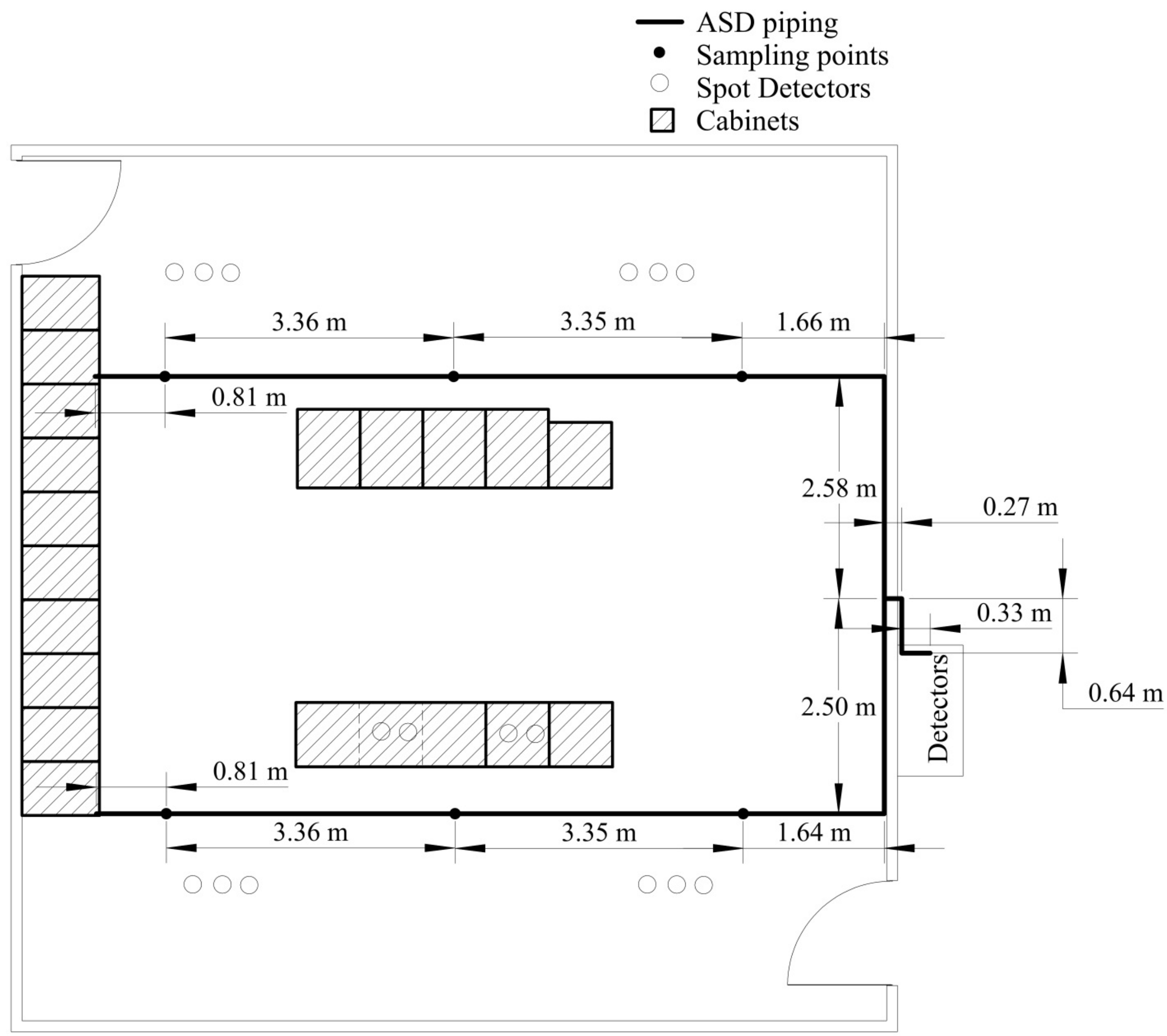


Figure 4-49. Areawide ASD5, piping layout

4.5 Experimental Procedure

The experimental procedure for each set of experiments is detailed below. The protocol included verifying detector configuration and design, including ASD smoke transport times and individual port suction pressures, and identifying individual spot detector locations.

4.5.1 Laboratory instrument cabinet experiments

The initial setup of the instrument cabinet detectors and ASDs verified that the spot detectors responded to challenging smoke; the pre-alarm and alarm times were recorded properly and the ASD system setups were performed, and faults cleared. The suction pressure at each ASD port was measured to verify that it was nominally the same as the others, and thus, presumably, produces equal flows for the ports leading to each ASD. A pressure gauge with a range of 0.20 kPa was used. Flexible tubing was attached to the low pressure port of the gauge and the

ASD port. The port pressures were 0.20 kPa, 0.14 kPa and 0.15 kPa for ASD1, ASD2 and ASD3, respectively. Smoke from a smoldering punk was used to verify the smoke transport times. Each ASD responded to smoke presented at the furthest sampling port within 10 s.

At the beginning of each day that experiments were to be conducted, the ASDs, FACP and electrical low pressure impactor were turned on and allowed to run for at least 30 minute before the start of an experiment. The data acquisition computer started logging typically 1 or 2 minute before starting the heating ramp. The end of the experiment was set at the end of the heating period. The bus bar was allowed to cool, and any residual smoke was exhausted from the enclosure during sample cool-down.

4.5.2 Laboratory large-cabinet experiments

The initial setup of the large-cabinet experiments followed the instrument cabinet setup. Only two ASDs were used to monitor the cabinets, ASD2 and ASD3. The measured port suction pressures were the same for each ASD piping arrangement, 0.11 kPa for ASD2, and 0.12 kPa for ASD3.

One large cabinet, used for ventilated cabinet experiments, had a cooling fan mounted on top. Experiments were conducted to estimate the fan flow given the specific internal arrangement of the cabinet as tested. Carbon dioxide was injected at a fixed rate into the fan inlet. The carbon dioxide mixed with the incoming air, and was diluted to a lesser value based on the ventilation air. Injection of ~ 10 l/min of carbon dioxide yielded 0.20 percent (by volume), once mixed with the ventilation air. The mean of four measurements was 4,800 l/min ± 100 l/min. Assuming a cabinet volume of 0.8 m^3, an air exchange rate of about 360 air changes per hour (ACH) would be expected.

4.5.3 Small room in-cabinet experiments

The small-room experiments posed some challenges, since the offsite test location had no central heating, and the experiments were conducted in the month of December. Electric space heaters were used to heat the small room and the attached data acquisition room. The heaters were turned on in the morning and allowed to heat the test room to a temperature above 12ºC. A vertical array of thermocouples stretching from 30 cm above the floor to the ceiling, was monitored to determine the temperature gradient. The maximum temperature difference was typically about 1ºC.

The suction pressures for the six in-cabinet sampling ports for the three ASDs were 0.123 kPa, 0.074 kPa, and 0.083 kPa for ASD1, AD2 and AD3, respectively.

The smoke transport time was measured at cabinets 1 and 6. Those cabinets represented the closest and furthest points in the setup. The average smoke response times for three measurements at the first cabinet were 19.4 ± 2.4, 33.2 ± 6.7 and 13.7 ± 0.2 seconds for ASD1, ASD2 and ASD3, respectively. The measurements at the last cabinet were 20.3 ± 1.8, 32.0 ± 1.7 and 15.3 ± 1.2 seconds for ASD1, ASD2 and ASD3, respectively.

Experiments were conducted with forced ventilation of the row of five interconnected cabinets. The air exchange rate between the cabinet and the room air was estimated by monitoring carbon dioxide concentration inside the cabinets, following a discharge of a carbon dioxide fire extinguisher. The decay in the concentration was fitted to an exponential equation to yield a time constant for the decay, giving the air changes per hour (ACH). A detailed description for

calculating the exchange rate can be found in the ASTM E741 standard. The combined relative uncertainty in this technique is ± 10 percent. For the row of five cabinets, two measurements were made following two separate extinguisher discharges yielding 8.4 ACH and 7.5 ACH, and a mean of 8.0 ACH.

Additional experiments were conducted with room ventilation air flow. The air exchange rate of the room with air ventilation was estimated by monitoring carbon dioxide concentration in the center of the room, following a discharge of a carbon dioxide fire extinguisher, and fitting the decay curve as described above. For the room with mechanical ventilation running, three measurements were made yielding a mean value of 9.2 ACH ± 1.4 ACH.

4.5.4 Small room areawide experiments

The small-room, areawide experiments were conducted with three ASD VEWFD systems monitoring ceiling-mounted pipe network. Four sampling holes were drilled into each piping network to cover each quadrant of the room. The suction pressures for the four sampling holes for the three ASDs were 0.14 kPa, 0.15 kPa, and 0.20 kPa for ASD1, AD2 and AD3, respectively. Smoke response times were less than 30 seconds for all ASDs and sampling holes.

Experiments were conducted with and without room ventilation air flow. The fan setting was the same one used during the in-cabinet room ventilation experiments (i.e. 9.2 ACH ± 1.4 ACH).

The room was heated with electric space heaters before the start of an experiment. For no room ventilation experiments, the heaters were turned off just before the start of an experiment. With no ventilation, the room temperature was nominally constant for the duration of an experiment. For experiments with room ventilation, after heating the room before the start of an experiment, the heaters were moved to the room where the blower was located, so the incoming air during an experiment was heated to maintain the room air temperature throughout an experiment.

4.5.5 Large room single-zone in-cabinet experiments

ASD2 (cloud chamber type) and ASD3 (light-scattering type) were used for the large-room, single-zone in-cabinet experiments, where a single cabinet (second in line) isolated from adjacent cabinets was one sample location configuration, and the fourth cabinet in line that had vent holes to the third and fifth cabinets was the other sample location. Sample port openings were 4.75 mm in diameter for both piping networks. The sample port suction pressures for ASD2 were 0.069 kPa for the first two sampling ports (closest to the detector), and 0.64 kPa for the last two sampling ports. For ASD3, the suction pressures were 0.088 kPa for the first two sampling ports, and 0.083 kPa for the last two sampling ports.

The air exchange rate of the room with the air exhaust fan fixed at a speed of 32 Hz was estimated by monitoring carbon dioxide concentration in the center of the room following a discharge of a carbon dioxide fire extinguisher, and fitting the decay curve to an exponential function. Three measurements were made yielding a mean value of 7.4 ACH ± 0.6 ACH.

4.5.6 Large room multi-zone in-cabinet experiments

ASD4 (cloud chamber type) and ASD5 (light-scattering type) were used for the large room multi-zone in-cabinet experiments. The configurations examined were the same as the single-zone experiments where a single cabinet (second in line) isolated from adjacent cabinets was one sample location configuration, and the fourth cabinet in line that had vent holes to the third and fifth cabinets was the other sample location. The multi-port ASDs were set up to monitor three separate zones, in-cabinet, areawide ceiling, and the exhaust grill representing a return air grill. Sample port openings were 4.75 mm in diameter for the ASD5 piping network. ASD4 used a vendor-provided design and verification (commissioning) testing. ASD4 used different sampling ports for in-cabinet applications. The flow through each port was adjusted to approximately 1.5 L/min from an adjustable inline pressure regulator. The smoke transport times for ASD5 in-cabinet piping was 25 ± 1 seconds for the last port (furthest from the detector) and 16 ± 2 seconds for the closest port. The transport time for ASD4 was 52 seconds for the last in-cabinet port.

The air exchange rates of the room with the room air exhaust fan fixed at speeds of 32 Hz and 60 Hz were estimated by monitoring carbon dioxide concentrations in the center of the room following a discharge of a carbon dioxide fire extinguisher, and fitting the decay curve to an exponential function. Repeated measurements were made yielding mean values of 6.5 ACH ± 0.6 ACH, and 14.0 ACH ± 1.0 ACH for 32 Hz and 60 Hz fan settings respectively. Note, there was a difference between single-zone and multi-zone the 32 Hz fan setting ACHs, which was because of a ducting configuration change between the two test series.

4.5.7 Large room multi-zone areawide experiments

ASD4 (cloud chamber type) and ASD5 (light-scattering type) were used for the large room multi-zone areawide experiments. The smoke transport times for ASD4 areawide and return air grill sampling ports furthest from the detector were 33 and 26 seconds, respectively. The smoke transport times for ASD5 areawide and return air grill sampling ports furthest from the detector were 45 ± 1 seconds and 25 ± 0.5 seconds, respectively.

4.6 Experimental Design

The following tables detail the experimental conditions for each experiment conducted. The experimental design evolved throughout the project schedule. Information gained from experiments, and feedback from observers was used to tailor successive experimental designs. As part of the experimental design, select experimental conditions were replicated to allow an assessment of repeatability of the experimental results.

4.6.1 Laboratory, instrument cabinet experiments

The laboratory instrument cabinet experiments were conducted at 15-, 60- and 240 minute HRPs each with a 5 minute fixed ending set point soak period. Samples were located with the bus bar block centered on the floor of the cabinet. The cabinet was naturally ventilated with vents located on the top of the cabinet or on the cabinet sides, 0.2 m below the top of the cabinet.

Table 4-4. Laboratory Instrument Cabinet Experiments

Configuration Number	Experimental Configuration			Experiments Conducted
	Material	Heating Ramp Period (min)	Vent locations	
1	XLPO2	15.0	Top	3
2	XLPO2	15.0	Side	1
3	XLPO2	60.0	Top	1
4	XLPO2	60.0	Side	3
5	XLPO2	240.0	Side	1
6	PFTE	15.0	Top	3
7	PFTE	15.0	Side	1
8	PFTE	60.0	Top	1
9	PFTE	60.0	Side	3
10	PFTE	240.0	Top	1
11	XLPE	15.0	Top	4
12	XLPE	15.0	Side	2
13	XLPE	60.0	Top	1
14	XLPE	60.0	Side	4
15	XLPE	240.0	Side	3
16	Silicone	15.0	Top	3
17	Silicone	15.0	Side	1
18	Silicone	60.0	Top	1
19	Silicone	60.0	Side	3
20	XLPO1	15.0	Top	3
21	XLPO1	15.0	Side	1
22	XLPO1	60.0	Top	1
23	XLPO1	60.0	Side	3
24	PVC1	15.0	Top	3
25	PVC1	15.0	Side	1
26	PVC1	60.0	Top	1
27	PVC1	60.0	Side	3
28	PVC2	15.0	Top	3
29	PVC2	15.0	Side	1
30	PVC2	60.0	Top	1
31	PVC2	60.0	Side	3
32	PVC2	240.0	Side	1
33	CSPE	15.0	Top	3
34	CSPE	15.0	Top	1
35	CSPE	60.0	Top	1
36	CSPE	60.0	Top	3
37	CSPE	240.0	Top	1
38	TB	15.0	Top	3
39	TB	15.0	Side	1
40	TB	60.0	Top	1
41	TB	60.0	Side	3
42	TB	240.0	Side	1
43	PCB	15.0	Top	3
44	PCB	15.0	Side	1
45	PCB	60.0	Top	1
46	PCB	60.0	Side	3

Table 4-4. Laboratory Instrument Cabinet Experiments (Continued)

Configuration Number	Experimental Configuration			Experiments Conducted
	Material	Heating Ramp Period (min)	Vent locations	
47	PCB	240.0	Top	1
48	Resistors	90 s	Top	3
49	Resistors	90 s	Side	3
50	Capacitors	30 s	Top	3
51	Capacitors	30 s	Side	3
Configurations below used different ASD2 and ASD3 detector sensitivities				
52	XLPE	15.0	Top	4
53	XLPE	60.0	Top	4
54	PVC2	15.0	Top	4
55	PVC2	60.0	Top	4
56	CSPE	15.0	Top	4
57	CSPE	60.0	Top	4
58	One Resistor	70 s	Top	3
59	Two Resistors	80 s	Top	3

4.6.2 Laboratory, large-cabinet experiments

Table 4-5. Laboratory Large-Cabinet Experiments

Configuration Number	Experimental Configuration			Experiments Conducted
	Material	Heating Ramp Period (min)	Cabinet Ventilation	
1	XLPE	16.3	Natural	3
2	XLPE	16.3	Forced	3
3	XLPE	65.0	Natural	3
4	XLPE	65.0	Forced	3
5	XLPE	260.0	Natural	1
6	XLPE	260.0	Forced	1
7	CSPE	16.3	Natural	3
8	CSPE	16.3	Forced	3
9	CSPE	65.0	Natural	3
10	CSPE	65.0	Forced	3
11	CSPE	260.0	Natural	1
12	CSPE	260.0	Forced	1
13	PVC2	16.3	Natural	3
14	PVC2	16.3	Forced	3
15	PVC2	65.0	Natural	3
16	PVC2	65.0	Forced	3
17	PVC2	260.0	Natural	1
19	PVC2	260.0	Forced	1
20	PCB	16.3	Natural	1
21	PCB	16.3	Forced	1
22	PCB	65.0	Natural	1
23	PCB	65.0	Forced	1
24	BS 6266	-	Natural	6

Table 4-6. Large Cabinet Experiments with Reducted HRP

Configuration Number	Experimental Configuration			
	Material	Maximum Set point (ºC)	HRP (min)	Hold Time (min)
1	XLPE	275	8.8	12.2
2	XLPE	300	9.7	60.3
3	XLPE	325	10.6	10.4
4	CSPE	200	6.2	14.8
5	CSPE	225	7.1	62.9
6	CSPE	250	8.0	13.0

4.6.3 Full-scale, small room tests

A series of mock cabinets was built in a 37.7 m^2 facility to simulate an electrical room. The cabinets were connected forming two rows of 5 cabinets each. One of the rows had a partition placed in between two cabinets, creating a set of four connected cabinets alongside a single one. The five-cabinet configuration had a set of fans installed, allowing for a comparison between naturally and forced-ventilated conditions. The sample was located either on the ground or about 1.2 m above the floor. The tests were performed with and without room ventilation. Table 4-7 through Table 4-11 list all the tests where the detectors and the aerosol sources were located inside the cabinet. For the tests in Table 4-12, the spot detectors from the front row of the cabinets were placed on the ceiling of the room. The source location varied from either inside the cabinet or outside.

Table 4-7. Full-Scale, Single-Zone, In-Cabinet XLPE Experiments

Configuration Number	Experimental Configuration					Experiments Conducted
	HRP (min)	Source Cabinet	Source Elevation (m)	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
1	16.3	1	0	0	0	1
2	16.3	4	0	0	0	1
3	16.3	5	0	0	0	2
4	16.3	5	1.2	0	0	1
5	65.0	1	0	0	0	1
6	65.0	4	0	0	0	3
7	65.0	5	0	0	0	1
8	65.0	5	1.2	0	0	1
9	65.0	5	0	7.9	0	1
10	65.0	5	0	0	9.1	3
11	260.0	5	0	0	0	1

Table 4-8. Full-Scale, Single-Zone, In-Cabinet CSPE Experiments

Configuration Number	Experimental Configuration					Experiments Conducted
	HRP (min)	Source Cabinet	Source Elevation (m)	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
1	16.3	1	0	0	0	1
2	16.3	4	0	0	0	3
3	16.3	5	0	0	0	1
4	16.3	5	1.2	0	0	1
5	65.0	1	0	0	0	1
6	65.0	4	0	0	0	1
7	65.0	5	0	0	0	1
8	65.0	5	1.2	0	0	1
9	65.0	5	0	7.9	0	1
10	65.0	5	0	0	9.1	1
11	260.0	5	0	0	0	1

Table 4-9. Full-Scale, Single-Zone, In-Cabinet PVC2 Experiments

Configuration Number	Test Configuration					Experiments Conducted
	HRP (min)	Source Cabinet	Source Elevation (m)	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
1	16.3	1	0	0	0	1
2	16.3	4	0	0	0	1
3	16.3	5	0	0	0	1
4	16.3	5	1.2	0	0	3
5	65.0	1	0	0	0	1
6	65.0	4	0	0	0	1
7	65.0	5	0	0	0	3
8	65.0	5	1.2	0	0	1
9	65.0	5	0	7.9	0	1
10	65.0	5	0	0	9.1	1
11	260.0	5	0	0	0	1

Table 4-10. Full-Scale, Single-Zone, In-Cabinet PCB Experiments

Configuration Number	Experimental Configuration					Experiments Conducted
	HRP (min)	Source Cabinet	Source Elevation (m)	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
1	16.3	1	0	0	0	1
2	16.3	5	0	0	0	1
3	65.0	5	0	0	0	1
4	65.0	5	0	7.9	0	1
5	65.0	5	0	0	9.1	1

Table 4-11. Full-Scale, Single-Zone, In-Cabinet Resistor Experiments

Configuration Number	Experimental Configuration					Experiments Conducted
	PS (s)	Source Location	Source Elevation	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
1	90	1	0	0	0	3
2	90	4	0	0	0	3
3	90	5	0	0	0	3
4	90	5	1.2	0	0	3

Table 4-12. Full-Scale, Single-Zone, Areawide Experiments

Configuration Number	Experimental Configuration				Experiments Conducted
	Material	HRP (min)	Source Location	Room Ventilation (ACH)	
1	Cable bundle	65.0	Center	0	1
2	Cable bundle	65.0	Corner	0	1
3	Cable bundle	65.0	Corner	9.1	1
4	Cable bundle	260.0	Corner	0	1
5	CSPE	16.3	5	0	3
6	CSPE	16.3	5	9.1	1
7	CSPE	16.3	Corner	9.1	5
8	CSPE	16.3	Center	0	1
9	CSPE	65.0	5	0	1
10	CSPE	65.0	5	9.1	1
11	CSPE	65.0	Corner	0	1
12	XLPE	16.3	5	0	3
13	XLPE	16.3	Corner	0	3
14	XLPE	65.0	5	0	3
15	XLPE	65.0	Corner	0	1
16	Shredded Paper		Corner	0	1
17	Shredded Paper		Center	9.1	1
19	BS Wire		Corner	0	3
20	BS Wire		Center	0	3
21	BS Wire		Corner	9.1	3
22	Mod BS Wire		Corner	0	3
23	Mod BS Wire		Center	0	3
24	Mod BS Wire		Corner	9.1	3

4.6.4 Full-scale, large room tests

Table 4-13 and Table 4-14 present the test matrix for the full-scale, large room experiments using single-zone and multi-zone detectors, respectively.

Table 4-13. Full-Scale, Single-Zone, In-Cabinet Experiments

Configuration Number	Experimental Configuration				Experiments Conducted
	Material	HRP (min)	Source Cabinet	Room Ventilation (ACH)	
1	CSPE	65.0	1	0	1
2	CSPE	65.0	1	7.4	1
3	CSPE	65.0	3	0	1
4	CSPE	65.0	3	0	1
5	CSPE	260.0	3	0	1
6	CSPE	260.0	3	7.4	1
7	XLPE	65.0	1	0	1
8	XLPE	65.0	1	7.4	1
9	XLPE	65.0	3	0	1
10	XLPE	65.0	3	7.4	1
11	XLPE	260.0	3	0	1
12	XLPE	260.0	3	7.4	1

Table 4-14. Full-Scale, Multi-Zone Experiments

Configuration Number	Test Configuration					Experiments Conducted
	Material	HRP (min)	Source Location	Source Elevation	Room Ventilation (ACH)	
1	CSPE	65.0	1	0	0	1
2	CSPE	65.0	1	0	6.5	1
3	CSPE	65.0	3	0	0	1
4	CSPE	65.0	3	0	6.5	1
5	CSPE	65.0	3	0	14	1
6	CSPE	260.0	3	0	0	1
7	CSPE	260.0	3	0	6.5	1
8	CSPE	65.0	Center	0	0	1
9	CSPE	65.0	Center	0	6.5	1
10	CSPE	65.0	Second row	0	0	1
11	CSPE	65.0	Second row	0	6.5	1
12	CSPE	65.0	Second row	0	14	1
13	CSPE	65.0	Left rear	0	6.5	1
14	CSPE	65.0	Right front	0	6.5	1
15	XLPE	65.0	1	0	0	2
16	XLPE	65.0	1	0	6.5	1

Table 4-14. Full-Scale, Multi-Zone Experiments (Continued)						
Configuration Number	Test Configuration					Experiments Conducted
	Material	HRP (min)	Source Location	Source Elevation	Room Ventilation (ACH)	
17	XLPE	65.0	1	0	7.4	1
18	XLPE	65.0	3	0	0	2
19	XLPE	65.0	3	0	6.5	1
20	XLPE	65.0	3	0	7.4	1
21	XLPE	65.0	3	0	14	1
22	XLPE	260.0	3	0	0	2
23	XLPE	260.0	3	0	6.5	1
24	XLPE	260.0	3	0	7.4	1
25	XLPE	65.0	Center	0	0	1
26	XLPE	65.0	Center	0	6.5	1
27	Cable Bundle	16.3	Center	0	0	1
28	Cable Bundle	16.3	Center	0	6.5	2
29	Cable Bundle	16.3	Center	0	14	1
30	Cable Bundle	16.3	Center	1.8	0	1
31	Cable Bundle	16.3	Center	1.8	6.5	1
32	Cable Bundle	16.3	1 (Back row)	2.11	14	2
33	Cable Bundle	65.0	Center	0	0	1
34	Cable Bundle	65.0	Center	0	6.5	1
35	Cable Bundle	65.0	1 (Back row)	0	0	1
36	Cable Bundle	65.0	1 (Back row)	0	6.5	1
37	Cable Bundle	65.0	1 (Back row)	0	14	1
38	Cable Bundle	65.0	Left rear corner	0	6.5	1
39	Cable Bundle	65.0	Left rear corner	0	14	1
40	Cable Bundle	65.0	Front right corner	0	6.5	1
41	Cable Bundle	65.0	Front right corner	0	14	1
42	Cable Bundle	260.0	center	0	0	1
43	Mod BS Wire		Front right corner	0	0	1
44	Mod BS Wire		Front right corner	0	6.5	1
45	Mod BS Wire		Front right corner	0	14	2

Table 4-14. Full-Scale, Multi-Zone Experiments (Continued)						
Configuration Number	Test Configuration					Experiments Conducted
	Material	HRP (min)	Source Location	Source Elevation	Room Ventilation (ACH)	
46	Mod BS Wire		Center	0	0	2
47	BS Wire		Center	0	0	1
48	Mod BS Wire		Center	0	6.5	1
49	BS Wire		Center	0	6.5	1
50	Mod BS Wire		Center	0	14	1
51	BS Wire		Center	0	14	1
52	Mod BS Wire		Left rear corner	0	0	1
53	Mod BS Wire		Left rear corner	0	6.5	2
54	BS Wire		Left rear corner	0	6.5	2
55	ModBS Wire		Left rear corner	0	14	1
56	Cable Bundle	16.3	Center	0	14	1

5. EXPERIMENTAL RESULTS

The test plan included a set of experimental configurations to assess performance over a range of conditions. The objective was to capture conceivable particle evolution scenarios that would be sensed by the various detectors, given the experimental conditions. It is impossible to ensure these experiments capture the most likely, along with the worst-case scenarios that would be experienced by systems deployed in nuclear power plants (NPPs). However, it is reasonable to assume the relative performance of aspirating smoke detection (ASD) very early warning fire detection (VEWFD) systems or sensitive spot detectors to conventional detectors observed in these experiments would apply in real-world scenarios.

Individual detector pre-alerts, alerts, pre-alarms and alarms, where applicable, were recorded during all experiments. The relative performance of the ASD and sensitive spot VEWFD systems were evaluated by comparing their activations to the ionization detector alarm for in-cabinet experiments and to the ionization and photoelectric detector for areawide experiments. For in-cabinet configurations, ionization detectors were considered to be the conventional detector for comparison to the ASDs or sensitive spots VEWFD systems for two reasons: (1) ionization alarms were observed in-service inside electrical cabinets in NPP visits, and (2) ionization alarms are typically more sensitive to the early pyrolysis smokes generated by the chosen sources.

An absolute performance measure of the time interval between activation and the end of a test was used to represent time available for response before a potential ignition event. The assumption made here is that the wire temperature at the end of the test is nominally at or above the piloted ignition temperature, which, given the measured wire temperature profile and thermal imaging camera images, appears to be a reasonable assumption (Ref. 34). Piloted ignition tests conducted after the experimental series was concluded and as detailed in Section 5.8 support this assumption.

For the experiments in which two light-scattering ASDs were monitored, only one of those ASDs was used in the analysis, since similar results were obtained. In addition, the analysis considered ASD VEWFD system Pre-alert and Alert settings the sensitive spot (SS) Alert setting, and the conventional ionization and photoelectric detector Alarm settings; the assumption here is that the ASD or SS Alert would initiate a defined VEWFD system response. The ASD Pre-alert and Alert settings were not held constant throughout the different experimental setups. In the case of light-scattering ASDs, the Pre-alert setting ranged from 4 to 10 times the sensitivity of the VEWFD Alert setting (0.2 %/ft obscuration). In the case of cloud chamber ASDs, the Pre-alert, Alert and Alarm settings were specified to cover a range of sensitivity settings in all experimental setups except the large-room, multi-zone experiments in which the vendor specified the sensitivity settings.

It is important to note that this experimental research was not designed to assess the performance of VEWFD models or types against one another, but rather, was designed to assess the potential VEWFD performance against conventional detectors. The VEWFD system sensitivity settings and system designs may not be optimal for the configuration being studied and will vary based on the environmental conditions of the application. The guidance on in-cabinet applications is less developed than the areawide design specifications, therefore in-cabinet designs rely on input from manufacturers and system integrators.

5.1 Laboratory, Small-Cabinet Experiments

These experiments were the first set conducted and were designed to gain an understanding of the heated wire/component source, typical ASD and conventional detector response to the various materials selected. In addition, it was a goal of these experiments to find a rational basis for down-selecting the number of materials to be used in subsequent experiments; the materials tested in this series are identified in Table 5-1.

Table 5-1. Material Identification Numbers Used in Laboratory—Small-Scale Tests

ID #	Name	Description of Material
1	PVC1	Polyvinyl chloride insulated, 18 AWG wire
2	PVC2	Polyvinyl chloride insulated, 14 AWG wire
3	Silicone	Silicone insulated , 18 AWG wire
4	PTFE	Polytetrafluoroethylene insulated, 14 AWG wire
5	XLPO1	Cross-linked polyolefin insulated, 12 AWG wire
6	XLPO2	Cross-linked polyolefin insulated, 12 AWG wire
7	XLPE	Cross-linked polyethylene insulated, 12 AWG wire.
8	CSPE	Chlorosulfonated polyethylene insulated, 10 AWG wire
9	PCB	FR4, glass-reinforced epoxy laminate circuit board
10	TB	Phenolic barrier terminal block

Two sets of experiments were conducted with different heating rate and experimental time conditions. One condition was a heating ramp period (HRP) of 15.0 minutes to a final set point of 450 degrees C, followed by a 5.0 minute period heating period at the final set point, for a total heating time (THT) of 20.0 minutes. The other condition was a heating ramp period (HRP) of 60.0 minutes to a final set point of 450 degrees C, followed by a 5.0 minute period heating period at the final set point, for a total heating time (THT) of 65.0 minutes. The results aggregate those experiments with top and side ventilation conditions, because there was no apparent response time difference between these configurations.

The ASD and spot detector sensitivities are listed in Table 5-2. ASD piping configuration was nominally 3.7 m long with four equally spaced tee'd sampling ports, three drawing ambient laboratory room air and one drawing cabinet air. In the case of the ASD3, the pre-alarm and alarm sensitivities represent the port sensitivities equal to 0.2 %/ft obscuration and 1.0 %/ft obscuration. The sensitivities for ASD2, the cloud chamber device, were factory default settings, and not necessarily what would be used for in-cabinet VEWFD system applications, but most likely less sensitive settings.

Table 5-2. Nominal Detector Sensitivities for Laboratory—Small Scale Tests

Sensitivity Setting	ASD1 Detector / Port %/ft Obsc	ASD2 Detector / Port Particles/cm^3	ASD3 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc	PHOTO %/ft Obsc
VEWFDS Pre-alert	0.013 / 0.05	$5.1x10^5$ / $2.4x10^6$	0.025 / 0.10	-	-	-
VEWFDS Alert	0.05 / 0.20	$1.2x10^6$ / $4.8x10^6$	0.05 / 0.20	0.20	-	-
VEWFDS Alarm	0.25 / 1.00	$1.5x10^6$ / $6.0x10^6$	0.25 / 1.00	1.00	-	-
Conventional Pre-Alarm	-	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	-	1.0	2.1

Figure 5-1 shows the pre-alert or alarm times for experiments conducted in the small cabinet with the 15.0 minute HRP. The materials are ordered in terms of increasing average ION spot alarm times. In most cases, ASD2 pre-alerted first, typically before 600 seconds of heating. With silicone and PTFE, ASD3 did not reach a pre-alert threshold before the end of experiments. The ION did not alarm with PTFE wire, while the PHOTO did not alarm with 6 out of 10 materials.

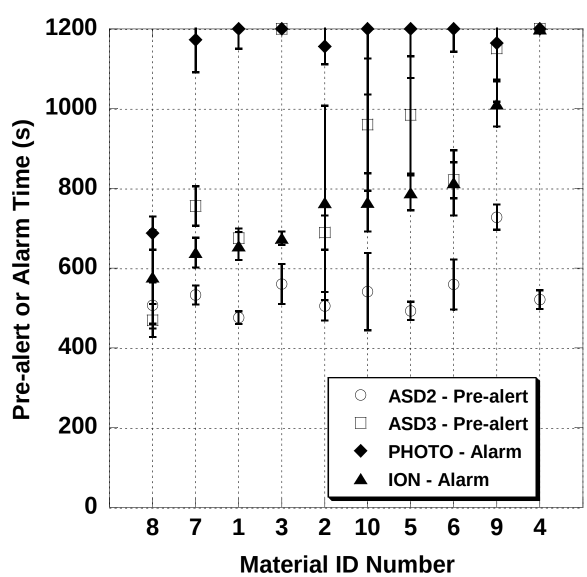


Figure 5-1. VEWFD pre-alert and conventional alarm times for the 15 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)

Figure 5-2 shows VEWFD system alert and ION alarm times for experiments conducted in the small instrument cabinet with the 15.0 minute HRP. Again, the materials are ordered in terms of increasing average ION spot alarm times. ASD2 alerted first for all materials except CSPE (chlorosulfonated polyethylene). ASD3 alerted before ION alarm with two materials. ASD3 typically alerted before SS, while neither alerted with two materials.

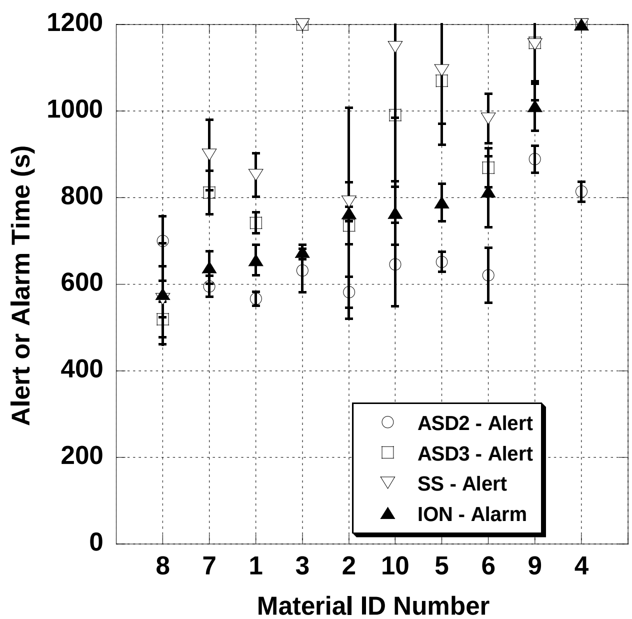


Figure 5-2. VEWFD alert and ION alarm times for the 15 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)

Figure 5-3 shows the pre-alert or alarm times for experiments conducted in the small cabinet with the 60.0 minute HRP, and Figure 5-4 shows alert and ION alarm times. In both figures, the materials are ordered in terms of increasing average ION spot alarm times. The trends are similar to the 15.0 minute HRP results. ASD3 pre-alerted and alerted before other detectors with CSPE, like the 15.0 minute HRP experiments. Neither ASD3 nor SS alerted before the end of test with four materials.

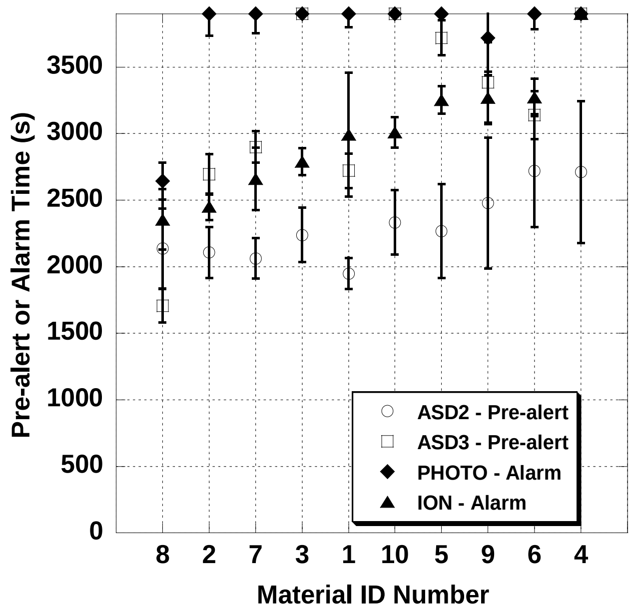


Figure 5-3. **VEWFD pre-alert and conventional alarm times for the 60 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)**

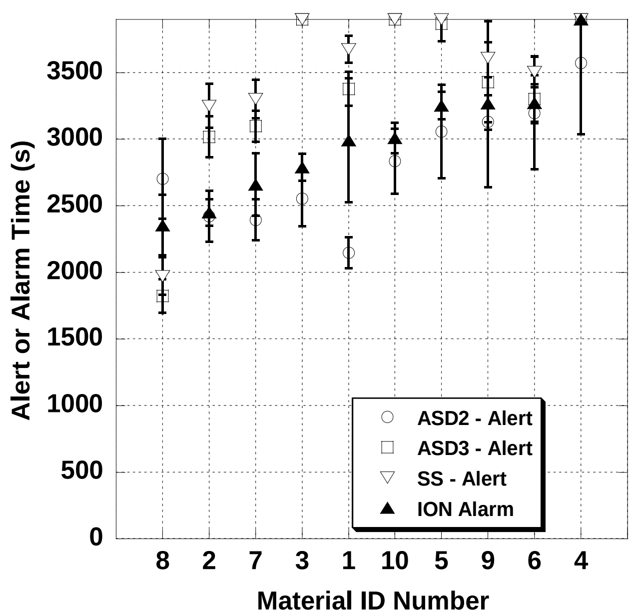


Figure 5-4. **VEWFD alert and ION alarm times for the 60 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)**

Figure 5-5 shows the pre-alert or alarm times for experiments conducted in the small cabinet with 240.0 minute HRP, while Figure 5-6 shows the alert and ION alarm times The materials are ordered in terms of increasing average ION spot alarm times.

The overall trend between the three heating rates was the same. Essentially the order and relative time that the detectors alarmed did not depend on the heating rate. Therefore, the concept of “end of test” (EOT), is used later in this report to merge test results from similar tests that only varied in heating rate and test length. ASD2 typically pre-alerted or alerted before ASD3 and the ION detector. The ION typically alarmed before ASD3 alerted, and ASD3 typically alerted before the SS detector alert.

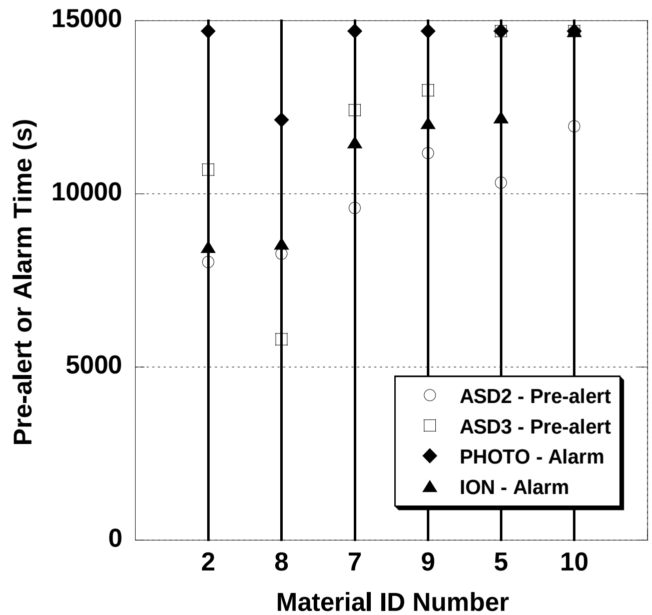


**Figure 5-5.	VEWFD pre-alert and conventional alarm times for the 240 minute HRP instrument cabinet experiments**

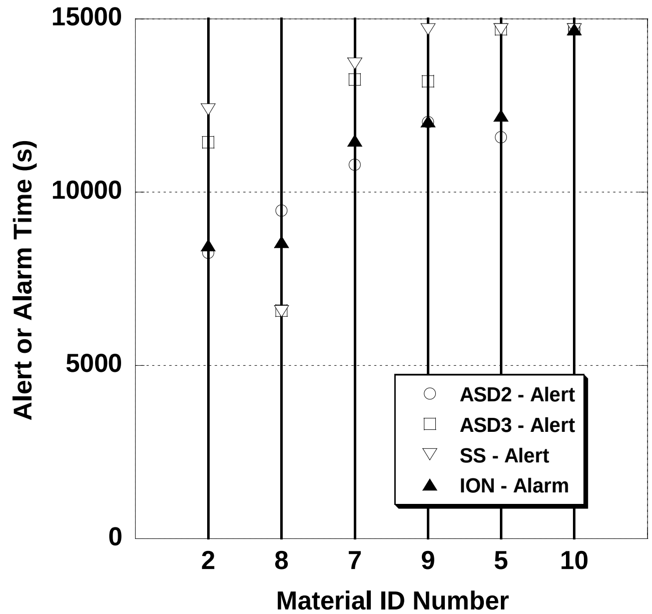


Figure 5-6. VEWFD alert and ION alarm times for the 240 minute HRP instrument cabinet experiments

Table 5-3 shows typical smoke particle arithmetic mean diameter (AMD) and mass mean diameter (MMD) results averaged over the 5 minute soak period for the 15.0 minute HRP experiments for each wire sample. Both the AMD and MMD vary by a factor of three from PFTE to CSPE insulation. These results, plus the alert and alarm activation results, were used to down-select the wire samples for full-scale experiments. PVC wire (2), XLPE wire, and CSPE wire materials were selected to (1) cover the observed (relatively) small, medium and large mean particle sizes, and (2) to have the ability to produce sufficient smoke to activate the detectors being studied in the various experimental configurations. Therefore, these selected materials (PVC, XLPE, and CSPE) are intended to represent the aerosol characteristics generated from a large variety of materials commonly found in NPP electrical enclosures. The selection is not intended to bound all materials and these materials (PVC, XLPE, and CSPE) likely do not represent the most difficult aerosols to detect.

Table 5-3. AMD and MMD Average over the 5.0 Minute Soak Time for 15.0 Minute HRP Tests

ID #	Name	AMD (µm) (± 20 %)	MMD (µm) (± 20 %)
1	PVC1	0.12	0.27
2	PVC2	0.11	0.26
3	Silicone	0.14	0.23
4	PTFE	0.10	0.21
5	XLPO1	0.13	0.21
6	XLPO2	0.23	0.45

Table 5-3. AMD and MMD Average over the 5.0 Minute Soak Time for 15.0 Minute HRP Tests (Continued)

ID #	Name	AMD (µm) (± 20 %)	MMD (µm) (± 20 %)
7	XLPE	0.20	0.33
8	CSPE	0.33	0.64

To examine trends by extending the HRP from 15.0 to 60.0 minutes, the block temperature[9] at alarm was plotted for the various detector activations in Figure 5-7. The trend between the 15.0- and 60.0 minute HRP for ASD2 and ASD3 was consistent for all three materials, but in opposite directions. ASD2 responded at higher block temperatures when the HRP was increased, while ASD3 responded at lower block temperatures. The magnitude of the temperature difference was not large, thus the practical implications may be minor.

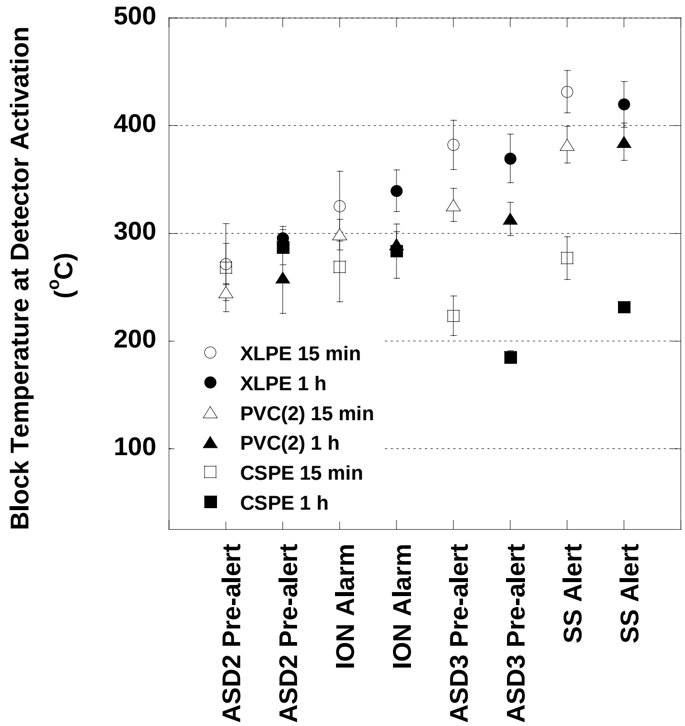


Figure 5-7. Block temperature at pre-alert, alert or alarm time for various detectors. (Error bars represent +/- one standard deviation for repeated tests)

For the small-cabinet laboratory results the following observations are made:

1. ASD2 pre-alerted and alerted before ASD3 and SS for all materials with the exception of CSPE.

[9] The "block temperature" is the surface temperature measured by the thermocouple attached to the surface of the copper bus bar block.

2. At both HRPs, ASD2 was the only detector to respond to PTFE samples before the end of test.

3. The overall trend between the three heating rates was the same, ASD2 typically pre-alert or alerted before ASD3 and the ION detector. The ION typically alarmed before ASD3 alerted, and ASD3 typically alerted before the SS detector.

4. By the end of the test, both the arithmetic mean diameter and the mass mean diameter of the smoke varied by a factor of three from PFTE wire (smallest particles) to CSPE wire (largest particles), but this made no difference except with ASD3 and SS's better performance in detection CSPE.

5. The heating ramp period affected the observed block temperature when ASDs responded. ASD2 responded at higher block temperatures when the HRP was increased, while ASD3 responded at lower block temperatures.

5.2 Laboratory, Large-Cabinet Experiments

Experiments were conducted in two surplus NPP cabinets, one with natural ventilation, and one with forced ventilation provided by a fan and ducting. The cabinet sizes were dimensionally the same, but the internal configurations were different. These tests primarily show the effects of natural ventilation versus high-flow forced ventilation cabinet conditions. These experiments were conducted in the laboratory with an ASD2, an ASD3, an ionization spot detector (ION) and a sensitive spot detector (SS). The detector sensitivities are listed in Table 5-4. The ION spot was installed in both cabinets and the sensitive spot was only installed in the naturally ventilated cabinet, as there wasn't sufficient room in the forced ventilation cabinet to install both. The ASD piping configuration was four equally spaced ports, three sampling laboratory room air and one sampling cabinet air. The materials used in these experiments were polyvinyl chloride insulated (PVC2), XLPE, CSPE, and PCB.

For these experiments, the heating ramp period and final set point were extended. Based on the results of the small-cabinet experiments, it was decided to increase the final block temperature set point to 485 degrees C. The slope of the set point ramp remained the same as the 450 degrees C final set point experiments, but the duration of the ramp period was increased to 16.3, 65, and 460 minutes for the new heating ramp periods. The total heating times (THTs) were 1,278, 4,200 and 15,900 seconds for the three HRPs, respectively.

Table 5-4. Nominal Detector Sensitivities for Laboratory—NPP Large-Cabinet Experiments

Sensitivity Setting	ASD2 Detector/Port Particles/cm^3	ASD3 Detector/Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc
VEWFD Pre-alert	$5.1 \times 10^5 / 2.4 \times 10^6$	0.0063/0.025	-	-
VEWFD Alert	$1.2 \times 10^6 / 4.8 \times 10^6$	0.05/0.20	0.20	-
VEWFD Alarm	$1.5 \times 10^6 / 6.0 \times 10^6$	0.25/1.00	1.00	-
Conventional Pre-Alarm	-	-	-	0.5
Conventional Alarm	-	-	-	1.0

Results are presented in box plots where the box's vertical limits represent the range in which the middle 50 percent of the data lay, the vertical line inside the box indicates the median, and bars above and below the box represent the upper quartile (UQ) and lower quartile (LQ), with individual outlier values represented by an open circle symbol. Outliers are defined as values greater than (UQ+1.5*(UQ-LQ)) or less than (LQ-1.5(UQ-LQ)), in other words, 1.5 times the inter-quartile range above the upper quartile or below the lower quartile. A filled circle symbol represents the mean of all values including outliers.

The first data set examined consists of the naturally ventilated cabinet, 16.3 minute HRP experiments. Three experiments with each of the four materials were conducted for a total of 12 experiments. Figure 5-8 shows the difference between the ION alarm and the ASD and SS alert times. Only ASD2 had mean and median values greater than 0, and in all cases, ASD2 alerted before the ION alarmed. ASD3 and SS have about the same average response.

Figure 5-9 shows the differences between the end of the test (1,278 s) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times. All detectors alerted or alarmed before the end of test.

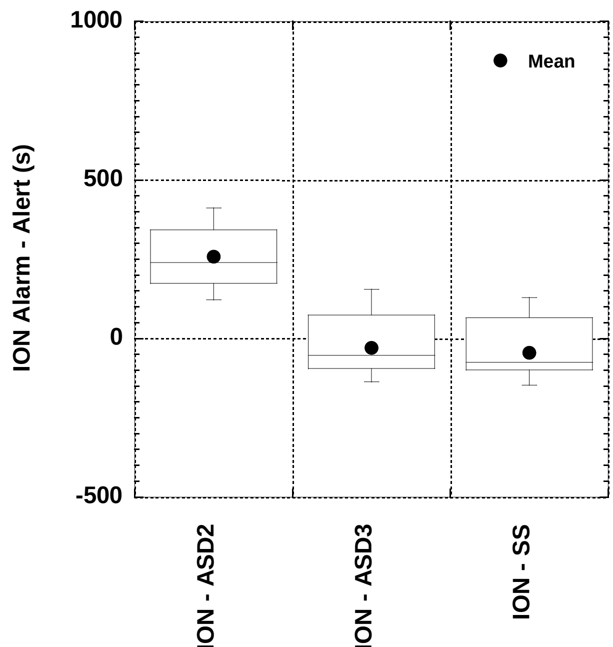


Figure 5-8. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 16.3 minute HRP experiments

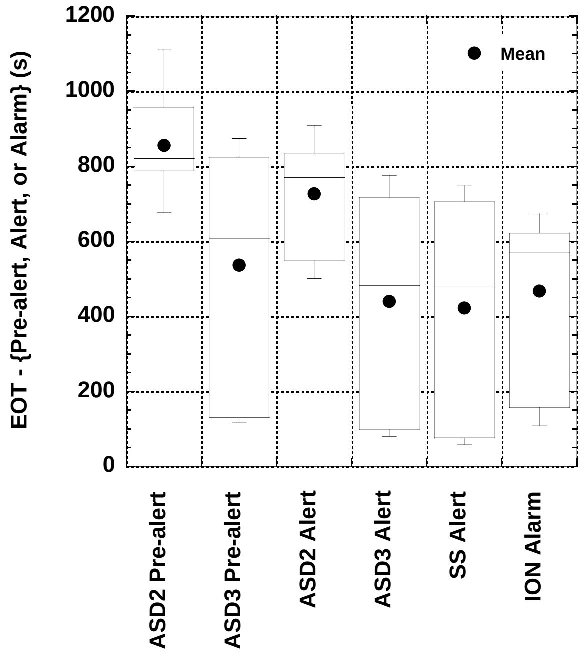


Figure 5-9. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 16.3 minute HRP experiments

The second data set examined consists of the forced ventilation cabinet, 16.3 minute HRP experiments. Three experiments with each of the four materials, plus an additional experiment with PCB were conducted for a total of 13 experiments. Figure 5-10 shows the difference between the ION alarm and the ASD alert times. Both ASD VEWFD systems alert before the ION alarmed on average.

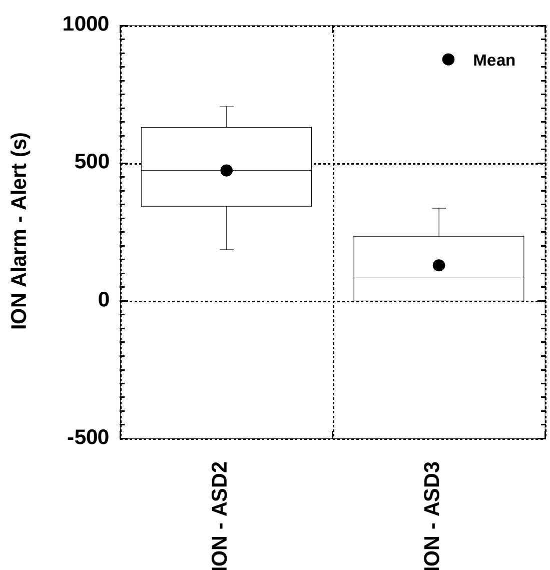


Figure 5-10. Time difference between ION alarm time and the ASD alert time for large cabinet, forced ventilation, 16.3 minute HRP experiments

Figure 5-11 shows difference between the end of the test (1,278 s) and the ASD VEWFD system pre-alerts, ASD VEWFD system alerts, and ION alarm times.

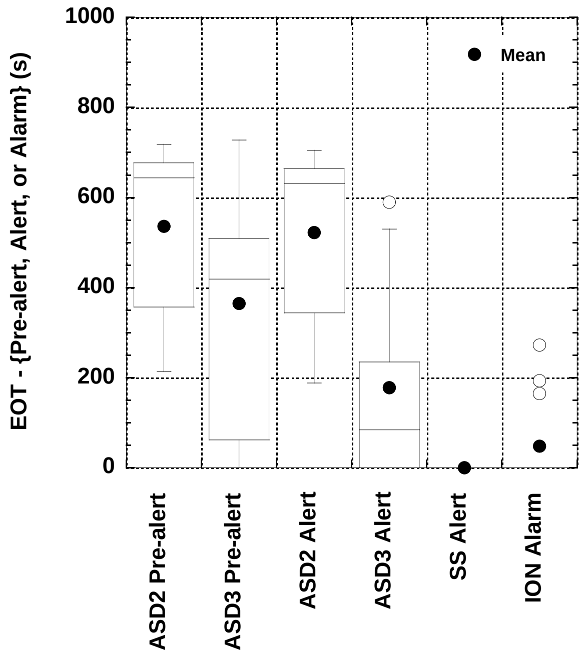


Figure 5-11. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation, 16.3 minute HRP experiments

The third data set examined consists of the naturally ventilated cabinet, 65.0 minute HRP experiments. Three experiments with each of the four materials were conducted for a total of 12 experiments. Figure 5-12 shows the difference between the ION alarm and the ASD and SS alert times. Only ASD2 had mean and median differences greater than 0, and it responded before the ION in all experiments.

Figure 5-13 shows the difference between the end of the test (4,200 s) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times. The average detector response was about 1,500 seconds or greater before the end of test.

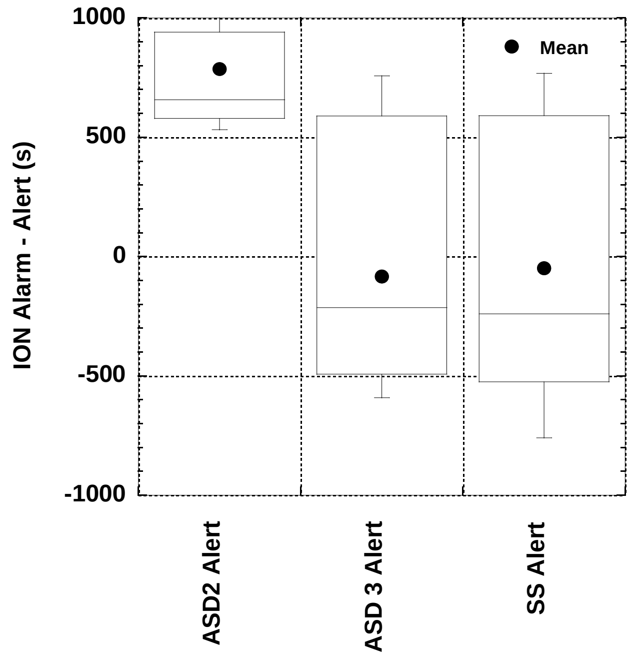


Figure 5-12. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 65.0 minute HRP experiments

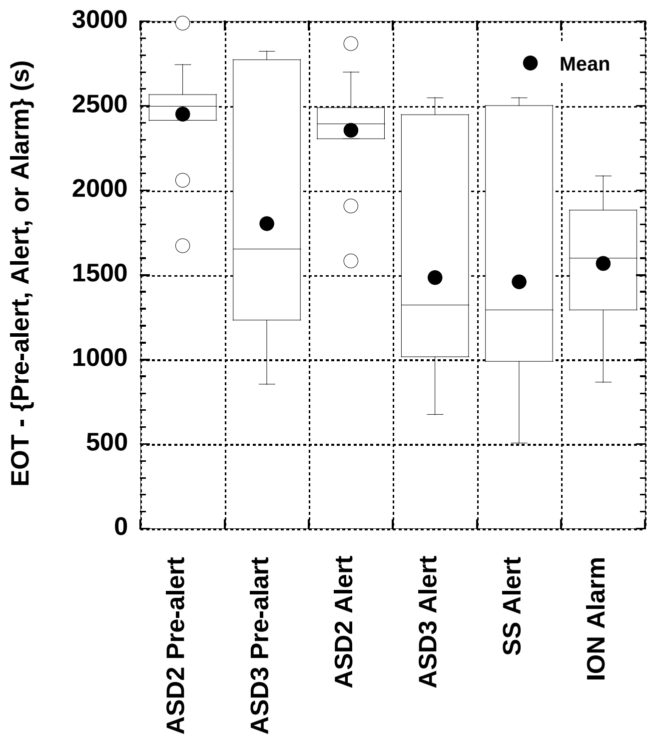


Figure 5-13. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 65.0 minute HRP experiments

The fourth data set examined consists of the forced ventilation cabinet, 65.0 minute HRP experiments. Three experiments with each of the four materials were conducted for a total of 12 experiments. Figure 5-14 shows the difference between the ION alarm and the ASD alert times. Both ASDs alerted before the ION alarm on average.

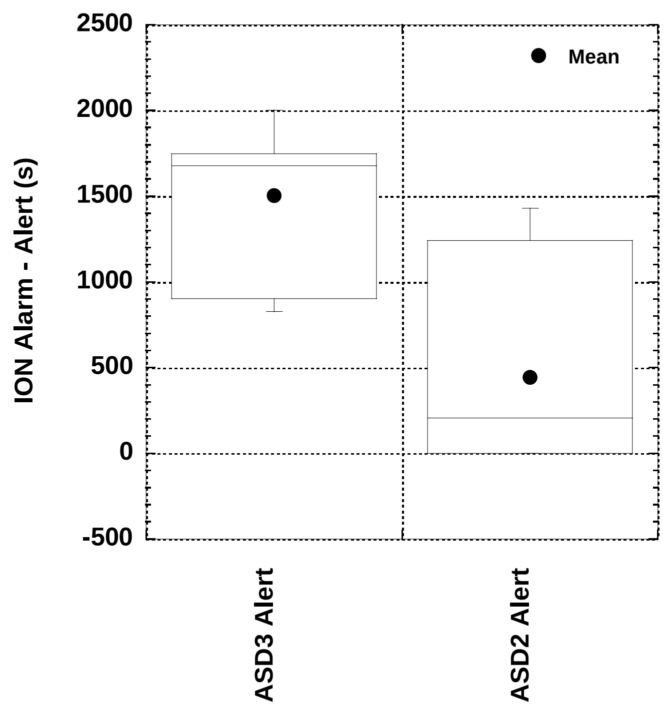


Figure 5-14. Time difference between ION alarm time and the ASD alerts times for large cabinet, forced ventilation, 65.0 minute HRP experiments

Figure 5-15 shows difference between the end of the test (4,200 s) and the ASD pre-alerts, ASD alerts, and ION alarm times.

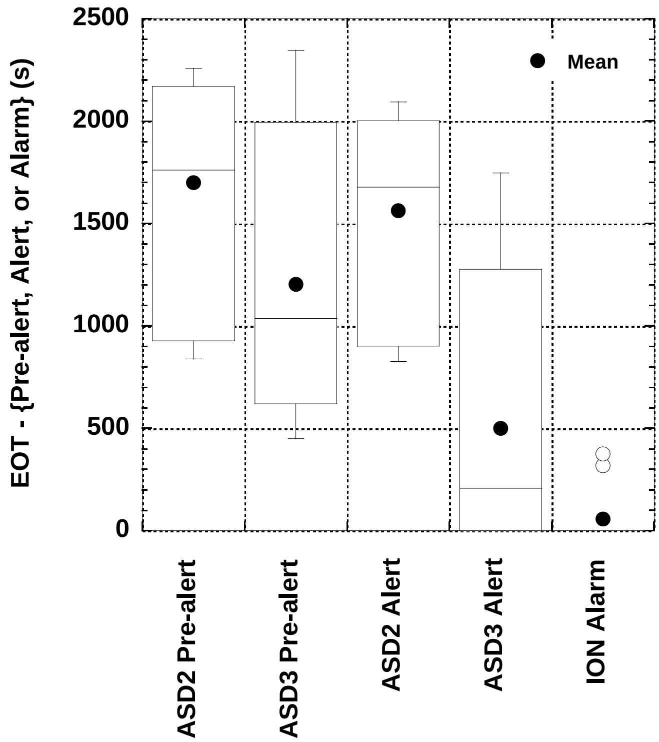


Figure 5-15. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation, 65.0 minute HRP experiments

The fifth data set examined consists of the naturally ventilated cabinet, 260.0 minute heating period experiments. Three experiments each with XLPE and CSPE materials were conducted for a total of six experiments. Figure 5-16 shows the difference between the ION alarm and the ASD and SS alert times. Both the median and mean are greater than 900 seconds for the ASDs and SS detector.

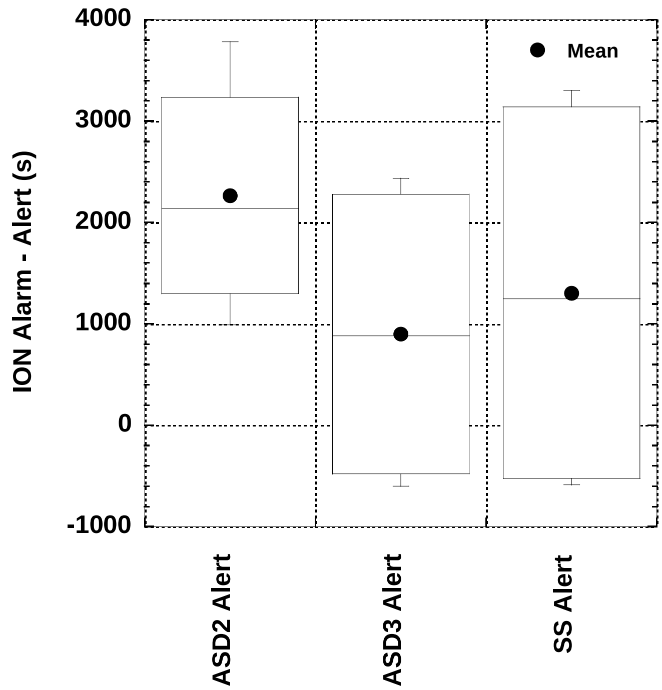


Figure 5-16. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 260.0 minute HRP experiments

Figure 5-17 shows the difference between the end of the test (15,900 s) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times. The ASDs pre-alerted more than 8,000 seconds before the end of the test on average. ASD3 typically pre alerted before ASD2, a distinct difference in the trend compared to 65 and 16.3 minute HRP experiments.

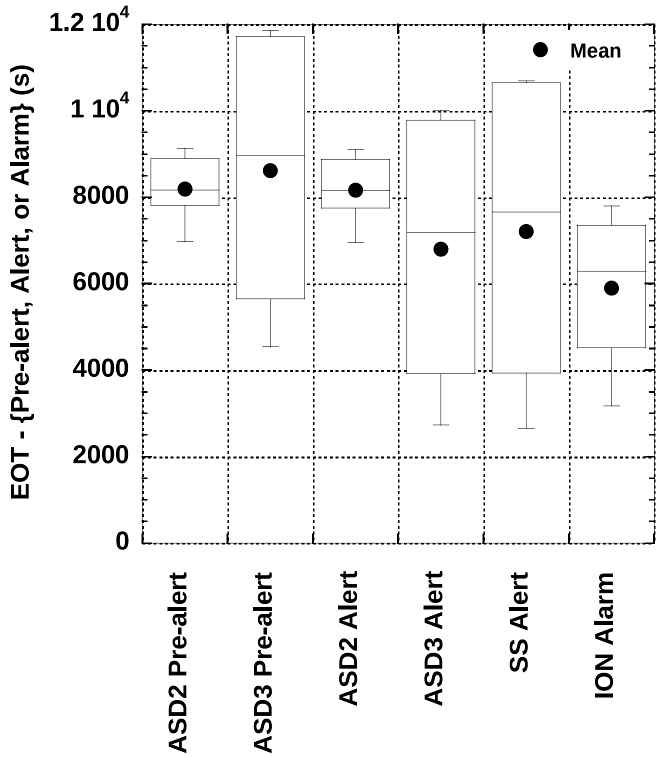


Figure 5-17. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 260.0 minute HRP experiments

For the large-cabinet laboratory results the following observations are made:

1. For the naturally ventilated cabinet, the ASD VEWFD systems tended to pre-alert before the conventional ionization alarm for all heating period experiments.

2. For the forced ventilation cabinet experiments, the ASD VEWFD systems significantly outperformed the ionization detector, which in many cases did not alarm during both 16.3 and 65.0 minute heating period experiments.

3. For the naturally ventilated cabinet, some of the difference between the 16.3 or 65.0 minute heating period experiment trend and the 260.0 minute heating period experiment trend is attributed to different sets of test materials.

5.3 Full-Scale, Small-Room, In-Cabinet Experiments

Experiments were conducted using cabinet mock-ups in the small room. As presented in Section 4.4.3, each ASD piping network covered a total of 10 cabinets divided into three separate spaces; a single, isolated cabinet monitored by one sampling port, a set of four cabinets monitored by two sampling ports, and a set of five cabinets monitored by three sampling ports. The cabinet sizes were the same, and the set of four and five cabinets were without internal side walls, effectively creating one large space. Experiments were conducted in each of the three separate spaces with no forced ventilation flow in the cabinet or in the room. Additional tests were conducted with the five-cabinet configuration with forced ventilation in the cabinet or in the room. Several tests included the smoke source elevated for the typical cabinet floor location to 2/3 of the cabinet height with the source located within the cabinet. The detector sensitivities are listed in Table 5-5. The materials used in these experiments were PVC2, XLPE, CSPE, and PCB.

Table 5-5. Nominal Detector Sensitivities for Small Room, Cabinet Mock-Up Tests

Sensitivity Setting	ASD1 Detector / Port %/ft Obsc	ASD2 Detector / Port Particles/cm^3	ASD3 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc	PHOTO %/ft Obsc
VEWFD Pre-alert	0.013 / 0.08	5.1×10^5 / 3.1×10^6	0.0083 / 0.05	-	-	-
VEWFD Alert	0.05 / 0.30	8.2×10^5 / 4.9×10^6	0.033 / 0.20	0.20	-	-
VEWFD Alarm	0.25 / 1.50	1.5×10^6 / 9.0×10^6	0.167 / 1.00	1.00	-	-
Conventional Pre-alarm	-	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	-	1.0	2.1

The <u>first data set</u> examined consists of 16.3 minute HRP experiments in the three cabinet configurations: single cabinet with XLPE, CSPE, PVC and PCB materials, the set of four cabinets with XLPE, CSPE and PVC materials, the set of five cabinets with XLPE, CSPE, PVC and PCB materials, and the set of five cabinets with XLPE, CSPE and PVC sources elevated to 2/3 of the cabinet height.

Figure 5-18 shows the difference between the ION alarm and the ASD and SS alert times. Both the median and mean are greater than 0 for the ASDs, and less than 0 for the SS.

Figure 5-19 shows difference between the end of the test (1,278 s) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times.

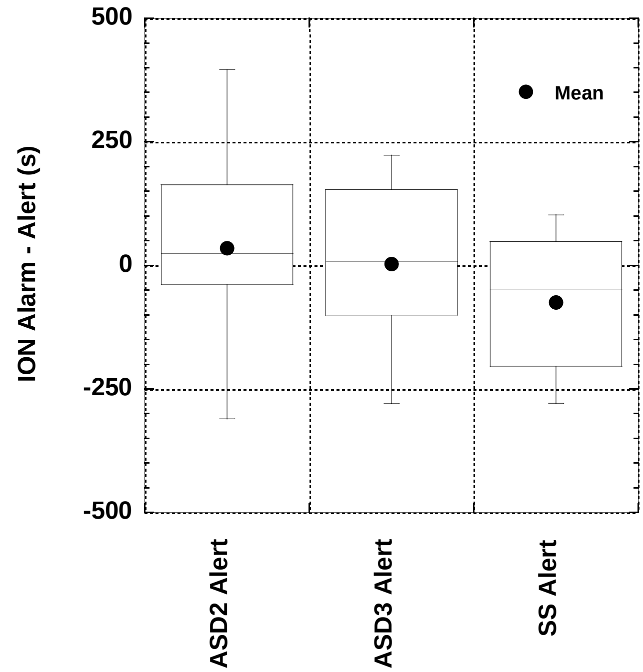


Figure 5-18. Time difference between ION alarm time and the ASD alerts and SS alert for small room, cabinet mock-up, 16.3 minute HRP experiments

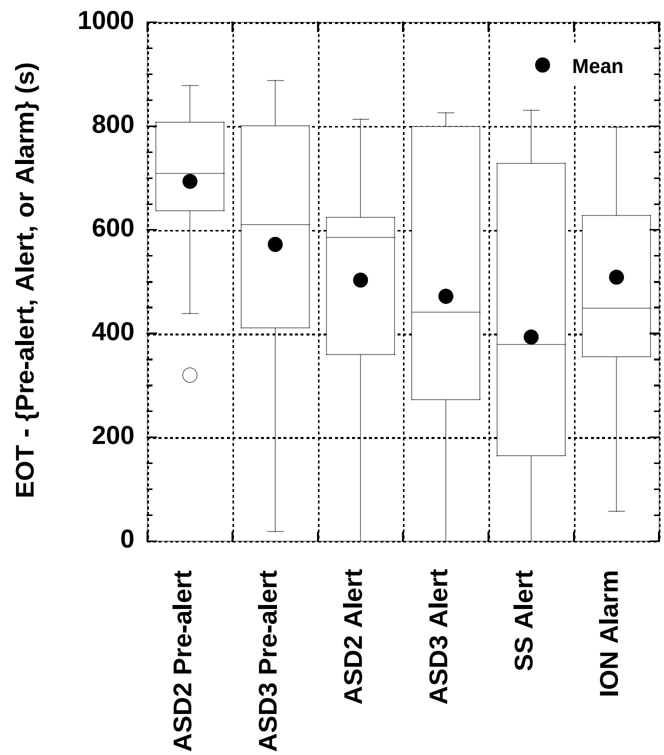


Figure 5-19. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 16.3 minute HRP experiments

The second data set examined consists of 65.0 minute heating period experiments in the three cabinet configurations: single cabinet with XLPE, CSPE, and PVC materials, the set of four cabinets with XLPE, CSPE and PVC materials, the set of five cabinets with XLPE, CSPE, PVC and PCB materials with no ventilation flows, cabinet ventilation and room ventilation, and the set of five cabinets with XLPE, CSPE and PVC sources elevated to 2/3 of the cabinet height. The single, four, and five cabinet configurations are presented in Section 4.4.3.

Figure 5-20 shows the difference between the ION alarm and the ASD and SS alert times. The ASD mean time differences were greater than 0 and less than 0 for the SS.

Figure 5-21 shows the difference between the end of the test (4,200 seconds) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times. Most detectors responded before 500 seconds to the end of test.

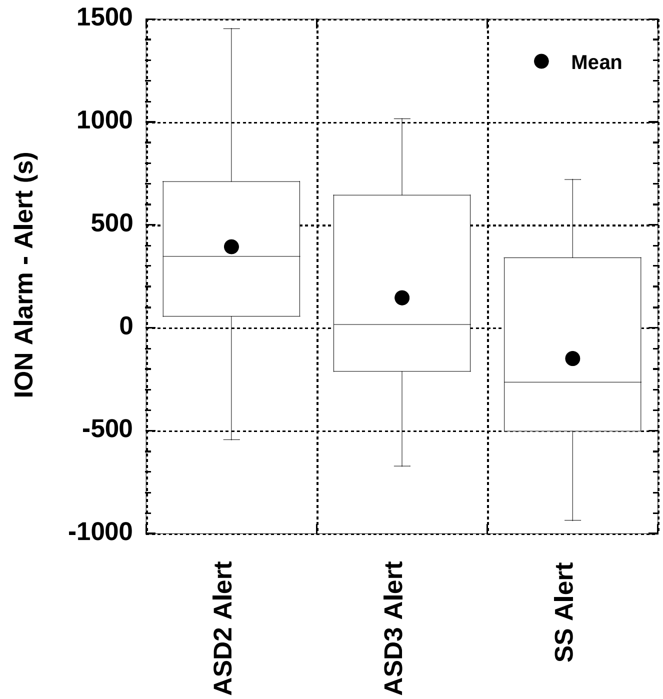


Figure 5-20. Time difference between ION alarm time and the ASD alerts and SS alert for small room, cabinet mock-up, 65.0 minute HRP experiments

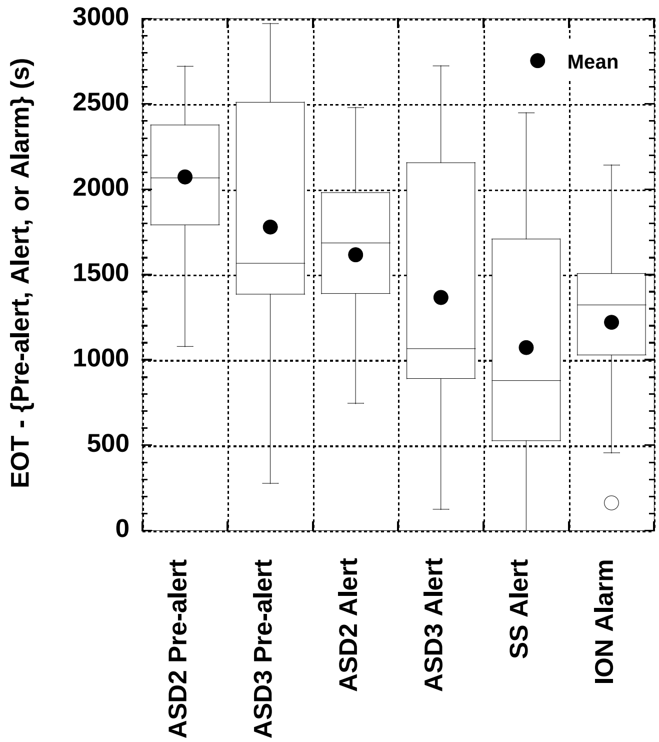


Figure 5-21. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 65.0 minute HRP experiments

The third data set examined consists of 260.0 minute HRP experiments in the set of five cabinets. Three experiments with XLPE, CSPE or PVC wire sources were conducted. Because only three data points are plotted, the box limits represent the minimum and maximum values.

Figure 5-22 shows the difference between the ION alarm and the ASD and SS alert times.

Figure 5-23 shows difference between the end of the test (15,900 s) and the ASD pre-alerts, ASD and SS alerts, and ION alarm times.

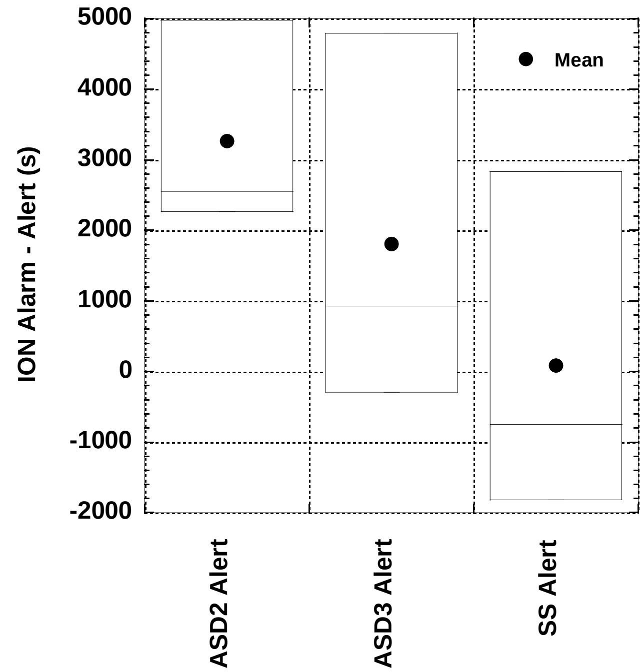


Figure 5-22. Time difference between ION alarm time and the ASD alerts and SS alert for small room, cabinet mock-up, 260.0 minute HRP experiments

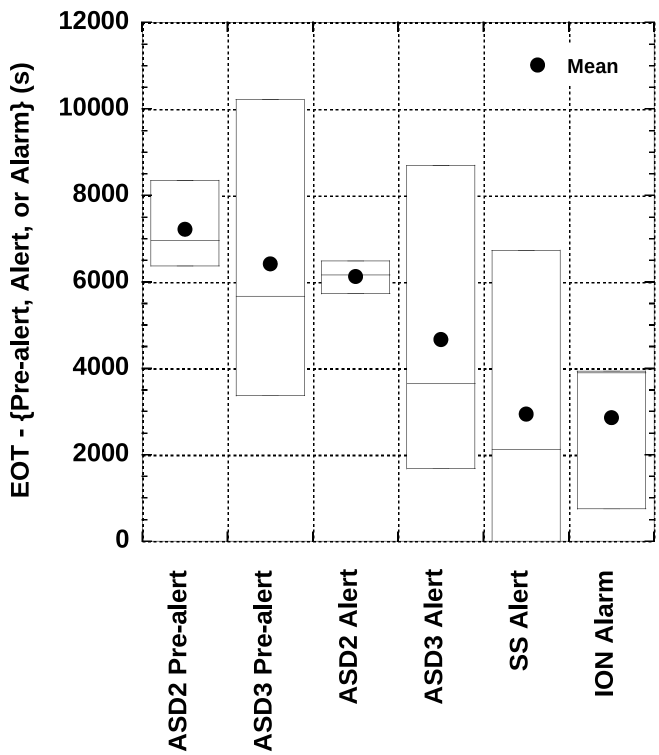


Figure 5-23. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 260.0 minute HRP experiments

The XLPE, CSPE, and PVC2 sources were each tested at 65.0 minute HRP in each of the six experimental configurations to examine the effect of the various configurations on time to alert or alarm. The six conditions were as follows: an isolated single cabinet with the source at the bottom (single cabinet—1C); a group of four cabinets and two sampling port locations with the source at the bottom (four cabinets—4C); a group of five cabinets with three sampling port locations with the source at the bottom of the cabinet (five cabinets—5C); configuration 5C with the source elevated two-thirds from the bottom of the cabinet (5 ES); configuration 5C with room ventilation (5 RV); and configuration 5C with cabinet ventilation (5 CV).

Figure 5-24 shows ASD alert, SS alert and ION alarm time averaged over the three materials experiments for the isolated cabinet (1C), group of four cabinets (4C), and group of five cabinets (5C). Pre-alarm or alarm times for XLPE, PVC2 and CSPE wire samples subject to 65.0 minute heating periods.

Figure 5-25 shows ASD alert, SS alert and ION alarm time averaged over the three materials experiments for the four group of five cabinets (5C) experimental configurations. Increasing and decreasing alert or alarm time trends were observed, moving from 1C to 4C to 5C configurations. Elevated-sample experiments tended to yield shorter alarm times than the base case (sample at bottom, no ventilation).

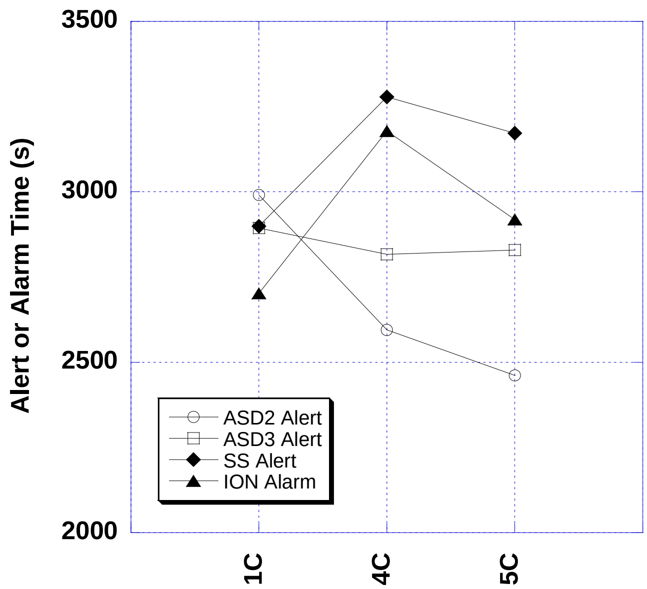


Figure 5-24. Mean alert or alarm times for small room, 1, 4, and 5-cabinet mock-up configurations, 65.0 minute HRP experiments

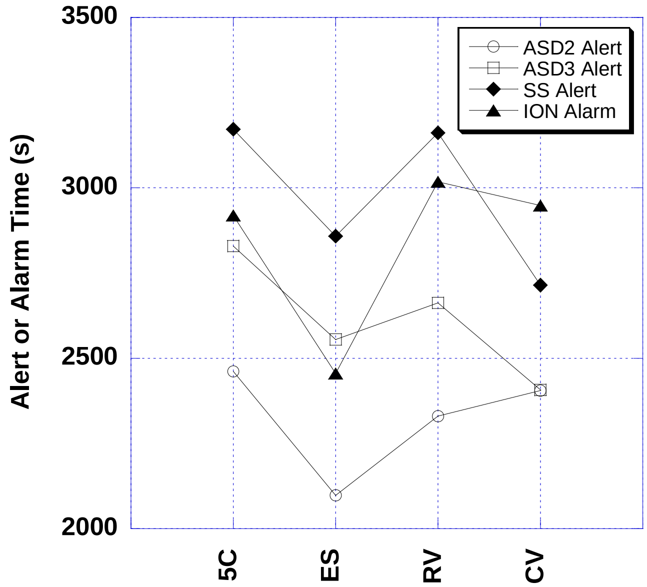


Figure 5-25. Mean alert or alarm times for small room, 5-cabinet mock-up configurations, 65.0 minute HRP experiments

The small-room cabinet mock-up results gave rise to the following observations:

1. The ASDs tended to pre-alert before the ION alarm for both heating period experiments.

2. All ASDs alerted before the end of test time,

3. On average, the SS detector pre-alarmed after the ION alarm for both heating period experiments

4. Cabinet-ventilated experiments and elevated-sample experiments tended to yield shorter alarm times than the base case (sample at bottom, no ventilation).

5.4 Full Scale, Large Room, Single-Zone, In-Cabinet Experiments

Eight 65 minute HRP in-cabinet experiments were conducted in the large room, four of which with XLPE wire sources and four with CSPE wire sources. For each wire source, experiments were conducted in the isolated cabinet with and without room air ventilation flow, and in the three-cabinet arrangement (where the cabinet with the source had openings to its two neighbors), with and without room air ventilation flow. The detector sensitivity settings are presented in Table 5-6. For ASD2, the highest sensitivity setting was often below background room concentrations before the start of an experiment. Therefore, the pre-alert and alert settings were shifted to the next highest sensitivity. ASD4 (cloud chamber) sensitivity setting were vendor-specified.

Table 5-6. Nominal Detector Sensitivities for Large Room, Single-Zone Cabinet Tests

Sensitivity Setting	ASD2 Detector / Port Particles/cm^3	ASD3 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc
VEWFD Pre-Alert	$4.0x10^4$ / $1.6x10^5$	0.0063 / 0.025	-	-
VEWFD Alert	$1.3x10^5$ / $5.2x10^5$	0.05 / 0.20	0.20	-
VEWFD Alarm	$6.4x10^5$ / $2.5x10^6$	0.25 / 1.00	1.00	-
Conventional Pre-alarm	-	-	-	0.5
Conventional Alarm	-	-	-	1.0

Results for the single cabinet and the three-cabinet arrangement are shown in Figure 5-26 and Figure 5-27. On average, the ASDs responded sooner than the ionization alarm for the three-cabinet arrangement suggesting some cooperative ASD sampling from adjacent cabinets.

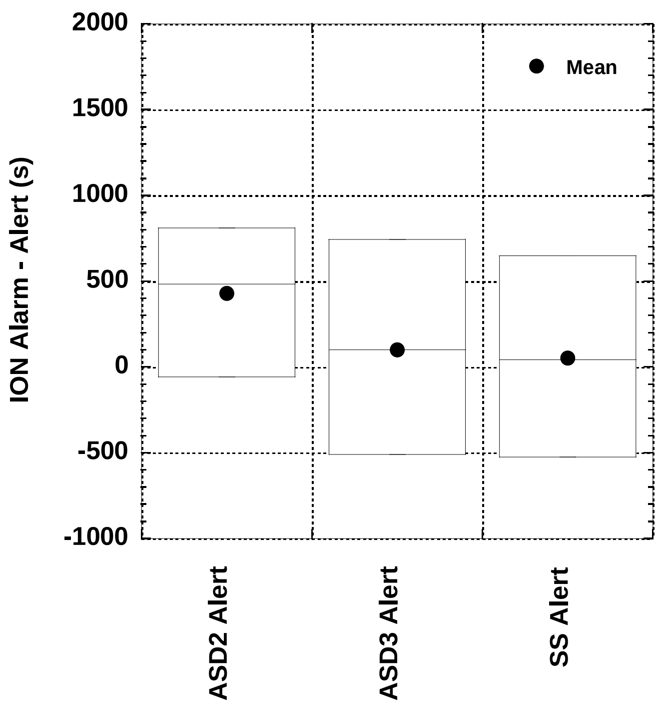


Figure 5-26. Time difference between ION alarm time and the ASD alerts and SS alert for large room, single-zone single-cabinet, 65.0 minute HRP experiments

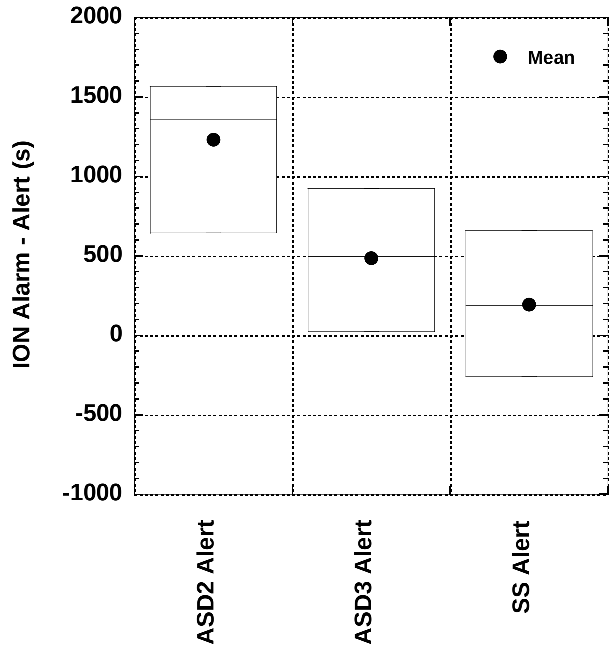


Figure 5-27. Time difference between ION alarm time and the ASD alerts and SS alert for large room, single-zone, three-cabinet configuration, 65.0 minute HRP experiments

Results for the ventilated and non-ventilated room experiments are shown in Figure 5-28 and Figure 5-29.

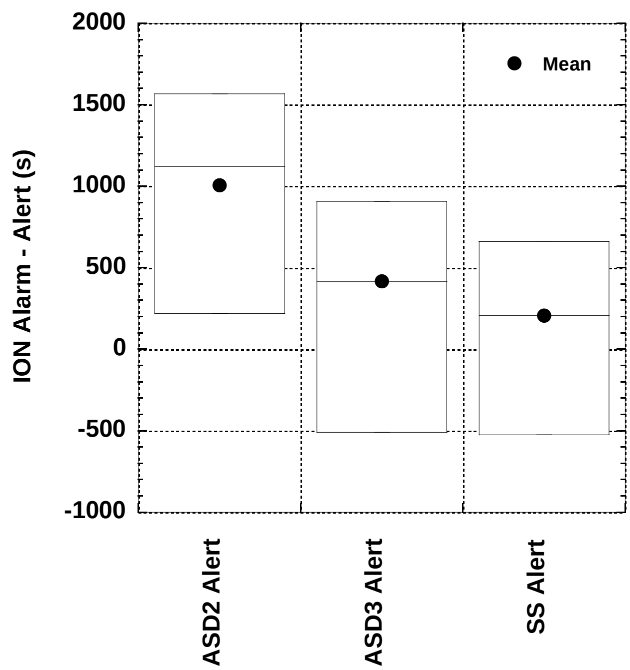


Figure 5-28. Time difference between ION alarm time and the ASD alerts and SS alert for large room, single-zone, no ventilation, in-cabinet, 65.0 minute HRP experiments

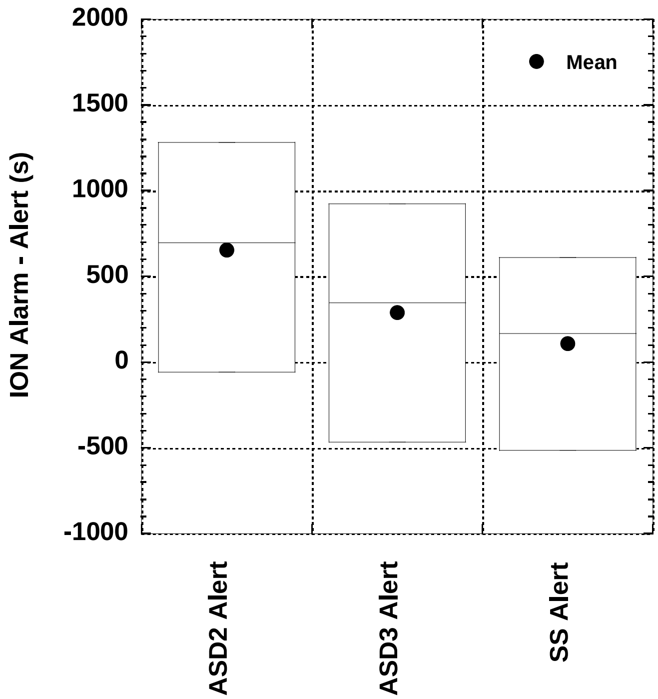


Figure 5-29. Time difference between ION alarm time and the ASD alerts and SS alert for Large room, single-zone, 7.4 ACH room ventilation, in-cabinet, 65.0 minute HRP experiments

Figure 5-30 shows the results of the difference between the ION alarm, and the ASD alerts or SS pre-alarm time for all eight experiments.

Figure 5-31 shows the results of the time difference between the end of the test (4,200 s) and the ION alarm, the ASD alerts, SS pre-alarm time and the PHOTO alarm time. Both ASD pre-alert mean and median time differences were greater than 1,900 seconds. The decreasing mean time difference trend was ASD2 alert, ASD3 alert, SS alert and ION alarm.

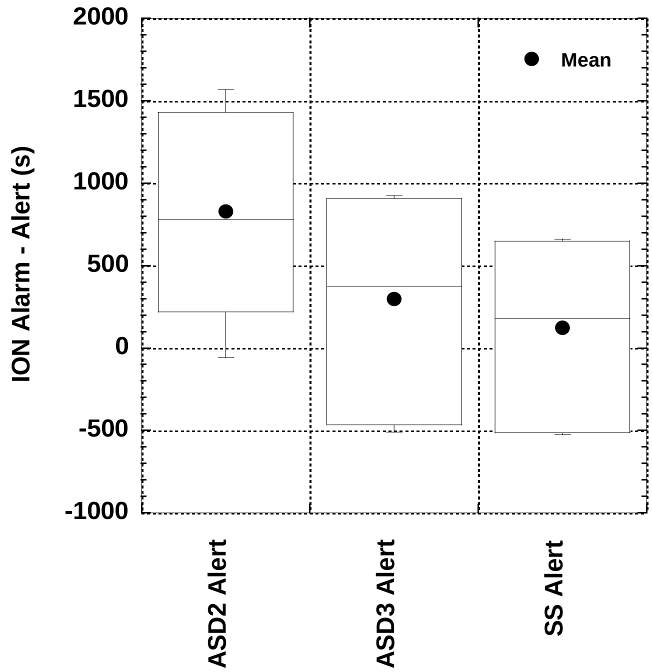


Figure 5-30. Time difference between ION alarm time and the ASD alerts and SS alert for large room, single-zone, in-cabinet, 65.0 minute HRP experiments

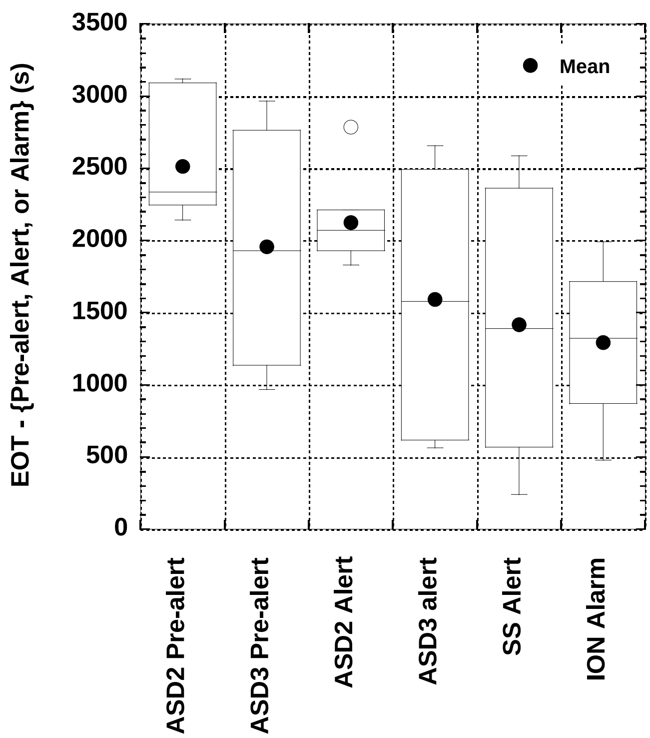


Figure 5-31. Time difference between the end of test (EOT) time (4200 s) and ASD Pre-alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet, 65.0 minute HRP experiments

Four 260.0 minute HRP in-cabinet experiments were conducted in the large room, two experiments with XLPE wire sources and two with CSPE wire sources. For each wire source, experiments were conducted in the three-cabinet arrangement with and without room air ventilation flow.

Figure 5-32 shows the results of the difference between the ION alarm, and the ASD alerts or SS pre-alarm time for all eight experiments.

Figure 5-33 shows the results of the time difference between the end of the test (15,900 s) and the ION alarm, the ASD alerts, SS pre-alarm time and the photo alarm time. The decreasing mean time difference trend was ASD2 alert, SS alert, ASD3 alert and ION alarm.

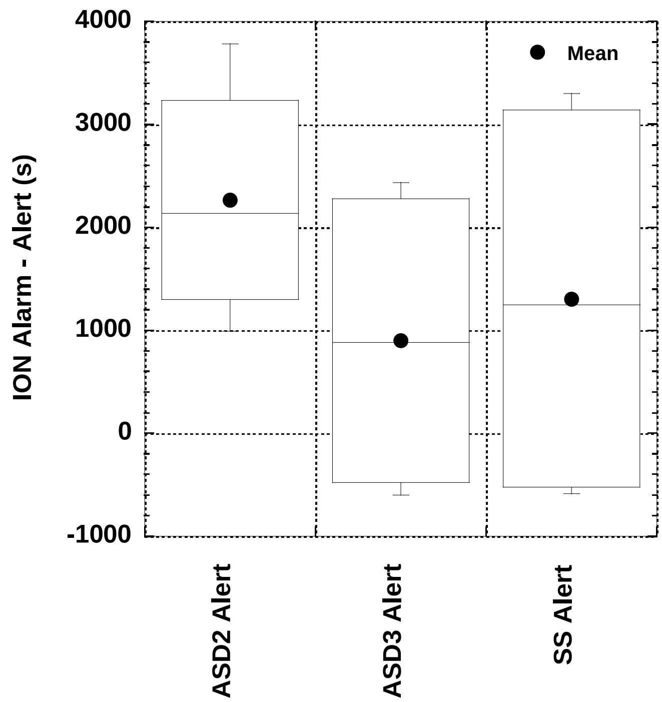


Figure 5-32. Time difference between ION alarm time and the ASD alerts and SS alert for large room, single-zone, in-cabinet, 260.0 minute HRP experiments

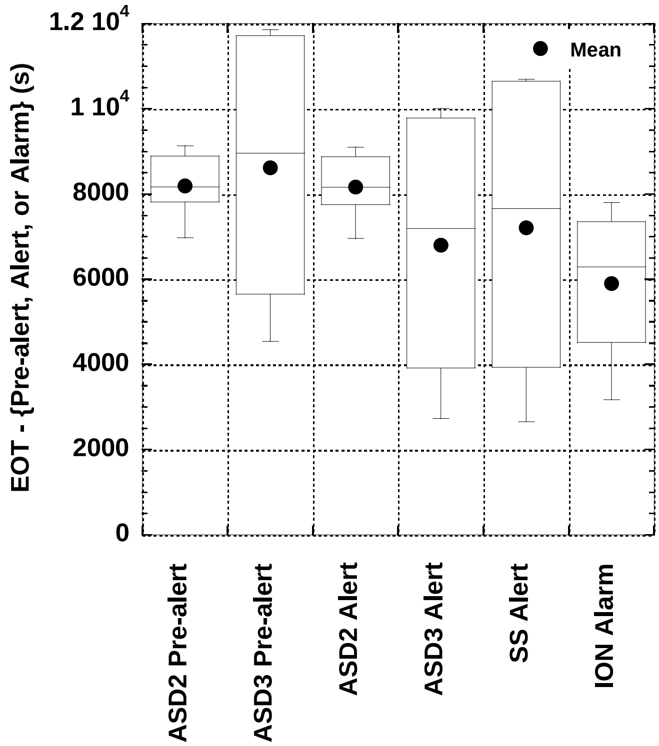


Figure 5-33. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet, 260.0 minute HRP experiments

The large room single-zone cabinet results gave rise to the following observations:

1. The time difference between the ionization alarm and the ASD alerts was greater for the three-cabinet arrangement than the single cabinet arrangement.

2. Room ventilation tended to reduce the time difference between the ionization alarm and the ASD alerts.

3. All detectors alerted before the end of test time for both heating periods.

5.5 Full-Scale, Large-Room, Multi-Zone, In-Cabinet Experiments

Ten in-cabinet 65 minute heating period experiments were conducted in the large room, five with XLPE wire sources and five with CSPE wire sources. For each wire source, experiments were conducted in the isolated cabinet with and without room air ventilation flow (7.5 ACH), and in a three cabinet arrangement (where the cabinet with the source had openings to its two neighbors), with and without room air ventilation flow (7.5 ACH and 15 ACH). Table 5-7 presents the detector sensitivity settings used in these tests.

Table 5-7. Nominal Detector Sensitivities for Large Room, Multi-Zone Cabinet Tests

Sensitivity Setting	ASD4 Detector / Port Particles/cm³	ASD5 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc
VEWFD Pre-Alert	1.5×10^5 / 6.0×10^5	0.0159 / 0.064	-	-
VEWFD Alert	2.5×10^5 / 1.0×10^6	0.0334 / 0.13	0.20	-
VEWFD Alarm	4.5×10^5 / 1.8×10^6	0.1665 / 0.67	1.00	-
Conventional Pre-alarm	-	-	-	0.5
Conventional Alarm	-	-	-	1.0

Results for the single cabinet are shown in Figure 5-34. ASD4 (cloud chamber) responded before the ION alarm in all experiments, while ASD5 (light-scattering) responded after the ION alarm on average. Results for the three-cabinet arrangement are shown in Figure 5-35. Results for the non-ventilated and ventilated room experiments are shown in Figure 5-36 and Figure 5-37. The results are mixed: however, ASD4 responded before the ION alarm in all experiments.

Results for all 10 experiments are shown in Figure 5-38. ASD4 responded 750 seconds sooner than the ION alarm on average, while ASD5 and SS responded about 150 seconds sooner than the ionization alarm, on average. The decreasing mean time difference trend was ASD4 alert, ASD5 alert and SS alert (tie), ION alarm and PHOTO alarm.

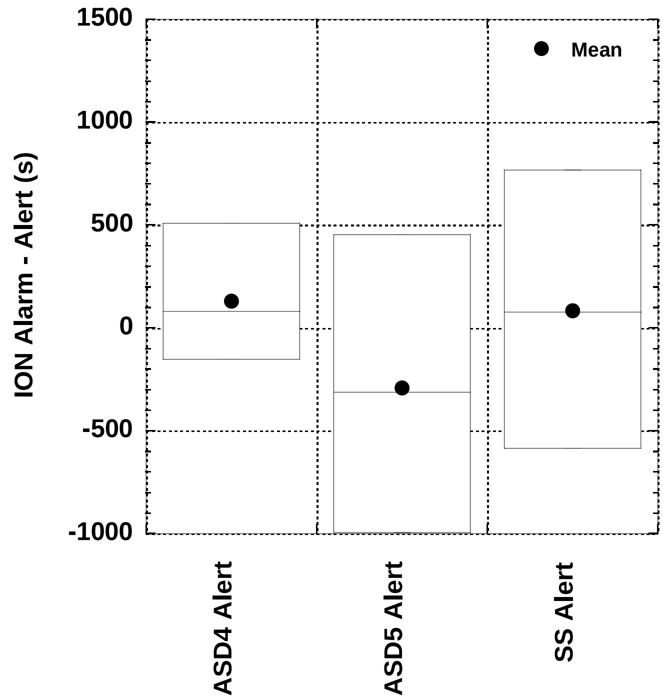


Figure 5-34. **Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, single-cabinet, 65.0 minute HRP experiments.**

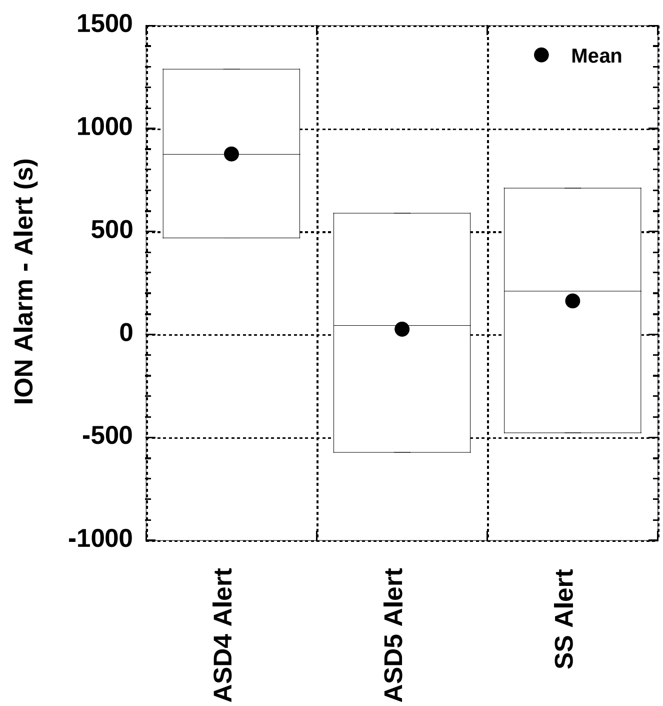


Figure 5-35. **Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, three cabinet configuration, 65.0 minute HRP experiments**

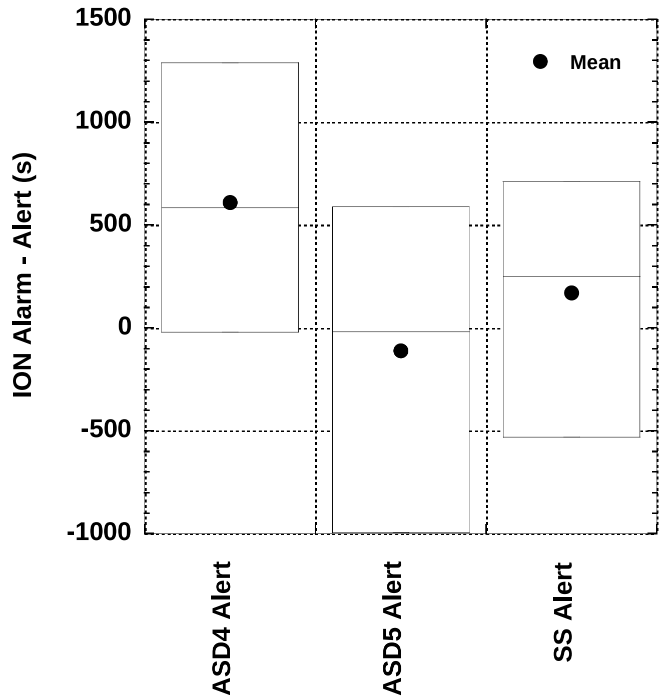


Figure 5-36. Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, no ventilation, 65.0 minute HRP experiments

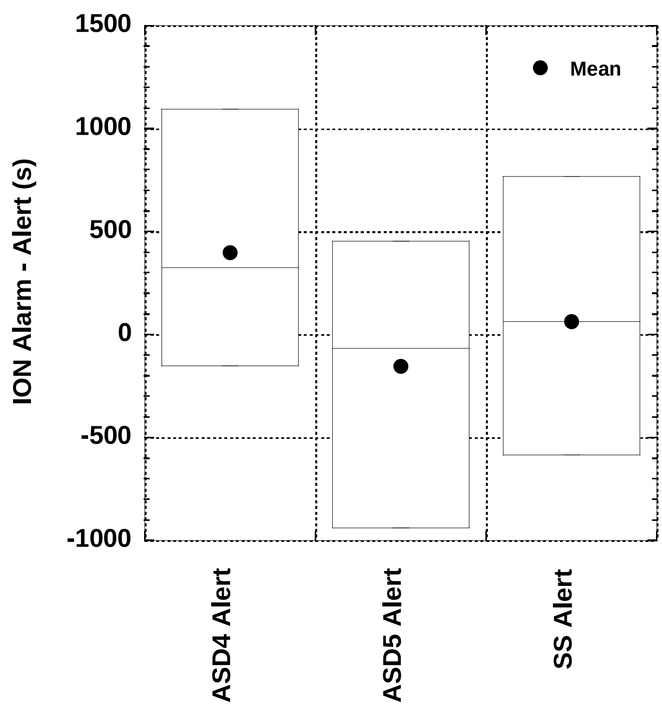


Figure 5-37. Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, 7.4 ACH room ventilation, 65.0 minute HRP experiments

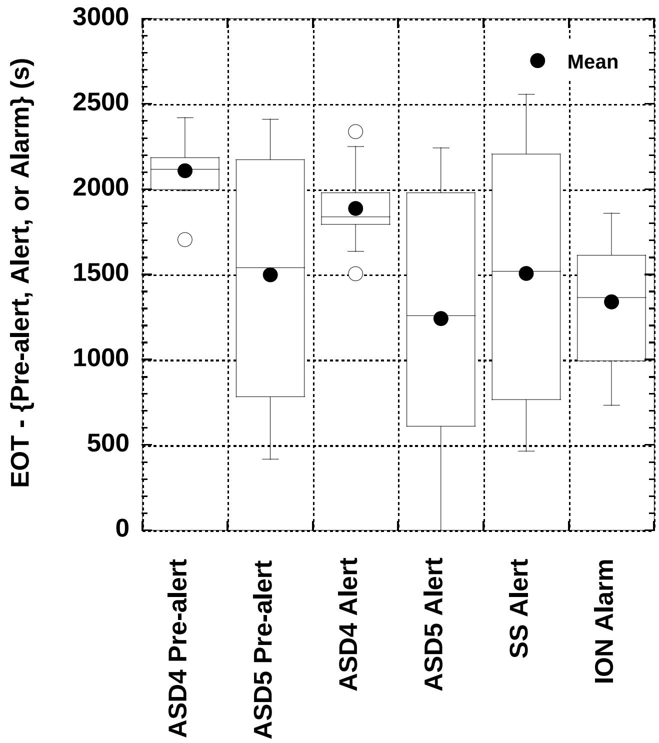


Figure 5-38. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, multi-zone in-cabinet, 65 minute HRP experiments

Four 260 minute heating period in-cabinet experiments were conducted in the large room, two experiments with XLPE wire sources and two with CSPE wire sources. For each wire source, experiments were conducted with the three cabinet arrangements with and without room ventilation (7.5 ACH).

Results for both the ventilated and non-ventilated room experiments are shown in Figure 5-39.

Figure 5-40 shows the results of the time difference between the end of test (15,900 seconds) and the detector response.

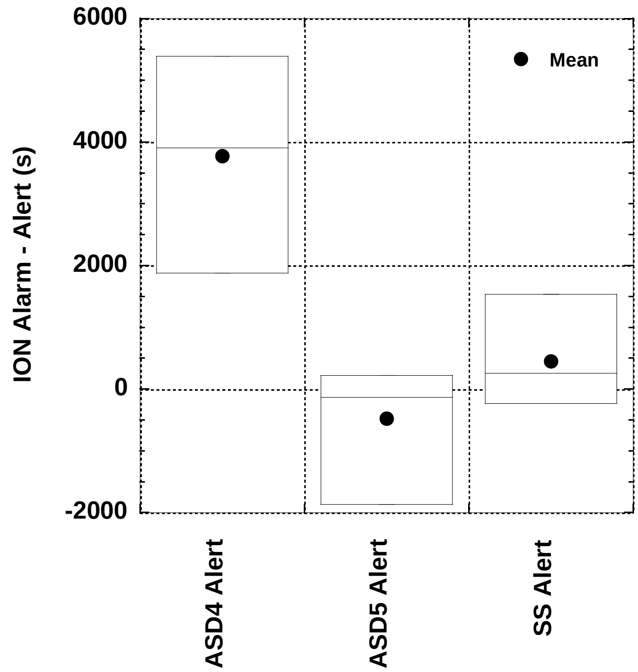


Figure 5-39. Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, in-cabinet, 260.0 minute HRP experiments

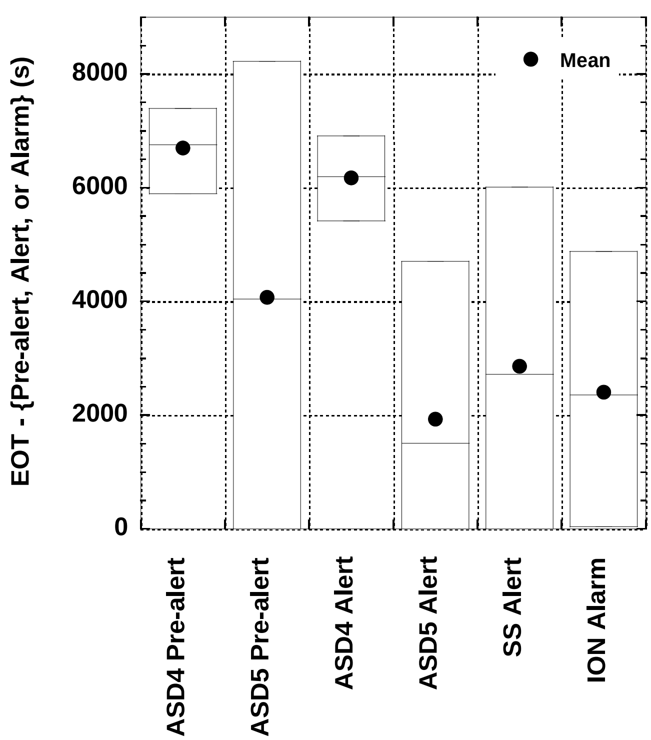


Figure 5-40. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, multi-zone in-cabinet, 260.0 minute HRP experiments

The large-room multi-zone in-cabinet results gave rise to the following observations:

1. ASD4 responded before the conventional ionization alarm for both heating period experiments.

2. The time difference between the ION alarm and the ASD alerts was greater for the three-cabinet arrangement than the single-cabinet arrangement.

3. Room ventilation tended to reduce the time difference between the ionization alarm and the ASD alerts.

4. All detectors responded before end of test for all 60 minute HRP experiments.

5. ASD5 and SS did not alarm with XLPE samples before end of test for 260 minute HRP experiments.

5.6 Full-Scale, Small-Room, Areawide Experiments

The data set examined consists of 65.0 minute heating period experiments for XLPE, CSPE and three cable bundle sources located on the floor. There was room air ventilation during one of the cable bundle experiments. The detector sensitivity settings used in these tests are shown in Table 5-8.

Table 5-8. Nominal Detector Sensitivities for Small Room, Single-Zone, Areawide Experiments

Sensitivity Setting	ASD1 Detector / Port %/ft Obsc	ASD2 Detector / Port Particles/cm^3	ASD3 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc	PHOTO %/ft Obsc
VEWFD Pre-alert	0.013 / 0.052	5.1×10^5 / 2.0×10^6	0.025 / 0.10	-	-	-
VEWFD Alert	0.05 / 0.20	8.2×10^5 / 3.3×10^6	0.05 / 0.20	0.20	-	-
VEWFD Alarm	0.25 / 1.50	1.5×10^6 / 6.0×10^6	0.25 / 1.00	1.00	-	-
Conventional Pre-alarm	-	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	-	1.0	2.1

Figure 5-41 shows the results for the time difference between the end of the test (4,200 s) and the ASD pre-alerts and alerts, SS alert, ION alarm, and the PHOTO alarm. The SS, photo and ION alarms did not respond before the end of the test in two of the five experiments.

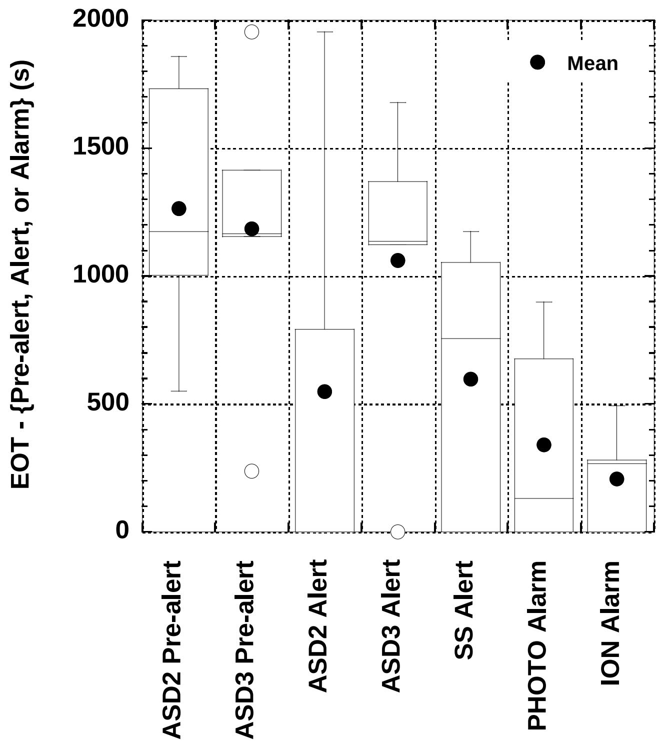


Figure 5-41. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts, PHOTO and ION alarm time for small room, areawide, 65.0 minute HRP experiments

From these experimental results the following observations are made:

1. The trend in mean alert/conventional alarm time from earlier to later was ASD3, SS, ASD2, PHOTO, and lastly ION.

2. Each detector failed to alert or alarm before the end of test in at least one experiment.

5.7 Large-Room, Multi-Zone Areawide Experiments

The large-room, multi-zone, areawide experiments included in-cabinet, return air grill, and areawide ceiling ASD coverage and conventional alarm coverage on the ceiling and inside cabinets. Table 5-9 documents the detector sensitivity settings used for these tests. ASD4 (cloud chamber) sensitivity settings were vendor-specified. Areawide and return air grill locations are referred to as AW and RA, respectively.

Table 5-9. Nominal Detector Sensitivities for Large Room, Multi-Zone, Areawide Experiments

Sensitivity Setting	ASD4 Detector / AW Port / RA Port Particles/cm^3	ASD5 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc	PHOTO %/ft Obsc
VEWFD Pre-Alert	$1.5x10^5$ / $9.0x10^5$ / $7.5x10^5$	0.0159 / 0.10	-	-	-
VEWFD Alert	$2.5x10^5$ / $1.5x10^6$ / $1.3x10^6$	0.0334 / 0.20	0.20	-	-
VEWFD Alarm	$4.5x10^5$ / $2.7x10^6$ / $2.3x10^5$	0.167 / 1.0	1.00	-	-
Conventional Pre-alarm	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	1.0	2.1

Figure 5-42 and Figure 5-43 show the results for 16.3 and 65.0 minute HRP areawide experiments with ventilation air flow.

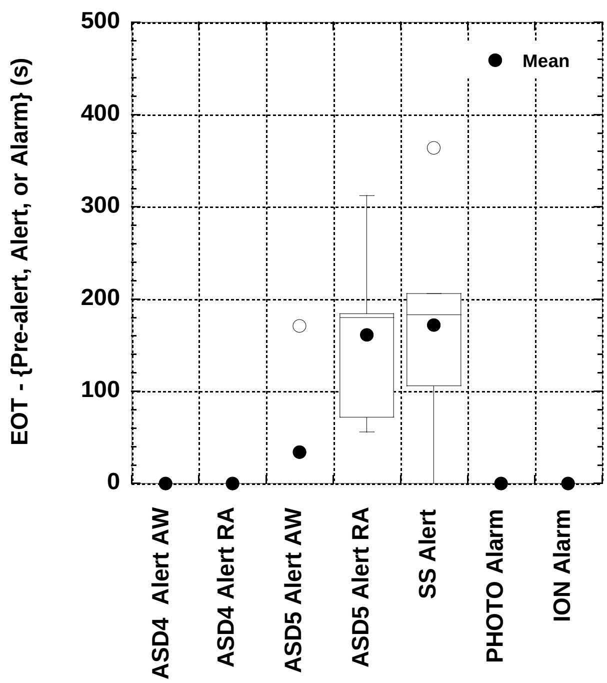


Figure 5-42. Time difference between the end of test (EOT) time (1278 s) and ASD alerts, SS alerts, PHOTO and ION alarm time for large room, areawide, 16.3 minute HRP experiments

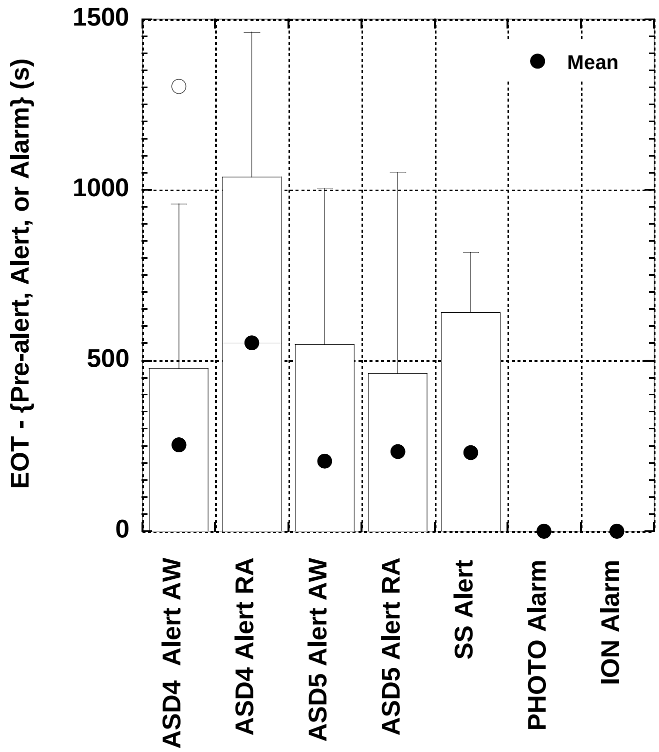


Figure 5-43. Time difference between the end of test (EOT) time (4200 s) and ASD alerts, SS alerts, PHOTO and ION alarm time for large room, areawide, 65.0 minute HRP experiments

From these experimental results the observations are made:

1. For the 16.3 minute HRP experiments ASD5 and SS detectors were the only systems that alerted before the end of test

2. For the 16.3 minute HRP experiments SS areawide outperformed the ASD5 return air zone and the ASD5 areawide.

3. For the 65.0 minute HRP experiments the ASD and SS detectors were the only systems that on average alerted before the end of test.

4. For the 65.0 minute HRP experiments the ASD5 areawide and return air zone provided about the same average alert times, while ASD4 return air zone outperformed all detectors on average.

5.8 Insulated Electrical Conductor Heat Conduction and Ignition Potential

Measurements were made to characterize the heat conduction from the heated bus bar block to wire samples, and the ignition potential of such heated wires to a small pilot flame. The wire temperature governs when and how much smoke is generated from the sample to some extent. The wire insulation temperature profile also determines the ease of ignition from a small pilot

flame. The ease of ignition from such a pilot flame is an indication of the potential hazard of the heated wire insulation.

Heat conduction from the block to the wire, down its length and through the insulation is a transient heat transfer process. The controlled variable is the block temperature via the temperature controller's power-cycling of the cartridge heater. The wire insulation closest to the block heats up first and produces the smoke particles sensed by detectors. Subsequently, more wire insulation is heated to produce more smoke. The IR camera recorded images at different times during HRPs. A series of images is shown in Figure 5-44. The temperature profile measured at the end of the nominal 60 minute test can be seen in Figure 5-45. The locations of the thermocouples were represented by the cross symbol, with the corresponding IR camera temperature measurements. The emissivity on the IR camera in was set for plastic (0.93).

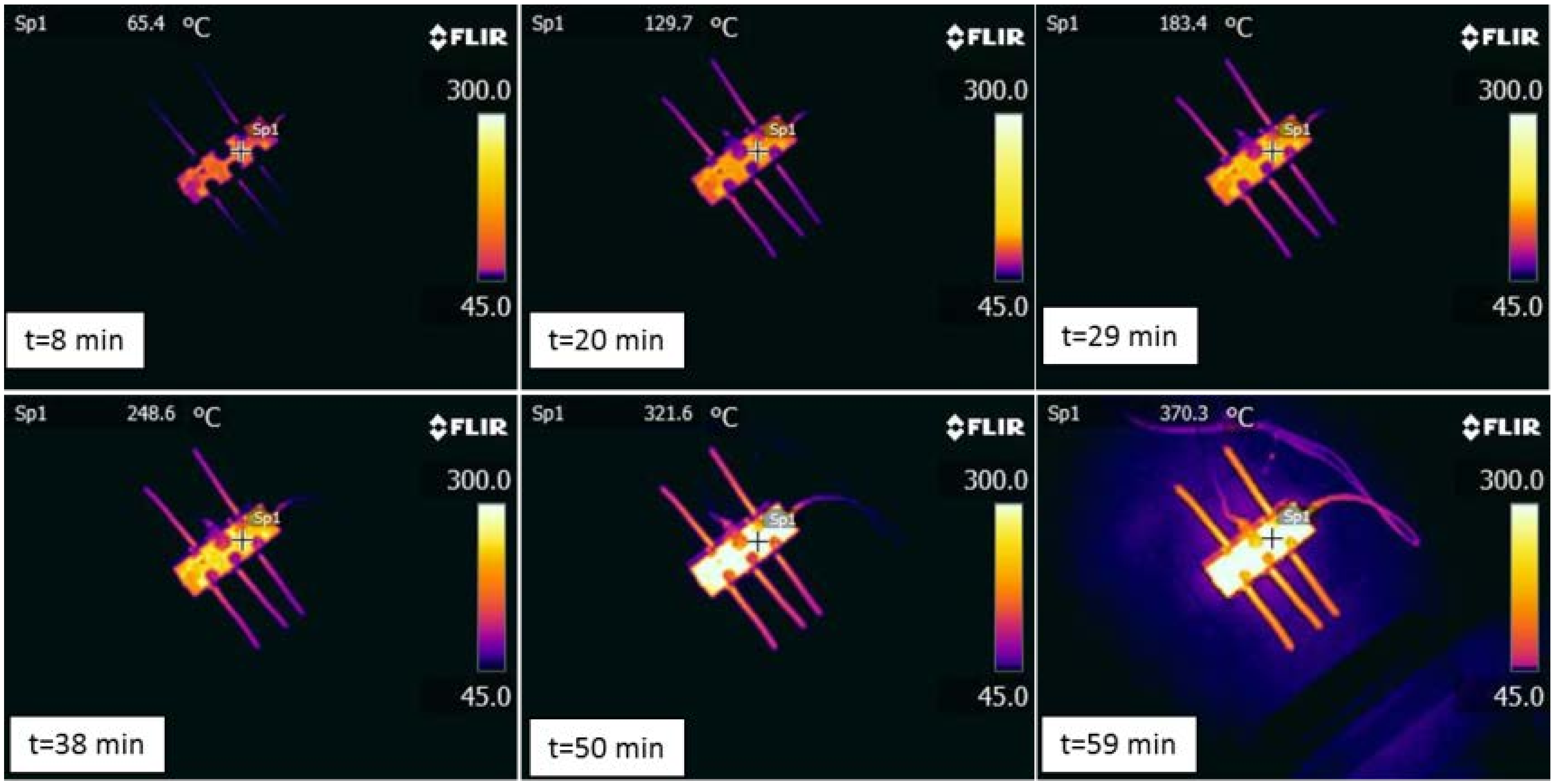


Figure 5-44. Heating profiles for 12 AWG XLPE wires at various times during the heating process. The temperature of the block can be seen in the top left corner in each image.

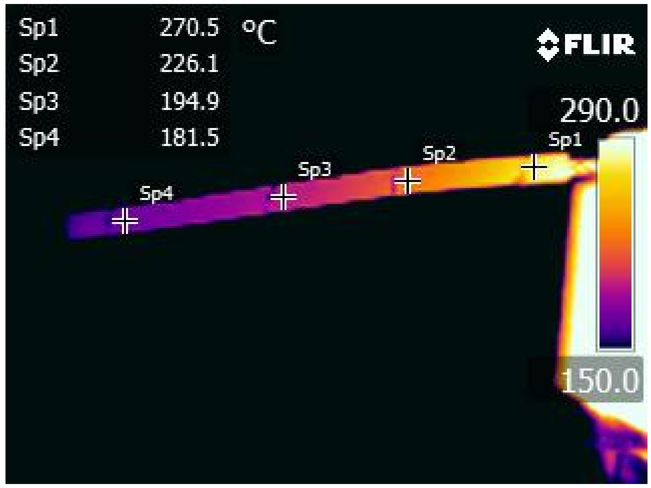


Figure 5-45. Temperature profile for a 12 AWG XLPE wire. The image was taken at the end of a 60.0+ minute HRP and a 5.0 minute set point hold at 450 °C. The bus bar temperature was 446 °C.

A series of tests was performed where the thermocouples measured the temperature along a single 12 AWG XLPE wire. Thermocouples were attached to the wire at 10, 30, 45 and 68 mm from the bus bar. Three tests were performed, one for each heating ramp. The thermocouple measurements along the wire and the bus bar can be seen in Figure 5-46. The figure shows the temperature profile at different times during the test, and for different locations along the wire. Both the thermocouples and the IR camera show about a 100 °C gradient across the wire.

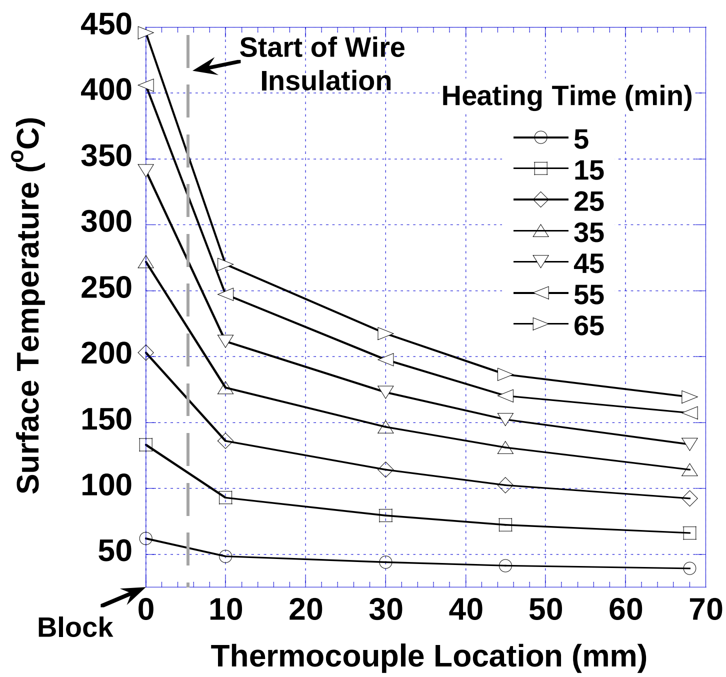


Figure 5-46. Wire surface temperature as a function of time for a 60.0 minute HRP followed by a 5.0 minute hold (± 2 °C). Thermocouples were located along the insulated surface of a 12 AWG XLPE sample

The temperature measurements suggest that the wire insulation closest to the bus bar approaches temperatures close to the piloted ignition temperature. During the experimental design, it was surmised that, given the final block temperature chosen, wire insulation would be easily ignitable by the end of the test period and thus, poses an imminent fire hazard. To support the assumption, ignitability experiments were conducted on the wire samples at different times during the HRP, and at the end of test time. XPLE, PVC2, and CPSE wire samples were attached to bus bars, and heated using the 16.3 minute HRP with the final set point of 485 degrees C. A small flame was positioned under a wire sample for 5 seconds then moved away. The time of persistent flame attachment after the pilot was moved was recorded. The flame was from a horizontal 0.3 mm ID tube with a flow rate of 25 L/min of propane. The end of the tube was 9.5 mm from the bus bar and the center of the tube was located 12.7 mm below the wire sample. The tube was attached to a slide rail so it could be positioned under heated wires rapidly. Figure 5-47 is a picture showing the bus bar mounted on its stand, two wire samples, the ignition tube, and an a enclosure located in a chemical hood. Each experiment used two wire samples and was videotaped for subsequent timing analysis. Figure 5-48 is a picture of the pilot flame before it was positioned under a wire sample.

Table 5-10 shows the results for the persistent burn time after the pilot flame was removed for the four different pre-heat times. The nominal block temperature for the pre-heat times is also indicated. After a heating period of 1,200 seconds and a block temperature of about 480 degrees C, the average persistent burn times were 5, 26, and 50 seconds for PVC2, XLPE and CSPE, respectively. After pre-heating for 900 seconds and a block temperature of about 435 degrees C, XLPE and CSPE wires continued to burn for greater than 20 seconds on average. After a heating period of 600 seconds and a nominal block temperature of about 300 degrees C, only the XLPE wire sustained flaming for longer than 1 second on average, with an average persistent burn time of 14 seconds. After a heating period of 500 seconds and a nominal block temperature of about 250 degrees C, none of the wire samples sustained flaming for longer than 1 s. XLPE appears to be the easiest of the three wires to ignite, followed by CPSE, then PVC2. The trend appears to be counter-intuitive, whereas thermoset insulation materials, such as XLPE and CSPE, burned longer after pilot flame removal, compared to the thermoplastic PVC. Possible factors affecting the ignitability here are possible flame retardant additives, and differences in the wire conduction, which could lead to different temperature profiles.

Figure 5-47. Experimental setup

Figure 5-48. Pilot flame

Table 5-10. Persisting Burn Time for Wire Samples after Pilot Flame Removed

Heating Period (s) (15 minute HRP)	Block Temperature (°C)	Persistent Burn Time (s)		
		XLPE	CSPE	PVC2
1,200	480	28	45	7
1,200	480	20	53	5
1,200	480	31	52	5
1,200	480			4
900	435	17	38	3
900	435	36	26	2
900	435	18	32	3
900	435			5
600	300	17	1	1
600	300	11	0	1
600	300	13	0	0
500	250	1		0
500	250	1		0
500	250	0		0

Although these experiments do show that a small pilot flame can ignite pre-heated wires, it is not unreasonable to expect that such pre-heated wire could ignite from a brief electric arc, or glowing conductor, following an electrical failure; without sufficient pre-heating, ignition would not occur.

5.9 Evaluation of Test Results

The results from testing provide information that supports several project objectives. This section presents the test results specific to those objectives.

5.9.1 System response to common products of combustion (Objective E)

Detector response to smoke signature from materials included in the test program is presented generically. The in-cabinet, naturally ventilated test data is used. This data set limits variability of cabinet ventilation rate, and areawide detector-to-source location influences on detector response. Figure 5-49 presents data from all one-hour HRP tests. The figure shows the detection time for each detector type and material. The "alert" response is reported for the VEWFD systems (SS, ASD CC, ASD LS1, ASD LS2) and the "alarm" response for the conventional spots (PHOTO, ION). Note that the "alert" response is the 0.2 %/ft obscuration of the laser based systems (ASD LS1, ASD LS2, and SS)[10], while the "alert" response for the ASD CC is the vendor recommended sensitivity. Since the latter doesn't report in percent obscuration per foot, comparisons between the ASD CC and other VEWFD systems *should not be inferred* to be tested at equivalent sensitivity settings. Instances in which the detector did not respond before the end of the test are *not shown*. Plots for the 15 minute and four-hour HRP show similar responses and are presented in Appendix B.

[10] LS1 and LS2 represent light-scattering ASDs from different vendors. LS1 represents the results from ASD1. LS2 represents the results from ASD3 and ASD5 which were from the same manufacture but differed in the model and number of sampling zones per detector. CC represents the results from ASD2 and ASD4 which were from the same manufacture but differed in the model and number of sampling zones per detector.

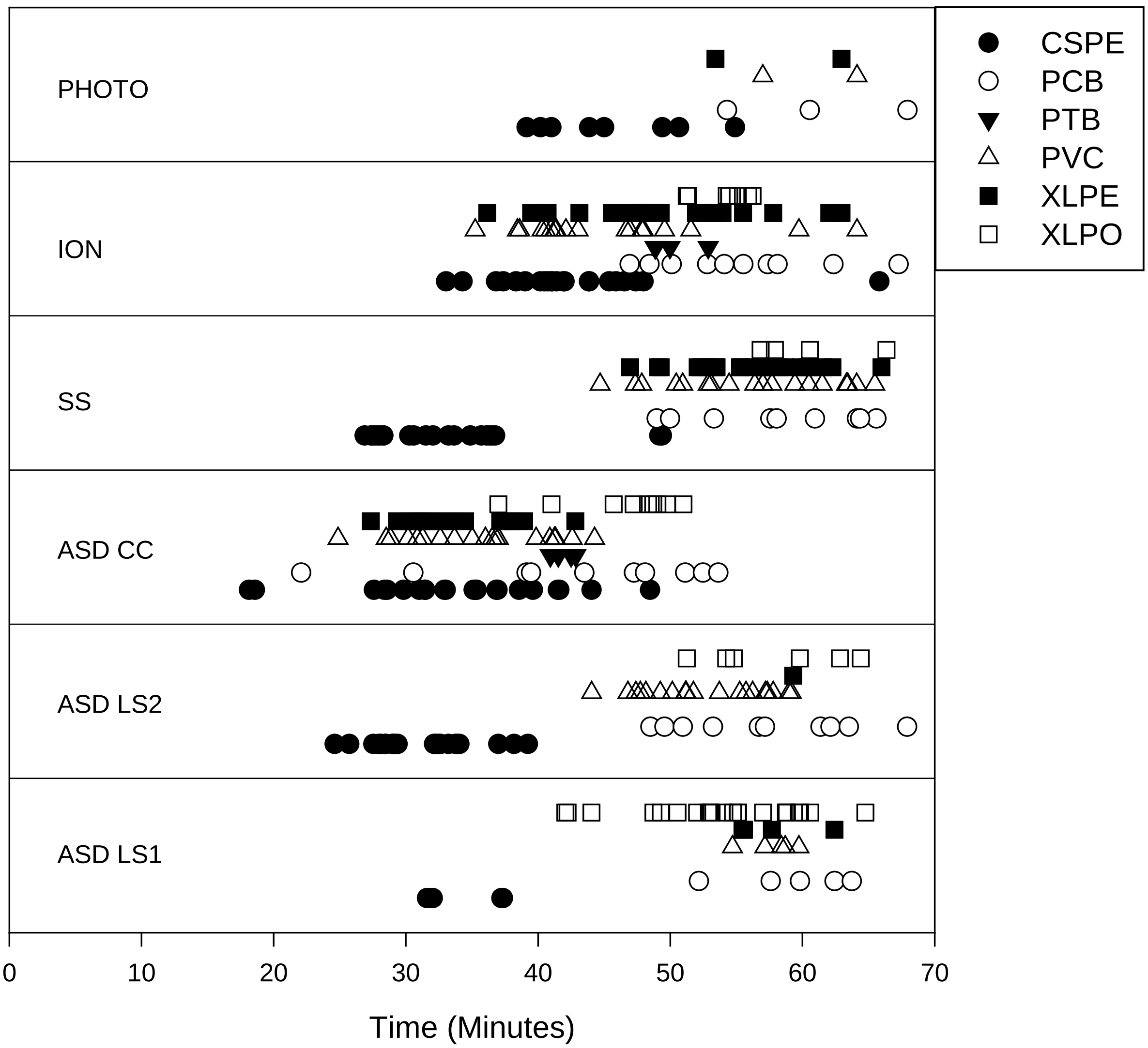
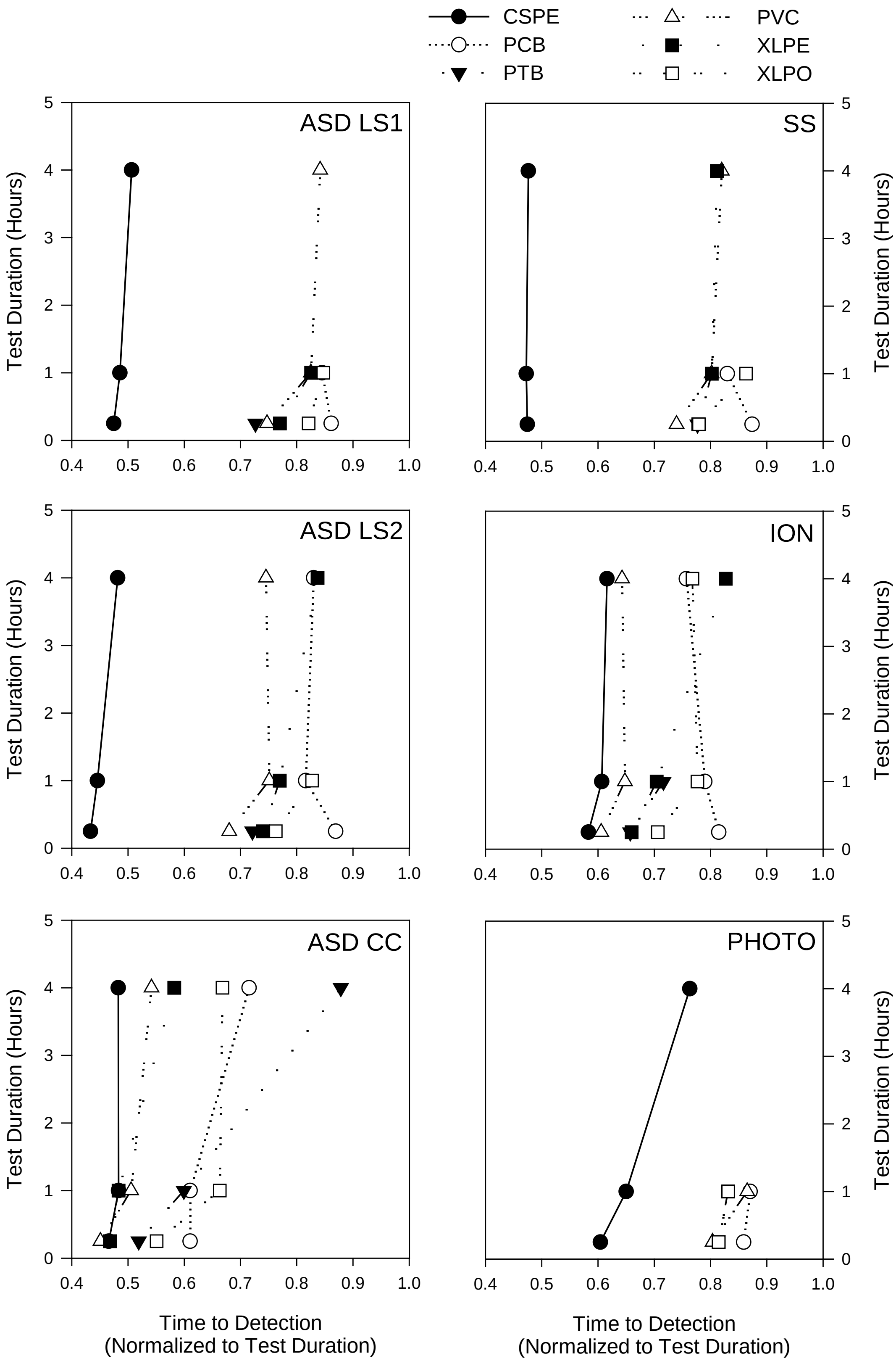


Figure 5-49. Detector response to selected materials (1-hour HRP)

Figure 5-50 presents the mean time to detection results for in-cabinet experiments. The results for all three HRP normalized to the respective HRP are presented by detector and material.



1

2 **Figure 5-50. Time to detection, by detector**

The insights from this data indicate:

1. Based on the mean detection time normalized to the test duration, there is no apparent trend for the mean time to detection and the HRPs used in testing. In general, the mean time to detect increases with increasing HRP in a non-linear manner. This change between the 15 minute and 1 hour HRP is more pronounced than the change between the 1 hour and 4 hour HRP. This likely indicates the aerosol characteristics are dependent on the rate of material heat up and aerosol generation.

2. The PHOTO spot-type detector only responded to the CSPE, PCB, PVC, and XLPE materials. CSPE was the only material that the PHOTO consistently detected.

3. The CSPE material appears to be the easiest to detect. All detectors were effective at detecting the CSPE. For VEWFD systems, including the sensitive spot detector, all responded to the CSPE aerosol at approximately the same time, with ASD LS2 responding earliest (on average).

4. PTB, SR, and TEF are typically detected latest in the early fire stage and are the most difficult to detect of the materials tested. The Silicone and Teflon conductor insulation materials were only effectively detected by ASD CC and ION.

5. The printed circuit board data shows an opposite trend compared to the other materials, in that the time to detect decreases with increased HRP from the 15-mintue to 1-hr HRPs.

6. With the exception of CSPE, the ASD CC and ION spot-type responded at an "alert" and "alarm" setting, respectively, before either ASD LS1 or ASD LS2 "alert" response.

5.9.2 Comparison between common detection systems and VEWFD systems (Objective B)

A comparison between the performance of conventional spot-type detectors (ION, PHOTO) and VEWFD systems (ASDs and sensitive spot) is presented in summary plots. Each point on the summary plots represents the time to detection within a single test. These plots present all three HRP data on a single plot. The diagonal line represents equal performance. In Figure 5-51 and Figure 5-52, points below the diagonal line represent a test in which the VEWFD system responded to an "alert" before the conventional detector "alarm." Points above the diagonal line indicate the conventional spot-type detector responded with an "alarm" before the VEWFD system "alert" response. The dashed diagonal lines represent two standard deviations from the mean conventional detector response used for evaluations.

Table 5-11 provides a summary of this data shown as the percent difference in time to detection between conventional and VEWFD systems. Negative values represent conventional detection responding before VEWFD systems. Based on these test results, the ION spot-type detector responded 2.9 percent slower on average than the VEWFD systems, whereas the PHOTO spot-type responded 19.3 percent slower, on average. Also, based on study observations, it is highly likely that the ASD CC will respond before the ION detector and the ASD LS2 will respond before the PHOTO. This is consistent with the technologies involved, in that both the ION and ASD CC perform well at detecting small particles, while the PHOTO and ASD LS perform well at detecting larger particles. It is also notable, that the results for the two ASD VEWFD LS

detectors show performance differences, even though both were set to the same port sensitivity of 0.2 %/ft. obscuration.

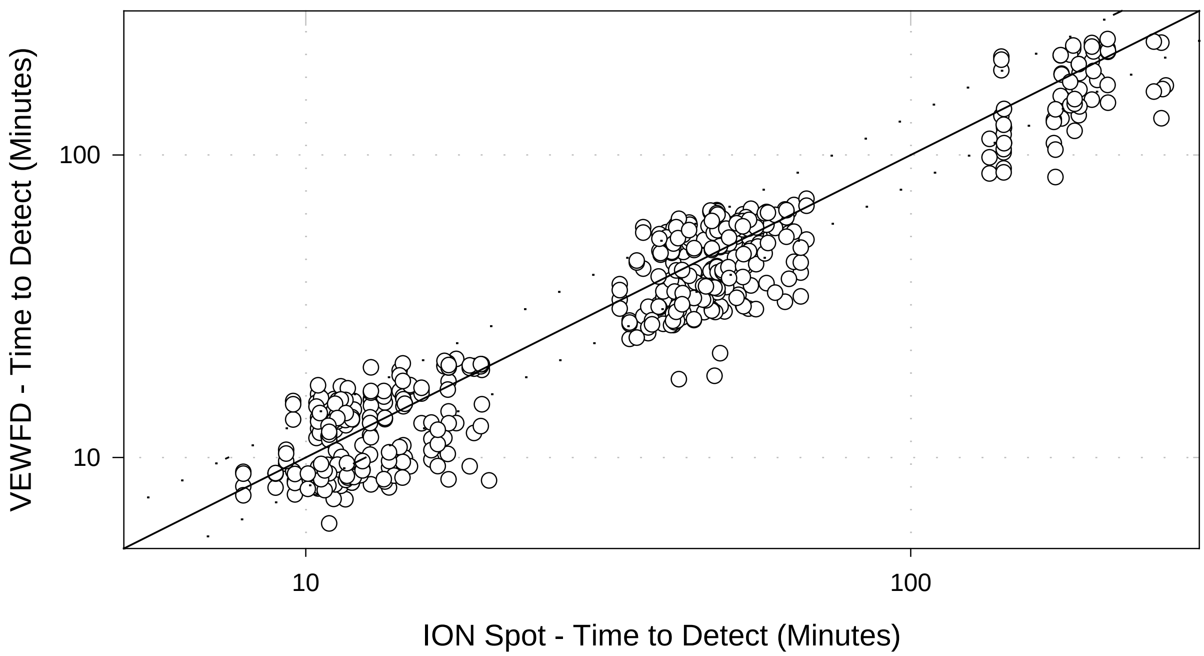


Figure 5-51. Summary plot – ION alarm versus VEWFD alert (in-cabinet, natural ventilation)

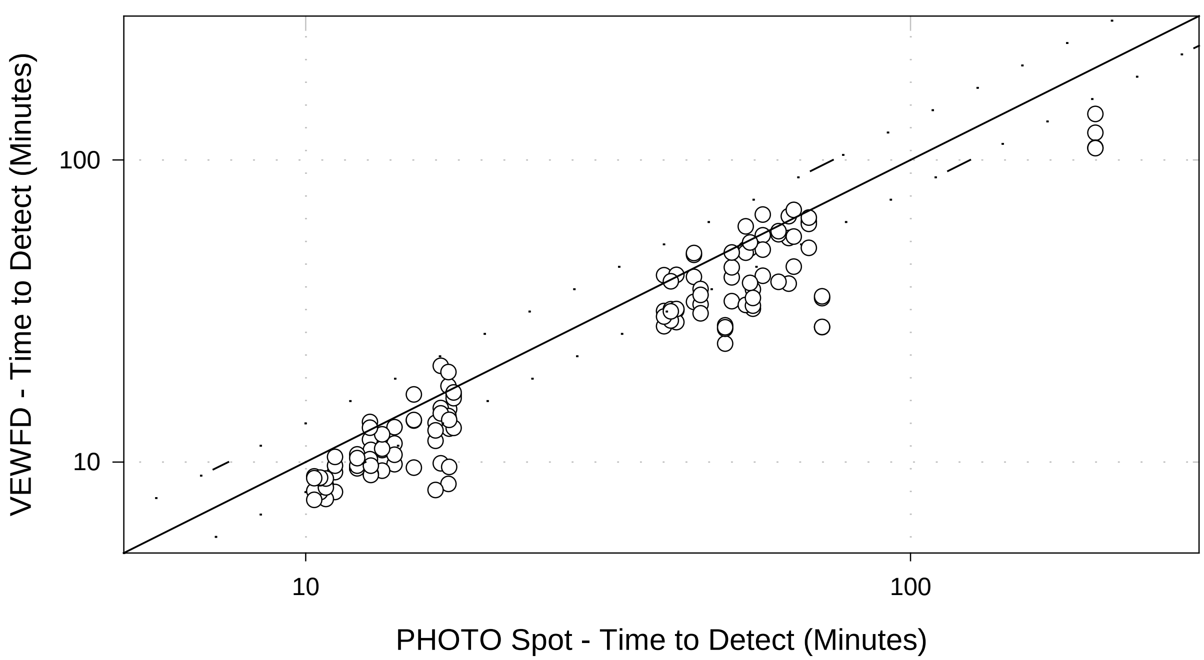


Figure 5-52. Summary plot – PHOTO versus VEWFD (in-cabinet, natural ventilation)

Table 5-11. Summary of Average Difference in Time to Detection Between Conventional and VEWFD Systems (Negative Values Represent Conventional Spot Responding on Average before VEWFD Systems)

	ION		PHOTO	
	Mean	5th/95th Percentile	Mean	5th/95th Percentile
ALL VEWFD	**2.9%**	-39.8/38.0%	**19.3%**	-10.7/50.4%
ALL ASD	**6.7%**	-38.8/40.0%	**20.6%**	-10.5/50.6%
ASD LS1	**- 15.7%**	-54.4/29.5%	**12.1%**	-18.7/45.7%
ASD LS2	**-0.1%**	-27.6/35.3%	**23.6%**	4.0/53.9%
ASD CC	**23.5%**	3.4/47.7%	**25.9%**	-7.6/50.8%
SS	**-7.9%**	41.1/30.0%	**15.2%**	-13.4/52.6%

5.9.3 Evaluation of in-cabinet VEWFD system layout and design versus system response (Objective F)

In-cabinet installations of VEWFD systems are consistent among vendors and with the community of practice in that it is recommended to locate the air sampling port in the upper 10 percent of the cabinet volume being protected. Since the testing followed vendor recommended practices, the evaluation presented here will focus on the detection system response to different cabinet configurations and operating conditions. The variations evaluated include cabinet ventilation conditions, such as forced versus natural ventilated cabinets; and cabinet bank arrangement, as single partitioned cabinets versus multiple connected cabinets, with a common air space.

Figure 5-53 illustrates the responses of several detectors to two different material aerosols for different cabinet configurations. The “1/C” case represents a cabinet where a single sampling port is located. The “M/C” case represents a cabinet space where multiple sampling ports protect a section of cabinets that have a shared air space without any partitions. The intent of presenting the data in this form is to evaluate the potential cumulative effect of ASDs. These results show that, in general, having more sampling ports within a cabinet will shorten the time to detection. However, for the CSPE case, the ASD LS2 shows an average increase in the time to detection between single and multiple sampling ports. These results also show that, in general, the spot-type detectors respond more slowly when used to protect multiple cabinets. A similar trend is shown in Section 5.5, Figure 5-24. On average, the spot-type detectors were approximately 2.9 percent slower and the ASDs were 2.6 percent faster in response when multiple detection points were used in a bank of cabinets compared to a single detection point in a single cabinet.

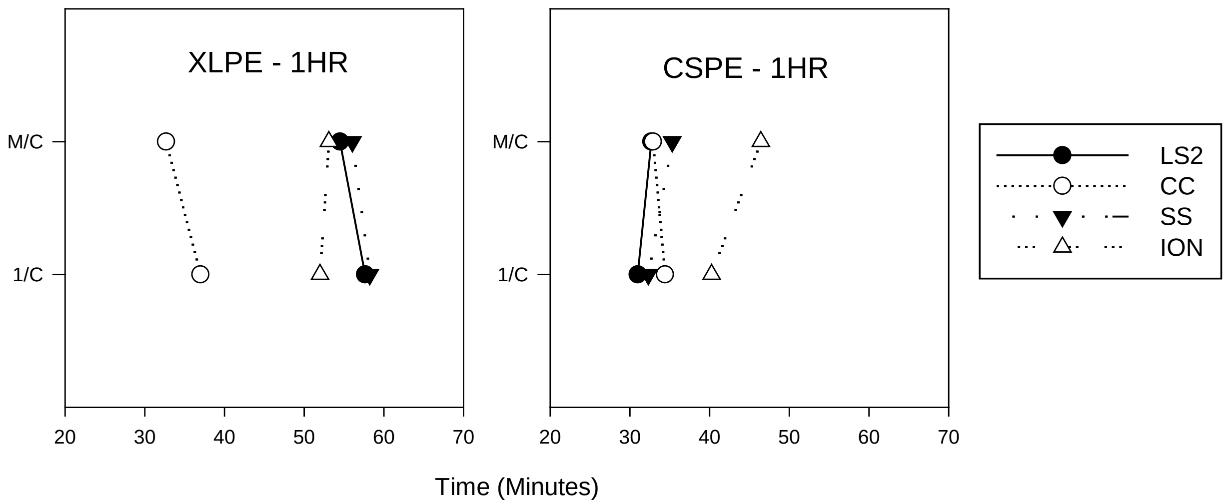


Figure 5-53. Detector response versus number of sampling ports in cabinet space

Figure 5-54 present the effect cabinet ventilation configurations have on detector response. Three states of cabinet ventilation are shown. The “Natural” state represents tests where no mechanical ventilation was used. The “Forced – Low” state represents cases in the full scale testing where an 8.0 ACH cabinet ventilation rate was used. The “Forced – High” state represents the NPP cabinet tests where the ventilation rate was estimated at 300 ACH. In general, as cabinet ventilation rate is increased, the time to detection also increases. This general trend does not hold for the CSPE material where the ASD LS2 and ION spot-type detector responded sooner at the “Forced – Low” state than at the naturally ventilated condition.

Figure 5-55 presents the results from in-cabinet detectors mean response time for all materials by cabinet ventilation conditions. From this graphic, it becomes apparent that the mean time for detector response increases with increasing cabinet ventilation conditions. It should also be noted that LS1 was only included in the naturally ventilated case and the PHOTO was no included in the high forced ventilation experiments.

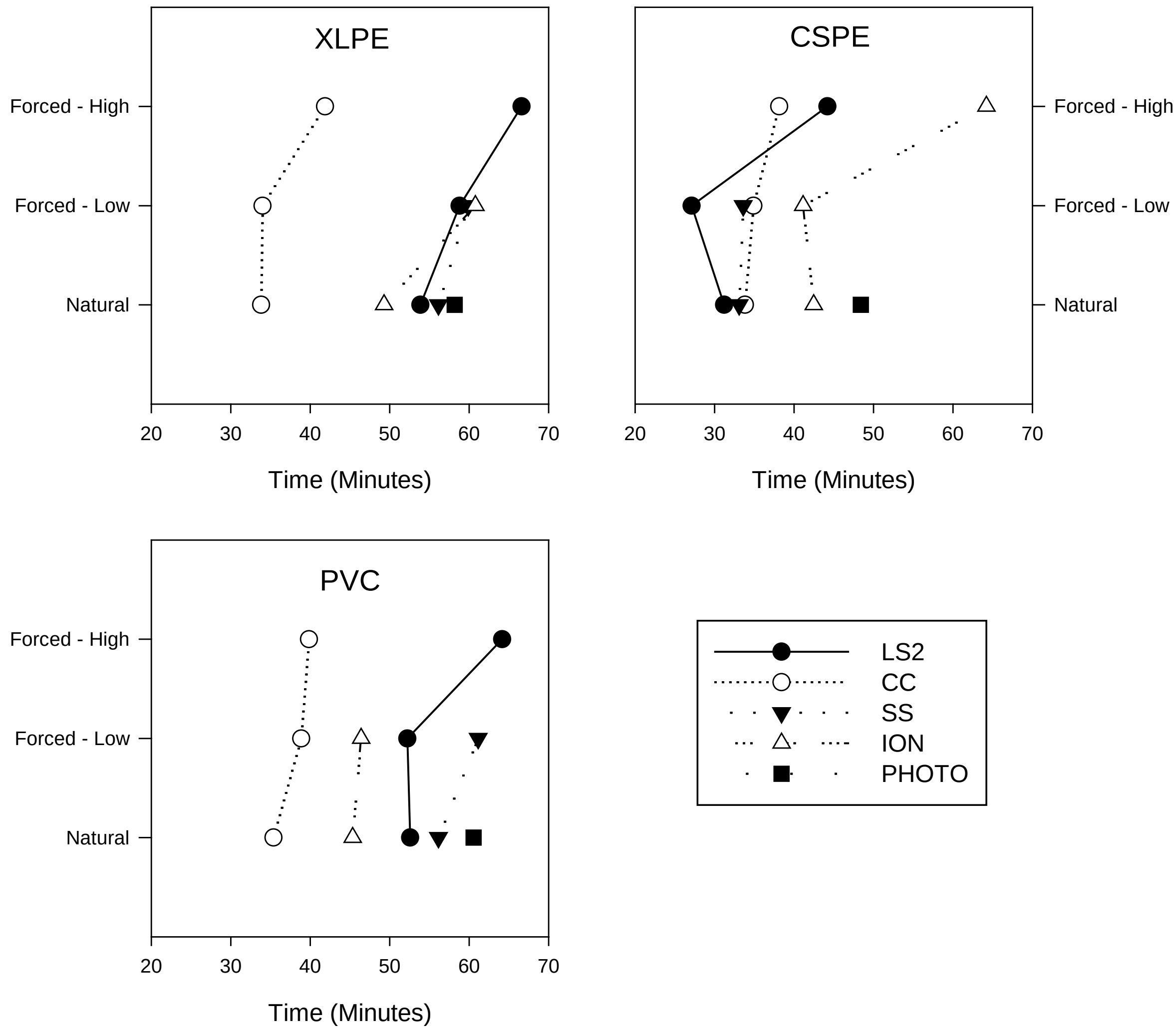


Figure 5-54. Effect of cabinet ventilation on in-cabinet detector response

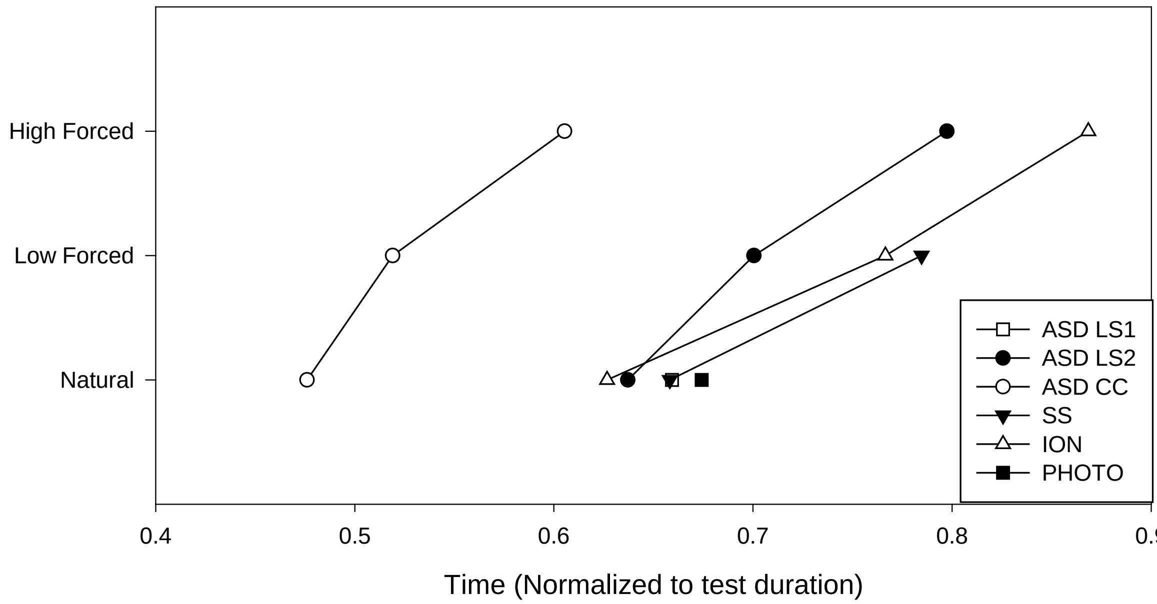


Figure 5-55. Effect of cabinet ventilation on in-cabinet detector response for all materials and all HRPs.

5.9.4 Effectiveness of in-cabinet and areawide VEWFD system applications, including an evaluation of system applicability for various NPP applications (Objective A)

System effectiveness is a measure of how well a design solution will perform or operate, given anticipated operational scenarios (Ref. 19). Effectiveness estimates for ASD VEWFD systems expected to operate during the pre-flaming (incipient) phase are based on the test data collected from the experiments conducted in this program. As indicated above, the source materials are heated to a temperature that can support flaming conditions. The effectiveness differs between in-cabinet and the two areawide configurations, primarily because of smoke dilution and stratification effects. Section 7.2 quantifies the effectiveness of the detection systems tested for use in the risk scoping study presented in Part II of this report. Figure 5-56 present the <u>mean</u> effectiveness for the systems and applications tested. As shown in Figure 5-55 and Figure 5-56, in-cabinet detection without forced ventilation provides the earliest and most effective application for detecting pre-flaming fire conditions.

For the in-cabinet applications, the test data was initially analyzed for system effectiveness for two cases (i.e., naturally ventilated and forced ventilation conditions). However, the data showed a large discrepancy, an order of magnitude difference between the two cases. Further evaluation of the forced ventilation data indicated that the reactor protection system cabinet, taken out of a U.S. NPP had a much lower VEWFD system effectiveness compared to the mock-up cabinet used in the MCPTA tests, and the naturally ventilated case. Further evaluation of the differences between cabinet design and testing conditions identified several parameters that are likely influencing these results.

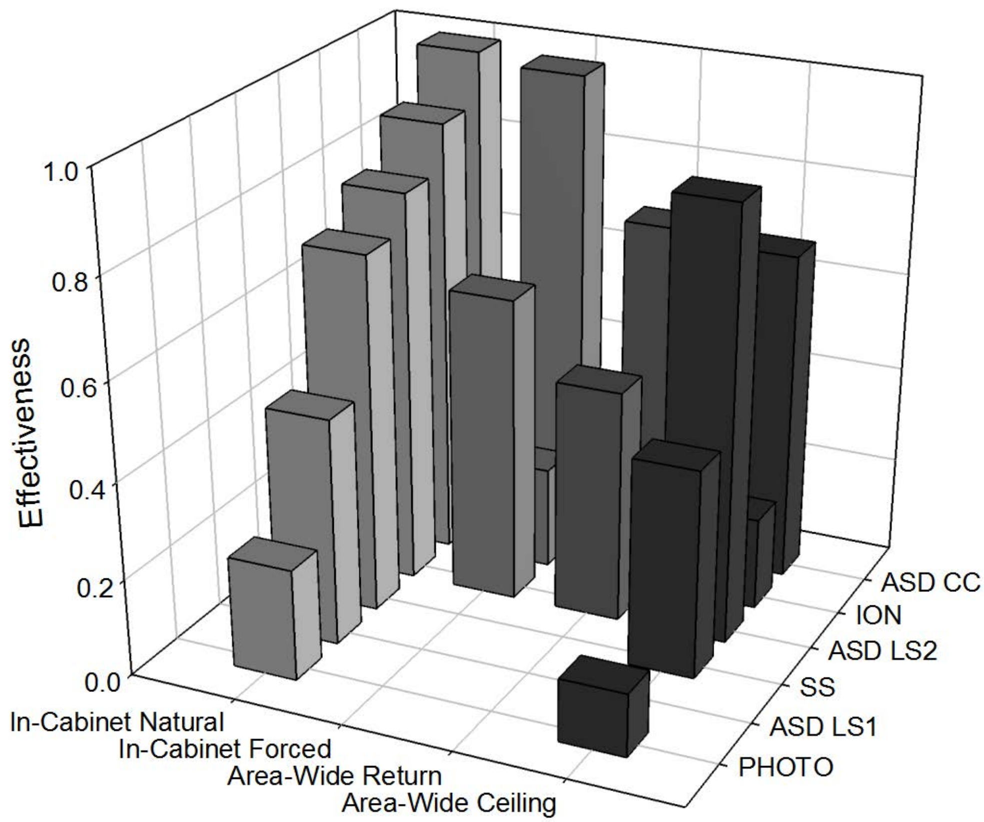


Figure 5-56. System effectiveness by detector and application (Note: no data for ION areawide return)

Cabinet Design Influence

Air streams within the cabinet caused by internal structural members used to hold circuit cards, power supply, electronic modules, etc., and cabinet vent locations in relation to the location of the ASD sampling point may reduce effectiveness. If the products of combustion cannot be sampled by the VEWFD system, the system should be expected to either not respond or to experience a delayed response. Electrical cabinets within NPPs have a variety of designs with regard to ventilation. Common examples include louvered vents on the full length of the front and back panels/doors; half height vents on the front and/or back cabinet panel height; vents on the top and bottom portion of the front and/or back panels/doors; vents on the bottom (floor) and top; combinations of these configurations also exist. Thus, the cabinet design, (with regard to ventilation), and physical component layout, (with regard to the location of the VEWFD system sampling point), have an effect on the availability of any combustion products reaching the VEWFD system sampling points. Because only a limited number of vent/cabinet layout designs were evaluated in the NIST testing, those results should be used with caution, and do not bound all cases found in NPPs.

Ventilation rate

Ventilation rate has a direct effect on aerosol dilution. As the ventilation rate increases, so does dilution, which results in lower concentration of combustion products. Dilution affects both particle concentration and light obscuration.

For in-cabinet applications, two parameters with an influence on system response were identified: cabinet ventilation rates and cabinet internal obstructions, the latter being a secondary or tertiary order effect. Three ventilation rates were available from the testing, namely, naturally ventilated, 7.9 and approximately 300 cabinet air changes per hour. The results indicated that, as the ventilation rate increased, the effectiveness of any smoke detector technology in detecting the incipient source decreased, whereas the influence on system response from cabinet internal obstructions is less clear. In the naturally ventilated cases, there isn't sufficient data to differentiate between the influences/impacts made from the various obstructions. In the force-ventilated cabinet cases, the test series which had differences in cabinet internal obstructions also had different ventilation rates. Because there is no constant for comparison, the results do not provide clear insights on the performance.

Additionally, cabinet configurations such as fully louvered doors with internal heat loading and room ventilation effects were not evaluated during this program; yet they could potentially have an effect on the system performance, especially if sufficient thermal gradients are present within the cabinet.

Cabinet internal component layout and ventilation configurations vary, and are likely to be an important influencing parameter on the effectiveness of the system. Because of the limited number of cabinets available for testing, the test data may not be representative of other configurations. Several different estimates of system effectiveness are developed as shown in Table 7-3. These estimates support the risk scoping study presented in Part II. The system effectiveness estimates are all based on test data, either from this program or other publically available test reports.

5.9.5 Areawide ASD comparison

The individual data sets were evaluated for the ability to be pooled into larger datasets using the Kolmogorv-Smirnov (K-S) tests. For ceiling-mounted ASDs, VEWFD systems the data was able to be pooled into the following three data sets: all tests using forced ventilation; naturally ventilated cases using block smoke source; naturally ventilated case using bundle smoke source. Figure 5-57 shows these data sets according to their time to detect the low energy sources. A similar evaluation was conducted for the tests using forced ventilation with a comparison between air return grill, and ceiling-mounted ASD performance. These results are shown in Figure 5-58 and indicate that the air return grill and ceiling-mounted performance results are similar enough to be pooled. From a practicality standpoint, given the fact that there are a variety of source materials found in electrical enclosures and testing materials that produce a range of aerosol characteristics representative of slow overheating conditions, pooling of these data sets seems reasonable.

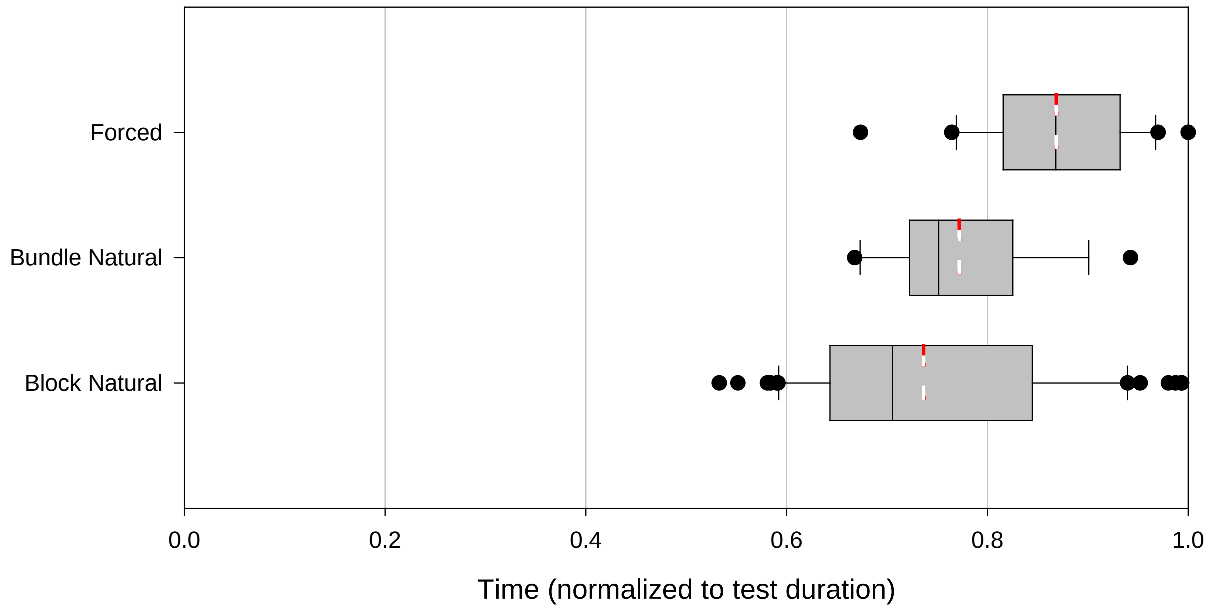


Figure 5-57. ASD time to detect areawide ceiling configurations

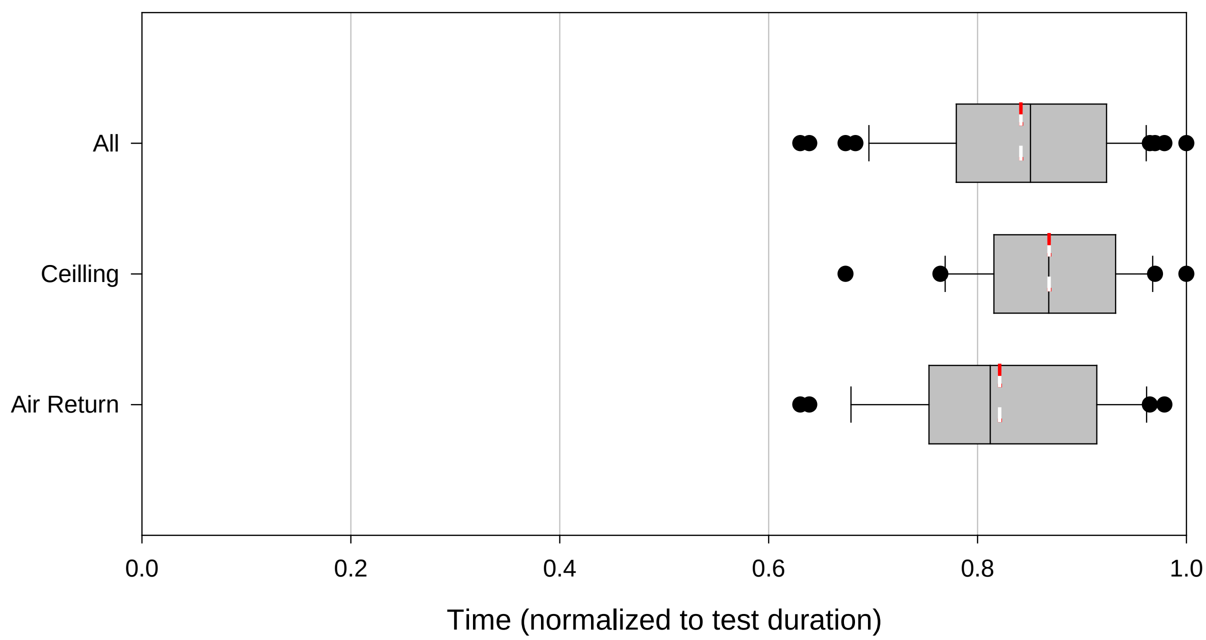


Figure 5-58. ASD time to detect areawide forced ventilation air return and ceiling pooled

The last comparison of the areawide data is to evaluate the effectiveness of the ASD system tests. The effectiveness estimates are shown in Figure 5-58. These results indicate that for the room air change rates tested, the air return grill application response sooner on average than ceiling-mounted ASD systems. With the bundle tests producing more smoke than the block tests, these results consistently show that either areawide application is better at detecting the bundle source.

5.9.6 ASD comparison: In-cabinet versus areawide

The ASD time to detection results for a variety of configurations are presented in Figure 5-59, including the effect of forced ventilation on the time for detection. As shown in Figure 5-59, forced-ventilation also impacts the effectiveness of smoke detection; however, the term 'effectiveness' is not incorporated into this assessment. As expected the closer a smoke detector is located to a potential hazard, the sooner the response.

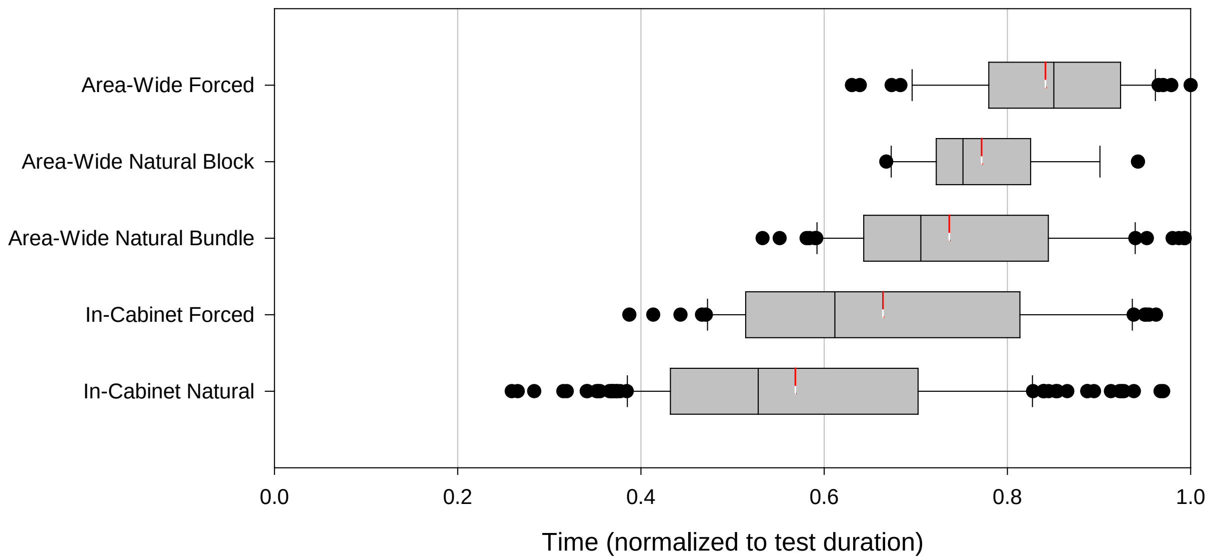


Figure 5-59. ASD time to detect low-energy incipient sources

PART II

Smoke Detection Risk Scoping Study

6. OVERVIEW OF QUANTIFICATION APPROACH

This section provides a high-level overview of the current fire probabilistic risk assessment (PRA) quantification method as described in NUREG/CR-6850; a summary of previous efforts; a discussion on possible approaches for quantifying smoke detector performance in fire PRA; and an overview of the method pursued under this research project.

6.1 Overview of Fire PRA Model

The fundamental concept of a fire PRA is to estimate the total core damage frequency (CDF) arising from fire initiators. The total CDF is the sum of the CDF contributions from individual fire-initiated scenarios. The CDF contribution from an individual fire scenario can be divided into three principal components (Ref. 35):

1. frequency of the fire scenario
2. conditional probability of fire-induced damage to critical equipment given the fire
3. conditional probability of core damage given the specific equipment damage

Mathematically, the total CDF is characterized as follows:

$$CDF = \sum_i \lambda_I \left[\sum_j p_{ed,j|i} \left(\sum_k p_{CD,k|i,j} \right) \right] = \sum_i CDF_i$$

Fire ignition frequency is defined as the occurrence rate of a *potentially challenging or greater fire* involving a specific component or specific compartment of the plant (Ref. 36).

The individual fire scenario CDF is:

$$CDF_i = \lambda_i \times p_{ed,j|i} \times p_{CD,k|i,j}$$

Where λ_i Frequency of fire scenario i

$P_{ed,j|i}$ Conditional probability of damage to critical equipment set (“target set”) j give the occurrence of fire scenario i

$P_{CD,k|i,j}$ Conditional probability of core damage caused by plant response scenario k given fire scenario i and damage target set j

The probability of equipment damage is decomposed into two parts:

$$P_{ed,j|i} = SF_i \times P_{ns,j|i}$$

Where SF_i severity factor for fire source i

$P_{ns,j|i}$ probability of non-suppression before damage to target set j given ignition source i

The severity factor reflects the fraction of fires that have the potential to damage the critical equipment in the fire scenario. The non-suppression probability represents the probabilistic outcome of the fire damage versus fire suppression race given a fire that has the potential to damage critical equipment. Therefore, the individual fire scenario CDF is:

$$CDF_i = \lambda_i \times SF_i \times P_{ns,j|i} \times p_{CD,k|i,j}$$

6.2 Summary of Previous Quantification Efforts

This section presents a summary of the previous approaches used to quantify the performance of VEWFD system fire PRAs. This summary does not present any new information nor does it evaluate the adequacy of previous approaches. It is suggested that the reader reference the associated documents for a full understanding of the methods summarized herein.

NUREG/CR-6850—EPRI 1011989, Appendix P, Detection and Suppression Analysis

NUREG/CR-6850 (EPRI 1011989), Appendix P, "Appendix for Chapter 11, Detection and Suppression Analysis, (2005)" provides an approach for solving the Detection-Suppression Event Tree to estimate a non-suppression probability. That event tree evaluates the prompt, automatic, and manual detection and suppression capabilities. For in-cabinet smoke detection devices, Appendix P provides the following information:

> If in-cabinet smoke detection devices are installed in the electrical cabinet postulated as the ignition source, the analyst should assume that the fire will be detected in its incipient stage. The incipient stage is assumed to have a duration of 5 minutes. To account for these 5 minutes, the analysts should add them to the time to target damage (or, equivalently, add them to the time available for suppression).

The non-suppression probability is calculated by the following equations:

$$\Pr(T > t) = e^{-\lambda t}$$

Where λ is the rate at which a fire is suppressed and t is the time available for suppression before target damage calculated as follows:

$$t = t_{dam} - t_{fb} - t_{det}$$

where t_{dam} is the time to target damage, t_{fb} is the response time of the fire brigade, and t_{det} is the time to detection. Given the information in NUREG/CR-6850 (EPRI 1011989), t_{det} can be set to -5. As shown in Figure 6-1, adding 5 minutes to the time available for suppression results in a reduction of 0.39 from the non-suppression probability, excluding the timing contributions from the t_{dam} and t_{det}.

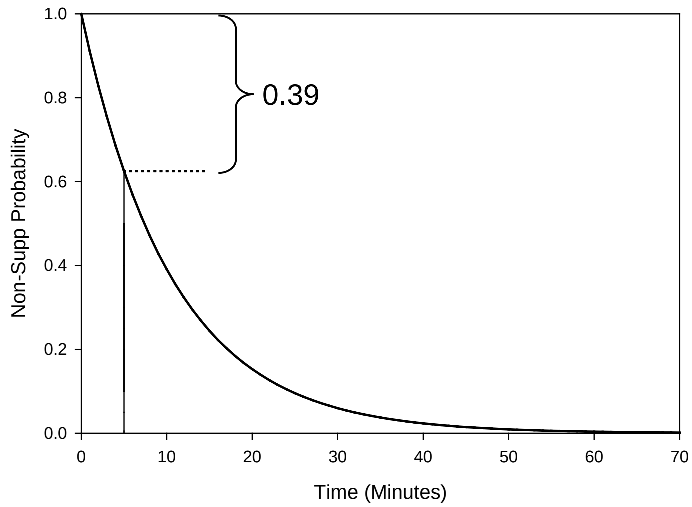


Figure 6-1. Electrical fires suppression curve showing 5 minute in-cabinet detection reduction

The NUREG/CR-6850 (EPRI 1011989) approach doesn't specify the type of in-cabinet smoke detection. Additionally, the NUREG/CR-6850 references "high sensitivity detectors" as a form of prompt detection, but does not define this term. The approach also specifies that prompt suppression is for hot work fires only.

Supplement 1 to NUREG/CR-6850, Section 14, titled "Manual Nonsuppression Probability (FAQ 08-0050)," presents clarifications on the use and updated to the non-suppression probabilities. The Supplement differs from NUREG/CR-6850 method in that the fire brigade response time is not directly used in the calculation of time available for suppression. Instead, an industry average is included in the non-suppression curves presented in the supplement. Thus Supplement 1 presents two approaches. The first approach assumes an industry-average fire brigade response. The time available for suppression is simply the difference between the time of detection and the time of damage. The second approach uses a correction factor for cases where it is judged that the scenario specific fire brigade response time distribution is significantly different from the underlying events reported in the EPRI Fire Events Database (the source of information used to develop the revised non-suppression probability curves). Under the scenario specific adjustment approach the non-suppression probability is calculated as;

$$P_{ns}(t) = \exp[-\lambda(t \cdot C_s)]$$

where C_s is a scenario-specific adjustment factor calculated as;

$$C_s = \left[\frac{\langle T_{fb-s}\rangle - \langle T_{fb-t}\rangle}{\langle T_{fb-s}\rangle + \langle T_{fb-t}\rangle}\right]$$

where T_{fb-s} and T_{fb-t} are the mean scenario specific and typical fire brigade response times, respectively.

EPRI 1016735 Fire PRA Method Enhancements

In 2008, EPRI published EPRI 1016735, "Fire PRA Methods Enhancements: Additions, Clarifications and Refinements to EPRI 1019189." In section 3 of that report, a method for quantifying the performance of aspirating smoke detection (ASD) is provided. Appendix C of the EPRI report also provides supporting information. The quantification approach is in the form of an event tree with three events. The method adjusts the fire ignition frequency by multiplying the location-weighted ignition frequency (λω) by:

1. μ : the fraction of ignition source J components in location L that are effectively covered by the very early warning fire detection (VEWFD) system, represented as (μ)
2. R : availability and reliability of VEWFD system in location L, and
3. P : the pre-emptive suppression probability

The ignition frequency adjusted to account for VEWFD systems, would then be:

$$\lambda\omega_{VEWFD} = \lambda\omega(1 - \mu RP).$$

The report limits the applicability of this method of using VEWFD systems to components 250V or less such as Bin 1 (batteries); 4 (main control board); 9 (air compressors); 10 (battery chargers); and 15 (electrical cabinet) components; and 480V or less components such as Bin 11 (welding and cutting); 14 (electric motors); 18 (junction box); 21 (pumps); and 22 (RPS MG set) components.

The method also makes the following assumptions:

- VEWFD alarms will indicate incipient conditions approximately an hour or more before ignition occurs (based on manufacturers' claims, NFPA 76 objectives).
- Technicians respond within 15 minutes.
- Incipient condition will be identified and prevented from achieving ignition for approximately 99.9 percent or more of true incipient conditions. Based on control room suppression curve and 15 minutes or more suppression time.
- Prompt detection (plus alarm delay time) for system excluded from guidance, but within coverage area of VEWFD system.

The report section concludes with two examples. In the first example the system is assumed to be highly capable of detecting incipient conditions and estimates a reduction in fire ignition frequency by 0.994. The second example assumes a more limited capability of the VEWFD system and estimates a reduction in the fire ignition frequency by 0.503.

NFPA 805 FAQ 08-0046, Incipient Fire Detection Systems

FAQ 08-0046, "Incipient Fire Detection Systems, (2009)" documents the NRC staff's interim position with regard to crediting VEWFD systems in fire PRAs to support NFPA 805. This position provides a method for determining the probability of non-suppression in fire areas where incipient fire detection systems are installed. The FAQ approach follows the EPRI approach using an event tree, but provides refinements intended to improve accuracy and realism. The FAQ event tree is shown in Figure 6-2. The event tree has five events with three possible outcomes.

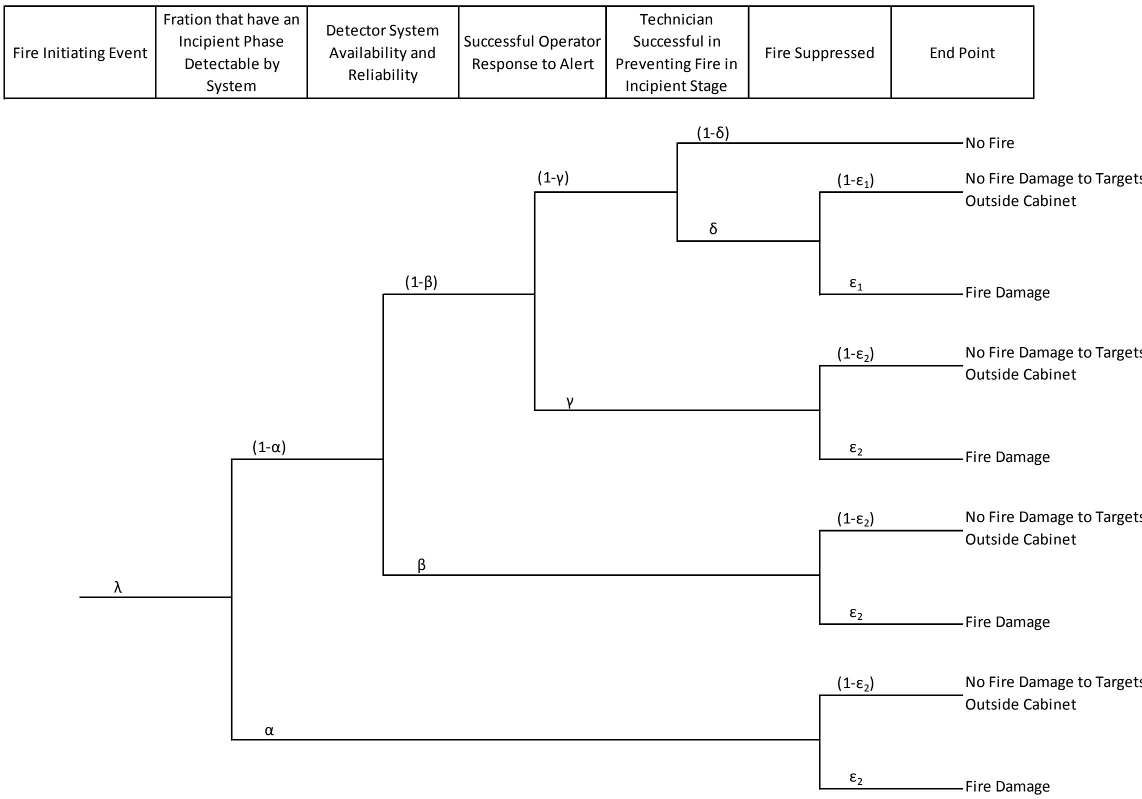


Figure 6-2. FAQ 08-0046 proposed event tree for assessing fire risk for installed VEWFDS in-cabinet

The first event represents the percentage of components that <u>do not</u> exhibit an incipient degradation phase: this is detectable by the ASD VEWFDS in cabinets containing components with voltages less than or equal to 250 Volts (represented by α). Components that do not exhibit this phase include fast-acting components defined in the FAQ as electrical/electronic circuit boards that contain the following:

- electrolytic capacitors
- chart recording devices
- cooling fans
- mechanical timers driven by electric motors
- other components that may fail abruptly without a degradation phase detectable by an ASD VEWFDS

The next event represents the failure probability for the ASD VEWFDS to issue an alert, provided that conditions exist within the protected cabinet that would cause a properly functioning system to go into alert (represented by β). The NRC staff's interim position suggests that this value can be set to 1×10^{-2}.

The next event represents the likelihood that plant personnel may/will fail to adequately respond to an alert signal in a timely manner (before flaming). Gamma (γ) can be determined based on a human reliability analysis (HRA) or conservatively set to 1×10^{-2} for applications in which an ASD VEWFDS zone is dedicated to multiple cabinets and γ can be set to 5×10^{-3} when the ASD VEWFDS is addressable to an individual protected cabinet. The recommended values *assume*

that the ASD VEWFDS provides *at least one hour of warning* before the actual outbreak of an open flaming fire.

The next event represents the probability of failure to remove power from the device once it has been located. The NRC staff determined that because of the complexity of identifying and removing all power from the affected component, this parameters (δ) value should be set to 1 representing a zero probability of successfully removing power.

The last event “Fire Suppressed” has two parameters associated with it. ε_1 is the “enhanced” non-suppression parameter, and represents the probability that, given the operator has successfully responded to the alert (1-λ), the personnel staged at the cabinet associated with the ASD VEWFSD alert fails to promptly suppress the fire. Here, failure represents a scenario in which the suppression activity is not performed quickly enough to prevent damage outside of the protected cabinet, once the affected components’ fire growth enters the flaming stage. The NRC staff’s interim position indicated that a value of 1×10^{-3} should be used for ε_1.

The second suppression parameter, ε_2 the probability of “normal” non-suppression, addresses cases in which the operator fails to properly respond to an alert, or cases in which the detector fails to issue an alert (availability/reliability). The values used for ε_2 in this event tree should be taken from the Detection Suppression Event Tree in NUREG/CR-6850, Appendix P, using the electrical suppression curve for manual suppression, as appropriate. Additionally, FAQ 08-0050 in Supplement 1 to NUREG/CR-6850 provides updated information to Appendix P of NUREG/CR-6850. Credit should be given as described in Appendix P for automatic detection and suppression (normal spot detectors and automatic suppression in the area), as well as delayed manual detection, manual actuation of fixed suppression, and manual suppression via the fire brigade. Using the updated numerical results presented in Table 14-1 of Supplement 1 to NUREG/CR-6850 for Electrical Fires, making the assumption that the fire brigade has 5 minutes to suppress the fire, the non-suppression probability value of 0.602 should be used for ε_2.

Given the discussion provided in the FAQ, and summarized above, a simplified event tree can be developed based on the fact that these systems can only be credited for protecting equipment that exhibits an incipient stage detectable by the system (α set to 0) and no credit is given for removing power from the component that caused the system alert (δ set to 1); this simplified event tree is presented in Figure 6-3. Given this treatment, the simplified FAQ 08-0046 event tree represents a reduction of 0.979 to 0.984 in the non-suppression probability, dependent on addressability of the system and ignoring normal non-suppression analysis.

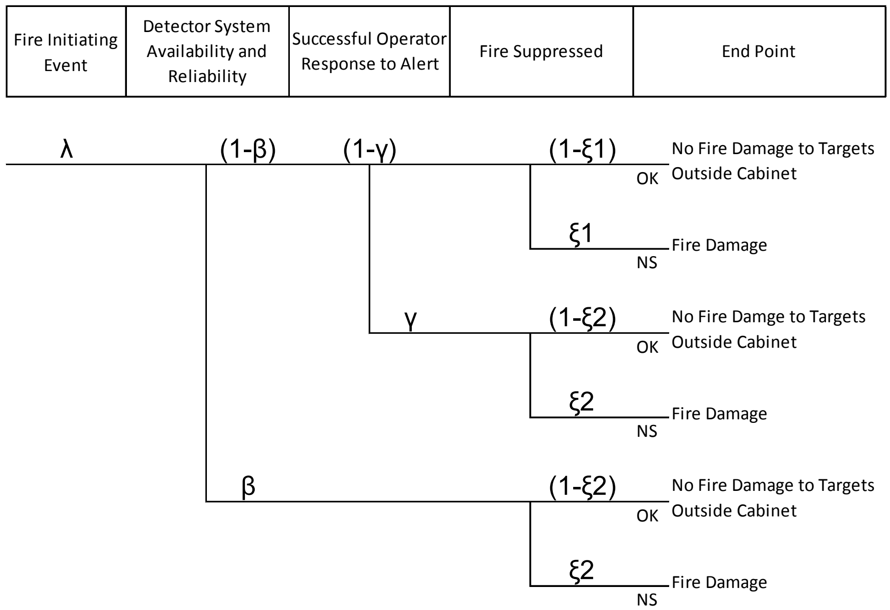


Figure 6-3. FAQ 08-0046 simplified event tree for assessing fire risk for installed VEWFDS in-cabinet

6.3 Approaches to Quantifying Smoke Detection Performance

There are several methods that could be applied to evaluate the detection/suppression estimates associated with smoke detection systems. Examples include simulation, decision trees, and expert judgment. Some past quantification efforts[11] have used event trees to quantify risk improvements. This report also uses an event tree approach to estimate the probability of non-suppression for different smoke detector technologies. Event trees are models that group a broad range of possible scenarios into a small number of categories. For example, there is an infinite variety of pre-flaming scenarios; however, the event tree groups this infinite variety into two categories: slowly developing (where VEWFD might give substantial improvement over conventional), and rapidly developing (where VEWFD and conventional are likely to perform about the same).

The method described here builds on the previous event trees' quantification efforts. However, this method attempts to provide improvements over past efforts by using test data, operating experience, and expected operational response to smoke detection alarms.

6.4 Event Trees and Definitions of Event Headings

Two event trees were developed. The first event tree, shown in Figure 6-4, estimates the non-suppression probability for in-cabinet smoke detection applications, while the second, shown in Figure 6-5, represents the non-suppression probability for areawide type applications. The event trees presented in Figure 6-4 and Figure 6-5 provide a structure to estimate the non-suppression probability for fire scenarios where smoke detection systems are used to protect electrical cabinet ignition sources.

[11] See EPRI 1016735 and NRC FAQ 08-0046

The non-suppression probability event trees have three end states (1) no damage beyond initiating component, (2) cabinet damage, and (3) fire damage outside cabinet. These end states are defined as follows:

No damage beyond initiating component end state assumes that the degrading component is damaged and incapable of performing its intended function. With a focus on electrical cabinets, the initiation component can include, but not be limited to components such as relays, coils, contactors, indication, circuit cards, terminal strips, cabinet ventilation blowers and other similar component types.

Cabinet damage end state assumes that damage is not limited to the initiating component and that other components within the cabinet are damaged. Suppression activities, regardless of form are also assumed to damage the ability of components located within a cabinet to perform their intended design function.

Fire damage outside cabinet assumes damage could not be limited to the initiating cabinet, and target sets outside of the initiating cabinet may be damaged.

The event tree headings include estimation of fire phenomena, detector performance, human performance measures, and fire suppression. The basis for the development of these estimates is provided in the subsequent subsections.

The first event, "Fractions that have an incipient phase" [shown on the success branch (up)] is separate from those that have shorter incipient stages. The next event "Detector System Availability, Reliability" quantifies the systems operational performance. The failure branch (down) represents the probability that a detection system will be unable to perform its function because of system outage or hardware failure. The next branch "Effectiveness," evaluates the system's ability to detect low-energy (pre-flaming) fires for a specific installed application. The success branch represents a detection system's probability of effectively detecting a low energy fire in its incipient stage. Success of the "MCR Response" event represents that the main control room (MCR) operating crew has acknowledged a smoke detector alert or alarm and has directed first level field response to the alerting/alarming fire location. Success in the "first Level Field Response (Technician/Field Operator) Fire Watch Posted" represents the probability that the field response plant personnel have arrived at the smoke detector alert/alarm location and have successfully located the source of the alarm before flaming conditions. Success in the enhanced suppression event represents the probability that any potential fire is suppressed before fire damage to targets of concern. The last event "Conventional Detection/Suppression" estimates the probability of successfully suppressing a fire given a failure of one of the earlier events. To estimate the success of these branches, timing considerations such as operator or fire brigade response, and time to target damage be estimated, and the suppression / detection event tree from NUREG/CR-6850 (EPRI 1011989) can be solved.

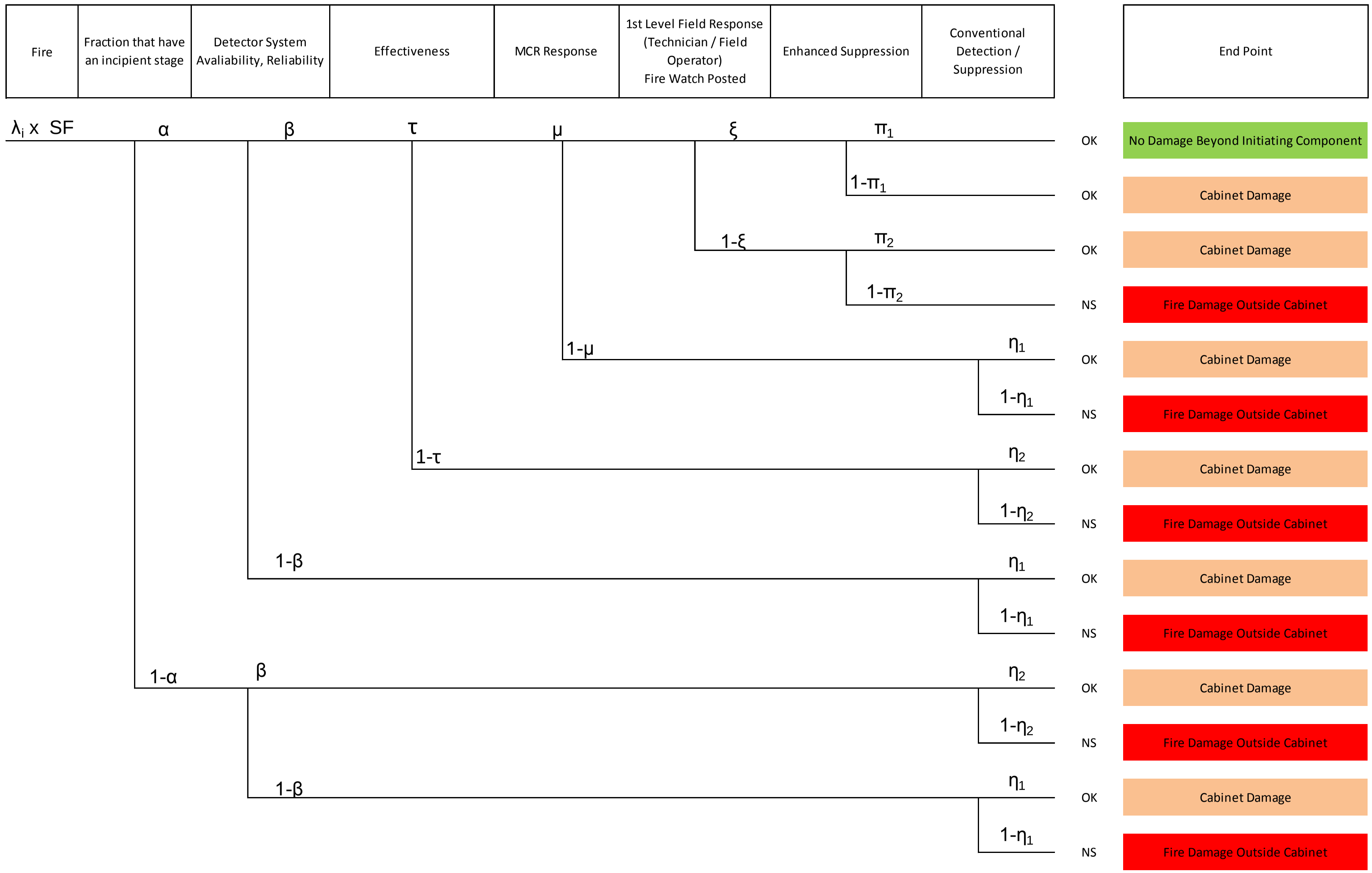


Figure 6-4. Basic event tree for in-cabinet smoke detection non-suppression probability estimation

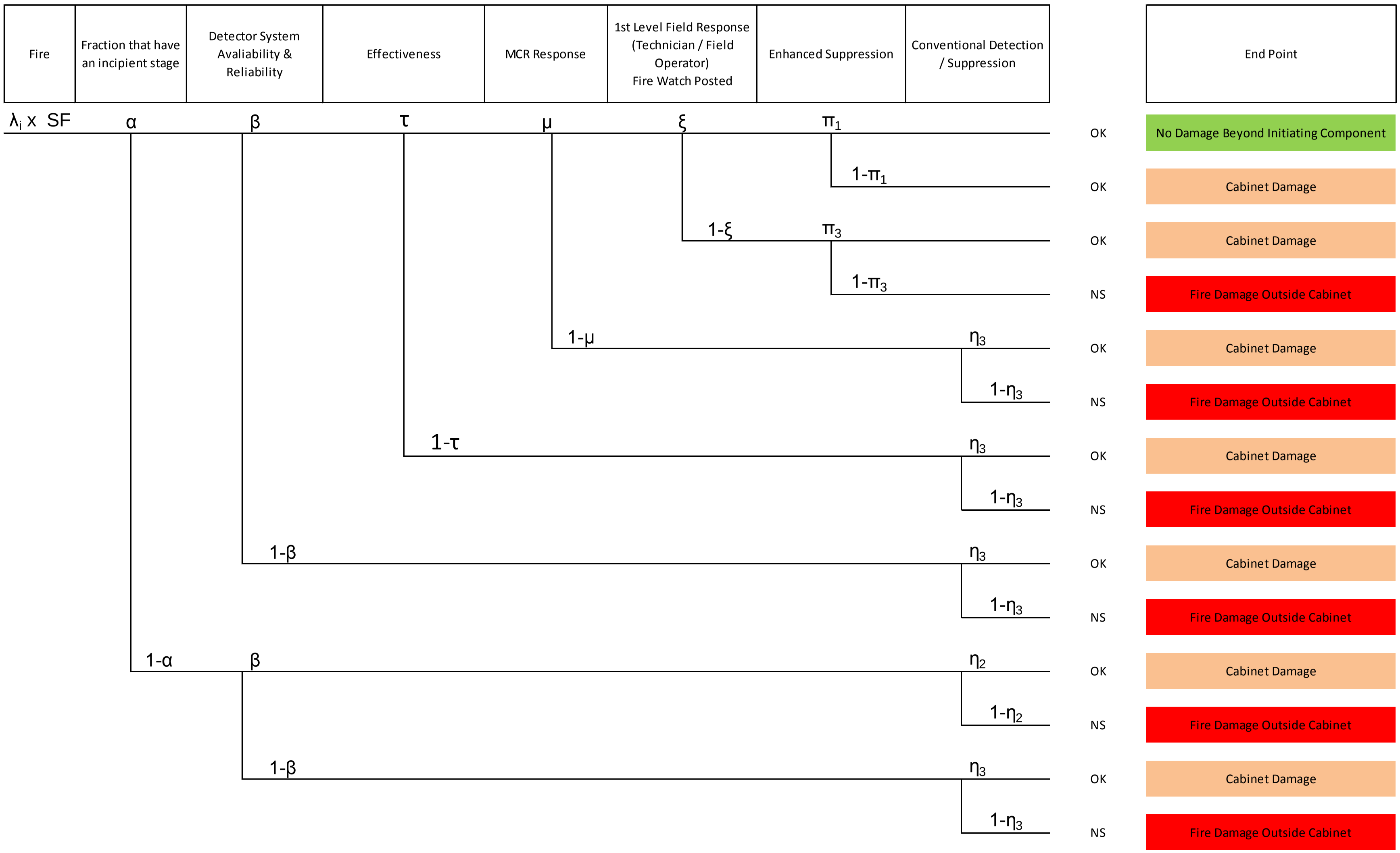


Figure 6-5. Basic event tree for areawide smoke detection non-suppression probability estimation

7. PARAMETER ESTIMATION BASED ON PART I

7.1 Fraction of Fires That Have an Incipient Stage

The first event represents the *fraction of potentially challenging or greater fires that have an incipient stage of greater than or equal to 30 minutes*[12]*.* This fraction is represented in the event tree as α. This event does not include the effectiveness measures of the performance of a smoke detection system. To estimate this parameter, the types of fires that are determined to be a *potentially challenging or greater fire* as represented by the fire ignition frequency "λ," were reviewed. Thus "α" is dependent on "λ". As such, the fire events used to estimate λ were reviewed to ensure that this dependency is understood and conserved.

Operating experience has shown that many, but not all, electrical cabinet fires[13] that occur in a nuclear power plant (NPP) and are considered *potentially challenging or greater fires* have an incipient stage (Ref. 37). *Potentially* c*hallenging or greater fires* are classified as challenging, potentially challenging, or undetermined with regard to the fire severity classification documented in Electric Power Research Institute (EPRI) 1025284, "The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance." Fires not considered important to risk are classified as "non-challenging." The fire ignition frequency (λ) is the occurrence rate on a generic plant wide basis of a *potentially challenging or greater fire* involving a specific type of component (Ref. 36). These generic plant fire frequencies are adjusted based on weighting factors for plant areas and the number of components in the plant. Non-challenging fires do not contribute to the development of the generic fire ignition frequency estimates. EPRI 1025284 defines non-challenging fires as, follows:

> Fires that did not cause or would not have caused adjacent objects or components to become damaged or ignite regardless of location for essentially any amount of time. These fires could be detected automatically by an incipient fire detection system and could be related to component failures involving ignition of the component followed by self- extinguishment without any required intervention. Fires that remained in a smoldering state with no apparent potential for open flaming might also be classified as non-challenging using the criteria provided in Appendix B. Another typical example of non-challenging would include component overheating incidents with light or moderate smoking but without any flaming. The non-challenging classification is also applied to fires of a type or in a location that would not be considered relevant to a fire PRA (e.g., an automobile fire in an on-site parking lot or an off-site grass fire). Fires that occurred during plant construction would also be classified as non-challenging. (See additional discussion and criteria in Appendix B, Section 2.5).

Additionally, the EPRI report states:

> The event classification criteria for non-challenging or undetermined categories are consistent with NUREG/CR-6850. The definitions for key terms used to determine whether a fire could be non-challenging, including 'incipient', 'flaming combustion', 'smoldering', and 'ignition' are now defined in accordance with

[12] The basis for the 30 minutes criterion is presented later in this section.
[13] Electrical cabinet fires are classified as Bin 15 in NUREG/CR-6850

NFPA 901, NFPA 921, and other NFPA standards and publications. These definitions are provided in Appendix A [of EPRI 1025284] and were used as a consistent means of classifying fire event information.

Thus, to understand the fraction of electrical panel fires that exhibit an incipient stage, the fire events database was reviewed. Bin 15 "Electrical Cabinet" of the EPRI fire events database was evaluated to inform the fraction of events, which exhibit an incipient stage of sufficient duration, (greater than or equal to 30 minutes) such that detection and operator response could enhance the suppression activities. All Bin 15 Electrical Cabinet events that contribute to fire ignition frequency (i.e., Challenging, Potentially Challenging, and Undetermined) were reviewed. Events classified as "non-challenging" were not evaluated because they do not contribute to the fire frequency and are not considered important to plant risk. However, review of these "non-challenging" events does indicate that the majority of these events exhibit failure mechanisms for which an in-cabinet smoke detection system could provide enhanced warning. Nonetheless, as they do not contribute to fire risk (as presented in Section 6.1), they are not examined further.

The results of this evaluation are documented in Appendix D. Determination of whether or not an event has an incipient stage is subjective in nature, and highly dependent upon the amount and quality of information available. As such, there were 'rules' developed to assist in making this classification exercise practical, and as consistent as possible.

First, an attempt was made to <u>make no assumptions</u> regarding the event. If the necessary information was not available, the reviewer ventured no guesses. In many events with limited information, this rule likely directed the classification as being "Undetermined." For example, many events identify a breaker fault, but do not identify the component of the breaker which failed. Since breakers have numerous failure modes that could result in a breaker fault, and because the various failure modes may or may not exhibit an incipient stage, there was no assumption made regarding any one particular failure mode; more-information was needed to make such a determination possible.

Next qualitative <u>definitions</u> for "Yes," "No," and "Undetermined" were developed to support a consistent classification of the events. The definitions used were as follows:

Yes, the description of the event provides sufficient detail to determine that slow component degradation occurred. Additionally, if the description of the event doesn't provide a direct indication of slow component degradation, but can be inferred from the component which failed, then it is still a 'yes'.

An example of the latter circumstance would be a control power transformer (CPT) within a motor control center (MCC) which fails due to internal winding failure, and not from an over voltage condition on the primary side of the CPT.

No, description of event identifies rapid failure, failure during work activities (maintenance, inspection, testing, cleaning, etc.), failure on demand, or the description of the event doesn't provide direct information regarding the time frame for component degradation but can be inferred from other information presented.

Undetermined, event doesn't provide sufficient details to determine that an incipient stage occurred or did not occur.

A nominal minimum threshold of 30 minutes should be used to classify as being of “sufficient duration.” The 30 minute threshold is assumed to be a factor of 2 larger than the assumed maximum 15 minute response time for plant personnel to arrive at the scene. However, the 30 minute rule is not the sole determiner of whether or not an event is classified as having an incipient stage. The reviewer should understand the failure mechanisms described in the event and make an informed decision based on the information and the objective of using a VEWFD system to provide sufficient time for operators to respond and be capable of providing suppression. Typically, the event descriptions do not have sufficient information to quantify the incipient stage in terms of seconds, minutes, and/or hours of pre-flaming degradation. Alternatively, if an event identifies a root cause as being (a result of) age or in-service use over many years or decades, this should not be used as justification that the incipient stage began when the component was installed.

The results of this event review process are presented in Appendix D. Table 7-1 summarizes the results of this review for Bin 15 fires. Two of the events resulted in a differing classification among the two reviewers. In both cases one reviewer assigned an “undetermined” classification, while the other classified the event as having an incipient stage (“yes” classification). For these two events, a 0.75 weight was applied. The last column identifies the mean point estimate for “α” shown in bold font, with the 5^{th} and 95^{th} percentiles shown in bracket. These estimates are calculated excluding the “Undetermined” category and using a Jeffery’s non-informed method to estimate the uncertainty.

Table 7-1. Summary of Fraction of Electrical Cabinet Fires (Bin 15) That Have an Incipient Stage Detectable by a VEWFD System

Category	Incipient stage Detectable by VEWFD System			Total # Events	Fraction (alpha) Mean [lower/upper]
	Yes	No	Undetermined		
Power Cabinets[#]	16.5	16	22.5	55	**0.50** [0.36 / 0.64]
Low Voltage Control Cabinets	6	2	5	13	**0.72** [0.46 / 0.92]

[#] Power cabinets include electrical distribution electrical enclosures such as motor control centers, load centers, distribution panels, and switchgear.

7.1.1 Discussion of difference between this method and FAQ 08-0046

This sub-section provides background information to support the approach described above as well as comparison to the interim staff position presented in Frequently Asked Questions (FAQ) 08-0046.

The estimates developed above differ from the deterministic criteria presented in the U.S. Nuclear Regulatory Commission (NRC) interim staff position FAQ 08-0046. In that FAQ, the alpha term was estimated using a criteria of “fast acting components,” and a limitation on the maximum voltage of electrical cabinets (<250V).

The FAQ 08-0046 defines “fast-acting components” as:

- Electrical/electronic circuit boards that contain electrolytic capacitors
- Chart recorder drives
- Cooling fan motors
- Mechanical timers driven by electric motors, etc.

Given these criteria are met, the FAQ presents a simplified model that assumes all fires have an incipient stage of sufficient duration that an ASD VEWFD system installed in the electrical enclosure containing the fire initiating component will provide at least one hour of advanced warning.

Per the FAQ approach, for electrical cabinets that contain “fast acting” components, those elements/parts are to be proportioned, and a fraction should be estimated as the (number of fact acting components) / (total number of components within the cabinet). The FAQ does not provide information on counting the number of components.

Although the intent of the FAQ approach was to eliminate those types of components that do not have long incipient stages; review the FEDB, inspection reports and licensee event reports (LERs); feedback received during site visits; and assess information from vendors (Ref. 20) it could not be confirmed that this approach adequately dispositions equipment that does not exhibit an incipient stage of sufficient duration to support enhanced suppression quantification.

Before the review of the EPRI Fire Events Database, the authors of this report were aware of at least two events that conflicted with the FAQ 08-0046 interim staff position with regard to the definition of fast acting components. The first event is documented in Inspection Report 05000348/364-11-012 and final significance determination process (SDP) (Refs. 38 and 39). In this fire event, the mis-wiring of the 1A reactor coolant pump oil lift pump pressure switch (cross-connection of 125 Vdc and 130 Vac circuit leads) caused a fire when the 1A RCP hand switch was taken to start. Within seconds of operating the hand switch a fire was observed. Given that the initiating component does not meet the definition of a fast-action component per the FAQ and was determined to be potentially challenging based on the SDP, an extended review of applicable operating experience was reviewed. The second event is documented in licensee event report (LER) 96-005-00, dated May 20, 1996. In this event, a turbine lockout relay failed when the turbine tripped on high vibration and resulted in a fire 3 minutes after the relay failure (Ref. 40).

Other examples that conflict with the FAQ position include FEDB FID #30276, #30338. In the first event, a malfunctioning charging circuit board caused a fire in a power transformer. The location of the fire was on the power transformer and not the charging board. In the second event, a panel blower (fan) failed because of accumulation of dust and dirt. The accumulation occurred over a long period of time and the panel blower did not fail abruptly, but over some period of time. During site visits (Section 3.1.1) an event was identified where VEWFD systems were installed where failure of an AHU fan motor was detected by the VEWFD system; operator actions were successful in responding to prevent a plant trip because of the unavailability of required equipment.

Review of the applicable operating experience indicates that it does not support the use of deterministic go/no-go criteria as presented in FAQ 08-0046. Although some of failure modes of the “fast-acting components” do not involve an incipient stage (i.e., locked rotor) using these deterministic criteria does not adequately represent the failure modes and associated length of the component degradation phase. In addition, review of the operating experience has

demonstrated that use of VEWFD system to protect power cabinets is applicable for Bin 15 type components as well as other types of components. However, the focus of this project is exclusively Bin 15 type equipment.

There may be cases where the use of VEWFD systems combined with appropriate operator actions may enhance the likelihood of preventing high-energy arc fault (HEAF) type events (Ref. 41). There are also cases where use of these systems has not prevented HEAF events (Ref. 42). Although the use of VEWFD systems to protect power distribution type equipment in combination with adequate and prompt operator response could help reduce the likelihood of HEAF (Bin 16) type event fires; it should not be considered a HEAF prevention system. Evaluating the risk benefit from the use of these systems with regard to HEAF events is outside the scope of this project.

7.2 System Performance Measures (Availability, Reliability, Effectiveness)

The next events quantified in the event trees represent the smoke detection system performance measures of availability, reliability, and effectiveness; system effectiveness (τ) is represented separately. The parameter "β" represents the availability and reliability of a smoke detection system to perform its intended design function. The success branch of "β" represents the smoke detector being both available and reliable, calculated as the arithmetic sum of these two estimates. The parameter "τ" represents the smoke detection system's effectiveness in detecting pre-flaming (incipient) phase conditions. The success in this branch represents that the smoke detection system has responded with an alert for the VEWFD system, or an alarm for the conventional system during the incipient stage. Other system effectiveness measures such as serviceability, maintainability, repairability, and operational readiness, although important to consider during system selection, are not useful measures when quantifying the system's ability to perform its intended function.

The availability and reliability of VEWFD systems are estimated generically below using information collected during site visits (Section 3.1.1), vendor supplied information and literature. The system effectiveness measure is also estimated below using available test data. In addition to the operating experience reported, vendor literature has identified that the following U.S. NPPs used ASD systems; Palo Verde, Calvert Cliffs, Nine Mile Point, Clinton Generation Station, Seabrook, and Ft. Calhoun. Availability estimates with higher certainty could be achieved if data from these sites could be collected and integrated into the assessment presented here. For air return applications, the unavailability and unreliability of the HVAC system must also be explained or justified.

7.2.1 Estimate of generic system unavailability

Availability is defined as the probability that a system is operating satisfactorily at any point in time and considers only operating time and downtime (Ref. 21). Availability is a measure of the ratio of the operating time of the system to the operating time plus downtime; its complement is referred to as unavailability. Unavailability can be estimated by:

$$U = \frac{t_d}{T_s}$$

Where t_d : system downtime for testing, preventative maintenance, and corrective maintenance

T_s : the surveillance test interval

Operating experience data collected from site visits shows that there is a large variation in system down time. The maximum likelihood estimate for an average annual system downtime is 14.7 hours (hrs)/year/device. This results in a generic unavailability estimate of $\underline{1.70\times10^{-3}}$.

For the air return application, the unavailability of the ventilation system should also be included since the function of the ASD system in this application relies on the operation of the ventilation system.

7.2.2 Estimate of unreliability

System reliability is the probability that an item (system) will perform its intended function for a specified interval under stated conditions (Ref. 43). Its complement is referred to as unreliability. The unreliability can be estimated by using the standby failure rate probability model. This model assumes that the detector transitions to the failed state while the system is in standby (i.e., period when no fire condition are present to detect). The transition to the failed state is also assumed to occur at a random time with a constant transition rate. The latent failed condition ensures that the detector will fail when it is next demanded, but the condition is not discovered until the next inspection, test, or actual demand. This model will be used to calculate smoke detector unreliability as:

$$\underline{R} = \frac{E(\lambda)T_s}{2}$$

Where $E(\lambda)$: expected failure rate (per hour)

T_s : the surveillance test interval

The expected failure rate is

$$E(\lambda) = \frac{k + 0.5}{T}$$

Where k : observed failures in T

T : total operating period (hours)

Several sources of information associated with ASD system reliability were identified. Each source is explored individually and a generic unreliability estimate is provided based on the average of the individual unreliability estimates.

<u>Germany NPPs</u>

Forell and Einarsson reported that three of the six German NPP units (2 PWR and 4 BWR) investigated for fire protection systems and component reliability data included data on the performance of ASD systems. Approximately 250 ASDs were included in the research, which identified 5 failures in 12.19 million operating hours (Ref. 25). This operating experience results in an expected failure rate of 4.5×10^{-7}/hr and an unreliability of 9.86×1010^{-4} based on a semi-annual surveillance.

Table 7-2. Information Gathered from Site Visits to Inform Availability and Reliability Estimates

Source	Technology (# Detectors)	Fire Events	System Failures	Total Operating Time (Years)	Down Time (hours)
TMI 1	Cloud Chamber (2)	2	PMT failure caused by improper maintenance	14.66 years per detector Total : 30 years	Maintenance 2-4hrs/qtr/device Trouble Alarms 4hrs/yr/device Hot work 20hrs/yr/device Total 12-20hrs/year/device
Robinson	Laser (1)	None	Power Supply 2002 (20day outage) Battery and Processor Replaced 2006 (27day outage)	Total : 17 years	Maintenance 24hrs/yr/device Trouble Alarms 2hrs/yr/device Total 26hrs/year
Harris	Cloud Chamber (10)	2	None identified	4 years per detector Total : 40 years	Maintenance 24hrs/yr/device Trouble Alarms 2hrs/yr/device Total 26hrs/year/device
Darlington	Laser (# not provided)	Machine belt smoke	None identified	8-9 years per detector	Maintenance Annual 1-2hrs/device
Pickering	Laser (# not provided)	Cork isolator overheating in air handling unit	None identified Nuisance Alarms Nitrogen Purging, Maintenance Activities	12 years per detector	No information provided
Bruce	Laser (24)	Incipient, source not identified before flaming fire conditions	None identified	19 years per detector Total : 456 years	Maintenance Annual:2-3hrs/device Quarterly:3 hrs/device Trouble Alarms 1-2hrs/yr/device Total 15-17hrs/yr/device
NASA	Laser (>100)	Circuit board failure, ShopVac, fire in lab space	Nuisance Alarms Ventilation Changes	>300 years	Maintenance 1-3 hrs/yr/device

U.S. NPPs

U.S. NPP unreliability estimates are based on information collected during the site visits and information obtained from the EPRI report 1016735. Information on 181 system years shows four system failures. This results in an expected failure rate of 2.84×10^{-6}/hr, and an unreliability of 6.22×10^{-3}.

ASD Vendors

Two of the ASD vendors provided or have available on their Web sites information on system reliability; one of whose unreliability estimates are based on the minimum acceptable reliability per the listing standard UL 268, namely;

Section 4.1 of UL 268 references a method for detector reliability prediction as follows (Ref. 44):

> The maximum failure rate for a detector unit shall be 4.0 failures per million hours as calculated by a full part stress analysis prediction as described in MIL-HDBK 217 or 3.5 failures per million hours as calculated by a simplified parts count reliability prediction as described in MIL-HDBK 217, or equivalent, see Annex D. A ″Ground Fixed″ (GF) environment is to be used for all calculations. When actual equivalent data is available from the manufacturer, it is permissible that it be used in lieu of the projected data for the purpose of determining reliability.

In addition, a component failure rate of not greater than 2.5 failures per million is referenced for light emitting diode (LED) type smoke detectors using a photocell-light assembly. The same component failure rate suggested for application specific integrated circuit (ASIC) employed in a smoke detector unit.

Vendor 1: a. Per UL268 simplified parts count reliability analysis
- 3.5 failures per million hours
- 4×10^{-6} mean
- Unreliability of 8.76×10^{-3}

b. Per UL268 full pats stress analysis
- 4 failures per million hours
- 4.5×10^{-6} mean
- Unreliability of 9.86×10^{-3}

Another vendor provided reliability estimates based on a Military Handbook method:

Vendor 2: Per MIL-HDBK-217 simplified parts count method
- Overall MTBF = 6.09×10^{6} hours
- Overall FITS = 164.149
- 2.46×10^{-7} mean
- Unreliability of 5.39×10^{-4}

The average vendor unreliability estimate is 6.4×10^{-3}

Based on the information collected from Germany and U.S. NPP operating experience along with the reliability estimates provide by the vendors (UL 268 or MIL-HDBK-217), the generic unreliability of $\underline{4.5\times10^{-3}}$ is estimated based on a semi-annual surveillance period and equal weighting of these four sources of data.

For the air return application the unreliability of the ventilation system should also be included since the function of the ASD system in this application relies upon the operation of the ventilation system.

7.2.3 Estimate of generic system ineffectiveness

System effectiveness is a measure of how well a design solution will perform or operate given anticipated operational scenarios (Ref. 19). Effectiveness estimates for ASD VEWFD systems expected to operate during the pre-flaming (incipient) phase are based on the test data collected from the experiments conducted in this program. As indicated above, the source materials are heated to a temperature that can support flaming conditions. The effectiveness differs between in-cabinet, and the two areawide configurations, primarily because of smoke dilution and stratification effects. The effectiveness of these systems is determined generically using data collected during the NIST experiments, which applied a "one-stage" bayes approach (Jeffery's non-informed). Only data from the 15, 60 and 240 minute HRP tests were used. Short tests such as resistor, capacitor, and shredded paper were not used.

Several different estimates of system in-effectiveness are developed to support quantification of the event tree parameter τ, as shown in Table 7-3. The specific datasets used to develop these estimates are identified in Table 7-4.

Table 7-3. ASD VEWFD System In-Effectiveness Estimates Based on Test Data

Application	Cabinet/Room Ventilation	Detector Type	Mean ($1-\tau$) [$5^{th}/95^{th}$ percentile]
In-Cabinet	Natural and Forced <100 cabinet ACH	ION Spot	**1.0E-01** [6.8E-02 / 1.4E-01]
		PHOTO Spot	**7.7E-01** [7.1E-01 / 8.3E-01]
		SS	**2.6E-01** [2.1E-01 / 3.2E-01]
		ASD CC	**2.7E-03** [1.1E-05 / 1.0E-02]
		ASD LS1	**5.3E-01** [4.5E-01 / 6.5E-01]
		ASD LS2	**1.9E-01** [1.4E-01 / 2.4E-01]
	Forced ≥100 cabinet ACH	ION Spot	**7.9E-01** [6.5E-01 / 9.0E-01]
		PHOTO Spot	No Data
		SS	No Data
		ASD CC	**1.9E-02** [7.8E-05 / 7.3E-02]
		ASD LS1	No Data
		ASD LS2	**3.7E-01** [2.2E-01 / 5.2E-01]
Areawide, Air Return Grill	HVAC in room	ASD CC	**3.0E-01** [1.7E-01 / 4.5E-01]
		ASD LS2	**5.2E-01** [3.6E-01 / 6.7E-01]

Table 7-3. ASD VEWFD System In-Effectiveness Estimates Based on Test Data (Continued)

Application	Cabinet/Room Ventilation	Detector Type	**Mean** (1-τ) [5^{th}/95^{th} percentile]
Areawide, Ceiling	Any	ION Spot	**8.1E-01** [7.3E-01 / 8.9E-01]
		PHOTO Spot	**8.7E-01** [8.0E-01 / 9.3E-01]
		SS	**5.7E-01** [4.7E-01 / 6.7E-01]
		ASD CC	**3.2E-01** [2.3E-01 / 4.2E-01]
		ASD LS2	**1.1E-01** [4.6E-02 / 1.8E-01]

Table 7-4. Identification of Datasets Used To Estimate the System In-Effectivness Estimates (See Table 7-3)

	In-Cabinet		Areawide	
	Natural and Forced <100 ACH	**Forced >100 ACH**	**Air Return Grille**	**Ceiling**
Laboratory Small				
ASD1 (LS1)	X			
ASD2 (CC)	X			
ASD3 (LS2)	X			
SS	X			
ION	X			
PHOTO	X			
Laboratory Large				
ASD1 (LS1)				
ASD2 (CC)	X	X		
ASD3 (LS2)	X	X		
SS	X			
ION	X	X		
PHOTO				
Full Scale, Small Room				
ASD1 (LS1)				X
ASD2 (CC)	X			X
ASD3 (LS2)	X			X
SS	X			X
ION	X			X
PHOTO	X			X

Table 7-4. Identification of Datasets Used To Estimate the System In-Effectivness Estimates (See Table 7-3)

	In-Cabinet		Areawide	
	Natural and Forced <100 ACH	**Forced >100 ACH**	**Air Return Grille**	**Ceiling**
Full Scale, Large Room				
ASD1 (LS1)	X			
ASD2 (CC)	X			
ASD3 (LS2)	X			
ASD4 (CC)	X		X	X
ASD5 (LS2)	X		X	X
SS	X			X
ION	X			X
PHOTO				X

8. TIMING ANALYSIS

To determine the likelihood of success in suppressing a fire, timing information needs to be provided such that operator failure rates and non-suppression probabilities can be estimated and used in the event tree. The timing information that is directly applicable includes the time frame that plant personnel have to respond to a smoke detection system alert, or alarm notification before commencement of flaming conditions. Figure 2-2 provides a conceptual illustration of the fire stages, showing the incipient, fire growth, steady state, and decay stages.

The flaming conditions' end point represents the demarcation between the event tree end states, "No Damage Beyond Initiating Component" and "Cabinet Damage." Cabinet damage in PRA terms refers to the point at which components other than the initiating component become damaged, or when suppression activities are initiated. This approach assumes that once flaming combustion commences, adjacent components to the initiating component are damaged. A more detailed fire modeling approach could potentially provide for an additional amount of time before other components within a cabinet being damaged, if initiating component growth profiles, peak heat release rates, and component physical layout information were known, along with the thermal failure threshold for the adjacent components. However, to model all of the ignition sources within a cabinet and evaluate the time delay in damage to adjacent components may provide too little additional benefit for the level of effort involved to be worthwhile.

In addition to estimating the duration of an incipient stage for an electrical panel fire scenario, the timing information of when the smoke detection system will respond with an alert or alarm must also be known, such that the time available for operator response can be estimated. Figure 8-1 presents timelines for the fire event for a generic fire scenario (top timeline), along with timelines for very early warning fire detection (VEWFD) and conventional spot-type smoke detection and operator response. Given the variability of the incipient stage duration, the start of flaming combustion could begin before or after the operator response event. The analysis assumes that since the fire probabilistic risk assessment (PRA) is quantifying the risk from p*otentially challenging or greater fires* that ignition can be expected to occur at some point if not prevented/hampered by plant personnel, per the definition of fires characterized by the fire ignition frequency.

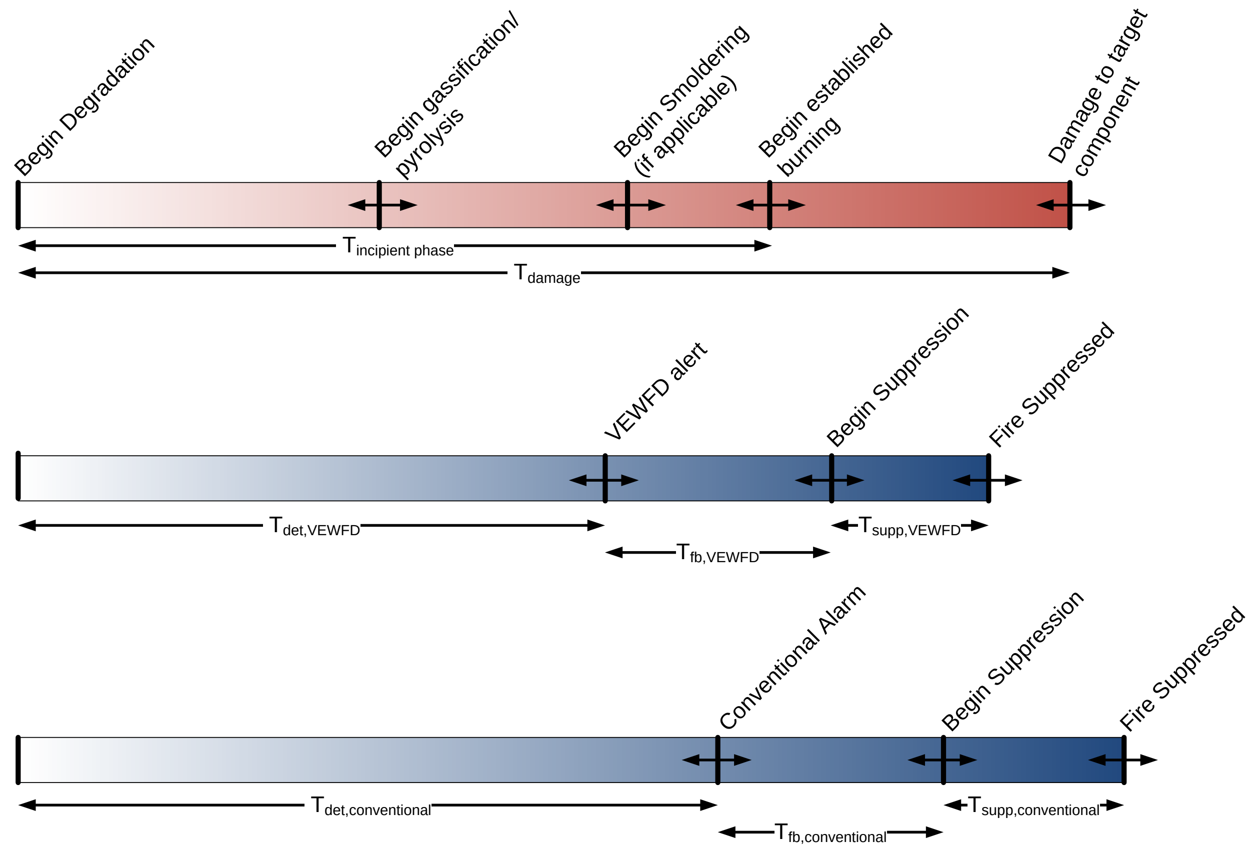


Figure 8-1. Generic fire scenario event timeline. Fire scenario progression (top), VEWFD/operator response (center), conventional smoke detection/operator response (bottom). Illustration only—event markers not indicative of actual system response

To estimate the time available for operators to respond (i.e., time between VEWFD alert or conventional alarm and flaming fire conditions), two approximations were actually needed:

- Timing of smoke detection systems response during an incipient fire phase
  - Results are presented in Section 8.1.1

- Estimate of incipient stage duration for electrical panel equipment
  - Results are presented in Section 8.1.2

At some point following flaming combustion, if the "fire" is not precluded from manifestation as such before the burning phase, the cabinet is damaged because of fire growth and if not successfully suppressed, the fire may develop such that targets external to the cabinet become damaged. Details on how to model the fire growth stages are not discussed here, however, the generic concepts will be highlighted as they relate to estimating the non-suppression probabilities.

The testing conducted as part of this program provides insights with regard to the amount of time available from the time a VEWFD system alert is received to the point where flaming combustion is assumed to occur (end of test). However, because the testing involved only three different incipient fire durations, the data must be normalized to some baseline that represents

typical incipient event duration for the types of components found in the plants which these systems are intended to protect. An analysis of available test data and operating experience are used to develop these estimates as presented below and in Appendix D.

8.1.1 Detector response time during the incipient stage

This subsection evaluates the performance of VEWFD system response with regard to the time of "alert" during an incipient stage. As discussed in Section 4, the copper block end point was 485 ˚C. This temperature is above the point in which piloted ignition of many polymer materials occurs (Ref. 34). Thus, the end of the test (including hold time) will be used as the point where the incipient stage ends. Figure 8-2 presents the test results showing the normalized time for in-cabinet VEWFD system response with an "alert." Statistical *K-S* tests were run between the groups and found to be poolable. The pooled dataset is shown as "All" in Figure 8-2 and has a median of 0.54 and mean of 0.56. These results support development of an estimate for operator response time availability as discussed in the next section. A similar approach is used for the conventional system evaluation. Those results are used in the following section.

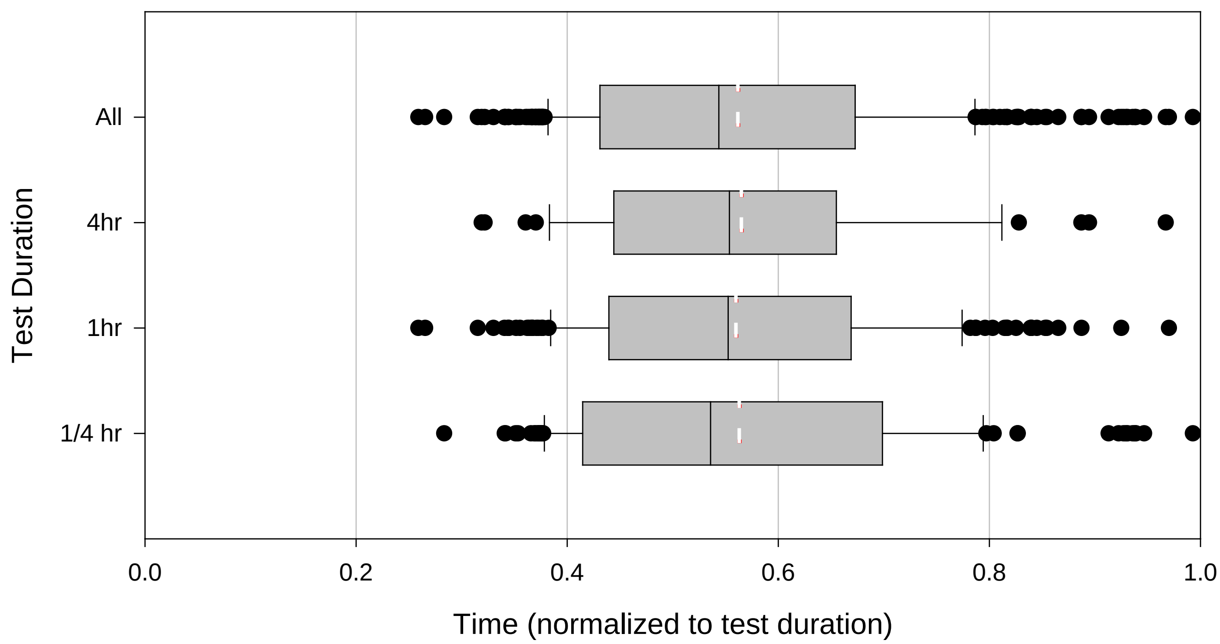


Figure 8-2. Summary of ASD VEWFD in-cabinet test results showing normalized time of alert (box and whisker plot shows 10th, 25th, 50th (median), 75th, and 90th percentiles with outliers shows as dots)

8.1.2 Estimating the duration of time available for operators to respond

The incipient stage was described previously in Section 2.1 as the preheating, gasification, and smoldering phases. Thus, the incipient stage includes everything from the start of component degradation up to ignition, which is the point of self-sustained flaming combustion.

The duration of an electrical component incipient stage may vary from less than a second to hours or days, and possibly even extended out to years; if age-related degradation mechanisms are considered as the fire initiator. With this variability it becomes difficult to quantify, with any

certainty, the phenomena that effect the duration of the incipient stage; this is primarily because of the sheer number of parameters affecting this data for many types of components, and the many failure modes that prevent development of a precise characterization of this phenomenon. This variability can be attributed to numerous factors, one being that, from a fire perspective, component degradation does not equate to a functional failure of a component or system; it is only (a breakdown) when the degradation progresses to a point where the thermal heat dissipation (development of a fire or flaming conditions) and combustion byproduct cause prompt or delayed component; or system functional failures. With no obvious failure, no action can be taken; no one attempts to fix things that he/she does not know are broken. Another related contributor is the lack of a detailed understanding of the failure mechanisms of electrical components, with regard to the duration of the incipient stage; further, and more importantly, there must be knowledge or understanding of the point during the incipient stage at which sufficient concentrations of products of combustion are available at the smoke detector to exceed a detector set point. The last point is particularly significant. In testing, a linear heating ramp was used as an approximation of the incipient stage; however, in reality, the smoke generation from degrading electrical equipment might not follow this approximation, but could potentially follow a logarithmic or, exponential growth profile, or anyone in between. Therefore, there is presently no agreed upon method to predict the time duration from when an electrical component begins to degrade, and degrading components show smoke characteristics, to when flaming combustion commences.

Although it can be said that most fires have an incipient stage, for a VEWFD system to be modeled in the event tree above, the duration of an incipient stage must be sufficient to allow the VEWFD system to respond to the products of combustion, *and* allow plant personnel sufficient time to locate and either (1) “preclude” the “fire” from ever manifesting itself by snuffing it out while still in the pre-fire stage (the “alpha” factor); or (2), if the “fire” cannot be precluded, then providing some additional time for suppression activity once the fire manifests itself (for the remaining [1-α] fires), translating into a reduction in the non-suppression probability. From a safety standpoint, use of smoke detection systems becomes increasingly beneficial, as additional time is available to respond to the particular event. Thus, the risk scoping study for ASD VEWFD systems hinges on being able to determine the time available for operators to respond to degrading conditions that have the potential to pose a *potentially challenging or greater fire* threat. For fires that have a short incipient stage, there may not be sufficient time for operators, technicians, or fire brigade to respond before fire damage occurring. For every scenario, the personnel response time will be different, as will the duration of the incipient stage. Thus, the variability of the response time and the incipient stage duration makes the quantification of a successful response both uncertain and difficult to estimate. In addition, although the incipient stage may last “x” minutes, the ASD VEWFD system (or spot-type detector) will not provide advanced warning of “x” minutes but rather some “x-y” minutes, with “y” not necessarily being less than “x”. That is, the VEWFD alert (spot-type alarm) threshold may not occur before the development of a flame or flaming conditions, in which case the only “benefit” may be additional time for suppression and a reduction in the non-suppression probability.

With the lack of available information and the importance of understanding the duration of an incipient stage, one approach could be to conduct a formal expert elicitation-type effort to develop a consensus opinion. Unfortunately, the efficacy for such an effort was not realized until late in this project, and as such, the needed resources, including budget and time, were not available. Consequently, in an attempt to estimate the necessary information, a detailed evaluation of the fire events database was conducted; the details of this research are

documented in Appendix D, identifying a limited number of cases to inform a duration estimate. (Ref. 45, 46).

For the fire PRA quantification to be of use, what is being quantified as an incipient stage must first be understood; then, using operational experience, test data, and judgment to develop an estimate of the amount of time available for operators to respond. Therefore, in developing a scenario that can quantify any potential risk enhancements from using these systems, several simplifying assumptions are required, and they are noted herein.

Assumption #1: Incipient duration information is collected only for fires that exhibit incipient stages of sufficient duration to allow for operator response before ignition.

> Because each specific plant scenario will differ in the determination of the time to damage and the specific target set, it would be unrealistic to use target damage as the end state of the incipient duration. This assumption is also consistent with the definition of the incipient stage provided in Section 2.1.

Assumption #2: Incipient duration information is collected only for electrical/electronic component failures which are contained within an electrical enclosure (cabinet).

> Interest in using ASD VEWFD systems in U.S. NPP applications has focused on electrical enclosure fires. In the EPRI/NRC-RES Fire PRA Methodology, 37 different generic fire frequency bins are identified. The fire frequency bin of most interest here is Bin 15, "Electrical Cabinet."

> Although other types of components found in an NPP can, and will exhibit an incipient stage of sufficient duration to allow enhanced suppression in applications in which VEWFD systems are able to detect the products of combustion early on, the need for such applications has not yet presented itself. However, a similar process could be followed to develop such estimates.

Assumption #3: Use the experimental test results based on a linear heating ramp to estimate the time available for operator response in instances in which the operating experience provides information of the incipient stage duration.

> In testing, a linear heating ramp was used as an approximation of the incipient stage. In reality, the smoke generation from degrading electrical equipment might not follow this approximation, but rather, could follow a logarithmic or exponential growth profile. Therefore, there is presently no agreed upon method to predict the time duration from when an electrical component begins to degrade, degrading component show smoke characteristics, and when flaming combustion commences. Thus, the use of the test data seems reasonable, but has inherent uncertainty associated with its ability to represent actual electrical equipment failure modes.

Appendix D provides a detailed description of the research undertaken to identify operating experience to support informing the duration of the available time for operator response. In addition, recent operating experience with VEWFD systems in NPPs has provided several data points on VEWFD system timing information. This information, along with the VEWFD system performance as presented above, allows for the development of a distribution representing the time available for operators to respond as shown in Figure 8-3. This time duration begins at VEWFD system "alert" or conventional system "alarm" notification, and ends at the fire flaming

stage. However, it should be understood that the process followed contributes its own uncertainties, which may not be adequately quantified to represent an informed technical community's beliefs. The authors of this report suggest that a formal process (such as an expert elicitation) be followed if better resolution of this quantification is needed. It is also suggested that any such effort employ experts knowledgeable in electrical component design and failure characteristics, such as individuals from vendors of the equipment being protected (i.e., relays, transformers, power distribution equipment, etc.) or from industries with extensive operating experience and components similar to those found in NPPs.

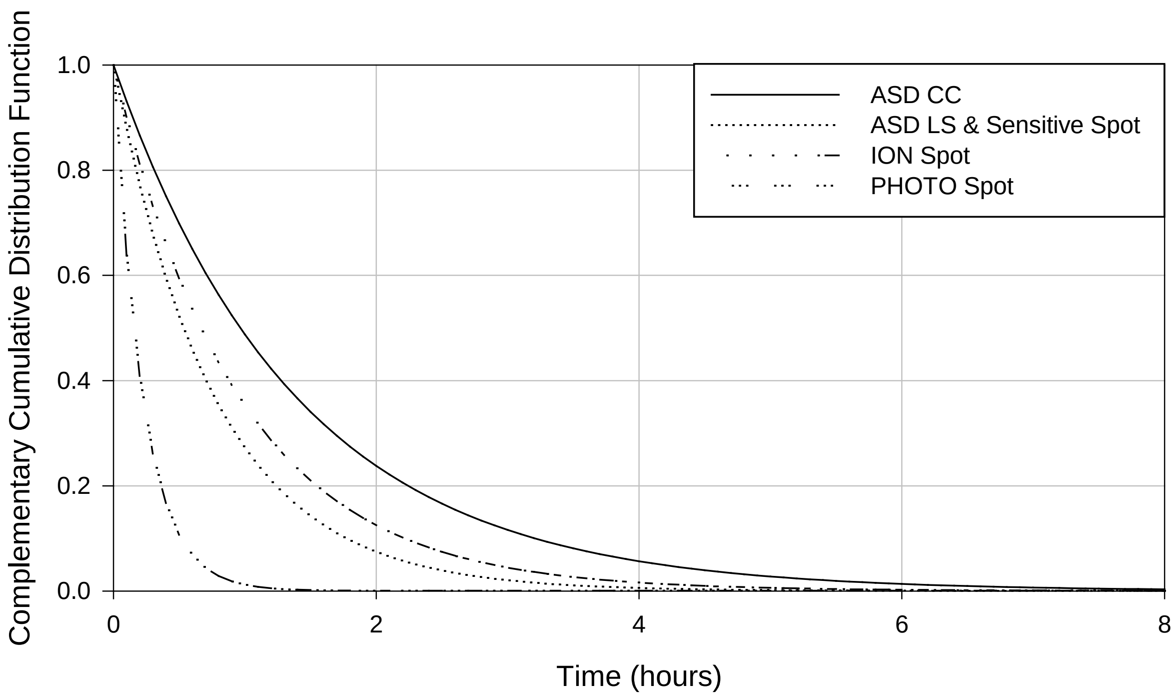


Figure 8-3. Distribution for duration of time available for plant personnel to respond to VEWFD system "alert" or conventional "alarm" notification of incipient fire conditions, for those fires, which exhibit an incipient stage for in-cabinet applications

Figure 8-3 illustrates the exponential distribution representing the duration of time available for operator response before the onset of flaming conditions. These distributions were developed using available operating experience and information from interim staff position (Ref. 1). Where operating experience provided the duration of the incipient stage, that time was adjusted by using the normalized mean response time for the smoke detection system in-cabinet response from the test results. That is, if the incipient duration lasted 60 minutes and the normalized mean detection time for detector X was 0.5, then the time available estimate for that event and detector is 30 minutes. Three events having incipient stage durations of 0.5, 0.9, and 7 hours, respectively, were identified from the fire events database. Each of these values involved cases in which timing information regarding system start or change of stage was documented, and ended when the potentially challenging or greater fire event was identified. Thus, it is assumed that the incipient stage started when the equipment was turned on, which may or may not be true, and therefore, these values could be shorter in duration. Two of the events identified were from recent operating experience in which ASD VEWFD systems were present. In both cases, the ASD VEWFD systems were located in equipment other than the initiating equipment; thus

these two values could be longer in duration. Since the VEWFD detection type was known (Cloud Chamber) the timing information from that event could be used directly for the cloud chamber estimate. However, those two events timing information was adjusted for the other detectors by using the normalized mean difference in performance. For instance, if a cloud chamber event provided for 60 minutes of advanced warning from the VEWFD “alert,” and detector X provided half of the advanced warning as the cloud chamber (based on normalized mean time to detection), then detector X would have allowed for 30 minutes of advanced warning for that event. The last estimate was from the interim staff position, and since this value was presented in both industry and NRC documents, it could be viewed as somewhat of a consensus opinion. However, neither the industry nor the NRC document provided any technical basis to support such an estimate. Review of operating experience has also demonstrated that these assumptions are not bounding. Since the interim staff position does not differentiate between detection technologies, the estimate is assumed to be applicable to all VEWFD systems.

These distributions are developed to support human error probability quantification (see Section 10.5) and to evaluate the varying performance of different smoke detectors, distributions for time available for ASD CC, ASD LS, SS, PHOTO and ION detectors. Appendix D.3 provides additional information on the events identified and the numerical estimates.

9. HUMAN FACTORS ANALYSIS

The objective of the human factors (HF) analysis was to identify personnel tasks involved in the planned response to aspirating smoke detection (ASD) very early warning fire detection (VEWFD) alerts and alarms; and factors that may adversely affect personnel task performance (e.g., insufficient training, poor alarm design) during response operations.

The way in which an ASD VEWFD system is implemented (e.g., planned response, system design, application) determines how humans will interact with the system and, ultimately, may affect whether prevention or prompt suppression is achieved. As such, variations in implementation of an ASD VEWFD system can impact the system's effectiveness in the amount of advanced warning. Thus, the results of the human factors analysis are used primarily as input to the detailed human reliability analysis and, consequently, the risk scoping study presented in this report (Section 12). However, the HF analysis also serves to inform designers, reviewers and users about potential factors related to the way in which ASD VEWFD systems are implemented, that may adversely affect human performance.

Few licensees have implemented ASD VEWFD systems within the context of quantifying system performance in a fire probabilistic risk assessment (PRA). Therefore, information is limited regarding system implementation practices and effectiveness; thus, this HF analysis should be considered an early analysis. To supplement our knowledge of ASD VEWFD systems, in addition to the U.S. nuclear industry, we studied non-U.S. NPPs and non-nuclear facilities using these systems. It is recommended that this analysis be updated as more information becomes available regarding the usage of ASD VEWFD systems in the U.S. nuclear industry.

9.1 Information Gathering

To support the HF analysis, information about ASD VEWFD systems was gathered using various methods. Information gathering activities were strategic or resourceful in nature and yielded qualitative data. The following activities were conducted:

1. Document Review:
   - o trip reports[14] from various facilities (nuclear and non-nuclear) currently using ASD VEWFD systems (trips are summarized in Section 3.1.1; See appendix C for detailed information) including:
     - 3 Canadian NPPs
     - NASA's Goddard Space Flight Center
     - 3 U.S. NPPs
   - o ASD VEWFD alert and alarm response procedures at two U.S. NPPs
   - o vendor documentation for special equipment (i.e., thermal imaging cameras and portable ASDs)

2. Expert consultation
   - o developed and administered a set of questions regarding ASD VEWFD response operations to: 1) personnel at a licensee intending to use ASD VEWFD systems

[14] The trips were conducted by the NRC team lead, Gabriel Taylor, and Tom Cleary from NIST. The HF and HRA NRC personnel (Amy D'Agostino and Susan Cooper) were not part of the team at this time and, thus, were not present during these trips.

to support its transition to NFPA 805 and 2) personnel at a licensee currently using ASD VEWFD to support an approved NFPA 805 transition (See Appendix C for questions and answers). One licensee provided written responses[15] and the other provided responses via teleconference. The following departments were represented on the teleconference[16]:

- fire protection
- licensing
- instrumentation and controls (I&C) maintenance
- systems engineering
- corporate
- operations (a senior reactor operator (SRO))

3. Site Visit:
   - o trip to a licensee currently using an ASD VEWFD system as a surrogate to a conventional spot-type smoke detector
     - plant tour focused on the ASD VEWFD system (e.g., ASD VEWFD alarm display in MCR, local fire alarm control panel)
     - discussions with personnel regarding system implementation and performance

9.2 Human Factors Analysis of VEWFD System Response Operations

This section describes a two-step HF analysis of ASD VEWFD alert/alarm response operations. The first step consisted of a tabletop analysis to identify the personnel tasks involved in the response operations, captured in Section 9.2.1. The second step was an evaluation to identify factors that may adversely affect task performance, captured in Section 9.2.2.

The HF analysis conducted was a generic analysis (i.e. not plant specific), which this was an intentional choice by the project team. As there is no standardized way in which licensees must implement these systems, a “generic analysis” allowed for exploration of various possible implementations, while concurrently developing an understanding of the fundamental tasks involved in response operations. The analysis identified the general structure of the human-system and human-human interactions that are, likely, common to all licensees during ASD VEWFD response operations. The analysis also highlighted variations in implementation (e.g., alarm location) that are a product of licensee-preferred practices. Variations are of interest because they can impact the efficacy of the human-machine system (i.e., interaction of detection system and personnel response), such that they can either facilitate or deter fire prevention or prompt suppression.

15 Positions and titles of the personnel that contributed to the written responses were not provided.

16 The staff members present for the teleconference were chosen by the licensee. The project team had no involvement in the selection process.

9.2.1 Step 1: Tabletop analysis

A tabletop task analysis is a technique that involves consulting with a group of experts who have an understanding of a system to define/assess particular aspects of that system. The discussions are typically directed around some basic framework (e.g., procedures). This technique can be used to "deepen task knowledge of a system …[It] can create (on-line) detailed task information and/or can analyze that information in a problem-solving and explanatory way." (Ref. 47)

A tabletop analysis was conducted on ASD VEWFD response operations, which rely solely on human response. Before consulting experts, the project team gathered information via document review (described in 9.1) to gain a basic understanding of ASD VEWFD response operations (e.g., necessary tasks/equipment/personnel). Experts were then asked targeted questions aimed at validating our understanding of response operations, gathering missing information, identifying gaps, and gaining a deeper understanding of specific aspects of response operations.

The scope[17] of the tabletop analysis was the personnel response to an ASD VEWFD alert followed by an alarm for an in-cabinet application. An alert occurs at 0.2 %/ft obscuration (effective sensitivity at each sampling port) and an alarm occurs at 1.0 %/ft obscuration (effective sensitivity at each sampling port). Plant personnel can take one of two strategies to respond to incipient fires, either a fire suppression strategy or a de-energizing strategy. A fire suppression strategy is one in which the end state is a posted fire watch at the affected cabinet and, thus, personnel are in position for prompt suppression. A de-energization strategy is one in which the end state is removing power from the affected cabinet (or part of the cabinet) and repairing the degraded component; this is a prevention strategy/approach.

The results of the tabletop analysis are depicted in Figure 9-1 and Figure 9-2. The figures are "generic" in the sense that they do not represent plant-specific response operations, but-, rather, depict an illustrative case. Figure 9-1 is a depiction of a fire suppression strategy and Figure 9-2 is a depiction of a de-energization strategy. Response operations primarily involve four types of personnel: 1) MCR operators 2) field operators 3) digital instrumentation and controls (DI&C) technicians and 4) fire brigade. MCR operators are responsible for detecting an alert, using the correct alarm response procedure (ARP), dispatching personnel to the fire location and, on alarm, activating the fire brigade. The field operator is responsible for serving as the initial fire watch (with suppression capabilities) and opening cabinets. The technician is responsible for gathering necessary equipment, traveling to the fire location, and using the equipment to find the incipient fire source. The fire brigade is responsible for suppression duties once they've arrived on the scene. Variations in system implementation and response operations that were observed during the information-gathering stage are noted by superscript letters in the figures and addressed further in Section 9.2.1.1.

[17] The scope of the analysis was determined by the information required to support the HRA (discussed in Section 10).

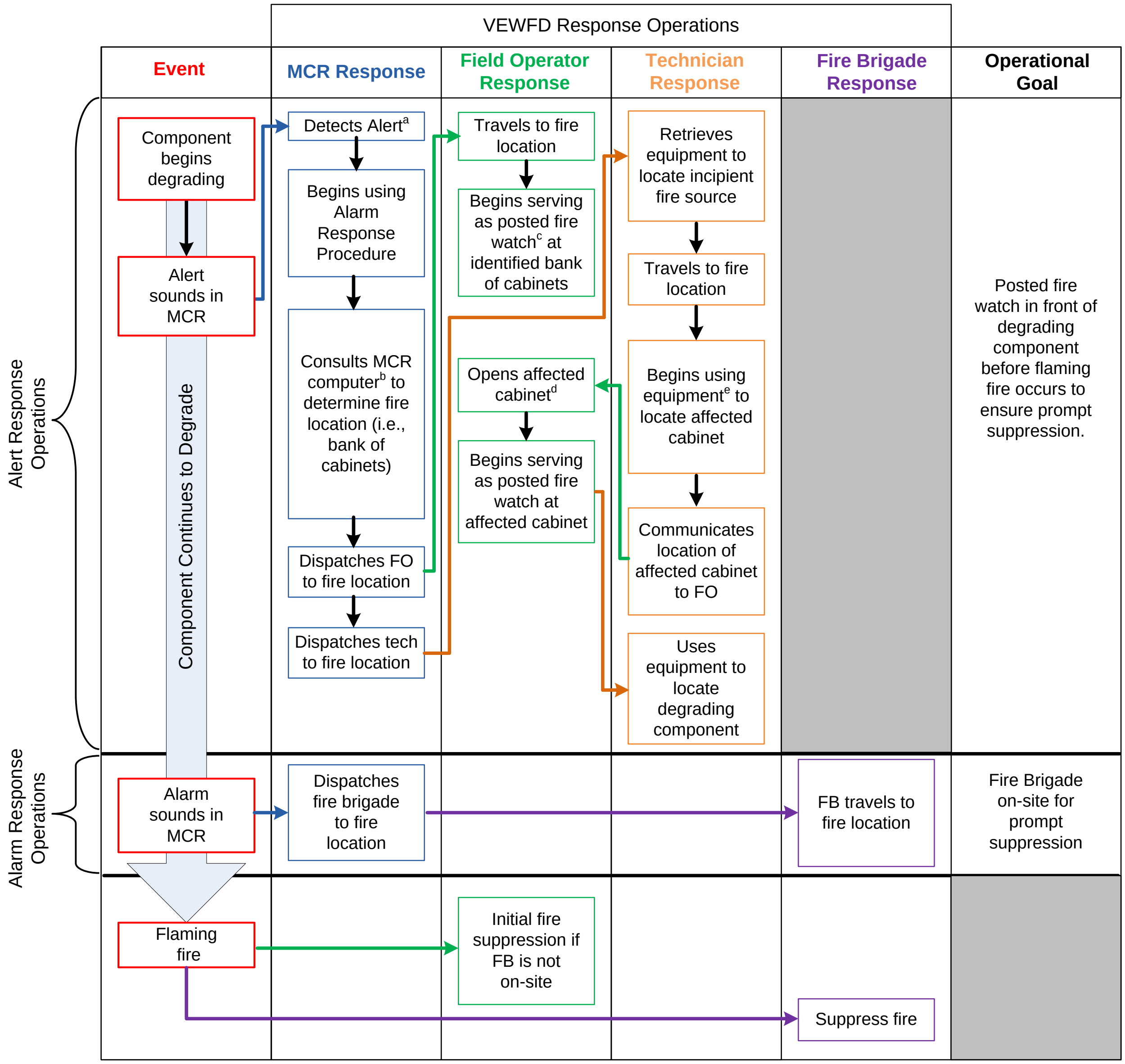


Figure 9-1. Generic depiction of operations in response to an in-cabinet ASD VEWFD alert followed by alarm where a suppression strategy is being used

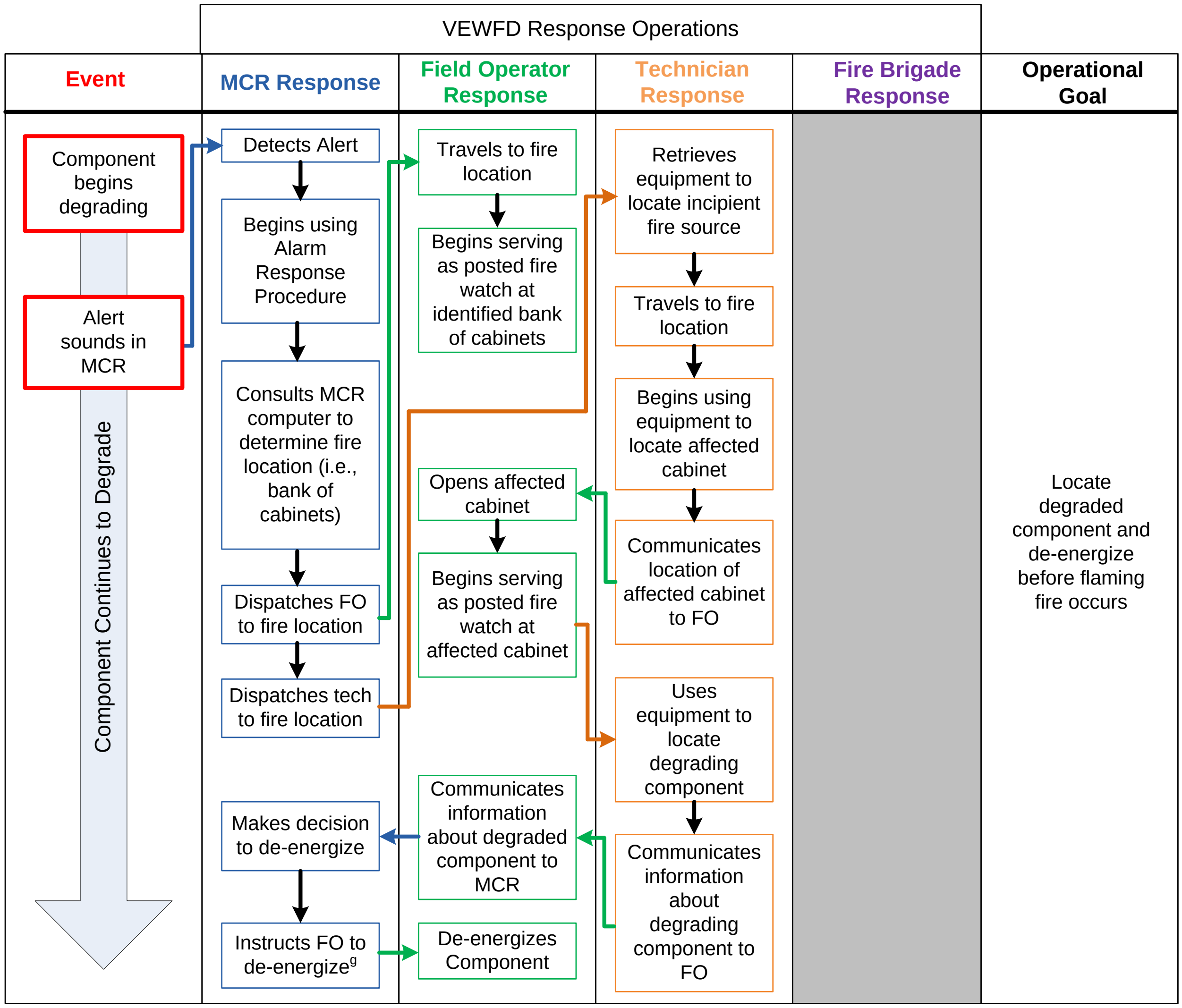


Figure 9-2. Generic depiction of operations in response to an in-cabinet ASD VEWFD alert followed by alarm where a de-energization strategy is being used

9.2.1.1 Variations in ASD VEWFD system implementation and response operations

Variations that were observed or discussed during the information-gathering stage and that were noted in Figure 9-1 and Figure 9-2 are addressed further here:

- Alarm location varies. There are licensees that located the ASD VEWFD alarm display on the front panel and others located it on a back panel. The implications of this variation are discussed in Section 9.2.2.2.

- Licensees differ with regard to how personnel retrieve information regarding fire location. At one licensee site, this information is provided via an MCR computer that indicates the fire location/bank of cabinets in an alarm (represented in Figures 9-1 and 9-2). Others require operators to consult a main fire alarm control panel in or near the MCR, which will indicate the room or area that is alarming; then, the field operator will check a local fire alarm control panel and/or a local ASD VEWFD detector to get more detailed location information (e.g., bank of cabinets). The more steps involved in determining the fire location, the longer the overall response will be delayed, which may decrease the probability of successful prevention or prompt suppression.

- The level and quality of training that fire-watch personnel receive varies. One licensee reported that fire-watch personnel are trained in basic fire suppression using a fire extinguisher and another reported that 95 percent of field operators are fire brigade trained. The implications of this variation are discussed in Section 9.2.2.4.

- Cabinets at some sites require keys to be opened. The implications of this variation are discussed further in Section 9.2.2.1.1.

- The type of equipment used to locate the degrading component varies. Some licensees use portable ASDs, and others use thermal imaging cameras. The impact of equipment type on response operations is discussed further in Sections 9.2.2.1.3 and 9.2.2.1.4.

- The personnel responsible (e.g., FO, MCR operator, another technician) for de-energizing equipment varies based on the type of components/equipment being de-energized. This variation may impact the necessary communications (e.g., the operators may have to dispatch personnel who are not currently at the fire location). This variation can affect the response timeline, and thus, impact the probability of successful response operations. For example, if the equipment can be de-energized from the MCR, this may shorten the timeline; however if other personnel have to be dispatched to the fire location, this can extend the timeline.

9.2.2 Step 2: Factors that Affect Human Performance

In this section, factors that may adversely affect human performance during ASD VEWFD response operations are identified and described. For each factor, there is a general discussion of the factor itself, the unique concerns regarding the factor's influence on ASD VEWFD response operations, and guidance and/or operational experience if relevant.

The factors include:

- special equipment
- human-system interface
- procedures
- training
- staffing
- communications
- complexity
- workload, pressure and stress

9.2.2.1 Special equipment

Special equipment is the unique equipment or tools needed to successfully carry-out human actions in a specified scenario or under certain conditions (e.g., fire, flooding) (Ref. 48). For VEWFD response operations, special equipment may include portable ASDs and/or thermal imaging cameras, keys and PPE. As noted in NUREG-1921, "EPRI/NRC-RES Fire Human Reliability Analysis Guidelines," special equipment must be readily available and functional, located in a known and designated area, and able to be located and accessed by plant personnel (Ref. 49). In addition, it is important that the equipment is used and maintained properly, so that staff may have confidence in the information it provides.

<u>9.2.2.1.1 Keys</u>

Keys may be required to access certain cabinets once the degrading component has been located. If all field operators do not routinely carry the keys to access locked cabinets, retrieving the keys will add time to the response operations timeline, and may decrease the probability of successful prevention or rapid suppression.

<u>9.2.2.1.2 Personal protective equipment</u>

Depending on the type of cabinet, personal protective equipment (PPE) may be required to open it. PPE may include protective clothing such as gloves, safety glasses, or other special purpose gear. The appropriate PPE will vary based on the cabinet's contents. PPE can have a significant effect on performance. For example, gloves may make manipulating portable ASDs/thermal imaging cameras more difficult, increasing the likelihood of errors or increasing the time required to complete the task.

<u>9.2.2.1.3 Portable ASDs</u>

Vendors of ASD systems market portable ASD equipment that can be used to help locate low energy pre-flaming fires. These systems are intended to help in cases in which the fire aerosol

signature is not producing visible smoke to aid the responding field operators in locating the fire source. These devices have the potential to locate the incipient fire before damage occurring to other equipment. However, there are certain aspects related to the use of these systems that affect their utility.

Differences in detection technologies (i.e., handheld and locally mounted ASD), should not be mixed. For instance, if an electrical cabinet is protected by a cloud chamber based ASD, a laser-based portable ASD is not suitable for use and vice-versa. This is because of the differences in these two technologies' ability to detect different fire aerosol signatures (i.e., a large number of small particles versus a small number of large particles). Therefore, there can be instances where a handheld light-scattering based detector may not be effective at locating a low energy fire source when a permanently mounted cloud chamber device is being used, and vice versa.

Maintenance and testing are important to ensure the operability of these handheld systems. The portable ASD systems are battery operated. Battery life typically varies from 2-3 hours. As such, the battery should be properly maintained to vendor recommendations to ensure that power is available when needed. Units based on cloud chamber technology require a suitable water source to function. Thus, the supply should be routinely inspected and maintained to ensure operability. Lastly, testing the units with the vendor-recommended frequency will ensure that they are functioning properly, or that malfunctions are discovered and repaired in a timely manner.

9.2.2.1.4 Thermal imaging cameras

A thermal imaging camera is a non-contact instrument which is able to quickly scan temperature distribution of entire surfaces of machinery and electrical equipment and detect infrared radiation (IR) emitted by objects. The amount of radiation emitted is dependent on the object's temperature and emissivity properties. Emissivity is the efficiency with which an object emits radiation and can range from 0 (not-emitting) to 1 (completely emitting). This is highly dependent on material properties and also varies with temperature. In order for the thermal imaging camera to read correct temperatures, emissivity must be taken into account. Most thermal imaging cameras allow for emissivity as an input and use an algorithm to calculate the temperature of a viewed object to most closely match the actual temperature. When using thermal imaging cameras to survey the internals of electrical cabinets, it is important to select an emissivity within an acceptable range.

The quality and effectiveness of thermal imaging cameras can vary with camera resolution, thermal sensitivity and camera accuracy. Equipment should be chosen that is appropriate for application in NPPs and is proven to be appropriately sensitive. Similar to portable ASDs, thermal imaging cameras require periodic calibration, maintenance, and testing to ensure that they are functioning properly.

When responding to a VEWFD "alert" or "alarm," the ability to use thermal imaging cameras to locate the incipient source will vary. If thermal imaging cameras are used in conjunction with portable ASDs, and a portable ASD is used to locate the affected cabinet, the thermal imaging camera may support locating degrading components. In this scenario, the cabinet configuration and thermal operating characteristics will affect the ability to locate the degrading component. For instance, if the camera's view is clear and unobstructed, the ability to locate degrading components should be enhanced. Conversely, if the cabinet has substantial partitions and obstructions which do not allow for a direct line of sight for the camera to sense

an object emitted IR, the thermal imaging camera is less effective; and consequently, locating the component may take substantially more time and the potential exists that the component may not be located before flaming conditions.

The use of thermal imaging cameras requires the user to process the viewed image. Thus, it may be beneficial to have accurate baseline images available and accessible. Baseline images are images taken when equipment is at normal operating temperatures. Baseline images serve as comparison data to assess whether or not acceptable temperatures have been surpassed, and are commonly used as a periodic surveillance tool. Depending on how thermal images must be processed, (e.g., operator compares current image to baseline, through the use of software that processes images, etc.), the timeline for incipient fire identification should be adjusted accordingly.

9.2.2.2 Human-system interface

A human-system interface (HSI) is the part of the system through which personnel interact to perform their functions and tasks. The availability, functionality, and usability of human-system interfaces can impact personnel performance. Guidance for the evaluation of HSIs is provided in NUREG-0700, Revision 2, "Human-System Interface Design Review Guidelines" (Ref. 50). HSIs that are poorly designed (e.g., poor labeling, subpar computer interfaces), have been damaged, or are difficult to use, can negatively impact performance. Also, if the HSI does not display required information, or if the information is inaccurate, performance can be adversely affected. HSIs involved in ASD VEWFD alarm response operations include MCR HSIs, portable equipment HSIs, and may include HSIs of local fire alarm control panels and local VEWFD detectors.

9.2.2.2.1 <u>MCR HSI</u>

The value of the ASD VEWFD system is in creating the opportunity for fire prevention or prompt suppression. As stated earlier, an effective response to a VEWFD signal relies on the actions of NPP personnel. Thus, ASD VEWFD MCR alarm displays are aspects of the MCR HSI that deserve consideration, as there can only be an effective operator response if the operator is aware there is a problem. Broadly defined, alarms are signals/warnings that inform personnel that a plant parameter, component, system, or function is currently in a state requiring the attention of plant personnel. Both ASD VEWFD alerts and alarms that require personnel to respond would fall under the broad definition of "alarm." This is pertinent because the subsequent information in this section will discuss "alarm" characteristics, which, in the current context, applies to both ASD VEWFD alerts and alarms that require personnel to respond.

As stated in NUREG-0700, Revision 2, "To be effective, an alarm system should attract attention and help the operator focus attention on more-important rather than less-important alarms." An alarm should be designed such that operators can reliably discern it. Alarms can be made discernible through aspects such as signal level, visual coding, visual intensity, and frequency of tonal signals. NUREG-0700, Revision 2, Section 4 provides detailed information for alarm system design.

With regard to ASD VEWFD, there are several aspects of alarm design that should be specifically noted:

- Signal level of alarms - NUREG-0700, Revision 2 states that the signal "should be such that users can reliably discern the signal above the ambient control room noise."

Specifically, it advises that a signal approximately 10 decibels (dB) above average ambient noise is adequate and that the sound intensity should be limited to a maximum of 95 decibels in most circumstances. NFPA 72, states that the combination of ambient noise and alarms “shall not exceed 110 dB at the minimum hearing distance” (Ref. 8). In NPPs, there are a multitude of alarms. Although NFPA 72 states that fire alarms shall not exceed 110 dB, caution should be taken to ensure that the ASD VEWFD alarms are not “drowning out” reactor alarms (Ref. 8). This is possible if the reactor alarms are set at 95 dB or less and the ASD VEWFD alarm at 110 dB.

- Alarm set-points - Nuisance alarms are alarms that have no operational significance to current plant conditions. One type of nuisance alarm occurs when alarm set-points are established so close to the normal operating value that many “false” alarms occur. If nuisance alarms occur frequently, operators may become less likely to respond. Operating experience indicates that VEWFD systems tend to alarm in response to maintenance activities (e.g., welding/grinding activities) and “dirty” environmental conditions (e.g., dust, charcoal in the air). Licensees have used several mitigating strategies to reduce the amount of false alarms including disabling the system and posting a fire watch during maintenance activities; and adjusting sensitivity settings that account for environmental conditions.

  Another variety of nuisance alarms is status indications or “messages that indicate the status of plant systems but are not intended to alert the user to the need to take action.” Status indications may increase the processing demand on operators and result in the operator being unsure when a response is required and/or delay operator response. ASD VEWFD systems offer users the capability to have multiple alert and alarm set-points. If used, those alerts and alarms with no associated operator actions are nuisance alarms. As suggested in Section 4.1.2-5 of NUREG-0700, Revision 2, status indications should be segregated from alarms and should be presented to operators via a non-alarm display unless there are unique aspects of the design that justify presenting the information within the alarm display.

- Alarm Location - According to NUREG-0700,Revision 2, Section 4.6-5, alarm displays and controls should be positioned such that responsible personnel can access the alarm information with adequate time to respond. For example, if the VEWFD alarm is located on the back panel in the MCR and only monitored periodically, it may take the MCR operators longer to detect the alarm than if it were on the front panel, thus reducing the time available to respond, and potentially decreasing the probability of fire prevention or prompt suppression. Through site visits and expert consultation, it was determined that there are licensee MCRs where the alarm is located on a front panel and others where it is located on a back panel.

9.2.2.2.2 <u>Local fire alarm control panels, local VEWFD detectors, and special equipment</u>

ASD VEWFD response operations require technicians to interact with HSIs of special equipment (portable ASDs/thermal imaging cameras) and may require field operators to interact with the HSIs of local fire alarm control panels and/or ASD VEWFD systems. As explained in NUREG-1921, MCR HSIs (including main fire alarm control panels) are subject to detailed control room design reviews (DCRDRs) which has led to modification or elimination of many problematic HSIs. However, local panels and special equipment have not received the same level of regulatory review. HSIs of local fire alarm control panels, local detectors and special

equipment deserve consideration with regard to their potential impact on VEWFD response operations.

Local fire alarm control panels and local detectors are akin to what NUREG/CR-6146, "Local Control Stations: Human Engineering Issues and Insights," refers to as local control stations (LCSs) (Ref. 51). LCSs are defined as "an operator interface related to process control that is not located in the main control room. This includes multifunction panels, as well as single-function LCSs, such as controls (e.g., valves, switches, and breakers) and displays (e.g., meters) that are operated or consulted during normal, abnormal, or emergency operations" (Ref. 50). Local fire alarm control panels and local VEWFD detectors are *displays* that are *consulted* during *abnormal operations*, thus, meeting the aforementioned definition.

In NUREG/CR-6146, the results of a study to evaluate human engineering of LCSs in the U.S. nuclear industry are captured. Approximately 3,000 LERs involving "poor ergonomics or human environment" were reviewed and in-plant assessments of LCSs were conducted. Several items of note resulted from this study: 1) many events were identified as having occurred as a result of a specific human interface deficiency, 2) human engineering deficiencies at LCSs are quite common across the industry and 3) human engineering deficiencies at LCSs can negatively affect plant operation. Interestingly, while reviewing the LERs, it was noted that nearly half of them involved equipment used for testing/calibration. Although testing/calibration equipment events were not of interest in the study, the information is relevant for VEWFD response operations. It suggests that special equipment HSIs may be less than ideal. Another complicating factor for both LCSs and special equipment may be that, as opposed to MCR HSIs that operators interact with frequently, personnel may rarely interact with LCSs and special equipment. They must take action in much less familiar surroundings, using equipment with less than ideal HSIs, potentially resulting in adverse effects on performance.

Project activities included one observation of a local fire alarm control panel and local VEWFD system. Both appeared to be located in a readily accessible area and had readable and understandable displays. Vendor documentation and videos were reviewed for thermal imaging cameras and portable ASDs; however, the images of the equipment were not clear enough to properly evaluate the quality of the HSIs. More research should be done to evaluate the quality of the thermal imaging camera/portable ASD HSIs, and to explore personnel usage difficulties.

As stated in NUREG/CR-6146, "Like the workstations in the control room, LCSs are interfaces between the operators and the plant, and the approach to their design should reflect the same human engineering considerations given to the main control room..." (Ref. 51). High-level guidance regarding design and evaluation of local control stations and portable diagnostic tools (e.g., portable ASDs) is provided in Sections 12.2 and 13.8.3.2 of NUREG-0700 Revision 2.

9.2.2.3 Procedures

Procedures or instructions for performing actions, can impact human performance negatively or positively depending on their availability, accessibility and quality. To create high-quality procedures, they should be developed using accepted human factors engineering principles. As stated in Section 9.2 of NUREG-0711, Revision 3, "Human Factors Engineering Program Review Model," procedures should be "technically accurate, comprehensive, explicit, easy to use, and validated" (Ref. 52).

Regarding ASD VEWFD response operations, MCR Alarm Response Procedures (ARPs) must be available and accessible to guide the human response to a MCR alert or alarm. Personnel should have immediate access to ARPs from the alarm location (Ref. 50). If procedures are not readily available or accessible, it may negatively impact performance by increasing the time to respond, thus decreasing the probability of fire prevention or prompt suppression.

Local actions (e.g., locating degrading components) are required in ASD VEWFD response operations. Typically, there are procedures available for local actions; however, some tasks may be considered “skill-of-the-craft”[18] and, thus, are not proceduralized. Project research did not yield information regarding the usage of procedures for local actions. If procedures are not used, a strong case must be made for labeling a task “skill-of-the-craft” to provide reasonable assurance of a safe operator response. Even when procedures do exist, it may not be practical to page through a procedure while performing a task. For example, if a technician is using a portable ASD to locate the degraded component, one hand would be used to hold the body of the device and the other would hold the probe, thus making paging through a procedure impractical. Thus, personnel must either be trained to perform the steps from memory or there must be a contingency plan for providing the procedural steps (e.g., via portable radio).

9.2.2.4 Training

Nuclear power plant personnel must receive training in accordance with current regulations. With regard to ASD VEWFD response operations, 10 CFR 50.120 applies to the non-licensed operators (FOs) and I &C technicians and10 CFR 55 applies to licensed operators. Both regulations identify a systems approach as acceptable methodology for training nuclear power plant personnel. A systems approach to training consists of the following five elements (10 CFR 55.4):

- systematic analysis of the jobs to be performed
- learning objectives derived from the analysis which describe desired performance after training
- training design and implementation based on the learning objectives
- evaluation of trainee mastery of the objectives during training
- evaluation and revision of the training based on the performance of trained personnel in the job setting

Ultimately, the training program must provide the instruction necessary to produce qualified personnel to operate and maintain the facility in a safe manner. In general, training should establish familiarity with procedures and operation of any special equipment; prepare personnel to handle departures from the expected sequence of events; and provide opportunities to practice the skills required to accomplish the task (Ref. 48).

Some of the training that may be necessary for ASD VEWFD response operations includes:

[18] “Skill of the craft” is a term describing those tasks in which it is assumed that the workers know certain aspects of the job and need no written instructions (NUREG/CR-1278) (Ref. U).

- training for MCR operators on ASD VEWFD ARPs
- training for FOs and technicians on any applicable procedures
- training for technicians on the operation of thermal imaging cameras and/or portable ASDs
- training for personnel who will serve as fire watch
- training for fire brigade personnel

Special equipment operation training may be especially important, as it is the key to locating the degrading component. Portable ASDs have, more often, been used in other domains (e.g., telecommunications); licensees should be cognizant that vendor training may have been developed with domains other than nuclear in mind. Nuclear power plants may introduce unique elements that warrant domain-specific training. Project research yielded limited information with respect to the U.S. nuclear industry's current approach to special equipment training. Personnel at one site receive initial training followed by retraining every 2 years for portable ASDs. The training has classroom and practical aspects and lasts approximately 4 hours. The practical section consists of simulating a situation in which technician has to find a degrading component by placing a "smoking" wire in a room beforehand that trainees must locate. Another site reported that, although training has not yet been implemented, they expect that all operators will have specific training in the use of portable ASDs, with a qualification sign-off, as part of their basic operator training

Training is also an important consideration with respect to fire-watch and fire-suppression activities. The level and quality of training that fire-watch personnel possess may vary. There may be cases in which posted personnel are not qualified to suppress the fire, as they have only been trained to detect visual signs of fire, and are required to report back to the MCR and wait for the fire brigade. In other cases, the personnel may be trained in basic fire suppression using a fire extinguisher or may have fire brigade level training[19]. If the fire watch personnel are not trained to suppress the fire and must wait for the fire brigade, this will extend the response timeline and may decrease the probability of prompt suppression.

One licensee reported that approximately 95 percent of its field operators are fire brigade qualified, FOs are qualified as incipient fire watch, and personnel receive refresher training yearly. Another licensee reported that all operators are trained in the proper use of fire extinguishers. It follows that more confidence can be placed in those with more extensive training to successfully suppress a fire.

9.2.2.5 Staffing

According to NUREG-0711, Revision 3, staffing levels are an important consideration when plant modifications are undertaken. Plant modifications can impact important human actions, thus, applicants should assess staffing needs to assure that required actions can be successfully accomplished. Applicants should determine the following needs: 1) the type of

[19] Fire brigade training acceptance criteria are laid out in the SRP section 13.2.2. Professional standards are further defined by NFPA 1081, "Standard for Industrial Fire Brigade Member Professional Qualifications."

staff (i.e., qualifications); 2) the number of staff and 3) the (required) availability of the staff. Information about regulations and guidance regarding staffing is provided in NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” Section 18 and NUREG-1764, “Guidance for the Review of Changes to Human Actions” (Refs. 53 and 54).

The installation of an ASD VEWFD system is a plant modification; thus, staffing needs should be assessed. ASD VEWFD response operations require both MCR and non-MCR staff. According to NUREG-1792, “Good Practices for Implementing Human Reliability Analysis (HRA),” “for control room actions, the availability of [MCR] staff is not a concern because plants are required to maintain a minimum crew with qualified staff in or near the control room” (Ref. 55). As a note of caution, applicants should ensure that MCR operators responsible for control room actions do not have collateral duties that would threaten their availability in the MCR. An operator who could be called upon to complete MCR actions should not, for example, also be a member of the Fire Brigade for the same fire.

Non-MCR staff including an FO for initial fire watch duties, a DI&C technician to locate the degraded component, and potentially, additional personnel for a long-term fire-watch, are also needed for ASD VEWFD response operations. According to the distribution presented in Section 8.1.2, Figure 8-3, the incipient stage duration distribution is not narrowly defined (i.e., ranges from four minutes to four hours). With a large amount of variability in the duration of the incipient stage, it is a reasonable conclusion that personnel involved in response operations need to be available on site to ensure a timely response. If a sufficient number of qualified personnel is not available, the planned response should not be considered feasible[20]. The information gained from trip reports and expert consultation indicated that FOs and technicians are available on site continuously. However, level of staffing may be of concern with regard to a long-term fire-watch. The time between an incipient alarm and flaming conditions may be an extended period of time (refer to Section 8 for timing estimates), hence necessitating that licensees have personnel available for an extended fire-watch. Depending on staffing levels, this may affect whether or not the fire watch is roaming or constant. A roaming watch is not desirable as it could extend the timeline for detecting and suppressing a fire.

9.2.2.6 Communications

Much of the communication during ASD VEWFD response operations takes place between the MCR and personnel outside the control room. The MCR must dispatch FOs, technicians and the fire brigade. This communication is critical as the success of the alarm response operations rests with the FO and technician arriving at the fire location and completing their tasks in a timely manner. Communications equipment must be available, accessible and functional to ensure communication can occur.

According to NUREG-0700, Revision 2, “Where communications are critical, users should not be precluded from communicating with other plant personnel by the loss of one method” (Ref. 50). A complement of communications equipment for this context might include phone lines, the intercom system, sound-powered phones and portable radios. Sound-powered telephone systems do not require a separate electrical power supply to transmit signals; the force of the user's speech on the mouthpiece generates small electrical impulses, which are transmitted as

[20] Feasibility is defined as the ability to accomplish a task in the context within which it will be performed and there is adequate time available to perform the action, considering any adverse contextual or personnel factors that may delay or degrade performance. (Ref. 45, 46)

a signal. They are beneficial for situations in which electricity is not available; however, it should be noted that training is required to operate them properly. Portable radio transceivers include battery-powered communication devices that transmit messages through the airways rather than through wires. However, there are places in the plant where radio usage is not permitted, thus, strengthening the case for having several diverse methods of communication. This complement to the communication equipment provides a variety of equipment that uses various media for communication, and is a good example of establishing diverse communication methods. Guidance for speech-based communications regarding topics such as sound quality and area coverage is provided in NUREG-0700, “Human-System Interface Design Review Guidelines,” Revision 2, Section 10.2.

9.2.2.7 Complexity

Complexity refers to the ambiguity and mental effort associated with the situation to be diagnosed, the decision to be made, or the action to be performed (Ref. 55). High levels of complexity, particularly in the absence of training and practice, can negatively impact human performance.

Sources of complexity that may affect task performance in VEWFD response operations include:

- ambiguity from difficult-to-interpret cues and indications
- the need to consider multiple variables simultaneously
- the need to perform many unfamiliar steps in rapid succession

The *indications* from portable ASDs and thermal images may be *ambiguous or difficult to interpret* because of the fact that, as stated previously, HSIs of special equipment often do not receive the same level of review as MCR HSIs. The equipment HSIs may be less than ideal, thus increasing the complexity of identifying the exact component that is degrading. Also, being *unfamiliar* with the necessary equipment and procedures/task steps can make the task more complex. If personnel use the portable equipment and perform the steps in VEWFD response operations rarely, this may result in a situation in which personnel are performing many *unfamiliar steps in rapid succession*. High-quality initial training and periodic refresher training along with well-designed procedures and equipment can help to mitigate complexity.

The decision to de-energize the affected cabinet may also be a complex task. There are *multiple variables* that personnel must take into consideration. First, personnel must have an understanding of the contents of a particular cabinet to determine the effect that de-energizing will have on the safe operation of the NPP. They must also consider the effort involved in the task of de-energizing. According to experts (see section 9.1), de-energizing equipment can be a very simple or a very involved and complex operation. For example, if an entire cabinet is being de-energized, there are instances in which it can be de-energized from the MCR within seconds. At one site, the logic for the cabinet power is laid out in MCR on control board, making the de-energization process simple. Alternatively, if only one breaker is being de-energized (partial cabinet), local action may be required, and the task would likely require multiple steps. This is an important consideration because if the process takes an extended amount of time, it may not be possible to complete it before the transition to a flaming fire. Personnel must weigh the benefits of de-energizing to preserve equipment with the ancillary effects on the rest of the plant. Some of the complexity associated with this task can be mitigated by pre-planning the steps needed to de-energize the cabinets. One strategy would be to “pre-locate” the isolation devices for all ignition sources within each cabinet in an effort to

speed up the process. This would include predetermining the isolation devices, conveniently displaying that information for use in response to VEWFD alerts, training responders to rapidly locate and operate the isolation device(s), and conducting drills to periodically demonstrate this ability.

9.2.2.8 Workload, pressure and stress

Workload, pressure and stress, collectively, refer to the extent to which personnel experience (time) pressure to perform an action, along with their overall sense of being threatened in some way with respect to accomplishing their task. The emphasis for this factor is on the amount of work that must be accomplished in the available time. If workload, pressure, and stress are too high, they may adversely impact personnel performance.

For ASD VEWFD response operations, it appears on the surface, that there would be little time pressure as this is *very early* warning fire detection. However, based on project research, personnel are trained to handle incipient alerts and alarms with urgency, such that they are to drop everything and respond. The value of these systems lies with the human reacting promptly to prevent a fire, or quickly suppress it. Thus, creating some time pressure is an important component of providing reasonable assurance of the feasibility and reliability of VEWFD response operations. However, while some time pressure may help provide a feasible reliable response, too much time pressure may result in degraded task performance (Ref. 56).

The fire itself can create time pressure because of the fact that the length of the incipient stage of a fire can vary widely (see Figure 8-3); thus, the time available for personnel to respond will also vary. It may be that being aware of the variability in the time available to respond, may alone, create pressure and stress for personnel. Assessing the time available is further complicated by the size of the zone in which the fire is located (e.g., 3 cabinets vs. 10 cabinets), such that larger zones will require more time to identify the degrading component, likely creating more workload pressure and stress.

Another source of stress during VEWFD response operations may be a concern for one's personal safety. If a VEWFD detector is being used for power distribution equipment, there is the potential for significant safety hazards (e.g., explosion upon opening a cabinet).

9.3 Areawide Applications

Areawide applications were not specifically addressed in the HF analysis. However, based on discussions with plant personnel, it is expected that the personnel response to an areawide incipient alert and alarm will be fundamentally the same as for in-cabinet applications. The only difference is that the FO and technician will be sent to a room rather than a bank of cabinets, after receipt of an "alert." The technician will need to locate the incipient fire source within that room. The larger area that must be surveyed should be accounted for in the timing analysis.

10. HUMAN RELIABILITY ANALYSIS

10.1 Human Reliability Analysis (HRA) Approach

The objective of this section is to develop an improved, detailed HRA quantification to support a fire PRA quantification of VEWFD system performance. To accomplish this objective, existing HRA approaches will be used to the extent applicable to this particular context.

First, the HRA process (i.e., steps needed to perform HRA) used in this report is based on existing HRA processes. The Joint EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (Ref. 49) and "A Technique for Human Event Analysis," (ATHEANA) (Refs. 57 and 58) describe two similar HRA processes. The HRA process given in NUREG-1921 is specific to a fire context. However, since the analysis in this report must address operator[21] actions taken before or without a reactor trip, the NUREG-1921 process is not general enough to adequately address this context. Therefore, the HRA process used in this analysis is a combination of those in NUREG-1921 and ATHEANA. Namely, the first two steps in ATHEANA are added to the NUREG-1921 HRA process. As a result, the HRA process used in this report consists of the following steps:

1. define and interpret the issue
2. define the scope of analysis
3. perform qualitative analysis
4. identify and define human failure events (HFEs)
5. perform quantitative analysis to develop the human error probability (HEP) for each HFE
6. perform dependency analysis
7. perform recovery analysis
8. perform uncertainty analysis
9. complete documentation

Second, as will be discussed further in Section 12.5, HRA quantification will be based on existing HRA methods and their associated HEPs.

Each of the HRA process steps is addressed in the sections below. There is no explicit discussion for documentation as this section represents the results of this step.

10.2 Define Issues and Scope to Be Addressed

The issue to be addressed in this study, as described in Section 1.3, is to provide HRA input (both qualitative and quantitative) to support fire PRA for VEWFD applications.

[21] For the application of incipient fire detectors discussed in this report, human actions and activities are required of: 1) MCR crew of operators and associated supervisor(s) 2) a field operator, 3) a technician (assumed to be an Instrument and Control technician), 4) the fire brigade, and 5) other plant personnel who may be needed for deenergization (e.g., electrical engineers, electricians). However, for simplicity, the authors describe the activities of all human activities (except the fire brigade) as "operator actions." Also, the failure probabilities associated with the fire brigade are quantified, as is described in NUREG/CR-6850 and elsewhere, using non-suppression curves that are supported by statistical data. The next section (i.e., Section 13) provides the quantification for suppression activities.

From the discussions in Section 9 regarding human factors analysis, it can be inferred that the HRA task for supporting fire PRA for VEWFD applications will be different from that in traditional HRA/PRA contexts.

Some of the key differences are as follows:

- **All operator actions are taken before (and, for success, without) a reactor trip, but do occur after a signal in the main control room (MCR).** HRA/PRA traditionally only addresses the time phase before reactor trip with operator actions that could result in system or component unavailability. Consequently, the type of operator actions associated with VEWFD installations has not been addressed in the development or application of previous PRA studies[22]. In addition, all of these actions are directed at prevention of a *potentially challenging or greater fire* (which would lead to a reactor trip). While all of the actions addressed in this report occur before (or even without) a reactor trip, in contrast, PRAs traditionally focus on operator actions in response to and after a reactor trip[23]. Some low power and shutdown (LP&S) PRAs include operator actions that cause reactor trips (i.e., human-induced initiators), but these actions also differ from the exact context of VEWFD applications in that they occur before or simultaneous with reactor trip (rather than after); and they do not have as their goal to prevent a reactor trip or other worsening condition.

- **There are no standard requirements for traditional job aids (e.g., procedures, training, human-machine interface) supporting the operator actions of interest.** While there are currently a few applications of VEWFD that are consistent with the objectives of this report, the operator response and supporting job aids have not been standardized either by regulation or common practice.

- **As discussed further in Section 10.5.1, the relevant success criteria, especially the time available after which operator actions are not helpful, have been difficult to establish.** Timing inputs are crucial to HRA. As discussed in NUREG-1921 (Ref. 49), for successful performance, there must be more time available for the action than the action requires; otherwise, the operator action is not feasible (i.e., guaranteed failure). Development of both time available and time required have been difficult in this analysis because of limited data.

- **In this analysis, a distribution for the time available for operator action has been developed, rather than a single data point. To address this distribution, the HRA has evaluated feasibility and quantified human failure probabilities for multiple times available, each of which can have a different associated success criterion**. As shown in the event tree for fire suppression strategy, in-cabinet installations (see Figure 6-4), there are two event tree headings following the two operator responses: 1)

[22] Initiating events for support system failures (e.g., loss of instrument air, loss of component cooling water) may involve control room alarms before reactor trip. However, as discussed later in this section, the time available for operator response to incipient fire detector alerts or alarms is limited, so operators must respond with some urgency. This is not typically the case for support system initiating events.

[23] Even those actions modeled in some fire PRAs that are preventive in nature, differ from those associated with incipient fire detector applications because, again, they occur following a reactor trip. Also, while some low power and shutdown (LP&S) PRAs include operator actions that cause reactor trips (i.e., human-induced initiators), these actions differ from the exact context of incipient fire detector applications in that: 1) they occur either before or simultaneously with reactor trip (rather than before) and 2) they do not have as their goal to prevent a reactor trip or other worsening condition.

enhanced suppression and 2) conventional detection/suppression. Also, each heading for suppression has multiple factors to be evaluated (e.g., π_1 and π_2 for enhanced suppression). As shown in Section 11, these factors are developed using non-suppression curves, with the associated timing inputs linked to the success (or failure) of field operator/technician response. Consequently, failure of the field operator/technician response essentially represents a failure to effectively use the "extra time" provided by the VEWFD system for fire suppression such that credit can be taken in the fire PRA.

These limitations indicate that a much more thorough qualitative HRA must be performed. In particular, the human factor analysis described in Section 9 is an important input to understanding the operational context (and potential variations with associated changes in human performance). For example, the tabletop analysis[24] (and associated Figure 9-1) described in Section 9.2.1 is an essential input to understanding what is required of operators and technicians to successfully implement VEWFD for fire PRA. In modern day, at-power, internal event Level 1 HRA/PRA studies, a formal task analysis is seldom required for any or all of the following reasons:

- Task analyses have already been performed in the development of the control room design and procedures (Ref. 59).
- Decades of simulator training and operating experience are available as inputs to the HRA analyst to understand the role and responsibilities of operators that are relevant to PRA.
- It is likely that a task analysis (probably something resembling a "cognitive task analysis") was performed as part of an earlier HRA/PRA study.

Overall, unlike the VEWFD application considered in this report, the HRA methods and approaches for addressing at-power, internal events Level 1 HRA/PRA are mature and supported with a wealth of relevant, realistic information.

Consequently, the development of an appropriate HRA approach for this study on VEWFD applications must recognize the following:

- There is no "standard" or requirement for how VEWFD is implemented (and, therefore, it resembles the equivalent of an "unconstrained, mathematical problem")
- There is very limited information on existing VEWFD applications in NPPs
- HRA results must support VEWFD applications, in general, rather than a plant-specific HRA of a VEWFD implementation (which is expected in HRA/PRAs that follow the ANS/ASME PRA Standard (Ref. 60))

[24] The "tabletop analysis" described in Section 9 is similar to a "task analysis" performed by HRA. However, "task analysis" is considered a more formal analysis by HF experts.

As a result, the HRA approach selected for this analysis relies on:

1. Whatever “real world” information is available, to the extent possible

2. Certain assumptions about performance shaping factors and other contextual factors that, based on current information and the human factors analysis in Section 9, would approximate:
   - a “best case” implementation of VEWFD
   - operator performance and response as modeled in at-power, internal events Level 1 HRA/PRA

In addition, this analysis, like the human factors discussion in Section 9, focuses on in-cabinet installations of VEWFD. Section 10.4 “Identification and Definition of HFEs” discusses the different types of installations and associated strategies for success.

10.3 Qualitative HRA

As is described in NUREG-1921 (Ref. 49), HRA qualitative analysis is a vital step in HRA that provides the foundation for all other HRA products (i.e., identified and defined human failure events, human error probabilities developed through application of HRA quantification tools). Also, qualitative HRA is performed throughout the analysis, ending only when final outcomes/output have been produced or claimed. Consequently, for this report, the qualitative analysis step is listed ahead of all other purely technical tasks.

As noted above, one of the ways that this analysis is different from other HRAs is that it has not been performed for a specific NPP installation of VEWFD. Without a plant-specific VEWFD installation and its associated alert/alarm designs; response procedures; operator and fire brigade training programs; control interfaces; conduct of operations (including protocols for communications); and other aspects of an NPP that are typically investigated in an HRA (through the collection and interpretation plant information, including a plant site visit), this analysis has taken the approach of making assumptions about such contextual elements for operator response, in place of the qualitative HRA traditionally performed.

The assumptions being used in place of the traditional qualitative HRA are that:

- To the extent possible, the data represent “real-world” information collected as part of this project, coupled with a general understanding of NPP operations and operators.

- The data is representative of a “good” or “best case” operational context for supporting successful and reliable operator performance for a VEWFD application.

- Based on the human factors analysis provided in Section 9 (especially, descriptions of contextual factors that either are licensing requirements or are common to the at-power internal events Level 1 PRA context).

- Based on the typical needs of HRA quantification tools.

The subsections below provide the assumptions for the MCR operator response and the responses of the field operator and technician at the plant location where a VEWFD system has detected a degrading component.

It should be noted that all of the assumptions below are intended to represent a fast response from both MCR operators, as well as from field operators and technicians. As discussed in Section 8.1.2, the currently available timing information indicates that the time available for operator response (see Figure 8-3) can be quite short (i.e., 10 minutes or less), especially when compared to timing information regarding the time required for combined operator response, both in control room and ex-control room (see Section 10.5.1). Consequently, the assumptions comprising the qualitative analysis below also attempt to capture those factors that support a relatively fast operator response.

10.3.1 Assumptions for MCR operator response

For the MCR operator response to in-cabinet installations of VEWFD, the following assumptions below are made, with the expectation that they collectively describe a “best case” context in which timely, successful, and reliable operator performance can be expected, and which closely resembles that for post-reactor trip MCR operator response for at-power, internal events Level 1 PRA:

- “MCR operator response” represents the collective effort of the MCR operating crew, including the understanding that:
    - once an VEWFD system alert/alarm occurs, response to the VEWFD system signal is the priority for all of the operating crew in the MCR
    - peer checking and other activities that support reliable response by the MCR operators are used
    - formal, 3-way communication protocols are used within the crew as an additional reliability measure to ensure accurate communication and to provide an additional avenue for peer checking
- VEWFD system alert/alarm control panel(s) is/are located in the MCR on the front panel (i.e., where operators are accustomed to seeing critical alarms).
- VEWFD system alert/alarm signals are audible, according to other MCR alarm standards (see Section 9.2.2.2).
- There is a main fire alarm control panel[25] in the MCR, providing MCR operators with quick and easy access to information on both the specific fire area or location of the VEWFD system zone in “alert” or “alarm” condition and the specific cabinet or bank of cabinets where the detector is installed.

[25] VEWFD system alarm control panels can be located in the MCR or in the plant. For one of the NPPs providing information for this project, a dedicated computer on the STA's desk provided all information collected by the VEWFD system. The authors have assumed an equivalent to this situation because: a) no additional time is required for a field operator to travel to a local fire alarm control panel and report back to the MCR, and b) the reliability of the MCR crew interpreting information from the main fire control alarm panel should be higher than that of a single field operator reading a local panel.

- Operators respond to VEWFD system alerts and alarms with urgency (that may be inconsistent with other alarms that occur during normal operating conditions). This sense of urgency is reinforced by training and procedures, and might be aided by distinguishing tape or other markings for VEWFD system alarm panels. In particular, MCR operators are trained to "**drop everything"** when a VEWFD system signals.[26]

- Along with the previous bullet, the number of VEWFD system alert/alarms that require such urgent response should be few as compared to other fire alarms, and measures should be taken to avoid confusion of such alerts/alarms with other alarms that do not require such urgency.

- Procedures (e.g., alarm response procedures (ARPs)) guide MCR response, including consultation of the main fire alarm control panel and calls to the field operators, technicians, and fire brigade. In addition, the instructions for VEWFD system response are formatted and worded consistently with other instructions given in the ARPs.

- MCR operators expeditiously dispatch the field operator closest to the detector in "alert," providing essential location information.[27]

- MCR operators use formal, three-way communication to describe the fire location to both the field operator and technician to minimize the likelihood of miscommunication. Three-way communication also can facilitate recoveries of miscommunication (e.g., repeat back from field operator while looking at the main fire alarm control panel can serve as a check, or other operators in the MCR who are also looking at the main fire alarm control panel can serve as an independent check).

- MCR operators expeditiously dispatch a technician trained in portable ASD use, providing essential location information.

- MCR operators expeditiously dispatch the fire brigade when the detector is in "alarm" state, providing essential location information.

- False alarms for the VEWFD system are minimal (e.g., through appropriate initial testing and appropriate set points), such that MCR operator response is not slowed or questioned to be correct.

- There is normal staffing, such that there is no shortage of manpower.

- Accessibility is not a concern (as the VEWFD system in "alert" or "alarm" is outside the MCR).

10.3.2 Assumptions for field operator response

For the field operator response, the following assumptions below are made, with the expectation that they collectively describe a context in which timely, successful, and reliable operator performance can be expected and which closely resembles that for post-reactor operator response outside the MCR for at-power, internal events Level 1 PRA:

---

[26] This specific response was provided by one of the licensees that provided input to this project.

[27] Again, this is consistent with information provided by one of the NPPs consulted in this project.

- The field operator closest to the fire location is dispatched by the MCR operator.[4]

- VEWFD system response is the highest priority job for the field operator (upon receiving dispatch from the MCR), such that no new activities will be started, and current, non-critical activities will be suspended.

- Formal three-way communication is used between the MCR operator and field operator so that the likelihood of miscommunication is very small.

- The field operator is trained to travel expeditiously to the low-energy (incipient) fire location.

- The field operator is trained to suppress fires (e.g., fire brigade training).

- Required equipment (e.g., portable fire extinguisher) is available and accessible.

- There is normal staffing, such that there is no shortage of manpower.

- Accessibility is not a concern (since the field operator is fire brigade-trained).

This last assumption is especially important. As discussed in Section 9.2.2.4, there are variations between plants on what, if any, fire training is provided to field operators. However, as will be discussed further in the context of the definition of a human failure event definition and associated success criteria, the time at which plant personnel having fire suppression capability arrive at the location of the VEWFD system in an “alert” or “alarm” will define operator “success” in the HRA/PRA quantification. Consistent with the general approach taken for this analysis, the “best case” (or case for which fire suppression capability arrives the fastest) is when field operators who may be dispatched have fire suppression training.

10.3.3 Assumptions for technician response

For the technician response, the following assumptions below are made, with the expectation that they collectively describe a context in which timely, successful, and reliable performance can be expected:

- Formal three-way communication is used between the MCR operator and technician so that the likelihood of miscommunication is very small.

- VEWFD system response is the highest priority job for the technician (upon receiving dispatch from the MCR); such that no new activities will be started, and current, non-critical activities will be suspended.

- The technician is trained to expeditiously collect necessary equipment and travel to the low-energy (incipient) fire location.

- Required equipment is available and accessible.

- The technician is adequately trained in using special equipment for identifying low-energy (incipient) fire conditions, including detection of both the relevant cabinet (if the

VEWFD installation is for a bank of cabinets) and the degrading component in the cabinet.

- There is normal staffing, such that there is no shortage of manpower.
- Accessibility is not a concern (since the field operator, who is fire brigade-trained, is responsible for operator response if the degraded conditions transition to a fire).

10.4 Identification and Definition of Human Failure Events (HFEs)

In traditional PRAs, operator actions that mitigate an accident or that worsen plant conditions should be considered for representation in PRA models as human failure events (HFEs). Consequently, this analysis considers only operator actions whose success would contribute to preventing a “fire,” as defined by a fire PRA and associated success criteria.

NUREG/CR-6850, Supplement 1 (Ref. 61) identified two event tree headings associated with human actions for determining fire PRA. While this earlier work was an important input to this report, human failure events (HFEs) are identified herein by using the more thorough analysis of human actions and associated performance provided by the human factors analysis discussed in Section 9. In particular, the overall tabletop task analysis discussion and Figure 9-1 and Figure 9-2 has been the basis for the identification and definition of HFEs. In addition, this project included extensive coordination between the HRA team and the event tree developers on the structure, headings and success criteria associated with the event trees shown in Section 6.4.

In particular, three VEWFD installation types were identified as follows:

1. In-cabinet installations of VEWFD where the cabinet(s) are not targets of concern for the fire PRA (i.e., “success” for the operator action is achieved when a field operator (or other appropriately trained plant personnel) arrives at the fire location to provide suppression capability **before** conditions transition from a low-energy (incipient) fire condition to a flaming fire),

2. In-cabinet installations of VEWFD where the cabinet(s) **<u>IS</u>** a target of concern for the fire PRA, i.e.,

    a. “Success” can only be achieved by de-energizing the degraded component, thereby preventing transition to a fire **before** transition from a low-energy (incipient) fire condition to a flaming fire

    b. De-energization cannot occur until:

        i. an I&C technician (or other appropriately trained personnel) identifies both the affected cabinet and the specific degraded component,

        ii. MCR operators determine that the degraded component can be safely de-energized without reactor trip, and

        iii. Appropriate step-by-step instructions for de-energization are available.

3. Areawide installations of VEWFD (which, according to Section 9.3, are similar to the other installation types, but require additional time needed for the I&C technician to survey the entire room or fire area to identify the affected bank of cabinets or other equipment, especially since in-cabinet installations can be addressable (i.e., the specific alarming cabinet can be identified immediately if each cabinet is linked to its own detector).

Each of these installations will have different success criteria and, again, there will also be differences in the operator actions required. **The first type of installation is analyzed in detail in the remainder of the HRA discussion.** For the other two installations, only some HRA-related notes are provided (see Sections 10.5.4 and 10.5.5).

HRA tasks, including identification and definition of HFEs, and coordination with event tree development were iterative, rather than serial. However, for the purposes of this report, the success criteria used to identify and define HFEs, are presented first, immediately below, followed by discussions of the HFEs modeled in this analysis.

10.4.1 Success criteria for in-cabinet, fire suppression strategy

Success criteria must be defined for each event tree heading, including identified HFEs. These criteria are:

- **MCR response.** After the detector "alert" signals in the MCR, both the field operator and technician must be dispatched to the correct location for the VEWFD system in "alert" and this must be performed in a timely manner.

- **Field operator response.** Once the detector "alert" signals, this must result in the field operator 1) arriving at the correct location for the VEWFD system in "alert," 2) having the ability to initiate suppression in the absence of the fire brigade, and 3) positioning himself or herself, in a timely manner, in close proximity to the specific cabinet where a degrading component is located.

- **Technician response.** The technician must 1) arrive at the correct location for the VEWFD system in "alert" with the required equipment, and 2) correctly and timely identify the specific cabinet where the degraded component is located, for cases in which there is more than one cabinet associated with a detector. (Note that identification of the specific degrading component within a cabinet is not required for this strategy.)

Timing inputs are almost always an important part of the success criteria defined for each operator action. First, the operator actions must be feasible i.e., sufficient time available as defined in NUREG-1921). Second, shortness of time to complete actions also can influence the reliability (therefore, the failure probability) of operator actions. Usually, operator actions must be completed before a worsened state occurs (e.g., equipment or plant damage).

In this analysis, success is defined as the field operator arriving before the start of flaming conditions (or soon enough after that the fire can be controlled before targets outside of the cabinet are damaged). Section 11 defines several cases for such "enhanced fire suppression" (i.e., fire suppression sooner than would be possible using conventional fire alarms), each corresponding with different arrival times for the field operator and different states of knowledge

with respect to the location of signaling VEWFD system. Consequently, critical timing inputs for this analysis are as follows:

1. the total time available for operator actions measured as the time starting from the "alert" to when the incipient stage ends and a fire begins (as discussed in Section 8), and

2. the total time required to complete all operator actions, ending with the field operator positioned and ready to perform fire suppression activities.

Timing inputs are discussed further in the HRA quantification section (i.e., Section 10.5).

10.4.2 HFEs for "fire suppression" strategy, in-cabinet installations

The tabletop analysis provided in Section 9 describes in detail the operator and technician actions that could be performed to prevent an in-cabinet fire (per definition by the fire PRA). These actions are, in turn, aggregated or collected logically, then represented as human failure events (HFEs) and, for this analysis, shown as top events in event trees.

Specifically, the operator activities for the in-cabinet, fire suppression VEWFD strategy that are represented in event tree headings (see Section 6.4) are:

1. MCR operator response to VEWFD system signals

2. field operator and I&C technician response

3. fire suppression

    a. "Enhanced" fire suppression (for cases in which fire suppression capability is provided by the field operator (or other appropriately trained personnel) who is **already at the fire location when the transition from low-energy (incipient) fire to a flaming fire condition** occurs)

    b. Conventional fire suppression (e.g., MCR operator response to VEWFD system signal fails)

It is important to note that all of the suppression activities in the list above are not addressed explicitly by HRA and are quantified using non-suppression curves as described in Section 11. Further details on the definitions of these two HFEs are given below.

10.4.2.1 HFE definition: MCR operator response (in-cabinet, fire suppression strategy)

Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with VEWFD installations, and the assumptions made in Section 10.3, the following are the key events and responsibilities for the MCR operator once the VEWFD system signals "alert" in MCR:

1. VEWFD system signals “alert” in MCR

2. MCR operators immediately note “alert” and switch focus on this signal [28]

3. MCR operators find the appropriate alarm response procedure (ARP) for the VEWFD system “alert”

4. MCR operators consult main fire alarm control panel in MCR to identify which detector is signaling and the associated location, including specific cabinet or cabinet bank

5. MCR operators dispatch field operator[29] closest to the alerting detector, providing location information

6. MCR operators dispatch technician to alerting detector

7. when VEWFD system signals “alarm,” MCR operators activate the fire brigade

For the fire suppression strategy addressed in this report, the seventh item above is not relevant to the HRA.

10.4.2.2 HFE definition: Field operator and technician response (in-cabinet, fire suppression strategy)

Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with VEWFD installations, and the assumptions made in Section 10.3, the following are the key events and responsibilities for the field operator and technician response in the fire suppression strategy for in-cabinet VEWFD installations:

1. Upon dispatch, the field operator expeditiously travels to the fire location provided by the MCR operator.

2. Upon dispatch, the technician expeditiously collects required equipment and travels to the fire location provided by the MCR operator.

3. Upon arrival at the fire location, the field operator takes up the responsibility of fire watch (with suppression capability). If there is only one cabinet served by the VEWFD system, the field operator posts his watch directly in front of this cabinet.

4. Upon arrival at the fire location, the technician begins use of special equipment to identify the affected cabinet.

5. The technician identifies the affected cabinet.

For this HRA, there are multiple end states modeled and these distinctions are related to the field operators positioning with respect to the location of the degrading component and then which fire non-suppression curves are appropriate to use for each of these end states. Some of

[28] Recall that no PRA credit for VEWFD system installations if a reactor trip or other similar higher priority event has occurred.

[29] Field operator is assumed to have fire brigade training.

these end states are shown in Figure 6-4, while others are related to the distribution of times available from time of alert to flaming conditions (i.e., timing inputs discussed in Section 8). Consequently, both qualitative and quantitative HRA inputs are important to the next heading in event tree (i.e., for fire suppression).

For example, if the in-cabinet, VEWFD installation (fire suppression strategy) is for a single cabinet, the field operator can immediately position himself/herself optimally[30] for fire suppression without any input from the technician. The success of the field operator in this case transfers to the event tree heading of “enhanced fire suppression.”

If, on the other hand, the VEWFD installation is for a bank of cabinets, the field operator can be positioned to provide fire suppression capability, but cannot have the “optimal” position and knowledge with respect to the location of the degraded component until the technician identifies, first, the affected cabinet, and, then, the degraded component. This case also is treated as “enhanced fire suppression” but uses a different non-suppression curve.

Section 10.5, immediately below, discusses these end states further and Section 11 continues this discussion with respect to which non-suppression curves are appropriate.

10.5 HRA Quantification

Because HRA quantification methods and associated human error probabilities (HEPs) were principally developed by and for post-initiator operator response, the overall strategy for quantification of the operator actions in this report is to either describe or prescribe operational conditions for the low-energy (incipient) fire response actions that are similar or parallel to the more familiar post-initiator operator actions. Section 10.3 (HRA Qualitative Analysis) is the starting point for the assumptions that will be used in HRA quantification to follow this strategy.

10.5.1 Timing inputs to HRA

HRA typically relies on inputs developed by and for other PRA tasks. While this research does not involve a formal PRA study, it follows the traditional path in that several inputs to the HRA are developed by other analysts. In particular, HRA-specific timing inputs were developed from information collected through interviews of operations and fire protection personnel at NPPs that have installed VEWFD.

It should be noted that, to the extent possible, the NUREG-1921 (Ref. 49) guidance on the development of timing inputs and on feasibility assessment has been followed in this analysis. For example, a feasibility assessment of the HFEs in this study (especially considering whether there is sufficient time for operator response) is provided in Section 10.5.2. However, some of the NUREG-1921 guidance could not be followed because of the lack of information. As discussed below, the time required for field operator and technician response is based on information provided by only two licensees. Also, in both cases, the timing information provided was not based on walkdowns or demonstrations. In addition, the inputs provided for time required (see Appendix C) were ranges with some recognition of variability in these times. The HRA quantification below represents these variabilities, potentially resulting in higher HEPs that

[30] The only remaining distinction is whether the cabinet door is open or not. However, the best plan for field operator response would be for operators to know in advance (via procedures and/or training) if the cabinet can opened and, if it cannot be opened, how fire suppression is to be accomplished.

what a plant-specific HRA for might produce for a location-specific VEWFD installation with an associated narrower range of times required for operator actions.

10.5.1.1 Time required for operator actions

For this analysis, time required for operator actions is defined to be the time from when the "alert" is received in the MCR until all operator actions, both those in the MCR and those taken by the field operator and technician locally, are expected to be completed. The two most essential HRA timing inputs are discussed below: 1) time required for operator action and 2) time available for operator action.

The time required for each of the operator actions was developed from information collected through interviews of plant personnel at two NPPs having VEWFD installations. (See Appendix C for the details of these interviews.)

Table 10-1 below summarizes the HRA timing inputs developed. The ranges of times are either directly provided by plant personnel or are interpretations of more informal estimates (e.g., a "few" minutes can be translated into 3 or 4 minutes). Also, the durations of the field operator response and technician response shown in Table 10-1 represent the range of time estimates provided by both NPPs. For example, the duration of the field operator response (i.e., average time between when the field operator receives dispatch call to arrival at the appropriate location) was reported as 2 to 8 minutes for Plant X and 3 to 4 minutes for Plant Y, while Table 10-1 uses the broader range of times provided by Plant X for this analysis. Although the information sources for this timing data are limited, it was the only such information available when this analysis was performed. As noted above, a plant-specific and location-specific analysis might be able to produce a narrower range of times.

Cumulative times are total times from alert signal, with the travel times for the field operator and technician being independent timelines. So, the range for cumulative time for completion of the field operator response is determined by adding together the shortest duration times for both MCR operator response and field operator response (i.e., 1 minute for MCR operator dispatch of the field operator plus 1 minute for field operator travel to location) and adding together the longest duration times for both (i.e., 2 minutes for MCR operator dispatch plus 8 minutes for field operator travel time). Cumulative times for the technician are calculated in the same way, with the shortest MCR response being 2 minutes (i.e., dispatch of the technician is performed after the field operator is dispatched) and the shortest time for the technician to collect necessary equipment and travel to the location.

Table 10-1. Summary of Timing Inputs for Operator Actions After "Alert" Signal

Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Cumulative Time from "Alert" (minutes)
Alert signal	MCR operator	Detect signal, use alarm response procedures, identify location of detector, and call to dispatch field operator	1-2	1-2
Alert signal	MCR operator	Dispatch technician to detector location	1	2-3

Table 10-1. Summary of Timing Inputs for Operator Actions After "Alert" Signal (Continued)

Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Cumulative Time from "Alert" (minutes)
Call from MCR	Field operator in plant	Travel to location of VEWFD system in "alert": standby as fire watch by cabinet(s)	2-8	3-10
Call from MCR	Technician	Obtain necessary equipment and travel to location of VEWFD system in "alert"	5-11	7-14
Arrival at location	Technician	Uses equipment to identify cabinet[31]	1 cabinet: 0	7-14
			3 cabinets: 5	12-19
			6 cabinets: 10	17-24
			10 cabinets: 15	22-29
Cabinet identified	Technician	Uses equipment to identify degraded component in cabinet	3-4	1 cabinet: 10-18
				3 cabinets: 15-23
				6 cabinets: 20-28
				10 cabinets: 25-33

Note that from the discussion of success criteria in Section 10.4.1, "success" (i.e., the field operator is positioned to immediately start suppression activities for the affected cabinet) can be claimed for the following situations:

- single-cabinet installations, as soon as the field operator arrives at the fire location
- three-cabinet installations, also as soon as the field operator arrives at the fire location[32] (with potential arguments that the same non-suppression curve can be used as for the single cabinet case)
- six-cabinet installations, after the field operator arrives AND the technician spends up to approximately 25 minutes using a portable ASD to identify the affected cabinet
- 10-cabinet installations, after the field operator arrives AND the technician spends up to approximately 30 minutes using a portable ASD to identify the affected cabinet

In principle, the times by which the technician identifies the specific, degraded component within the affected cabinet could be used to represent a different "success" state (with correspondingly different non-suppression curves). However, as discussed in Section 11, this distinction is not used in this analysis; yet, this timing information is used to discuss the de-energization strategy in Section 10.5.4.

31 Estimated times are based on the use of the portable ASD without opening up the cabinet to determine which cabinet contains the degraded component.

32 This assumption can be made if the cabinets are not too large and the field operator is appropriately trained such that the field operator's field of vision can encompass three cabinets in essentially the same way as for a single cabinet.

10.5.1.2 Time available for operator actions for in-cabinet, fire suppression strategy

In this analysis, time available for operator action is defined as the time from when an “alert” signal from the VEWFD system is displayed in the MCR (i.e., when the cue for action is received) until the incipient stage ends (e.g., a flaming conditions begin).

As discussed in Section 8, there is limited appropriate data for the duration of the incipient stage, starting from “alert.” However, Figure 8-3 (and the associated raw data given in Appendix D), shows probability distributions developed to represent the duration of the time available from “alert” for four (4) fire detectors, including three (3) VEWFD systems and a conventional fire detector; respectively, they are:

- air-aspirated (cloud chamber)
- air-aspirated (light-scattering) and sensitive spot (light-scattering)
- spot detector (ionization)
- spot detector (photoelectric)

Typically, a single value for time duration is developed for defining success criteria. Also, usually when timing ranges or distributions are developed, the shape of the distribution resembles either a normal distribution, or another distribution with small “tails” at the low and high probability ends.

Based on the timing information developed in Section 8.1.2, neither of these typical conditions applies to this research. Nevertheless, since Section 8.1.2 represents the time available for operator actions as a probability distribution for each of the four detectors investigated in this study, as opposed to one or more point values, the HRA task must sample these distributions by selecting specific time points to perform the HRA quantification
For this analysis, the selection of time available points was driven by the need for the following:

- representation of the “most likely” situation with respect to duration of the time available for operator response following an VEWFD system “alert” signal

- representation of the situations in which all variations of in-cabinet, VEWFD installations are feasible (i.e., the time available is equal to or less than the total time required for all operator responses)

- representation of the median probability distribution and/or the approximately 1 hour time available duration (which represents more time available than time required for all cases of operator response)

Using both the time required information in Table 10-1 and the cumulative probability distributions, the following cases were chosen with respect to the duration of the time available (from “alert”):

- the time from “alert” that corresponds with a 90 percent likelihood that the transition to a fire has **NOT** occurred

- 30 minutes after “alert” (which, from Table 10-1) is approximately the maximum amount of time for the field operator to be positioned for immediate fire suppression

- 1 hour

The cumulative probability distributions for each of the four detectors investigated is shown in Figure 10-1 (These cumulative distributions are based on the same data and curves fit as the complimentary cumulative density functions are shown in Figure 8-3.) In addition, Appendix D provides minute-by-minute cumulative probabilities for each of the detectors. This information from Appendix D was used to information to develop Tables 10-2, 10-3, and 10-4 that display the fraction of the cumulative probability represented by each of these time points for the ASD VEWFD cloud chamber, ionization and VEWFD light-scattering (both ASD and SS) detectors, respectively. These fractions, in turn, can be are used as split fractions for the outcome of the HFE for “First Level Field Response.” In Section 10.5.3 and 10.5.4, human error probabilities are developed to be paired with each of these split fractions.

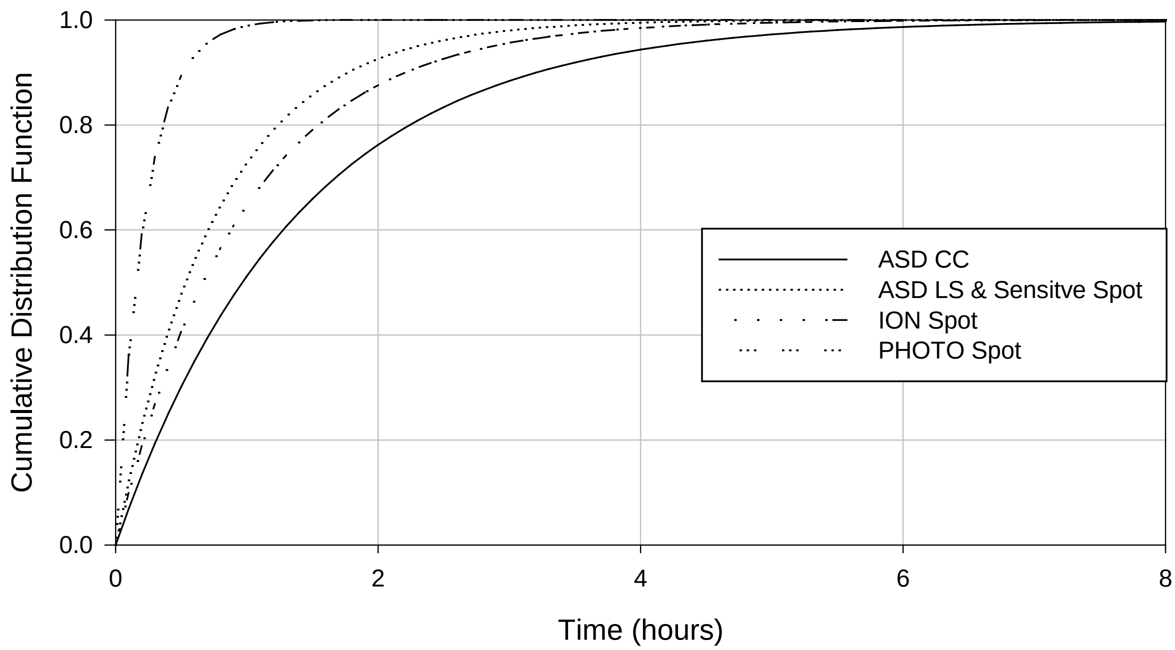


Figure 10-1. Cumulative distribution function of time available for operator response by detection type

The four sample points selected for this analysis are as follows:

- Sample 1: Incipient stage ends in only 10 percent of cases
- Sample 2: Incipient stage ends by 30 minutes after “alert” for VEWFD, “pre-alarm” for conventional ION
- Sample 3: Incipient stage ends after 30 minutes but before approximately1 hour
- Sample 4: Incipient stage ends after approximately1 hour

Note that, with these selections, the cumulative probability is fixed for one sample point (i.e., time available for operator response ends in 10 percent of cases) but the time from alert is not. All other sample points are associated with certain times and, therefore, the cumulative probabilities will be different for different detectors.

In the next section (Section 10.5), human error probabilities are developed for each of the four distribution sample points and their associated-split fractions.

Table 10-2. Fraction of Probability Distributions for ASD VEWFD, Cloud Chamber

Sample	Cumulative probability for incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-9 minutes*	0.10
2	0.30	>9 minutes AND <30 minutes**	0.20
3	0.51	> 30 minutes AND < ~1 hour**	0.21
4	1.0	> ~ 1 hour**	0.49

* From the text above, this is the definition of this sample point

** From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

Table 10-3. Fractions of Probability Distribution for Conventional Spot-Type, ION Detector

Branch	Cumulative probability for Incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-6 minutes*	0.10
2	0.41	> 6 minutes AND < 30 minutes**	0.31
3	0.65	> 30 minutes AND < ~1 hour**	0.24
4	1.0	> ~ 1 hour**	0.35

* From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

** From the text above, this is the definition of this sample point

Table 10-4. Fractions of Probability Distribution for VEWFD, Light-Scattering Detector

Branch	Cumulative probability for Incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-5 minutes*	0.10
2	0.48	> 5 minutes AND < 30 minutes**	0.38
3	0.73	> 30 minutes AND < ~1 hour**	0.25
4	1.0	> ~ 1 hour**	0.27

* From the text above, this is the result from the cumulative distribution function associated with the definition of this sample point

** From the text above, this is the definition of this sample point

10.5.2 Feasibility assessment

Section 4.3.4 of NUREG-1921 (Ref. 49), identifies the following criteria for determining the feasibility of an operator action:

- sufficient time
- sufficient manpower
- primary cues available and sufficient
- proceduralized and trained actions
- accessible location
- equipment and tools available and accessible

NUREG-1921 further states that if an operator action is not feasible, it should be assigned a failure probability of 1.0.

As a result of the assumptions made in Section 10.3, all of the above criteria are met for MCR operator response and field operator/technician response, **except** sufficient time.

To determine the feasibility of overall operator response to in-cabinet, VEWFD installations for the fire suppression strategy, the time required for operator actions shown in Table 10-1 must be compared with the time available shown in Tables 10-2, 10-3, and 10-4 for the different detectors.

From Table 10-1, the total time required for operator success (i.e., MCR operator and field operator/technician success) is different depending on the VEWFD installations with respect to the number of cabinet:

- For one cabinet, success is achieved when the field operator arrives on location: 3 to 10 minutes.

- For 3 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 3 cabinets contains the degraded component: 12 to 19 minutes.

- For 6 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 6 cabinets contains the degraded component: 17 to 24 minutes.

- For 10 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 10 cabinets contains the degraded component: 22 to 29 minutes.

These ranges for time required are compared to the available times (shown in Tables 10-2, 10-3 and 10-4) for each detector, with Sections 10.5.2.1, 10.5.2.2, 10.5.2.3, and 10.5.2.4 respectively, for each of the four sample points selected for this analysis, i.e.:

- Sample 1: Incipient stage ends in only 10 percent of cases
- Sample 2: Incipient stage ends by 30 minutes after “alert”

- Sample 3: Incipient stage ends after 30 minutes but before approximately1 hour

Sample 4: Incipient stage ends after approximately 1 hour

10.5.2.1 Sample 1: Feasibility assessment

As defined above, Sample Point 1 corresponds with those cases in which the cumulative probability distributions show that the likelihood of transition to fire conditions is 10 percent (or less).

For the cloud chamber detector, Table 10-2 shows that there are 9 minutes of time available when there is a 10 percent chance of the incipient phase ending. This time is approximately equal to the time required for the one cabinet VEWFD installation. Because, in this case, the longest time, in the range of required times, is only 1 minute greater than the time available. This represents the situation discussed in NUREG-1921 regarding "tipping points" (i.e., a significant change in HRA results with a small change in HRA inputs). Consequently, if this analysis supported a plant-specific HRA/PRA, the recommended approach would be to collect additional information on the time required (e.g., plant walkdowns or demonstrations) for a location-specific VEWFD installation, with the expectation that the range of required times and associated uncertainties would be reduced.[33] For the purposes of this analysis, the range of required times is treated as being equal to the time required; therefore, the operator actions are considered feasible for the cloud chamber, one-cabinet case.

For installations involving cloud chamber detectors and more than one cabinet, the time required for MCR response, field operator/technician response is greater than the time available. Consequently, these cases[34] are not feasible and should be assigned a failure probability of 1.0.

Tables 10-3 and 10-4 for conventional spot-type ION and VEWFD light-scattering detectors show that the time required for operator response is always greater than the time available for this sample point. Therefore, all of these cases for these two detectors are not feasible for this sample point and should be assigned a failure probability of 1.0.

10.5.2.2 Sample 2: Feasibility assessment

Sample Point 2 corresponds with cases in which the incipient stage ends sometime between when 10 percent of incipient stages end and 30 minutes. As discussed earlier, the "10 percent case" is different for each detector, namely:

- greater than 9 minutes to 30 minutes for ASD VEWFD cloud chamber
- greater than 6 minutes to 30 minutes for ION detectors
- greater than 5 minutes to 30 minutes for VEWFD light-scattering detectors

[33] Another way to reduce such uncertainties would be to establish a job performance measure (JPM) for these operator responses, especially that for the field operator.

[34] As is done later in Section 10.5, there might be legitimate arguments for treating the 3-cabinet and 1-cabinet cases in the same way so far as the time required for the field operator to be optimally positioned for fire suppression when the incipient phase ends.

Because the single-cabinet (and 3-cabinet), cloud chamber installation was feasible for the first sample point, this case also is feasible for this sample point (and all other sample points to follow).

For all other cabinet configurations of cloud chamber installations, the cloud chamber time available range for this sample point is considered to be roughly equivalent to the ION and VEWFD light-scattering detectors. So, for all detectors, comparison of the range of available times with overall operator response times shown in Table 10-1 reveals the following with respect to the "success" of operator actions (with the corresponding transfer to the "enhanced fire suppression" event tree heading):

- For shorter times required, operator actions associated with the single cabinet and three cabinet-per-bank installations are potentially feasible; however, since there is a relatively small amount of overlap of the range of available times with the range of time required, some adjustment to HEPs (e.g., multiplier of 3) would be appropriate
- The range of times required for operator actions associated with six cabinet-per-bank installations (i.e., 17 to 24 minutes) is entirely within the range of available time for this sample point; consequently, operator actions for this cabinet configuration are only marginally feasible
- Operator actions associated with 10 cabinet-per-bank installations are not likely to be feasible and should be assigned a failure probability of 1.0.

10.5.2.3 Sample 3: Feasibility assessment

Sample Point 3 corresponds with cases in which the incipient stage ends sometime between 30 minutes and 1 hour.

Comparison of this timing with overall operator response times shown in Table 10-1 reveals that operator actions for all installations should be feasible. For 1- and 3-cabinet installations, this represents expansive time available, compared to time required. Also, the HEP assignment for 10-cabinet-per -bank installation should be adjusted upward (as compared to the other cabinet-per-bank installations) since the longest required times are essentially equal to the shortest time available represented by this branch.

10.5.2.4 Sample 4: Feasibility assessment

Sample point 4 corresponds with cases in which the incipient stage ends sometime after 1 hour.

Comparison of this timing with the overall operator response times shown in Table 10-1 reveals that operator actions for all detectors and cabinet configurations considered in this analysis should be feasible. Furthermore, even for 10-cabinet-per-bank installations, the time available represented by this branch is, at least, twice as long as the longest required times for overall operator response

10.5.3 Basis for human error probabilities

Since the objective of the VEWFD installations for the scope of this analysis is to prevent a fire, by definition of a fire PRA, the context for operator response is very different than that traditionally modeled by HRA. Discussions given in Section 9 and earlier in this section have been aimed at describing such important differences.

However, since most HRA quantification methods, and their associated human error probabilities (HEPs), are intended for post-reactor trip response, the strategy for identifying appropriate HEPs for this fire prevention analysis using VEWFD installation is to: 1) identify or define similarities in the characteristics of the two contexts, and 2) use identified similarities in context to justify similar HEPs. In addition, the authors have chosen to analyze a "best case" set of conditions for HRA quantification, as illustrated below.

The HRA quantification approaches used in this comparison are not exhaustive. Methods included are:

1. technique for human error rate prediction (THERP) (Ref. 62)

2. EPRI's HRA Approach (Ref. 63), consisting of two methods addressing cognition:
    a. cause-based decision tree method (CBDTM)
    b. human cognitive reliability and operator reliability experiments (HCR/ORE) method

3. standardized plant analysis risk human reliability analysis (SPAR-H) (Ref. 64)

4. ATHEANA (Ref. 58)

10.5.3.1 HEP basis for MCR operator response (in-cabinet, fire suppression)

Combining and building on the descriptions of MCR operator response given in the success criteria and the HF analysis, respectively, the principal activities required for MCR operator response for the in-cabinet VEWFD installation and the suppression strategy are:

1. detection of the VEWFD system alert (and, later, alarm), and

2. use of alarm response procedures (ARPs) to:
    a. identify the fire location and cabinet bank for VEWFD system in "alert," and
    b. make phone calls to dispatch to fire location:
        i. first (on alert), a field operator
        ii. next (on alert), to an I&C technician
        iii. finally (on alarm), to the fire brigade response

In the context of post-reactor trip for at-power, internal events PRA, alarm detection and use of procedures to guide response are typical activities for MCR operator response. In general, these MCR operator activities comprise the cognitive (or diagnostic) portion of overall operator response. Communication between operators in the crew is most typical, but occasionally, emergency operating procedures (EOPs) will require MCR operators to make a phone call to a dispatch field operator. Explicit concerns for such communications to personnel outside the MCR have been more thoroughly considered in the context of fire PRA (e.g., NUREG-1921).

In the context of post-reactor trip MCR operator actions, there are many design requirements and associated guidance for supporting such MCR operator actions (as discussed in Section 9). This analysis assumes that these same requirements are used to support the pre-trip, "fire prevention" MCR operator responses. As a result, failure modes associated with diagnosis or cognition are expected to be the dominant contributor to these MCR operator activities.

THERP is not appropriate to use directly for this analysis (and, often, generally, for current NPP designs) because it does not explicitly address cognition or diagnosis as most modern HRA methods do; and it was developed before the Three Mile Island 2 accident (Ref. 59) and the ensuing upgrades to NPP control room designs, operating procedures, operator licensing and training programs. In addition, THERP's "annunciator response model" does not appropriately take into account the pattern-matching of annunciator tiles that modern NPP operators do when responding to an event. Human error probabilities for THERP's "annunciator response model" (shown in Table 20-23 of NUREG/CR-1278) range from 1×10^{-4} to 2.5×10^{-1}.

The EPRI HRA approach includes two quantification methods that address cognitive failures. EPRI HCR/ORE method is a time reliability correlation and typically used when available time is relatively short. However, the HCR/ORE method should not be used for operator actions that are extremely well-practiced or skill-based, such as manual reactor trip after trip signals and alarms are received. The qualitative analysis in Section 10.3 is intended to describe a similar operator response. Consequently, for this reason (and because of the HCR/ORE method provides little insight on the potential causes of operator failure), EPRI's CBDTM method is used to calculate the cognitive contribution to operator failure.

EPRI's CBDTM model consists of eight decision trees, four of which address failures in the plant information-operator interface and another four that address failures in operator-procedure interface. Both sets of these decision trees match well with the MCR operator actions described above. The contextual factors assumed in Section 10.3 (as they relate to the VEWFD system alarm in the MCR, the ARP used, the interface used to identify the fire and cabinet bank location, and the phone calls made to the FO, I&C technician, and brigade) are used to apply the CBDTM decision trees.

Table 10-5 summarizes these assessments and shows the resulting HEP assignments. For instance, EPRI's CBDTM assigns as "negligible" the contribution from all of the "data" decision trees, and all but one of the "procedure" decision trees. The results in Table 10-5 also show that the contribution from "procedures" for this HFE is the lowest possible HEP (i.e., 1E-3 in decision tree pc-e). If CBDTM recovery factors (e.g., self-recovery and other, or extra crew) are applied, this HEP can be reduced to an HEP in the 1×10^{-4} range.

A similar analysis using SPAR-H for at-power contexts and the assumptions in Section 10.3 would result in the following assessments:

- available time is nominal
- stress ot stressors is nominal
- with respect to complexity, it is an "obvious diagnosis" (i.e., better than nominal)
- experience and training are nominal
- procedures are diagnostic/symptom-oriented (i.e., better than nominal)
- ergonomics/HMI is good (i.e., better than nominal)
- fitness for duty is nominal
- work processes are good (i.e., better than nominal)

Using the worksheets in Appendix A of NUREG/CR-6883 with the information above, an HEP of $2{\times}10^{-4}$ is obtained.

Table 10-5. MCR Operator Response Assessed with EPRI's CBDTM HRA Method

Decision Tree Type	Decision Tree Branch	Decision Tree Branch Assessment	Associated HEP Assignment
Plant Information (regarding VEWFD system “alert” and “alarm”	Pc-a (Data not available)	• is available in the MCR • is accurate (e.g., no spurious signals or nuisance alarms) • is trained upon	negligible
	Pc-b (Data not attended to)	• occurs during low workload conditions • is a “check” (by virtue of this cue being an “alarm”) • is on the MCR front panel	negligible
	Pc-c (Data misread or miscommunicated)	• is easy to locate • is a “good” indicator with respect to HSI concerns • is communicated to the crew using formal, 3-way communications	negligible
	Pc-d (Information missing)	• cue is “as stated”	negligible
Procedure	Pc-e (Relevant step in procedure missed)	• is obvious (i.e., stand-alone step) • is the only guidance being used at this time (i.e., no other procedures or activities are in play) • is graphically distinct (e.g., typical HSI concerns with respect to procedure formatting have been addressed) • is followed using place keeping aids	1E-3
	Pc-f (Information misleading)	• uses standard, unambiguous wording • contains all required information	negligible
	Pc-g (Error in interpreting logic)	• does not contain “NOT” statements • does not contain “and” or “or” statements • does not contain both “and” and “or” statements	negligible
	Pc-h (Deliberate violation)	• is relevant for a practiced scenario • is appropriate to the situation	negligible

10.5.3.2 HEP basis for field operator and technician response (in-cabinet, fire suppression)

As has already been discussed, the principal activities for the field operator are as follows:

- take call from MCR operator
- travel to low-energy (incipient) fire location
- position in close proximity to the affected cabinet (with or without input from the technician following his/her use of a portable AS)
- stand at-ready for fire suppression[35]

These activities are similar to those which might be modeled for an ex-control room action modeled in an at-power, post-reactor trip Level 1 PRA, including some time urgency. However, typically, such field operator activities also would involve some sort of equipment manipulation. In this case, however, the only "execution" modeled for the field operator is the success or failure of fire suppression (which is addressed in Section 11 with the assignment of appropriate non-suppression curves). Therefore, the field operator activities modeled in this HRA represent only part of what is typically modeled in HRA/PRA. Consequently, only the general HEP guidance given in THERP or ATHEANA associated with "unlikely" or "very unlikely" failure probabilities (i.e., 1×10^{-2} or 1×10^{-3}, respectively) is appropriate.

Similarly, for the technician, the principal activities are:

- take call from MCR operator
- gather necessary equipment
- travel to low-energy (incipient) fire location
- use portable ASD to identify affected cabinet (only needed for installations involving more than three cabinets)

These activities are very different than those usually modeled in at-power, post-reactor trip Level 1 HRA/PRA. Instead, these activities are similar to those modeled with pre-initiator HFEs (e.g., test or maintenance activities), except these actions may be performed with some urgency, and there is no opportunity to verify the actions. Consequently, an HEP (more) typical of THERP or ASEP (Ref. 65) is the best fit (e.g., 1×10^{-3}).

10.5.4 Results: HFE quantification for in-cabinet, fire suppression strategy

This section presents the HRA quantification results for operator actions associated with the in-cabinet, VEWFD system installations (ASD VEWFD cloud chamber, conventional spot-type ionization, and VEWFD light-scattering detectors), using the fire suppression strategy.

HFE quantification results are obtained by using the following: 1) the assumptions discussed in HRA qualitative analysis section, Section 10.3, 2) the timing inputs discussed in Section 10.5.1, 3) the feasibility assessments in Section 10.5.2, and 4) the basis for HEPs discussed in Section 10.5.3.

[35] This analysis that plant staff fire suppression capability will need to be present until either the incipient stage ends or the degraded component and/or cabinet is de-energized.

Tables provided in this section summarize the HRA results developed with the following quantification steps:

1. Any cases where operator actions are not feasible are assigned a failure probability of 1.0.

2. Base HEPs are developed for HFEs representing both the MCR operator response and the field operator/technician response:

   a. For the HFE representing the MCR operator response, Section 10.5.4.2 discusses the development of the base HEP which is used in all cases (e.g., different durations of the time available for operator response)

   b. For the HFE representing the field operator/technician response, Section 10.5.4.3 discusses how base HEPs are developed for different sample points on the probability distributions for the time available for operator action following "alert." Differences between base HEPs for different times available is based on comparisons between the time required with times available.

3. For the HFE representing the field operator/technician response, the base HEP is multiplied by the associated split fraction for each sample point

4. The total HEP is determined as follows:

   a. For the HFE representing the MCR operator response, the total HEP is the same as the base HEP

   b. For the HFE representing the field operator/technician response, the total HEP equal to the sum of all sample point calculations of "Base HEP x Split Fraction"

Finally, the results for "total HEP" for each HFE (along with the results of Section 11) are used to quantify the event trees shown in Section 6.4. More detailed discussions of how these HEPs were developed are given in Sections 10.5.4.1 and 10.5.4.2 for MCR operator and field operator/technician HFEs, respectively. In addition, the feasibility assessments given in Section 10.5.2 provide the basis for assessing field operator/technician failure probabilities with respect the comparison of time required to time available, including considerations of HEP adjustments with multipliers to address interim cases.

Tables 10-6, 10-7, and 10-8, respectively, summarize the HRA quantification results for both HFEs, specifically for air-aspirated, cloud chamber detectors, configured for VEW, categorized into the following groups:

- 1 and 3 cabinet-per-bank installations
- 6-cabinet-per-bank installations
- 10-cabinet-per-bank installations

Table 10-6. HEPs for 1 and 3-Cabinet—ASD VEWFD Cloud Chamber Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1E-02	0.10	1E-03	1.2E-3**
	2	1E-03	0.20	2E-04	
	3	1E-04	0.21	2.1E-05	
	4	1E-04	0.49	4.9E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

** Only two significant digits shown for this calculated results.

Table 10-7. HEPs for 6-Cabinet – ASD VEWFD Cloud Chamber Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.1	0.12**
	2	0.1	0.20	2.0E-02	
	3	1E-02	0.21	2.1E-03	
	4	1E-04	0.49	4.9E-04	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

** Only two significant digits shown for this calculated results.

Table 10-8. HEPs for 10-Cabinet—ASD VEWFD Cloud Chamber Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.30**
	2	1.0	0.20	0.20	
	3	3E-02	0.21	6.3E-03	
	4	1E-04	0.49	4.9E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Similarly, Table 10-9 through 10-11, summarize the HRA quantification results for ionization detectors:

- one and three cabinet-per-bank installations
- six-cabinet-per-bank installations
- 10-cabinet-per-bank installations

Table 10-9. HEPs for 1 and 3-Cabinet - Ionization Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.11**
	2	3E-02	0.31	9.3E-03	
	3	1E-04	0.24	2.4E-05	
	4	1E-04	0.35	3.5E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Table 10-10. HEPs for 6-Cabinet - Ionization Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.13**
	2	0.1	0.31	3.1E-02	
	3	1E-02	0.24	2.4E-03	
	4	1E-04	0.35	3.5E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Table 10-11. HEPs for 10-Cabinet - Ionization Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.41**
	2	1.0	0.31	0.31	
	3	3E-02	0.24	7.7E-03	
	4	1E-04	0.35	3.5E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Finally, Tables 10-12 through 10-14, respectively, summarize the HRA quantification results for ASD VEWFD light-scattering detectors:

- one and three cabinet-per-bank installations
- six-cabinet-per-bank installations
- 10-cabinet-per-bank installations

Table 10-12. HEPs for 1 and 3-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.11**
	2	3E-02	0.38	1.1E-02	
	3	1E-04	0.25	2.5E-05	
	4	1E-04	0.27	2.7E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Table 10-13. HEPs for 6-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.1	0.14**
	2	0.1	0.38	3.8E-2	
	3	1E-2	0.25	2.5E-03	
	4	1E-04	0.27	2.7E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.
** Only two significant digits shown for this calculated results.

Table 10-14. HEPs for 10-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.48**
	2	1.0	0.38	0.38	
	3	3E-2	0.25	7.5E-3	
	4	1E-04	0.27	2.7E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

** Only two significant digits shown for this calculated results.

Many spot-type smoke detectors (initiating devices) are capable of being installed as addressable devices. That is, an addressable smoke detector and associated system can have a discrete identification allowing for the ability of its status to be identified. For in-cabinet applications, addressability can allow for the identification of the specific cabinet where an addressable detector is located and alarming. As shown above, having an addressable ION detector (for example), would allow the use Table 10-9 and a total HEP of 0.11. Whereas, if the ION detector were not addressable to the specific cabinet, but to the bank of ten cabinets, then the total HEP increase to approximately 0.41. Based on these estimate, the ability to use addressable detectors to identify the cabinet of concern reduces the HEP by a factor of 4. If the detection system only identifies the fire area or room, then an even higher HEP should be expected such as in the case of an areawide system.

A similar approach could be used for ASD VEWFD or spot-type VEWFD systems where an individual zone was associated with a single cabinet. The ability of a detection system to identify the cabinet or location where abnormal conditions exist, should result in a shorter time to locate the potential fire source and allow for the use of a reduced HEP compared to a system that is not addressable to a specific cabinet.

10.5.4.1 MCR operator response

The state-of-practice in HRA currently is to treat each HFE, and its associated operator actions, holistically, rather than analyzing a breakdown of the various subtasks and individual influencing factors then "adding them up." In particular, operator response in an existing U.S. NPP, in the MCR, following a reactor trip, and using the existing emergency operating procedures (EOPs), is understood to be supported by, for example (Note: this is not a complete or comprehensive list):

- a well-designed control room (including alarm panel placement and layout, clear indication of different trains, appropriate lighting and ventilation)

- effective training and certifications

- job aids (such as procedures that follow human factors guidance with respect to content, presentation and format)

- communication protocols

- a co-located crew and adequate and qualified staffing

- a strong safety culture

The combination of factors such as those given above may result in a certain expectation and reliability of operator performance. Because of differences between NPPs and even operator crews, there is no set combination of factors or features, or right or wrong implementation of job aids or designs except that they must be demonstrated (via operating experience, namely); each NPP's combination of job aids, influential factors and EOPs achieves the level of performance expected. If a plant design (e.g., size of steam generators) is such that faster response is required, then certain steps, training and procedures may be altered to compensate for or address this need.

Consequently, the “right” set of design features, job aids, and so forth cannot be definitively identified as it may come in a variety of forms. However, certain factors are expected to be important to successful operator response (since they underlie operator response for post-reactor trip events and using EOPs). For the purposes of this analysis, the assumptions described in Section 10.3 are taken to be adequate to describe a context in which the MCR operator response is similar to that for post-reactor trip response. Thus, under those conditions described and assumed above, MCR operators are expected to act quickly, and with a reliability consistent with alarm response and procedural use traditionally addressed by PRAs for post-initiator actions.

Overall, with the assumptions made, and the implication that MCR operator response for the fire suppression strategy of in-cabinet VEWFD installations, should mirror that for alarm response in HRA:

- Does not consider any failure modes associated with detection.

- Considers only two potential failure modes for situation assessment (which are delays in response and difficulties in identifying the specific cabinet(s) associated with the VEWFD system signal, which is expected to be manifested as a delay also).

- Does not consider any failure modes associated with response planning.

- Considers only delays as potential modes associated with execution.

Based on this discussion, an HEP for this HFE is justified in being similar to those HEPs developed in Section 10.4; namely, an HEP of 1×10^{-4} is assigned (which is independent of the number of cabinets per bank in the installation and type of VEWFD system) for failure of MCR response.

10.5.4.2 Field operator and technician response

The key to the success of this HFE is to locate the relevant cabinet so that the field operator can be positioned to immediately suppress the fire when it starts. Consequently, the field operator and technician are coupled in defining this HFE.

As summarized in the timing input tables and feasibility assessments (Sections 10.5.1and 10.5.2, respectively), the assignment of HEPs for the combined field operator and technician response is more complicated than that for the MCR operator response because of variations in HRA inputs, namely:

- different times required, as a function of the number of cabinets per bank in the VEWFD installation
- different “branches” that represent different times available (i.e., durations of the time available for operator response measured from “alert”), as a function of probability distributions
- feasibility assessments for each combination of timing inputs
- differences in the sensitivity of detectors

Using the base HEP of $1{\times}10^{-3}$ developed in Section 10.5.3, the following considerations were used to develop the HEPs shown in Tables 10-6, 10-7, and 10-8:

- If the overall operator response is not feasible, then an HEP of 1.0 is assigned.
- If the range of times available overlaps the entire range of times required, an HEP of 0.1 is assigned.
- If the time available is just adequate compared to the time required, an HEP of $1{\times}10^{-2}$ is assigned.
- If the time available is significantly more than that required (but not more than twice as much), then an HEP of $1{\times}10^{-3}$ is assigned.
- If the time available is more than twice that required, an HEP of $1{\times}10^{-4}$ is assigned.
- An HEP floor of $1{\times}10^{-4}$ is used.

For example:

- an HEP of 0.1 (i.e., marginal feasibility) is assigned to:
    - six-cabinet configurations for both ion and light-scattering detectors, Sample point #2 (i.e., time available ranges from 5 or 6 minutes to 30 minutes)
- an HEP of $1{\times}10^{-2}$ (corresponding with “just enough time”) is assigned to:

  - Sample point #1 for one- and three-cabinet configurations for cloud chamber detectors

  - Sample point #3 (i.e., time available 30 minutes to 1 hour) for six-cabinet configurations of all detectors

- an HEP of 1×10^{-3} (i.e., significantly more time available than required is assigned to:

  - Sample point #2 (i.e., time available from 9 to 30 minutes) for one- and three-cabinet configurations of cloud detectors

- an HEP of 1×10^{-4} (representing "expansive time") is assigned for:

  - Sample point #4 (i.e., time available greater than 1 hour), for all detectors and cabinet configurations

  - Sample point #3 (i.e., time available between 30 minutes and 1 hour) for all one- and three-cabinet configuration

In a few instances, an interim multiplier has been used because the range of times available completely engulfs with the range of times required (see, for example, the feasibility assessment discussion for sample point #2 (i.e., Section 10.5.2.2). In such cases, the otherwise applicable HEP is multiplied by a factor of three (3). For example, an HEP of 3×10^{-2} is assigned to:

- Sample point #2 (up to 30 minutes time available) for one- and three-cabinet configurations of ion and light-scattering detectors

- Sample point #3 (i.e., time available 30 minutes to 1 hour) for 10-cabinet configurations of all detectors

Also, the following cases are not feasible (i.e., HEP of 1.0):

- Sample point #1:
  - one- and three-cabinet configurations for ion and light-scattering detectors
  - six-cabinet configurations for all detectors
  - 10-cabinet configurations for all detectors

- Sample point #2, 10-cabinet configurations for all detectors

10.5.4.3 Exploration of a variation in HRA quantification

From the discussion above, it is apparent that the HRA quantification results for the HFE representing the field operator and technician response are extremely sensitive to the comparison between the time required for operator actions, and the time available from VEWFD system "alert" to when the incipient stage ends. For this reason, this section explores how a variation in HRA timing inputs would influence HRA quantification results.

For example, as shown in Table 10-1, the time required for the field operator to arrive at the location where the VEWFD system is in "alert" varies from 2 to 8 minutes. In addition, the answers to Question #14 in Section C.1.1 were:

- Plant X: varies but typically, 2 to 8 minutes
- Plant Y: 3 to 4 minutes

These variations in reported times could be explained by a variety of factors (principally related to the field operator travel time), including:

- plant-to-plant differences in layout of fire areas

- for a specific plant, differences in field operator travel times, depending on the specific location of the VEWFD system and where the field operator is located when the MCR operator calls

- lack of operational experience with this field operator action

The qualitative analysis chapter in NUREG-1921 (Ref. 49) provides guidance on the development of timing inputs for fire HRA, especially the discussions of sufficient time as a feasibility assessment criterion (see Section 4.3.4.1 in NUREG-1921) and of timing as a performance shaping factor (see Section 4.6.2 in NUREG-1921). This guidance, along with the possible explanations for variations given above, points to a corresponding selection of ways to explore variations in this timing input, such as:

1. The “Plant Y” data could be used as a plant-specific input (rather than a generic representation of this input), or

2. uncertainty in the estimate of this timing input could have been reduced by either: a) collecting a more robust set of operational experience that reduces such variations, or b) establishing a job performance measure for this field operator action (or, even better, for the integrated response of the MCR operators and the field operator) that requires operator performance to meet certain targets (usually time required for performance).

Despite uncertainties regarding the time required for field operator actions, this analysis explores the change in HRA quantification results if the time required for the field operator to arrive on location is assumed to be four minutes. Investigating a single-cabinet installation of an ION detector results in variations of time required (shown in Table 10-1 and Table 10-9) and HRA quantification results (shown in Tables 10-15 and 10-16, respectively).

Table 10-15. Variations in Timing Inputs for Field Operator Actions after "Alert" Signal

Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Time from "Alert" (minutes)
Alert signal	MCR operator	Detect signal, use alarm response procedures, identify location of detector, and call to dispatch field operator	1-2	1-2
Call from MCR	Field operator in plant	Travel to location of VEWFD system in "alert": standby as fire watch by cabinet(s)	4	5 - 6

The revised time of 5-6 minutes required for a single-cabinet installation is now equivalent to (or maybe slightly less than) the 6 minutes that represents the shortest time available of the samples points for the probability distribution. Consequently, using the same considerations for developing HEPs that are described in Section 10.5.4.2, the results for the revised base HEPs and total HEP are shown in Table 10-16 below.

Table 10-16. Variations on HEPs for Single-Cabinet—ION Detector

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response	N/A	1E-4	N/A	N/A	1E-4
Field operator & technician response	1	1E-02	0.10	1E-03	1.3E-3**
	2	1E-03	0.31	3.1E-04	
	3	1E-04	0.24	2.4E-05	
	4	1E-04	0.35	3.5E-05	

* The total HEP is the sum of each split fraction multiplied by the associated base HEP for the sample point.

** Only two significant digits shown for this calculated result.

10.5.5 HFE quantification notes for de-energization strategy

As described in the HF tabletop analysis (Section 9.2.1) and Section 10.4, in-cabinet installations of VEWFD that use a de-energization strategy will involve additional operator

actions and associated times (all of which must be performed before the incipient stage ends), such as:

1. The technician must identify the degraded component first.

2. The field operator must communicate to the MCR operators what component is degraded.

3. MCR operators must:
   a. Determine **if** the degraded component can be de-energized.
   b. Determine **how** (e.g., with what steps and by whom) the degraded component can be safely de-energized (and without reactor trip).

4. The degraded component must be de-energized by plant personnel, such as:
   a. Electrical engineers or electricians (who may assist in developing the de-energization strategy and in actually performing de-energization steps.

5. The field operator may assist in the de-energization.

Based on NPP interviews conducted for this project (see Appendix C), the complexity and associated amount of time needed to de-energize can vary widely (e.g., from minutes to a "research project" that takes days or more).

Similarly, the determination **of whether or not** a degraded component can be de-energized is not always straightforward.

Consequently, given the varying times available (including some very short times), it is recommended that pre-planning be done to:

- Identify which components within an in-cabinet, VEFWD installation **can** be de-energized .

- Distinguish the specific steps needed for de-energization, to the extent possible.

- Determine how much time is needed to de-energize, to the extent possible.

10.5.6 HFE quantification notes for areawide applications

HRA for areawide applications of VEWFD would be similar to that for the in-cabinet, de-energization strategy, except that even more time will be needed for field operator and technician actions. A value of 1.0 was used to represent the HEP failure based on area wide applications. That is, the timing information available for detecting fires before flaming conditions will vary widely on a room by room basis. To inform HEP's for area wide application analysts should perform timing feasibility studies which take into account room factors such as; area (i.e. size, ceiling height), contents of room (i.e. number of cabinets protected, alternative fire sources), accessibility of room (i.e. ease of movement within the room, security, locked doors, radiation areas etc.).

10.6 HRA Dependency and Recovery Analysis

Dependencies between HFEs addressed in this analysis have been treated directly through the event tree representation.

Self- or within-crew recoveries have been addressed in the development of base HEPs (see Section 10.5.3). Recoveries, as traditionally defined by PRA, are only addressed with respect to fire suppression capability (i.e., “enhanced” versus “conventional”).

10.7 HRA Uncertainty Analysis

The uncertainty analysis guidance provided in Section 6.3 of NUREG-1921 (Ref. 49) is appropriate for this study. However, because of the limitations in the information inputs for this project, new uncertainty sources could not be identified (and uncertainty sources identified in NUREG-1921 could not be proved as inapplicable).

11. FIRE SUPPRESSION

The objective of this section is to describe how the suppression events are modeled. Enhanced and conventional detection/suppression modeling is presented. The modeling of both events are adopted and modified as needed from the current suppression and detection analysis approach described in NUREG/CR-6850 and supplemental documents such as Supplement 1 and NUREG-2169. Reliance on current models allows for any future updates or advancements to be incorporated into this analysis. In other words, the suppression modeling presented in this section relies on current state-of-the-art methods and this dependence allows for the suppression portion of the event tree presented in Section 6.4 to be changed, as the state-of-the-art methods for suppression and detection analysis is advanced.

11.1 Enhanced Fire Suppression

Enhanced Fire Suppression is credited following the *success path* of the following branch points:

1. fraction of fires that have an incipient stage of sufficient duration (α)
2. very early warning fire detection (VEWFD) system availability, reliability, and effectiveness (β)
3. main control room (MCR) response (μ)

The "π" factor in the event tree represents the enhanced suppression probability. There are three cases for this factor which are dependent upon the success criteria provided in Section 10.4 for the "1st level field response (technician or field operator) fire watch posted (ξ)".

The "$1\text{-}\pi_1$" factor represents the probability that, given **success** of event ξ, the technician or field operator staged directly at the specific cabinet responsible for the VEWFDS alert, fails to promptly suppress the fire quickly enough to prevent damage to targets outside the initiating component. That is, the fire has progressed past the incipient stage and has begun to damage additional targets within the cabinet before the field operator and technician can take action to prevent failure or promptly suppress a fire, if flaming does occur. "$1\text{-}\pi_1$", the probability of "enhanced" non-suppression, may be set to 1×10^{-3}. This is considered to be reasonable given that a trained field operator will be stationed at the initiating cabinet with the suppression equipment in the event that open flaming does occur.

The "$1\text{-}\pi_2$" factor is applicable for the in-cabinet event tree and represents the probability that, given **failure** of event ξ, the technician or field operator in the area of the cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. This branch path takes into account that the field operator and technician have arrived at the bank of cabinets causing the VEWFDS alert, but were unable to locate the cabinet causing the VEWFD system "alert" before the incipient fire progressed to a flaming condition. The MCR curve (λ=0.324) should be used for this case. This is considered to be reasonable representation given that a trained responder will be near the bank of cabinets where the VEWFDS alert was initiated, actively searching for the source location of the alert.

The "$1\text{-}\pi_3$" factor is applicable for the areawide event tree and represents the probability that, given **failure** of event ξ, the technician/field operator in the room responsible for the VEWFDS

alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. This branch path takes into account that the field operator/technician has arrived at the room causing the VEWFDS alert, but was unable to locate the source of the condition causing the VEWFD system “alert” before the low-energy (incipient) fire progresses to a flaming condition. A newly developed non-suppression probability curve should be used with $\lambda = 0.194$. This value is based upon an analysis of fire events from the Updated Fire Events Database (Ref. 63). All fires in electrical cabinets were sampled for occurrences in which an operator was present in the room of origin when a flaming condition began. The approximation for the non-suppression value to be used was then evaluated against the MCR suppression curve. Differences between the MCR and newly developed curve were sufficient to warrant a new suppression curve for this application. This is considered to be reasonable representation given that a trained responder will be in the room where the VEWFDS alert was initiated, actively searching for the source location of the alert.

The probability that the fire brigade or other first responders will fail to suppress the fire [Pr(Tsupp ≥ t)] is estimated with suppression probability curves developed using the suppression time data reported in FEDB. In EPRI 3002001989 (NUREG-2169), new non-suppression probability estimates are provided. These new estimates are used in Section 12 “Illustrative examples.” These curves were developed using U.S. Fire Event Experience through 2009 where manual suppression was involved and suppression time information was available. Suppression time was defined as the time the fire was extinguished *or* the time the fire was reported to have been under control by the fire brigade on scene (Ref. 45). Events including self-extinguished fires, supervised burnouts, and fires extinguished with automatic fire suppression systems were excluded from the curves. If the time from detection to suppression was not known, but the duration of the fire event from start to suppression was known, then the reported fire duration was used instead.

The mathematical model to derive $\Pr(T_{supp} \geq t)$ is described in NUREG/CR-6850 as follows:

> *The data for analysis consists of reported fire durations in commercial U.S. NPPs. These times are treated as being generated by an underlying probabilistic model. The final output of interest is the suppression curve, which gives the probability that a fire lasts longer than a specified time. If T is the random variable describing when the fire is suppressed, and λ(t) is the rate at which the fire is suppressed (possibly time-dependent), this probability of non-suppression is given by:*
>
> $$\Pr(T > t) = e^{\left(-\int_0^t \lambda(s)ds\right)}$$
>
> *In this equation, λ(t) is a function of the parameters of the probabilistic model chosen for T. The simplest model for T is the exponential distribution, whose probability density function is:*
>
> $$f(t) = \lambda e^{-\lambda t}$$
>
> *In this model, λ is estimated directly and is not a function of time, giving*
>
> $$\Pr(T > t) = e^{-\lambda t}$$

The non-suppression probability is calculated using the above equation, usually selecting t as the time to target damage.

The same mathematical model was used to derive the non-suppression probability curve related to "1-π_3".

11.2 Conventional Fire Suppression

Conventional detection/suppression is credited following the *failure path* of the following branch points:

1. fraction that have an incipient stage of sufficient duration (α)
2. detector system availability, reliability, and effectiveness (β_1 and β_1)
3. MCR Response (μ)

The "η" factor in the event tree represents the conventional suppression probability. There are three cases for this factor which are dependent upon the detection strategies used within the fire area. The probability of "normal" non-suppression should be taken from the Detection Suppression Event Tree in NUREG/CR-6850, Appendix P, using the electrical fire suppression curve for manual suppression as appropriate. The conventional detection suppression event tree is shown in Figure 11-1. The end points for conventional suppression are shown below in Table 11-1.

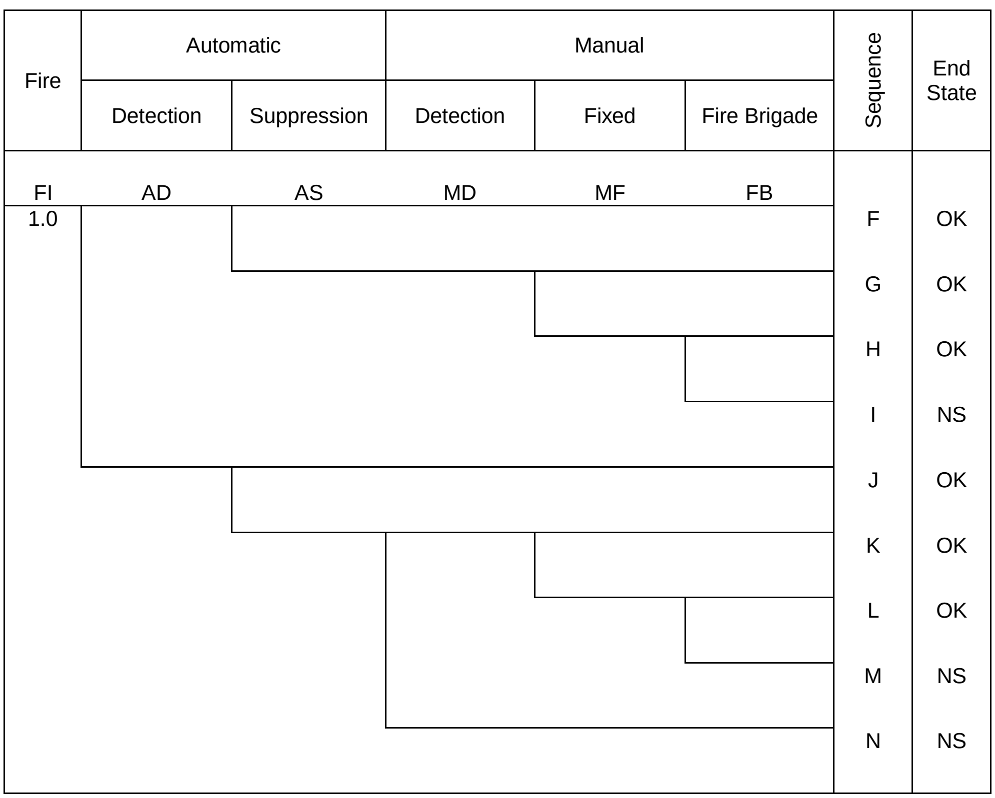


Figure 11-1. Conventional detection suppression event tree

Table 11-1. Conventional Detection Suppression Event Tree Outputs

Sequence	Detection	Suppression
F	Automatic detection by • Heat detectors • Smoke detectors	Fire suppression by an automatically actuated fixed system
G		Fire suppression by a manually actuated fixed system
H		Fire suppression by the fire brigade
I		Fire damage to target items
J	Delayed detection by • Roving fire watch • Control room verification	Fire suppression by an automatically actuated fixed system
K		Fire suppression by a manually actuated fixed system
L		Fire suppression by the fire brigade
M		Fire damage to target items
N	Fire damage to target items	

For **In-Cabinet** applications (Figure 6-4 only), in which redundant spot-type detection and automatic suppression systems are available in the area, “$1-\eta_1$” represents sequences F – N from Figure 11-1. That is, given a failure of the in-cabinet VEWFDS system or MCR to respond, the room spot-type detection capability still exists within the room to detect the fire before delayed detection. From NUREG-6850, the probability of random failure of a conventional spot-type smoke detector system is assumed to be no larger than 0.05.

For **In-Cabinet** and **Areawide** applications (both Figures 6-4 and 6-5), “$1-n_2$” represents sequences F – N from Figure 11-1. That is, given a failure of the VEWFD system to provide sufficient advance warning, the VEWFD system will still perform normal automatic detection functions comparable to that of normal spot detection.

For **Areawide** applications (Figure 6-5 only), “$1-\eta_3$” represents only sequences J – N from Figure 11-1. That is, given a failure of the areawide VEWFDS system there is no redundant normal detection capability within the room to detect the fire before manual delayed detection. Delayed detection is assumed 1.0 for cases in which no prompt or automatic detection is credited (or failed) if the estimated time for manual detection is less than the time to target damage.

12. QUANTIFICATION OF SMOKE DETECTION PERFORMANCE

The purpose of this section is to provide a description and evaluation of a method to estimate the non-suppression probability associated with using different types of smoke detectors in nuclear power plant (NPP) applications.

12.1 Illustrative Examples

This subsection provides illustrative examples of how the information developed in the report could be used in the detection/suppression analysis to estimate a probability of non-suppression for several smoke detection systems. For these examples, the same room will be used to evaluate different fire scenarios, smoke detection applications, and ventilation conditions. The room contains both control and power-type electrical enclosures. The examples evaluated include the following five cases:

Case 1 Control cabinet ignition source, in-cabinet aspirating smoke detection (ASD) very early warning fire detection (VEWFD), bank of 10 cabinets that are naturally ventilated

Case 2 Single partitioned control cabinet, in-cabinet ASD VEWFD, forced ventilation

Case 3 Power cabinet ignition source, in-cabinet ASD VEWFD, bank of 10 partitioned cabinets that are naturally ventilated

Case 4 Mix of control and power cabinets, areawide air return grill mounted ASD VEWFD

Case 5 Mix of control and power cabinets, areawide air return grill mounted ASD VEWFD with room suppression system

All cases consist of an electrical cabinet fire (ignition source) affecting a cable tray containing a fire PRA target cable. In typical fire PRA analyses, the time to damage will vary depending on the cabinet configuration (associated heat release rate value from Table G-1 of NUREG/CR-6850), level of fire modeling (empirical, zone, CFD, THIEF, etc.), and the location of the cable tray. For these illustrative examples, it will be assumed that the time to damage this target cable is 10 minutes, regardless of the electrical cabinet fire hazard characteristics. This approach was chosen such that the resulting effects not associated with the suppression/detection aspects of the analysis are held constant, allowing for a direct comparison of the benefit from the use of ASD VEWFD among applications.

For each example, the results using the approach presented in this report will be shown, along with the results from using NUREG/CR-6850 Appendix P, and the FAQ 08-0046 simplified model approach on page 13-8 of NUREG/CR-6850, EPRI 1019259, Supplement 1.

12.1.1 Case 1: In-cabinet ASD VEWFD, bank of 10 control cabinets, natural ventilation

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in a bank of 10 low voltage control cabinets with natural ventilation. In addition, the room is also equipped with areawide conventional spot smoke detection mounted on the ceiling. The benefit from the use of ASD VEWFD systems will be evaluated for both cases where conventional detection is and is

not evaluated. Each in-cabinet smoke detection system will be evaluated separately. It is assumed that a single zone of the ASD protects the entire cabinet bank and the spot-type detectors are addressable to a single cabinet. The following information is necessary before proceeding with the analysis:

- Based on fire modeling analysis, the estimated time for conventional areawide smoke detection is 2 minutes, for this example.

- Based on fire modeling analysis, the estimated time to target damage is 10 minutes.

- From fire drills records, the reasonable fire brigade response time is 10 minutes.

Based on the preceding information, the values presented in Table 12-1 are to be used in applying the incipient event tree approach; each parameter estimate is provided with source information as to where the particular estimate value can be located.

Table 12-1. Case 1 Input Parameters: Multi-Control Cabinet, In-Cabinet

Parameter	Estimate	Source
α	7.2E-01	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control Cabinet
1-β	6.2E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
1-τ	2.7E-03 : ASD CC 1.9 – 5.3E-01 : ASD LS 2.6E-01 : SS 1.0E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Natural Ventilation
1-μ	1E-04	MCR operator response Section 10.5.4
1-ξ	0.30: ASD CC 0.48 : ASD LS 0.48 : SS 0.41 : ION	Field operator & technician response Table 10-8, 10-Cabinet – ASD VEWFD CC Table 10-14, 10-Cabinet – LS and SS Table 10-11, 10-Cabinet – Ionization
1-π1	1.0E-03	Technician / Field operator staged directly at the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets outside the initiating component.
1-π2	3.9E-02	See discussion below
1-η1	4.8E-01	
1-η2	4.6E-01	

Table 12-1. Case 1 Input Parameters: Multi-Control Cabinet, In-Cabinet (Continued)

RESULT	With Conventional Detection	Without Conventional Detection (setting "η1" to 0)
	Detection Type Pr_{n-s} (Factor) ASD CC : 1.4E-01 (7.1) ASD LS : 2.0E-01 (4.9) 3.1E-01 (3.2) SS :2.4E-01 (4.2) ION : 1.9E-01 (5.4) FAQ 08-0046 : 1.1E-02 (94.5) NUREG/CR-6850 : 5.82E-01 (1.6)	Detection Type Pr_{n-s} (Factor) ASD CC : 1.8E-01 (7.0) ASD LS : 2.4E-01 (4.8) 3.3E-01 (3.2) SS :2.6E-01 (3.8) ION : 2.2E-01 (4.7) FAQ 08-0046 : 1.0E-02 (47.9) NUREG/CR-6850 : 5.82E-01 (1.6)

Figure 12-1, Figure 12-2, and Figure 12-3, illustrate the solution of the detection suppression event tree from NUREG/CR-6850 for the terms $1-\pi_2$, η_1 and η_2 respectively.

Figure 12-1 represents $1-\pi_2$, the probability that, given **failure** of event ξ, the technician/field operator in the area of the electrical cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. $1-\pi_2$ is calculated using the MCR curve. For this case, both the time to detection of the VEWFDS system and time to fire brigade response are set to 0 minutes, considering that the system has already gone into alarm and the technician/field operator is present in the room. The technician/field operator acts as the fire brigade as he/she has been trained to suppress fires (e.g., fire brigade training). The failure probability of the automatic detection, in this case, the VEWFDS system, is set to 0 as well. At this point in the event tree the system is assumed to have already operated successfully and the appropriate response is underway.

The probability of failure to extinguish the fire, once ignition has occurred, is calculated using the MCR curve (λ = 0.324) using a manual suppression time of 10-0-0 = 10 minutes as:

$$e^{(-\lambda_{MCB}*10)} = e^{(-0.324*10)} = 3.9E-02$$

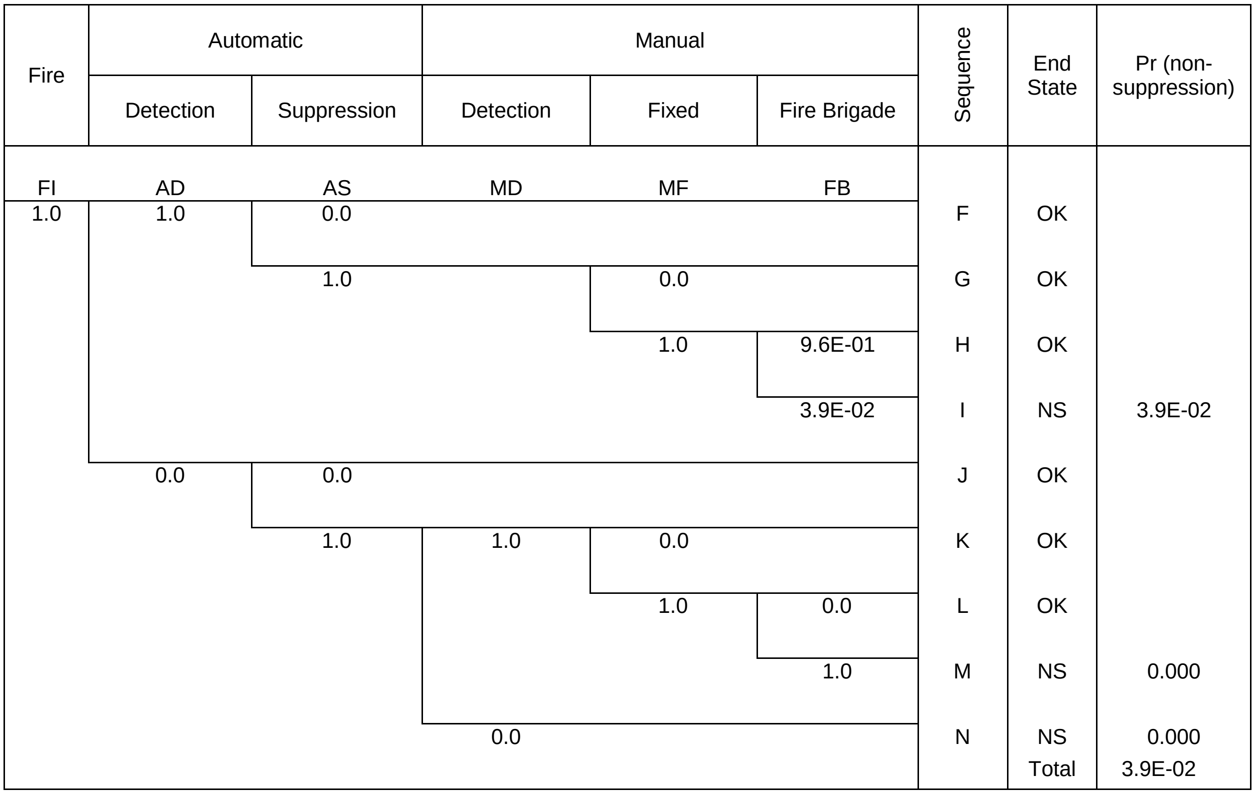


Figure 12-1. Case 1, detection suppression event tree (1-π$_2$)

Figure 12-2 represents (1-η_1), the presence of redundant conventional spot-type detection and automatic suppression systems available in the area. (1-η_1) is calculated through sequences F to N. Automatic conventional spot-type detection has a failure probability of 0.05 (Ref. 36). The probability of failure for the fire brigade is calculated using the electrical suppression curve using a manual suppression time of 10 - 2 = 0 minutes ($t_{ms} = t_{dam} - t_{det}$) as:

$$e^{(-\lambda_{electrical}*8)} = e^{(-0.098*8)} = 0.457$$

If the automatic detection fails, delayed detection is credited. Sequences J to N refer to this situation. Assuming a time to delayed detection of 15 minutes, the fire brigade has no time to suppress the fire before target damage (i.e., 10-15-7 < 0 minutes).

Accordingly, the non-suppression probability is the sum of sequences I, M and N, which is 0.457+ 0.050+ 0.00 = 0.507.

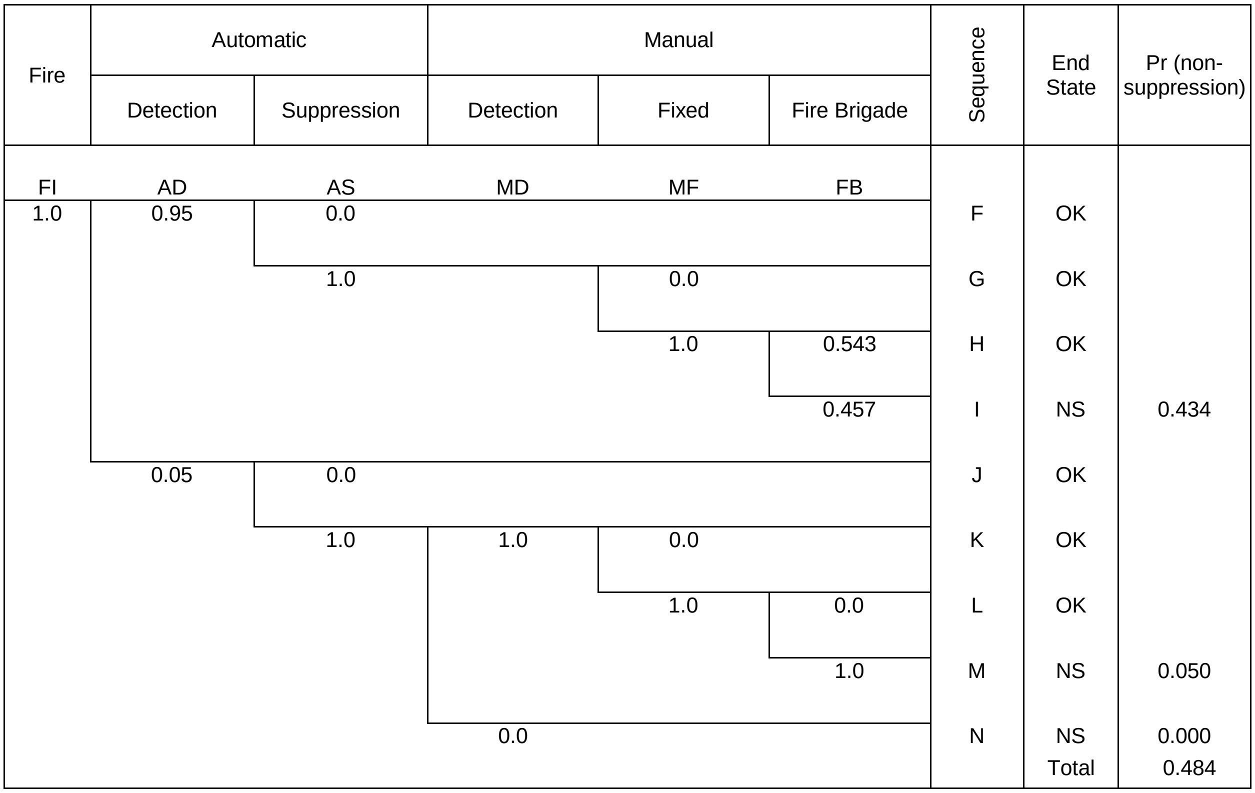


Figure 12-2. Case 1, detection suppression tree for (1-η_1)

Figure 12-3 represents (1-η_2), the presence of redundant conventional spot-type detection and VEWFDS systems. That is, given a failure of the in-cabinet ASD VEWFD system to provide sufficient advance warning, the VEWFD system will still perform normal automatic detection functions comparable to those of normal spot detection. For in-cabinet applications, the ASD VEWFD system time to detect is assumed to be 0 minutes. (1-η_2) is calculated through sequences F to N. Automatic conventional spot-type detection along with VEWFDS detection, has a failure probability of 6.2×10^{-3} per Section 7.2.2. The probability of failure for the fire brigade is calculated using the electrical suppression curve using a manual suppression time of 10 - 2 = 8 minutes as:

$$e^{(-\lambda_{electrical}*8)} = e^{(-0.098*8)} = 0.457$$

If the automatic detection fails, delayed detection is credited. Sequences J to N refer to this situation. Assuming a time to delayed detection of 15 minutes, since the time for manual suppression is less than zero, the fire brigade has no time to suppress the fire before target damage.

Accordingly, the non-suppression probability is the sum of Sequences I, M and N, which is 0.454+ 0.006+ 0.00 = 0.460

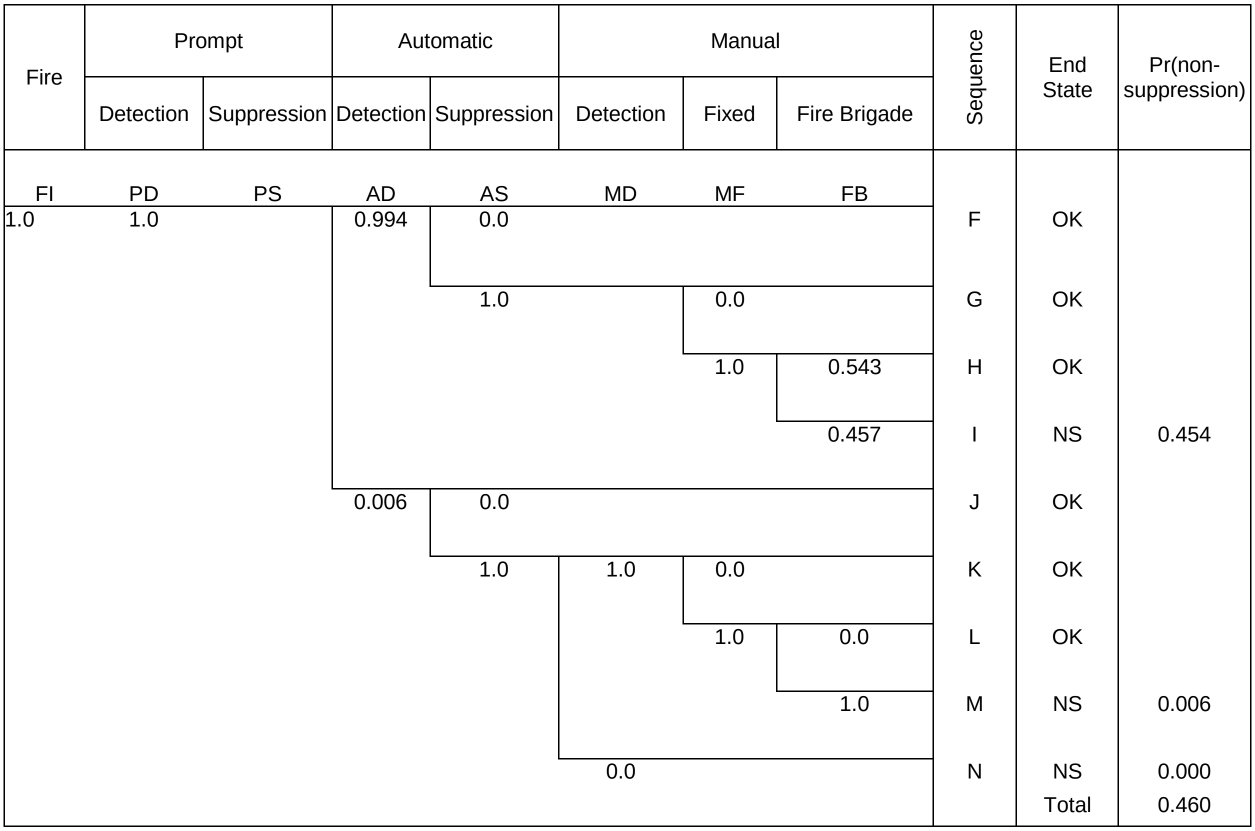


Figure 12-3. Case 1, detection suppression event tree (1-η_2)

12.1.2 Case 2: In-cabinet, single control cabinet, force ventilation high ACH

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in a single control cabinet with a high rate of forced ventilation (approximately 300 cabinet ACH). In addition, the room is also equipped with area wide conventional spot smoke detection mounted on the ceiling. Each in-cabinet smoke detection system will be evaluated separately. The following information is necessary before proceeding with the analysis.

- Based on fire modeling analysis, the estimated time for conventional area wide smoke detection is 2 minute.

- Based on fire modeling analysis, the estimated time to target damage is 10 minutes.

- From fire drills records, the brigade response time is 10 minutes.

Based on the above information the values presented in Table 12-2 are to be used in applying the in-cabinet ASD VEWFD event tree approach;

Table 12-2. Case 2, Input Parameters: Single Low Voltage Control Cabinet, In-Cabinet

Parameter	Estimate	Source
α	7.2E-01	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control cabinet
$1-\beta$	6.2E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
$1-\tau$	1.9E-02 : ASD CC 3.7E-01 : ASD LS 7.9E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Forced Ventilation
$1-\mu$	1E-04	MCR operator response Section 10.5.4
$1-\xi$	1.2E-3 : ASD CC 0.11 : ASD LS 0.11 : ION	Field operator & technician response Table 10-6, 1&3-Cabinet – ASD VEWFD CC Table 10-12, 1&3-Cabinet – LS and SS Table 10-9, 1&3-Cabinet – Ionization
$1-\pi 1$	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u>.
$1-\pi 2$	3.9E-02	Same as Case 1
$1-\eta 1$	4.8E-01	
$1-\eta 2$	4.6E-01	
RESULT	With Conventional Detection	Without Conventional Detection (setting "$\eta 1$" to 0)
	ASD CC : 1.4E-01 (7.3) ASD LS : 2.5E-01 (3.9) ION :4.0E-01 (2.5) FAQ 08-0046 : 8.2E-03(122.5) NUREG/CR-6850 : 5.82E-01 (1.6)	ASD CC : 1.4E-01 (7.1) ASD LS : 2.6E-01 (3.9) ION :4.2E-01 (2.4) FAQ 08-0046 : 1.6E-02 (62.8) NUREG/CR-6850 : 5.82E-01 (1.6)

For this case the solution of the conventional detection suppression event tree from NUREG/CR-6850 for the terms $1-\pi_2$, η_1 and η_2, are identical to Case 1 and will not be repeated here.

12.1.3 Case 3: In-cabinet ASD VEWFD, power cabinet with 10 vertical sections, natural ventilation

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in power cabinets (motor control center with ten vertical sections) with natural ventilation. In addition, the room is also equipped with area wide conventional spot smoke detection mounted on the ceiling. The following information is necessary before proceeding with the analysis.

- Based on fire modeling analysis, the estimated time for conventional area wide smoke detection is 2 minute.

- Based on fire modeling analysis, the estimated time to target damage is 10 minutes.

- From fire drills records, the brigade response time is 10 minutes.

Based on the above information the values presented in Table 12-3 are used.

Table 12-3. Case 3 Input Parameters: Multi-Power Cabinet, In-Cabinet

Parameter	Estimate	Source
α	5.1E-01	Fraction of fires that have an incipient phase Table 7-1, Power Cabinets
$1-\beta$	6.2E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
$1-\tau$	2.7E-03 : ASD CC 1.9 – 5.3E-01 : ASD LS 2.6E-01 : SS 1.0E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Natural Ventilation
$1-\mu$	1E-04	MCR operator response Section 10.5.4
$1-\xi$	0.30 : ASD CC 0.48 : ASD LS 0.48 : SS 0.41 : ION	Field operator & technician response Table 10-8, 10-Cabinet – ASD VEWFD CC Table 10-14, 10-Cabinet – LS and SS Table 10-11, 10-Cabinet – Ionization
$1-\pi 1$	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u>.
$1-\pi 2$	3.9E-02	Same as Case 1
$1-\eta 1$	4.8E-01	
$1-\eta 2$	4.6E-01	
RESULT	With Conventional Detection	Without Conventional Detection (setting "η1" to 0)
	<u>Detection Type</u>: <u>Pr_{n-s} (Factor of credit)</u> ASD CC : 2.3E-01 (4.4) ASD LS : 2.8E-01 (3.6) 3.7E-01 (2.71) SS : 3.0E-01 (3.3) ION :2.7E-01 (3.7) FAQ 08-0046 : N/A NUREG/CR-6850 : 2.9E-01 (3.42)	<u>Detection Type</u>: <u>Pr_{n-s} (Factor of credit)</u> ASD CC : 2.3E-01 (4.3) ASD LS : 2.8E-01 (3.5) 3.6E-01 (2.8) SS : 3.2E-01 (3.0) ION :2.9E-01 (3.4) FAQ 08-0046 : N/A NUREG/CR-6850 : 2.9E-01 (3.42)

For this case the solution of the detection suppression event tree from NUREG/CR-6850 for the terms 1-π_2, η_1 and η_2, are identical to Case 1 and 2, and will not be repeated here.

12.1.4 Case 4: Areawide ASD VEWFD installed on air return grill, mix of control and power cabinets

In this example, various room smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in a mix of power and control cabinets all. The room has an HVAC system. The following information is necessary before proceeding with the analysis.

- Based on fire modeling analysis, the estimated time for conventional area wide smoke detection is 2 minute.
- Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
- From fire drills records, the brigade response time is 10 minutes.

Based on the above information the values presented in Table 12-4 are to be used in applying the incipient event tree approach;

Table 12-4. Case 4 Input Parameters: Mixed Cabinet Type, Areawide

Parameter	Estimate	Source
α	5.4E-01	Fraction of fires that have an incipient phase Table 7-1, Bin 15 – All Cabinet Types
1-β	6.6E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P 4E-04 HVAC unreliability estimate used
1-τ	<u>Ceiling</u> 3.2E-01 : ASD CC 1.1E-01 : ASD LS 5.7E-01 : SS 8.1E-01 : ION	System ineffectiveness Table 7-3, Areawide, Ceiling
	<u>Air Return</u> 3.0E-01 : ASD CC 5.2E-01 : ASD LS	System ineffectiveness Table 7-3, Areawide, Air Return Grill
1-μ	1E-04	MCR operator response Section 10.5.4
1-ξ	1.0	Field operator & technician response Section 10.5.6
1-π1	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u>.
1-π3	1.4E-01	See discussion below
1-η2	5.7E-01	
1-η3	1.00	

Table 12-4. Case 4 Input Parameters: Mixed Cabinet Type, Areawide (Continued)

RESULTS	Ceiling Detection		Air Return Detection	
	Detection Type	Pr_{n-s} (Factor)	Detection Type	Pr_{n-s} (Factor)
	ASD CC :	5.5E-01 (1.8)	ASD CC :	5.4E-01 (1.9)
	ASD LS :	4.1E-01 (2.4)	ASD LS :	6.8E-01 (1.5)
	SS :	7.7E-01 (1.4)	SS :	N/A
	ION :	8.8E-01 (1.1)	ION :	N/A
	FAQ 08-0046 :	N/A	FAQ 08-0046 :	N/A
	6850 :	1.0 (1.0)	6850 :	N/A

Figure 12-4, and Figure 12-5, illustrate the solution of the detection suppression event tree from NUREG/CR-6850 for the terms $1\text{-}\eta_2$ and $1\text{-}\eta_3$, respectively. The estimate for π_3 uses the non-suppression probability curves with λ=0.194.

$1\text{-}\pi_3$, the probability that, given **failure** of event ξ, the technician/field operator in the room responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets <u>outside the cabinet</u>. $1\text{-}\pi_3$ is calculated using a suppression curve with λ= 0.194. For this case both the time to detection of the VEWFDS system and time to fire brigade response are set to 0 minutes considering that the system has already gone into alarm and the technician/field operator is present within the room. The technician/field operator acts as the fire brigade as they have been trained to suppress fires (e.g., fire brigade training).

The probability of failure to extinguish the fire, once ignition has occurred, is calculated using the field operator detection curve (λ = 0.194) at time 10-0-0 = 10 minutes as:

$$e^{(-\lambda_{area}*10)} = e^{(-0.194*10)} = 0.144$$

Figure 12-4 represents $1\text{-}\eta_2$, the probability that the VEWFDs system will activate given a fire without an incipient stage. That is, given a failure of the VEWFD system to provide sufficient advance warning, the VEWFD system will still perform normal automatic detection functions comparable to that of normal spot detection. $1\text{-}\eta_2$ is calculated through sequences F to N with VEWFD system represented with a failure probability of 0.0 given that detector system availability, reliability, and effectiveness is accounted for with the β_4 branch point. The probability of failure for the fire brigade is calculated using the “All fires” suppression curve at time 10 - 2 = 8 minutes as:

$$e^{(-0.070*8)} = 0.571$$

According to Section P.1.5, the non-suppression probability is the sum of Sequences I, M and N, which is $5.0\times10^{-1} + 0.0 + 0.0 = 6.1\times10^{-1}$

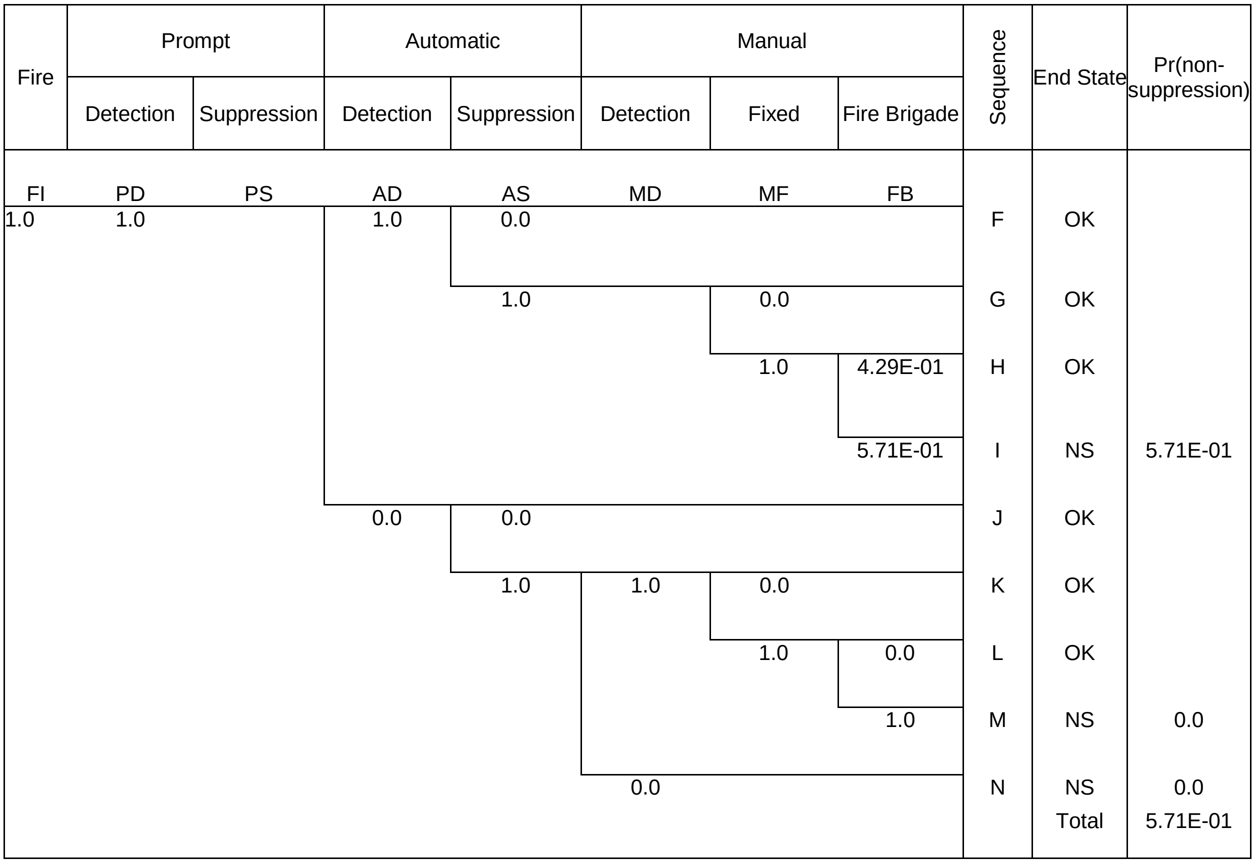


Figure 12-4. Case 4, conventional detection suppression tree for (1-η2)

Figure 12-5 represents η_3, the probability that the ASD VEWFD system fails. That is, given a failure of the areawide VEWFDS system or main control room response to an ASD VEWFD response there is no redundant normal detection capability within the room to detect the fire before manual delayed detection. Delayed detection is assumed 1.0 for cases where no prompt or automatic detection is credited (or fails) if the estimated time for manual detection is less than the time to target damage. $1-\eta_3$ is calculated through sequences J – N. Assuming a time to delayed detection of 15 minutes, the fire brigade has no time to suppress the fire before target damage.

Accordingly, the non-suppression probability is the sum of Sequences I, M and N, which is 0.0 + 1.0+ 0.0 = 1.0

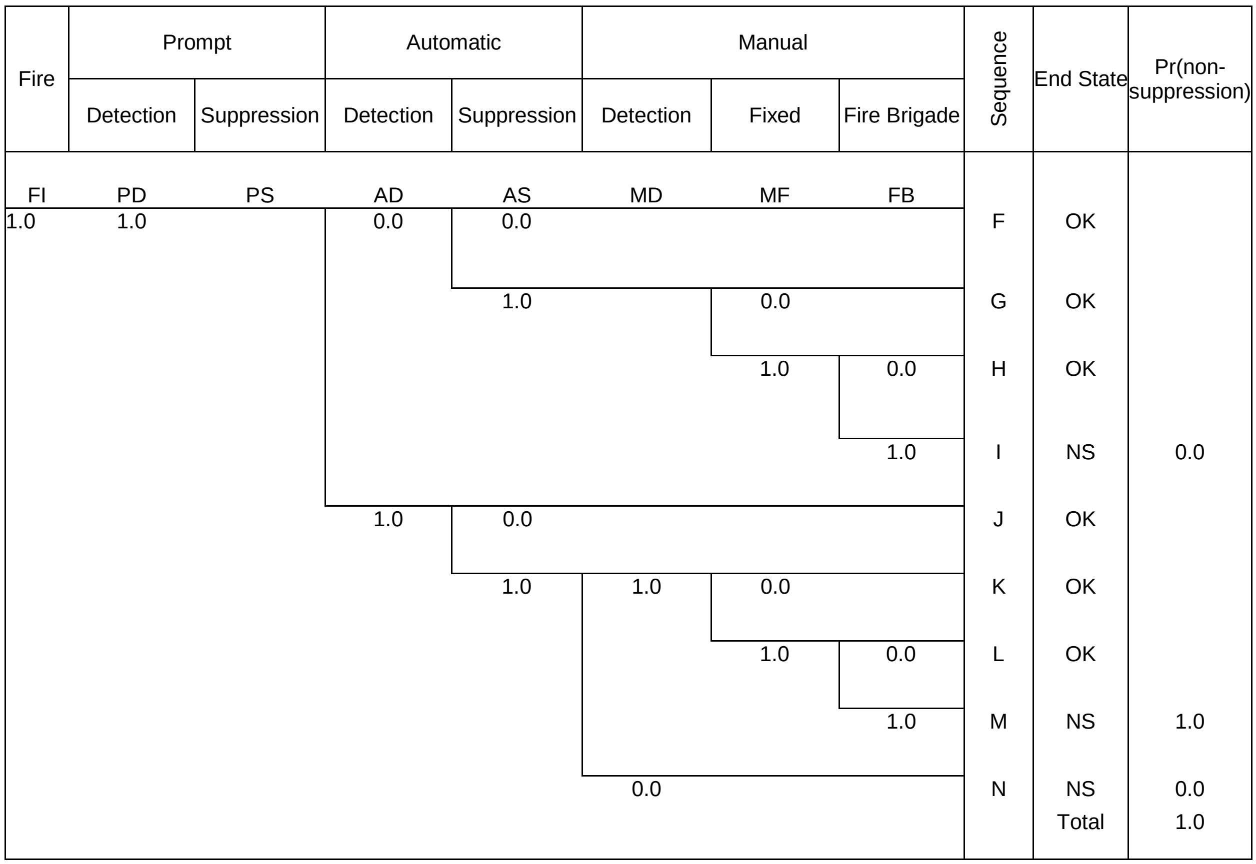


Figure 12-5. Case 4, conventional detection suppression tree for (1-η3)

12.1.5 Case 5: Areawide ASD VEWFD installed on air return grill, mix of control and power cabinets, with room suppression

This example is identical to Case 4, with the exception that an automatic Halon suppression system is available in the room. The only event tree parameter that changes is (1-η2), as shown in Figure 12-6. Here the probability of the Halon system failure is 0.05 per NUREG/CR-6850 guidance in Appendix P.

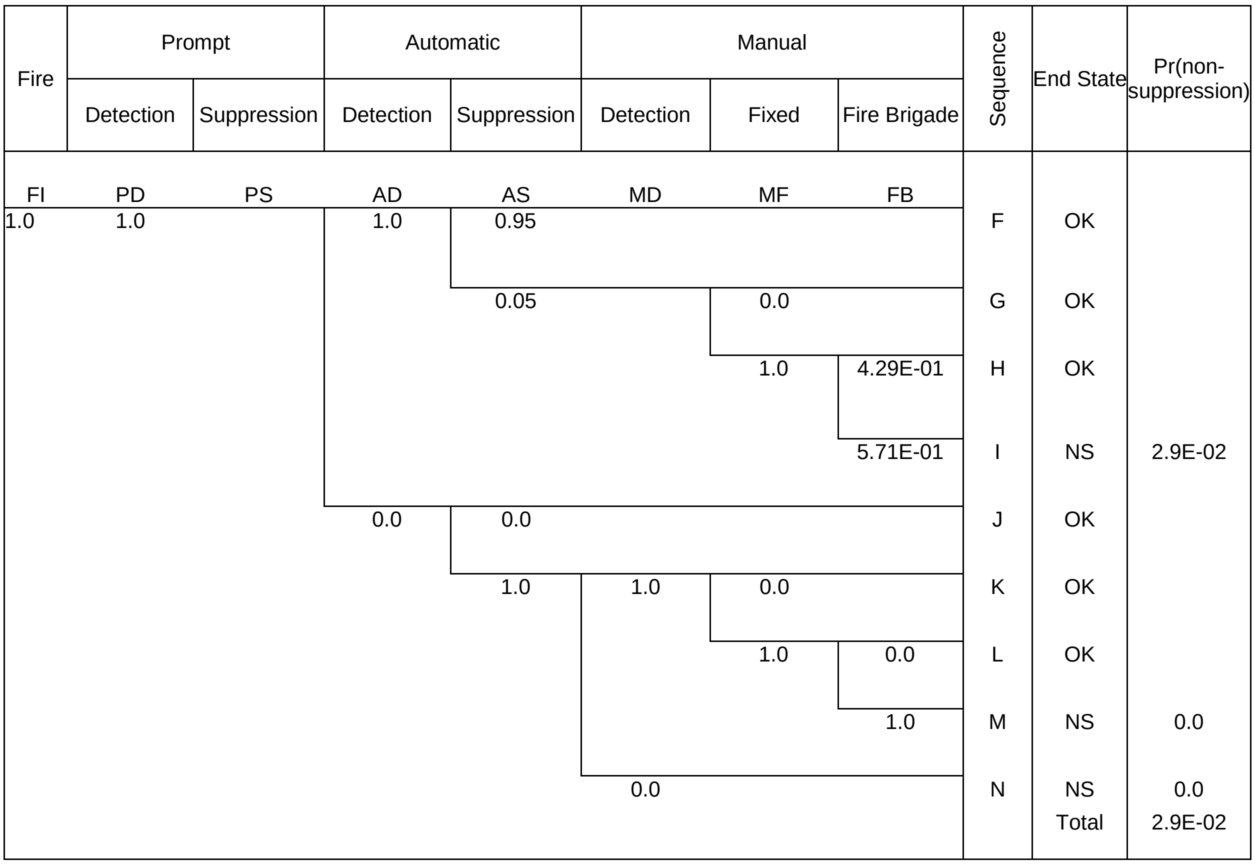


Figure 12-6. Case 5, conventional detection suppression tree for (1-η2)

Table 12-5 presents the results.

Table 12-5. Case 5 Input Parameters: Mixed Cabinet Type, Areawide with Halon

Parameter	Estimate	Source
α	5.4E-01	Fraction of fires that have an incipient phase Table 7-1, Bin 15 – All Cabinet Types
1-β	6.6E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P 4E-04 HVAC unreliability estimate used
1-τ	<u>Ceiling</u> 3.2E-01 : ASD CC 1.1E-01 : ASD LS 5.7E-01 : SS 8.1E-01 : ION 8.7E-01 : PHOTO	System ineffectiveness Table 7-3, Areawide, Ceiling
	<u>Air Return</u> 3.0E-01 : ASD CC 5.2E-01 : ASD LS	System ineffectiveness Table 7-3, Areawide, Air Return Grill
1-μ	1E-04	MCR operator response Section 10.5.4
1-ξ	1.0	Field operator & technician response Section 10.5.6
1-π1	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u>.
1-π3	1.4E-01	See discussion above
1-η2	2.9E-02	
1-η3	1.00	
RESULTS	Ceiling Detection <u>Detection Type Pr_{n-s} (Factor)</u> ASD CC : 3.8E-01 (2.6) ASD LS : 1.9E-01 (5.2) SS : 6.2E-01 (1.6) ION : 8.3E-01 (1.4) FAQ 08-0046 : N/A 6850 : 1.0 (1.0)	Air Return Detection <u>Detection Type Pr_{n-s} (Factor)</u> ASD CC : 4.0E-01 (2.06) ASD LS : 5.7E-01 (1.7) SS : N/A ION : N/A FAQ 08-0046 : N/A 6850 : N/A

12.2 Evaluation of the Event Tree Sensitivity

The in-cabinet event tree was evaluated for the “Fire Damage Outside Cabinet” damage state sensitivity to parameters. The conventional suppression was not modeled such that the results are applicable to the probability of non-suppression contributed to the use of in-cabinet VEWFD systems with appropriate operator response. Since conventional detection is set to fail (i.e., “η” set to 0), and the small HEP for MCR response “1-μ” 5×10^{-4}; the only two parameters that affect the damage states are α and β. The results of the sensitivity are presented in Figure 12-7 showing the change in the factor of credit ($1/Pr_{non\text{-}supp}$).

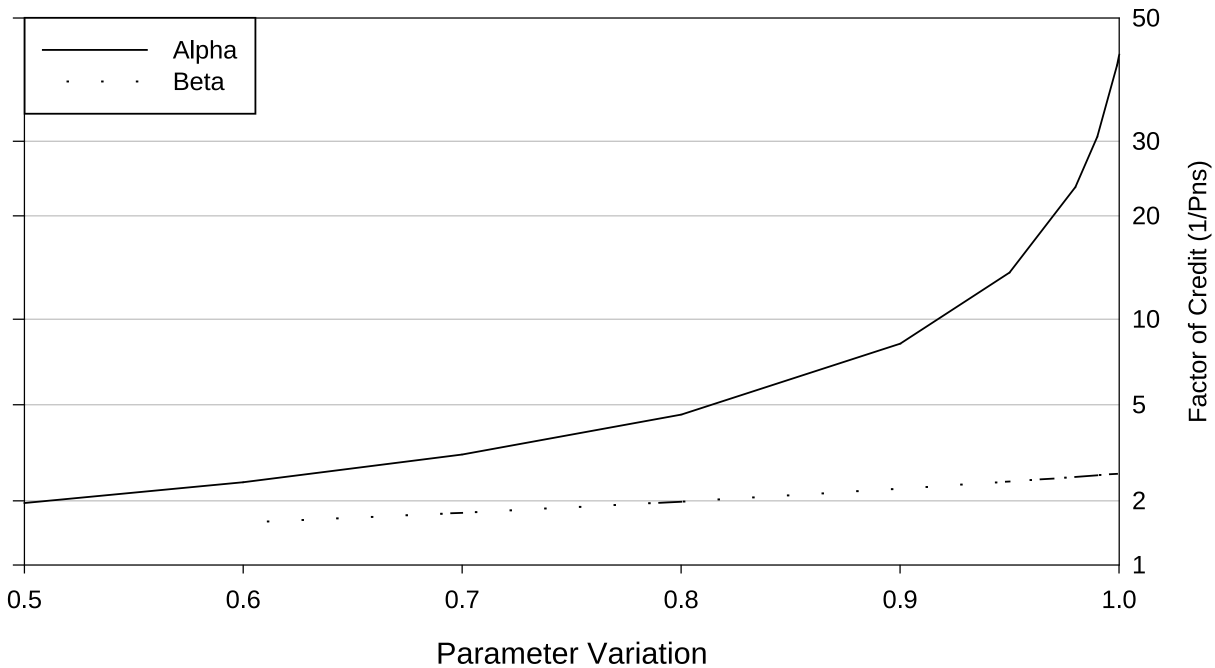


Figure 12-7. Probability of non-suppression sensitivity to α and β for ASD only (in-cabinet, conventional suppression not modeled).

12.3 Assumptions, and Limitations

The aforementioned quantification effort is based on the following assumptions and limitations:

1. System is designed and installed by trained and qualified technicians following appropriate vendor guidance. Any deviations between as-built and as-designed should be evaluated for effects on system performance

2. Systems are inspected, tested and maintained per vendor recommendations or applicable national consensus standards

3. Functionality testing via detector alarm response to smoke stimulus should be conducted following guidance in Annex A of NFPA 76 or vendor equivalent methods. Air flow through each sampling port credited for protection is verified.

4. Cabinet characteristics allow for the application of VEWFD systems, such that they are not tightly sealed.

5. The sensitivity settings of the VEWFD system is setup to meet or exceed (be more sensitive than) the NFPA 76 sensitivity requirements, namely

   Light-scattering
   a. an *alert* is set to 0.2 %/ft obscuration at the sampling point above background, and

   b. an *alarm* is set to 1.0 %/ft obscuration at the sampling point above background

   Cloud Chamber
   a. an *alert* is set to 1.0×10^6 particles/cm^3 at the sampling point, based on tested configurations.

6. The sensitivity setting for the conventional system used for in-cabinet applications meet or exceed the sensitivities tested, namely;

   ION Spot-type
   a. An *alarm* is set to 1.0 %/ft obscuration

   PHOTO Spot-type
   b. An *alarm* is set to 2.0 %/ft obscuration

7. The VEWFD system *alert* corresponds to the field operator or technician response and a VEWFD *alarm* corresponds to an expeditious fire brigade response as described in Section 10.

   a. When using a detection strategy with no ability to differentiate between the alert and alarm set points (i.e., in-cabinet ionization detectors with one setpoint), the alarm response should correspond to an expeditious fire brigade response as described in Section 10.

8. The approach presented is not applicable to main control room applications or other spaces that are continuously occupied. No human subject testing was performed to assess the performance of human senses to the response of smoke detection systems.

9. Compensatory measures are put in place whenever the VEWFD or conventional spot-type smoke detection system is unavailable.

10. Plant personnel responding to VEWFD or conventional spot-type systems are trained in the use of the systems, and any portable devices used to locate the degrading component.

11. The use of VEWFD or conventional spot-type systems does not replace the requirement to demonstrate the ability to meet the nuclear safety performance criteria for a fire scenario and its impact(s) on safe shutdown equipment.

12. Alarm response procedures are specific to VEWFD and training

13. Areawide HEP’s are 1.0. The above examples do not include timing feasibility considerations as discussed in Section 10.5.6.

PART III

Conclusions and Perspectives

Definitions and References

13. REPORT SUMMARY AND CONCLUSIONS

This section summarizes the specific findings based on the analysis of the test data and review of the operating experience and literature related to the performance of very early warning fire detection systems, specifically aspirating smoke detection (ASD) configured as very early warning fire detection (VEWFD) systems. These findings are specific to the objectives outlined in Section 1.3

Operational experience and the tests performed under this program show that aspirated VEWFD systems, when designed, installed, and maintained are effective in detecting low-energy pre-flaming fire conditions. However, the testing has also shown that other forms of smoke detection such as conventional ION spot-type detectors perform equally well in naturally ventilated in-cabinet applications. The test results show that in-cabinet applications are the most effective use of smoke detection technologies in detecting low-energy incipient stage electrical cabinet fires as compared to areawide ceiling level detection. Areawide applications using an air return grill and those using ceiling-mounted air sampling port locations perform similarly. However, as ceiling height increases, ceiling areawide aspirated VEWFD applications will become less effective at detecting low-energy incipient fire sources, unless system sensitivities are increased or sampling port spacing is decreased.

VEWFD systems don't always provide enhanced warning over conventional spot-type detection during the low-energy incipient stage. The performance of either type of system (VEWFD or conventional spot-type) is dependent upon the material thermal decomposition rate, and aerosol characteristics. For in-cabinet applications, the cloud chamber ASD typically outperformed the other systems tested, followed by the ION spot-type detector which typically outperformed the light-scattering ASD and sensitive spot-type detectors. The PHOTO spot-type detector typically responded the slowest during the in-cabinet tests. The cloud chamber and ION in-cabinet performance is largely because of the aerosol characteristics at the early stage, which are typically spherical in nature; also the effects of aerosol aggregation and agglomeration have not developed to a point where light-scattering type detectors can be effective. However, the exception is CSPE material (or materials with similar aerosol characteristics), which had the largest partial size for the materials tests.

In areawide applications, the ASD and sensitive spot-type VEWFD systems typically performed better than the ION and PHOTO spot-type detectors. The ASD's ability to use cumulative sampling is largely the cause of the effect. ASD systems also have the added benefit of using filters to reduce nuisance alarm rates and can be designed to allow for more efficient inspection, maintenance, and testing. For fast-developing fires, the amount of additional warning between VEWFD and conventional systems is marginal at best.

With the exception of ASD systems designed to protect a single electrical cabinet, human interaction with equipment such as handheld thermal imaging cameras or portable ASDs will be needed to pin point the incipient fire. As part of the human factors analysis, a table top analysis of a generic plant personnel response to ASD VEWFD system alarms was conducted. The task analysis supports a human reliability analysis. Based on the expected operational response and timing estimate developed from operating experience and test results, a human reliability analysis was conducted based on the overall strategy that parallels post-initiator operator actions. The results of this HRA indicate that human error probabilities vary but combined with the suppression analysis, conclude that the trained human response is likely to succeed.

Review of operating experience, vendor supplied information, and literature has shown agreement with the unreliability estimate provided in EPRI 1016735, "Fire PRA Methods Enhancements: Additions, Clarification, and Refinements to EPRI 1019189." However, ASD system unavailability differs from that report in the EPRI document, and is estimated at 1.7×10^{-3} per detector unit per year, based on an average annual system down-time from plants where information was collected. A wide variance of system downtime was observed from site visits and literature. It was noted that system unavailability improved for facilities that had these systems installed and operating for a number of years. Facilities which were using ASD systems for the first time indicated longer system downtime, likely because of the lack of understanding of the system maintenance requirements to ensure proper operation. For areawide air return grill applications, the unreliability/unavailability of the ventilation system should also be modeled, since the air return grill application requires forced ventilation to perform as designed.

The experimental testing program has confirmed that cabinet design, fill/obstructions and ventilation effects can influence the performance of VEWFD systems. Forced cabinet ventilation is a primary influence factor on detector response, especially with high rates of cabinet air exchange. As cabinet ventilation rates increase, so does smoke dilution. For the forced-ventilation rates used in this project's tests, the ASDs were slower to respond in force-ventilated (high air exchange rate) cabinets than naturally ventilated cabinets. In addition the ASDs were less effective in reaching an "alert" threshold in force-ventilated cabinet (high air exchange rate) tests.

For in-cabinet applications, the presence of openings or lack of partitions between adjacent cabinet sections having ASD sampling ports enhances the time to detection; this is because of the cumulative effect of drawing samples from multiple sampling ports. For this effect to be beneficial openings between cabinets would have to be sufficient in size to allow for the air space communication between cabinet vertical sections.

Smoke source location also has an effect on VEWFD response. The closer the source is to the detector or sampling point, the more rapid the response. In the full-scale small room tests where the source was elevated approximately two-thirds of the height of the cabinet off the cabinet base; the ASDs responded approximately 9 percent faster than when the sources were located on the base.

Other parameters not explicitly explored in this program's tests, but covered in the literature relate to soot deposition and loss of aerosol thorough ventilation. Soot deposition internal to the electrical cabinet will be influenced by the obstructions/fill (impaction), thermal gradients (thermophoresis), and electric fields (electrophoresis). Cabinets with a large surface area of ventilation, such as louvered vents compounded by thermophoresis, could result in a fraction of aerosol being lost through these vents. These phenomena would cause less aerosol to be transported to the ASD sampling ports located at the ceiling of the electrical cabinet resulting in a delay in detection (compared to the data in this report), and a decrease in the effectiveness in detection of low-energy fires during the incipient stage.

An evaluation of the non-suppression probability shows that the use of these systems can reduce plant risk from the consequences of electrical cabinet fires. It has been shown that a dominant contributor to the risk model is the estimation of the fraction of *potentially challenging or greater fires* which exhibit an incipient fire stage of sufficient duration to allow for operator response. Since fire PRAs only quantify those fires that initiate and can potentially grow to a

damaging state, the majority of smoking events are not modeled (included as a fire initiator). The previous methods (EPRI 1011989 and FAQ 08-0046) used to estimate this characteristic could not be confirmed based on the evaluation of the operating experience.

The risk benefit for using these systems varies by application with in-cabinet detection being the best approach for detecting low-energy incipient sources early enough to allow for suppressing before target damage to multiple components within or outside the electrical cabinet. Areawide applications also provide some risk benefit; however, they are usually slower to detect low energy fires because of a number of previously discussed contributing factors.

13.1 Conclusions

This confirmatory research program has shown that the performance of smoke detection to detect low-energy pre-flaming conditions varies by detection technology, application, and aerosol characteristics (dependent on material degradation characteristics).

For in-cabinet applications, the ASD cloud chamber VEWFD and ION spot-type detection systems performed better than all light-scattering based technologies (three of the five ASD VEWFD systems, sensitive spot VEWFD and PHOTO spot-type detector). This conclusion is based on the systems response (ability to detect and mean time to detection) to the materials and methods used in testing.

In areawide applications, the ASD systems outperformed the conventional spot-type detectors (ION, PHOTO) for detecting low energy fire sources. This program has also confirmed that the earliest and most effective method of detecting low energy fires is when the detector or sampling port is located within the NPP electrical enclosure being protected.

This research has also provided a refined approach to quantify the performance of smoke detection systems that could be used in fire PRA applications to estimate the non-suppression probability. This refined approach uses operating experience, literature, test results, human reliability methods, and the exponential suppression model to characterize the systems performance. The approach relies more heavily on timing based information to characterize the performance of the systems tested. Because of the uncertainty associated with characterizing the duration and aerosol generation of the incipient stage for equipment commonly found in nuclear power plant electrical enclosures, there are several parameters and assumptions that could enhance the overall risk characterization. Most notably, the refined approach is sensitive to the characterization of *Potentially Challenging or Greater Fires*[36] which exhibit an incipient stage with a short duration and the timing associated with fires which do have a longer duration incipient stage.

All methods currently available use some form of assumptions and limitations to bound the evaluation. Validation of these assumptions and limitations could be better understood by industry and regulatory support to facilitate collecting operating experience directly related to the performance of these ASD VEWFD systems in NPP applications or within other industries with similar components and equipment. Information such as nuisance alarm rate, scheduled and unscheduled system down time, total number of operating detectors and years of operation for each system would be useful in evaluating ASD performance. In addition, consistent and

[36] Potentially challenging or greater fires are classified as challenging, potentially challenging, or undetermined with regard to the fire severity classification documented in EPRI 1025284, “The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance.”

detailed reporting of instances where potential fires were caught in an incipient stage, how long it took operators from time of VEWFD system alert to de-energize the equipment, instances where flaming fires occurred and the associated time to suppress those fires that did occur would help support any future risk quantification effort. Complete and consistent reporting could be coordinated by a nuclear industry users group. General information on lessons learned from the use of these systems in NPPs could be communicated via industry forums to benefit the use of these systems such that an understanding of the performance of these systems could be achieved.

14. RECOMMENDATIONS FOR FUTURE RESEARCH

This report has provided a consolidation of the best information to date related to aspirating smoke detection (ASD) system response to smoke sources typically found in U.S. nuclear power plant (NPP) electrical enclosures, along with a method for quantifying the performance of these systems in fire probabilistic risk assessment (PRA). In the process of quantifying these systems several assumptions had to be made. The most important quantity to define is the time duration distribution of the incipient stage. However, design fires typically do not model the incipient growth stage of fire. NUREG/CR-6850 (EPRI 1011989) models fires with a power law growth profile starting at time zero. Thus, following this model provides little to no incipient stage, depending on how you define the transition point of incipient to growth. Thus, for a more consistent application of this technology's potential advantages in performance-based applications, it would be desirable to develop scenario-specific (electrical enclosures, pump fires, transient fires, etc.) design fires that account for the incipient stage of burning. This is not to say that the incipient stage would exist in all scenarios, but development of a consensus definition of the incipient stage for various scenarios, and a consensus on how and when to model the incipient stage, could allow for greater certainty on the quantification of these systems in fire PRA.

With the limited knowledge of the incipient stage duration for *potentially challenging or greater fires* and the use of event trees to model risk, only a few conclusions can be drawn; the results of any research are only as good as the assumptions made. The human error probabilities (HEPs) were based on an estimate of time available for operator response developed from only a small sample of fire events in which sufficient information was available to quantify this duration; as such, this estimate is inherently uncertain. An alternative method to quantify this duration would be to conduct a formal elicitation process whereby a group of qualified experts with diverse backgrounds and knowledge provide professional judgment for use in quantifying the incipient stage duration. A panel constituted of NPP equipment manufacturing experts, fire PRA experts, and experts from other industries with fire response field experience, could develop a comprehensive view point to represent the scientific communities view.

A better measure of ASD very early warning fire detection VEWFD system performance may occur when sufficient operating experience in nuclear facilities is obtained and compared to similar applications lacking the use of this technology. Depending on the provenance of the use of this technology, operating experience gained over a period of 10 years, may provide a sufficient database to support such an evaluation. However, to make for a useful measure of system performance, it is recommended that a group associated with the nuclear industry's research arm, or operating experience, support a comprehensive and consistent reporting program. Such a program would provide useful information such as the number of detectors in use; nuisance alarm rate; availability estimates; reporting of operator response; including time to locate incipient source; number of cabinets being protected per detector zone; flaming fires that do occur in equipment protected by ASD VEWFD systems; and associated time to suppress such fires.

The testing program was limited by the availability of electrical enclosures to test. As such, the applicability of the test results for cabinets with louvered doors and/or back panels has not been determined. Additional data on cabinet ventilation configurations and a more rigorous evaluation of the effects of varying mechanical ventilation rates, would help support an evaluation of the performance of these systems.

As mentioned in the experimental approach section, an issue was identified concerning sensitivity settings for the cloud chamber ASDs, which was not fully resolved. These ASDs do not report detector sensitivity in terms of U.S. detection industry standard engineering units of percentage of obscuration per foot, but in terms of numeric (dimensionless) settings. Although the authors are not implying that the cloud chamber technology is deficient, guidance to support the selection of set points to achieve the NFPA 76 sensitivity settings would be beneficial.

This report focused exclusively on the fire hazards associated with electrical enclosure fires. Other types of equipment found in NPPs such as pumps, motors, air handling units, transient combustibles, among others can exhibit an incipient stage and ASD VEWFD systems may provide enhanced warning and a risk reduction. An evaluation similar to what was done in this report would be beneficial. Follow-on work could catalog the types of smoke sources and materials found in NPPs that contribute to the *potentially challenging or greater fires* characterized by fire PRA.

15. DEFINITIONS

Acceptance test – The process wherein every sampling port is provided an appropriate stimulus that simulates the existence of the design fire, and the design sequence of operations of each system component in the entire system is verified and recorded in written form.[1]

Alarm condition – An abnormal condition that poses an immediate threat to life, property, or mission.[4]

Aspirating smoke detector (ASD) – A detector that consists of a piping or tubing distribution network that runs from the detector to the area(s) to be protected. An aspiration fan in the detector housing draws air from the protected area back to the detector through air sampling ports, piping, or tubing. At the detector, air is analyzed for fire products. This type of detector is also known as an *Air Sampling-Type Detector*.[2]

Diffusion flame – A flame in which fuel and air mix or diffuse together at the region of combustion.[4]

Early warning fire detection systems (EWFDS) – Systems that use smoke, heat, or flame detectors to detect fires before high heat conditions threaten human life or cause significant damage to telecommunications service.[3]

Pre-alarm condition – An abnormal condition that poses a potential threat to life, property, or mission, and time is available for investigation.[4]

Pyrolysis – A process in which material is decomposed or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion.[4]

Response time – The time between the generation of combustion aerosols at their source and the indication of their presences at the ASD. [5]

Sampling port – An orifice, through which air is drawn to an air sampling-type detector.[3]

Sensitivity – Relative degree of response of a detector measured in percent per meter obscuration (%/ft obscuration). A higher sensitivity denotes response to a lower concentration of smoke than a low sensitivity, under identical smoke build-up conditions.[6]

Sensitivity measurement – A quantitative measurement and recording of the stimulus necessary to achieve an alarm signal from an initiating device. A sensitivity measurement determines how large a stimulus is necessary to cause an alarm response. This measurement is to be compared to the value for the unit as shipped [as designed] to quantify any change in the performance one can anticipate from the unit. Thus, the sensitivity measurement is intended to assess the ability of the detector to perform its intended function when the design fire occurs. A sensitivity measurement differs from a test in that a test does not imply that the stimulus is of a similar magnitude to that obtained from the design fire.[1]

Smoke - The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise missed into the mass.[1]

Smoke dilution – A reduction in the quantity of smoke per unit of air volume of smoke reaching the detector.[2]

Smoldering combustion – A slow, low-temperature, flameless form of combustion, sustained by the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel.[7]

Spot-type smoke detector – A device whose detecting element is concentrated at a particular location.[6]

Standard fire detection systems (SFDS) – Systems that use fire detection-initiating devices to achieve certain life-safety and property protection in accordance with applicable standards.[3]

Stratification – The phenomena whereby the upward movement of smoke and gases ceases because of loss of buoyancy.[2]

Very early warning fire detection systems (VEWFD systems) – Systems that detect low-energy fires before the fire conditions threaten telecommunications service.[3]

<u>Definition references:</u>

1. National Fire Protection Association (NFPA) Fire Protection Handbook, 20th Edition, National Fire Protection Association, Quincy, MA, 2008.

2. NFPA Standard 72, National Fire Alarm and Signaling Code, National Fire Protection Association, Quincy, MA, 2010.

3. NFPA Standard 76, Standard for the Fire Protection of Telecommunications Facilities, National Fire Protection Association, Quincy, MA, 2012.

4. NFPA Glossary of Terms, Quincy, MA, 2014.
5. Fire Industry Association, Code of Practice; Design, Installation, Commissioning & Maintenance of Aspirating Smoke Detector (ASD) Systems (Vol. Issue 3). Middlesex, Hampton, England, 2012.

6. Underwriters Laboratories Standard 268, Smoke Detectors for Fire Alarm Systems, 2009.

7. Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering, Third Edition, National Fire Protection Association, Quincy, MA, 2008.

16. REFERENCES

1. Electric Power Research Institute (EPRI), “Submittal NFPA 805 Transition Pilot Plant FAQ 08-0046, ‘Incipient Fire Detection Systems’,” 2008. Agencywide Documents Access and Management System (ADAMS) Accession No. ML081200120.

2. U.S. Nuclear Regulatory Commission (NRC), Safety Evaluation, “Exemption from Apx. R Section III.G.2 of 10 CFR 50,” 1997. ADAMS Accession No. 9707170067.

3. Krich, R. M., “H.B. Robinson Unit 2, Response to GL-88-20, Supplement 4, IPEEE for Severe Accident Vulnerabilities,” 1995. ADAMS Accession No. 080100059.

4. NRC, “Closure of National Fire Protection Association 805 Frequently Asked Question 08-0046 Incipient Fire Detection System,” 2009. Accession No. ML0932220426.

5. National Fire Protection Association (NFPA), “NFPA Fire Protection Handbook, 20th Edition,” Quincy, MA, 2008.

6. NFPA, “Society of Fire Protection Engineering Handbook of Fire Protection Engineering,” Quincy, MA, 2002.

7. Gottuk, D., et al., “Validation of Modeling Tools for Detection Design in High Air Flow Environments,” The Fire Protection Research Foundation, NFPA Quincy, MA, 2012.

8. NFPA, “NFPA Standard 72, National Fire Alarm and Signaling Code,” NFPA, Quincy, MA, 2010.

9. NFPA, “NFPA Standard 921, “Guide for Fire and Explosion Investigations,” NFPA, Quincy, MA, 2014.

10. Heskestad, G., and C. Yao, “A New Approach to Development of Installation Standards for Fire Detectors,” FMRC Technical Proposal 19574, 1971.

11. Bukowski, R.W., R.J. O’Laughlin, and C.E. Zimmerman, “Fire Alarm Signaling Systems Handbook,” National Fire Protection Association, Quincy, MA, and The Society of Fire Protection Engineers, Boston, MA, 1987.

12. Drysdale, D., “An Introduction to Fire Dynamics,” West Sussex, Wiley, 2011.

13. NFPA Glossary of Terms, Quincy, MA, 2013.

14. Meacham, B.J., “Factors Affecting the Early Detection of Fire in Electronic Equipment and Cable Installation,” International Telecommunications Fire Protection Symposium, pp. 34-59, 1992.

15. Custer, R.L., and R.G. Bright, “Fire Detection: The State-of-the-Art,” U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1974.

16. NRC, “Fire Protection for Nuclear Power Plants,” Regulatory Guide 1.189, Revision 2, 2009.

17. Bryan, J., “Fire Suppression and Detection Systems,” Englewood Cliffs, NJ, Prentice-Hall, Inc., 1993.

18. NFPA, “NFPA Standard 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants,” NFPA, Quincy, MA, 2001.

19. Institute of Electrical and Electronics Engineers (IEEE), “IEEE Standard 100, The Authoritative Dictionary of IEEE Standards Terms, 2000.

20. Xtralis, “Letter to Barrett, H. and Moulton, C. Regarding FAQ 08-0046 - Crediting Incipient Fire Detection Systems (IFDS) for Fire PRA,” 2009. ADAMS Accession No. ML091970034.

21. Kapur, K. L., “Reliability in Engineering Design,” John Wiley & Sons, Detroit, MI., 1977.

22. NFPA, “NFPA Standard 76, Standard for the Fire Protection of Telecommunications Facilities,” 2012.

23. NRC, “IPEEE H.B. Robinson Review,” 2000.

24. NASA-STD-8719.11 Revision A, Safety Standard for Fire Protection

25. Forell, B., and S. Einarsson, “Extension of the Plant Specific Database of Fire Protection Systems and Components,” International Conference on Fire PRA, OECD/NEA Committee on the Safety of Nuclear Installations, Garching, Germany, 2014.

26. Groves, “Illinois Bell Telephone Fire, 1988,” 2006. Retrieved from IDEALS: https://www.ideals.illinois.edu/bitstream/handle/2142/95/Illinois%20Bell%20Telephone%20Fire,%201988.pdf?sequence=2.

27. Xtralis, “IT/Server Room Fire Test Demonstrations – VESDA & photoelectric conventional point detectors, Technical Report,” October 2008.

28. Peters, A., “E-mail to Salley, M.H., Re: Does the Navy use Incipient Fire Detection systems?” 2014. ADAMS Accession No. ML14211A409.

29. Fire Industry Association, “Code of Practice; Design, Installation, Commissioning and Maintenance of Aspirating Smoke Detector (ASD) Systems,” Issue 3, Middlesex, Hampton, England, 2012.

30. Meese, W., and R. Beausoliel, “Exploratory Study of Glowing Electrical Connections,” NBS Building Science Series 103, October 1977.

31. Babrauskas, V., “Mechanisms and Modes for Ignition of Low-Voltage PVC Wires, Cables, and Cords,” pp. 291-309 in Fire & Materials 2005, Interscience Communications Ltd., London (2005).

32. Keski-Rahkonen, O., J. Mangs, and A. Turtola, A., “Ignition of and fire spread on cables and electronic components,” VTT Building Technology, VTT Automation, Technical Research Centre of Finland, Espoo, 1999.

33. Babrauskas, V., “Ignition Handbook, Fire Science Publishers/Society of Fire Protection Engineers, Issaquah, WA, 2003.

34. Fernandez-Pello, A., et al., “A study of the Fire Performance of Electrical Cables,” pp. 237-247, Fire Safety Science, Proceedings of the third International Symposium (IAFSS).

35. Siu, N.O., et al., “Fire Risk Analysis for Nuclear Power Plants,” 2014. ADAMS Accession No. ML14084A314.

36. NRC and EPRI, “NUREG/CR-6850, EPRI 1011989, EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities,” 2005.

37. EPRI, “Fire PRA Methods Enhancements, Additions, Clarifications, and Refinements to EPRI 1019189,” Electric Power Research Institute, 2008.

38. Joseph M. Farley Nuclear Plant, NRC Inspection Report 05000348/2011-012 and 05000364/2011-012 and Preliminary White Finding, June 2011. ADAMS Accession No. ML111590912.

39. Joseph M. Farley Nuclear Plant, Final Significance Determination of a Green Finding (NRC Inspection Report 05000348/2011013 and 05000364/2011013), August 2011. ADAMS Accession No. ML112270513.

40. Licensee Event Report 1996-005-00, “Automatic Scram due to Turbine Vibration During Planned Power Reduction,” ADAMS Accession No. 9605280291.

41. Licensee Event Report 2014-001-00, “Manual Reactor Trip due to Indications of a Fire,” 2014. ADAMS Accession No. ML14078A320.

42. Event Notification 49249, “Alert Declared due to a switchgear explosion that supplies safe shutdown equipment,” 2013.

43. Roush, M., and W. Webb, “Applied Reliability Engineering,” Volume 2, 5th Edition, The Center for Reliability Engineering, University of Maryland, College Park, MD, 2006.

44. Underwriters Laboratories Inc., “Standard for Safety, Smoke Detectors for Fire Alarm Systems,” Sixth Edition, 2009.

45. NUREG-2169, EPRI 3002002936, “Fire Ignition Frequencies and Non-Suppression Probability Estimation Using the Updated Fire Events Database,” 2014.

46. EPRI, “The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance,” EPRI 1025284, Palo Alto, 2013.

47. Kirwan, B., and L.K. Ainsworth, “A guide to task analysis,” London, UK, p. 156, 1992.

48. NRC, “NUREG-1852, Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire,” 2007.

49. NRC and EPRI, “NUREG-1921, EPRI 1023001, EPRI/NRC-RES Fire Human Reliability Analysis Guidelines,” 2012.

50. NRC, “NUREG-700, Human-System Interface Design Review Guidelines,” Revision 2, 2002.

51. NRC, “NUREG/CR-6146, Local Control Stations: Human Engineering Issues and Insights,” 1994.

52. NRC, “NUREG-0711, Human Factors Engineering Program Review Model,” 2012.

53. NRC, “NUREG-800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition.”

54. NRC, “NUREG-1764, Guidance for the Review of Changes to Human Actions,” 2007.

55. NRC, “NUREG-1792, Good Practices for Implementing Human Reliability Analysis,” 2005.

56. Yerkes, R.M., Dodson, J.D., “The relation of strength of stimulus to rapidity of habit-formation,” *Journal of Comparative Neurology and Psychology* 18: pp. 459–482, 1908.

57. NRC, “NUREG-1624, Technical Basis and Implementation Guidelines for a Technique for Human Event Analysis (ATHEANA),” 2000.

58. NRC, “NUREG-1880, ATHEANA User’s Guide,” 2007.

59. NRC, “NUREG-1355, The Status of Recommendations of the President’s Commission on the Accident at Three Mile Island, A ten year review.”

60. ASME/ANS RA-Sa-2009, “Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,” The American Society of Mechanical Engineers, 2009.

61. NRC and EPRI, “NUREG/CR-6850 Supplement 1, EPRI 1019259, Fire Probabilistic Risk Assessment Methods Enhancements,” 2010.

62. NRC, “NUREG/CR-1278, Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications,” 1983.

63. EPRI, “An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment,” EPRI TR-100259, Palo Alto, CA, 1992.

64. NRC, “NUREG/CR-6883, The SPAR-H Reliability Analysis Method,” August 2005.

65. NRC, “NUREG/CR-4772, Accident Sequence Evaluation Program Human Reliability Analysis Procedure,” 1987.

APPENDIX A
VIEWGRAPHS FROM MEETING WITH ASD VENDORS

A.1 Summary of Meeting

On May 16, 2013, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research conducted a meeting between the three aspirating smoke detection (ASD) vendors whose equipment was tested. Staff from NRC, National Institute of Standards and Technology (NIST), and at least one technical representative from each ASD vendor were present. The purpose of this meeting was to inform the vendors of how their systems were being setup and tested, present how their systems may be used in fire probabilistic risk assessment applications, and to elicit feedback from the vendors on specific engineering design guidance regarding ASD systems for nuclear power plant applications. Additionally, discussion on equipment listings and approvals occurred. The morning portion of the meeting consisted of presentations given by NRC and NIST staff; these presentations are located in the NRC Agencywide Document Access and Management System (ADAMS), under Accession No. ML14356A581. The afternoon portion of the meeting consisted of open discussions among all participants.

APPENDIX B
SUPPORTING EXPERIMENTAL DATA

B.1 Alarm Times and Experimental Conditions and Sample images

A file naming convention was followed to distinguish the various experiments, data files, and image files, and it is described in Table B1. An example of this naming convention is "A_XLPE_5_E_2.1" which represents an (A) areawide test, using XLPE source material located in a 5-cabinet configuration, with (E) cabinet ventilation, a 1-hour nominal heating ramp and this is the (.1) first test.

Table B-1. File name convention

Alarm configuration	C: In-Cabinet; A: Areawide M: Multi-zone
Material	PVC1: PVC wire (1) PVC2: PVC wire (2) Teflon: PTFE wire Silicone: Silicone wire XLPO1: XLPO wire (1) XLPO2: XLPO wire (2) XLPE: XLPE wire CSPE: CSPE wire 1XLPE : Single XLPE wire 1wire: Single wire test 2wire: Dual wire test #Resistor: # of resistors Capacitor: 2 Capacitors PCB: Epoxy Printed Circuit Board PTB: Phenolic Terminal block
Cabinet configuration	L: Laboratory Instrument cabinet 1: Single cabinet 3:Three cabinets configuration 4: Four cabinets configuration 5:Five cabinets configuration B: Laboratory Bellefonte cabinet O: Center of the Room C: Corner (Small Room) RL: Rear Left corner (Large Room) FR: Front right corner (Large Room)
Test conditions	A:Top vents B:Side vents C: Room Ventilation D: Elevated Sample E: Cabinet Ventilation F: 7.4 ACH Room Ventilation G: 6.5 ACH Room Ventilation H: 14 ACH Room Ventilation
Heating rate	0 : Single Wire test: 60 second charge Dual Wire test: 90 seconds charge 1: 15 min nominal heating ramp 2: 1 hour nominal heating ramp 3: 4 hours nominal heating ramp 4: 15 min nominal ramp with extended hold period.
Test repeat #	

B.1.1 Raw Data File Header Descriptions

The following text describes the column header for the (raw) experimental data files for each set of experiments conducted:

Alarm Time Files—Laboratory Instrument and Large Cabinet Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the instrument cabinet .
PHOTO (1) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the instrument cabinet.
PHOTO (2) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
PHOTO (2) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
SS (3) Pre-alert -SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
SS (3) Pre-alert-SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
ION (4) Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
ION (4) C Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument cabinet.
Temperature at Humidity Probe (oC) – The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%)– Relative humidity (%) inside the instrument cabinet.
Temperature, Top cabinet (^{o}C) – Temperature (^{o}C) measurement, at the base of the Instrument cabinet.
Temperature, Bottom cabinet (^{o}C) - Temperature (^{o}C) measurement , at the ceiling of the Instrument cabinet.

Alarm Time Files – Small Room In-cabinet Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
PHOTO (1) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
ION (2) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the single cabinet.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the single cabinet.
SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
SS (3) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
PHOTO (4) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the four- cabinet configuration.
PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four-cabinet configuration.
ION (5) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four-cabinet configuration.
ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four-cabinet configuration.
ION (7) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
PHOTO (8) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.
PHOTO (8) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four-cabinet configuration.

SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.

SS (9) Alarm - SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet configuration.

ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

Temperature at Humidity Probe (oC)– The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.

Relative humidity (%) – Relative humidity (%) inside the test room.

Alarm Time Files – Small Room Areawide Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (1) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (2) Alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (2) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (3) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (4) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (5) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON Located on the ceiling.
SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON Located on the ceiling.
SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (7) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (8) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
PHOTO (8) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.
PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet configuration.

Temperature at Humidity Probe (oC)– The temperature (ºC) at the location of the humidity probe inside the instrument cabinet.

Relative humidity (%)– Relative humidity (%) inside the test room.

Alarm Time Files – Large Room Single-zone Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.
PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.
ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.

ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.

SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

Temperature at Humidity Probe (oC) – The temperature (^{o}C) at the location of the humidity probe inside the instrument cabinet.

Relative humidity (%) – Relative humidity (%) inside the test room.

TC1 – Not used

Alarm Time Files – Large Room Multi-zone Experiments

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
ASD4_Zone1_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 1.
ASD4_Zone1_Alert- ASD 4 system Alert relay (0 : OFF, 1 : ON) , located in zone 1.
ASD4_Zone1_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 1.
ASD4_Zone1_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON), located in zone 1.
ASD4_Zone2_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 2.
ASD4_Zone2_Alert- ASD 4 system Alarm relay (0 : OFF, 1 : ON) , located in zone 2.
ASD4_Zone2_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 2.
ASD4_Zone2_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON) , located in zone 2.

ASD4_Zone3_Alarm- ASD 4 system Fire 3 alarm relay (0 : OFF, 1 : ON), located in zone 3.
ASD4_Zone3_Alert- ASD 4 system Fire 2 alarm relay (0 : OFF, 1 : ON) , located in zone 3.

ASD4_Zone3_I1- ASD 4 system Fire 1 alarm relay (0 : OFF, 1 : ON) , located in zone 3.
ASD4_Zone3_Pre-alert- ASD 4 system Pre-alarm relay (0 : OFF, 1 : ON) , located in zone 3.

ASD4_Zone4_Alarm- Not used
ASD4_Zone4_Alert- Not used
ASD4_Zone4_I1- Not used
ASD4_Zone4_Pre-alert - Not used
ASD4_Fault - ASD 4 system Fault relay (0 : OFF, 1 : ON)
ASD5_Global_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), for all 3 zones (global.)

ASD5_Global_Alarm- ASD 5 system Fire 1 alarm relay (0 : OFF, 1 : ON), for all 3 zones (global.)
ASD5_Global_C Alarm- ASD 5 system Fire 2 alarm relay (0 : OFF, 1 : ON), for all 3 zones (global.)
ASD5_Zone2_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 2.
ASD5_Zone2_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Zone3_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 3.
ASD5_Zone3_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Zone1_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 1.
ASD5_Zone1_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

ASD5_Fault- ASD 5 system Fault relay (0 : OFF, 1 : ON)
FACP Alarm - Fire alarm control panel alarm relay (0 : OFF, 1 : ON)
FACP Trouble - Fire alarm control panel trouble relay (0 : OFF, 1 : ON)
SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.
ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.

PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.

PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front right corner of the room.

ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right corner of the room.

PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left corner of the room.

ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left corner of the room.

ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.

ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.

ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet configuration.
SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet configuration.
Temperature at Humidity Probe (oC)– The temperature (ºC) at the location of the humidity probe inside the instrument cabinet.
Relative humidity (%) – Relative humidity (%) inside the test room.

Bus Bar Heater File (Files ending with _T)

Column 1 - CPU time (Hour : Minute : Seconds)
Column 2 - Counter (s)
Column 3 – Set point temperature (ºC)
Column 4 – Actual Bus Bar temperature (ºC)

Room Temperature File (Files ending with _RT)

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
TC 1 - Temperature (ºC) in the center of the room, 2.54 cm below the ceiling.
TC 2 - Temperature (ºC) in the center of the room, 5.08 cm below the ceiling.
TC 3 - Temperature (ºC) in the center of the room, 7.62 cm below the ceiling.
TC 4 - Temperature (ºC) in the center of the room, 0.31 m below the ceiling.
TC 5 - Temperature (ºC) in the center of the room, 0.61 m below the ceiling.
TC 6 - Temperature (ºC) in the center of the room, 0.914 m below the ceiling.
TC 7 - Temperature (ºC) in the center of the room, 2.13 m below the ceiling.
TC 8 - Ceiling temperature (ºC) in the corner of the room.
TC 9 - Ceiling temperature (ºC) in the corner of the room.
TC 10 - Ceiling temperature (ºC) in the corner of the room.
TC 11 - Ceiling temperature (ºC) in the corner of the room.
TC 12 - Room ventilation inlet temperature (ºC).
TC 13 - Room ventilation outlet temperature (ºC).

Wire Thermocouples (Files ending with _WT)

Time - CPU time (Hour : Minute : Seconds)
Count - Loop time increment (s)
TC 1 (X mm)- Thermocouple #1 located X mm form the bus bar.
TC 2 (X mm)- Thermocouple #2 located X mm form the bus bar.
TC 3(X mm)- Thermocouple #3 located X mm form the bus bar.
TC 4(X mm)- Thermocouple #4 located X mm form the bus bar.

B.1.2 Sample before and after experiment images

Before and after sample images use the file naming convention appended with “Before” or “After”. Sequences of thermal images at fixed time intervals are given in folders labeled using the file naming convention appended with “TI”. The name of each thermal image corresponds to the time in minutes at which it was taken.

Table B2. Exemplar image file names for materials tested.

Material	Heating ramp	Before and after images	Thermal images folder
PVC wire (1)	15 min	N/A	C_PVC1_L_B_1.1_TI
	1 hour	C_PVC1_L_B_2.3_Before C_PVC1_L_B_2.3_After	C_PVC1_L_A_2.1_TI
PVC wire (2)	15 min	C_PVC2_L_A_1.2_Before C_PVC2_L_A_1.2_After	C_PVC2_L_B_1.1_TI
	1 hour	C_PVC2_L_B_2.2_Before C_PVC2_L_B_2.2_After	C_PVC2_L_A_2.1_TI
	4 hours	N/A	C_PVC2_L_B_3.1_TI
Silicone wire	15 min	C_Silicone_L_A_1.2_Before C_ Silicone_L_A_1.2_After	C_Silicone_L_B_1.1_TI
	1 hour	C_Silicone_L_B_2.3_Before C_ Silicone_L_B_2.3_After	C_Silicone_L_A_2.1_TI
PTFE wire	15 min	C_Teflon_L_A_1.2_Before C_Teflon_L_A_1.2_After	C_Teflon_L_B_1.1_TI
	1 hour	C_Teflon_L_B_2.2_Before C_Teflon_L_B_2.2_After	C_Teflon_L_A_2.1_TI
XLPO wire (1)	15 min	C_XLPO1_L_A_1.2_Before C_XLPO1_L_A_1.2_After	C_XLPO1_L_B_1.1_TI
	1 hour	C_XLPO1_L_B_2.2_Before C_XLPO1_L_B_2.2_After	C_XLPO1_L_A_2.1_TI
XLPO wire (2)	15 min	C_XLPO2_L_A_1.2_Before C_XLPO2_L_A_1.2_After	C_XLPO2_L_B_1.1_TI
	1 hour	C_XLPO2_L_B_2.2_Before C_XLPO2_L_B_2.2_After	C_XLPO2_L_A_2.1_TI
	4 hours	C_XLPO2_L_A_3.1_Before C_XLPO2_L_A_3.1_After	C_XLPO2_L_A_3.1_TI
XLPE wire	15 min	C_XLPE_L_A_1.3_After	C_XLPE_L_B_1.1_TI
	1 hour	C_XLPE_L_B_2.2_Before C_XLPE_L_B_2.2_After	C_XLPE_L_A_2.1_TI
	4 hours	N/A	C_XLPE1_L_B_3.1_TI
CSPE wire	15 min	C_CSPE_L_A_1.2_Before C_ CSPE_L_A_1.2_After	C_CSPE_L_B_1.1_TI
	1 hour	C_CSPE_L_B_2.2_Before C_ CSPE_L_B_2.2_After	C_CSPE_L_A_2.1_TI
Epoxy Printed Circuit Board	15 min	C_PCB_L_A_1.2_Before C_PCB_L_A_1.2_After	C_PCB_L_B_1.1_TI
	1 hour	C_PCB_L_A_2.2_Before C_PCB_L_A_2.2_After	C_PCB_L_A_2.1_TI
	4 hours	C_PCB_L_B_3.1_Before C_PCB_L_B_3.1_After	C_PCB_L_B_3.1_TI
Phenolic Terminal block	15 min	C_PTB_L_A_1.2_Before C_PTB_L_A_1.2_After	C_PTB_L_B_1.1_TI
	1 hour	C_PTB_L_B_2.2_Before C_PTB_L_B_2.2_After	C_PTB_L_A_2.1_TI
	4 hours	N/A	C_PTB_L_B_3.1_TI
Single XLPE wire	1 hour	N/A	C_1XLPE_L_A_2.1_TI

B.2 Smoke Aerosol Measurements

Instrumentation descriptions

Aerosol characterization equipment included an electrical low pressure impactor (ELPI) (Dekati, ELPI) to record aerosol concentration and size distribution, a condensation particle counter (CPC, TSI Model 3775) to provide the aerosol number concentration, an electrical aerosol detector (EAD, TSI Model 3007) to provide a measure of the sum of particle diameters, and a tapered element oscillating microbalance (R&P Inc. TEOM Model 1105) to record aerosol mass concentration.

The ELPI consists of a 13-stage multi-orifice, low-pressure impactor that classifies particles according to their aerodynamic size (equivalent diameter unit density sphere). A schematic diagram of the instrument is shown in Figure B1. Beginning at the first stage, particles of a narrow size range (defined by a cut-off size, $d_{50\%}$, where 50 percent of particles of a given size are collected) impact on that stage's collection plate, while smaller particles move on to the next stage. The process repeats itself until the last stage is reached. The particle concentration below 0.03 μm is not measured, thus the size distribution is truncated. This may affect concentration and average size measurements, and the instrument results are subject to this bias.

The particles are separated according to their inertial properties, thus sizes are reported in terms of the diameter of unit density spheres with the same inertial properties, termed the aerodynamic diameter. The flow through the instrument is 10 l/min. Typically, cascade impactors rely on a gravimetric determination of the number of particles collected on any stage, thus the sampling time must be sufficient to gather a weighable amount of material on each stage. This impactor is unique in that it detects particles that impact the different stages by measuring the charge transferred to the stage from the elemental charges carried by the particles. Aerosol particles will achieve a statistically average charge level based on particle diameter, initial charge state, and exposure to charging mechanisms.

The ELPI conditions the aerosol to such a state by a two-step process. The initial charge state is forced to an equilibrium, Boltzmann charge distribution by passing the aerosol through a charge neutralizer (external to the ELPI). Then, a high-voltage corona wire unipolar charger puts known excess charge on the aerosol particles based on their size and the residence time the aerosol remains in the charging section. Excess ions and very small, charged particles are removed by an ion trap just past the charger. Each impactor stage, (excluding the first, which removes particles with aerodynamic diameters larger than 10 μm) is electrically isolated and connected to an electrometer. As aerosol particles impact on the various stages, they transfer their charges and a current is measured. Based on the current measurement, the impactor stage cut-off sizes, flow through the instrument, and the relationship between the particle size and average charge, the number of particles that impact each stage is computed and the number size distribution is characterized. The number distribution can be converted into diameter, surface area, or mass distribution, etc., and the total number, or mass (assuming spherical unit density particles) can be computed.

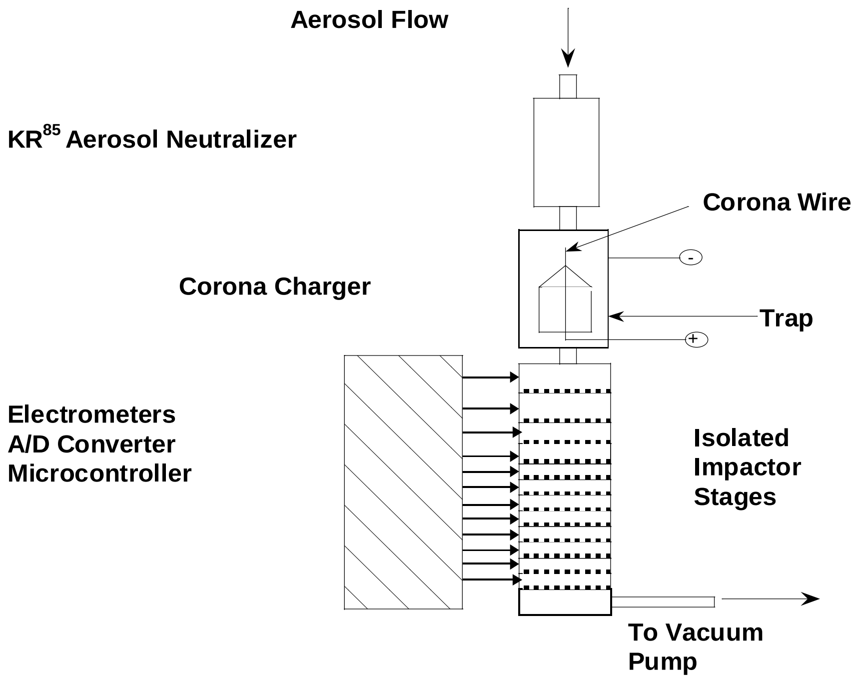


Figure B1. Schematic diagram of the electrical low pressure impactor

Table B3 shows the impactor stage cut-off sizes and the geometric mean of the size range of particles collected on a given stage, d_i, for standard impaction plates covered with aluminum foil.

Table B3. ELPI Imactor Plate Cutoff and Median Diameters

Impactor Stage	Standard Impactor Plates	
	Aerodynamic $d_{50\%}$ (μm)	Aerodynamic d_i (μm)
1	0.0280	0.0395
2	0.0557	0.0727
3	0.0948	0.122
4	0.157	0.203
5	0.263	0.317
6	0.383	0.485
7	0.615	0.764
8	0.950	1.23
9	1.60	1.96
10	2.40	3.10
11	4.00	5.18
12	6.70	8.16
13	9.93	-

If density is known, then the aerodynamic diameter can be replaced with the Stokes diameter, defined as the diameter of a sphere with the same density and settling velocity of the particle. The analysis of the ELPI data takes into account known aerosol particle densities. For the unknown aerosol densities of the smoke generated from material degradation, a density of 1.00 g/cm^3 is assumed, but this adds to the uncertainty of the results for the aerosol concentrations and size distribution.

The CPC can detect and count particles 4 nm in diameter and larger up to number concentrations of 1×10^7 #/cm^3. The CPC draws aerosols into a heated saturator where alcohol vapor and the aerosol mix; this particle/vapor mixture then flows to a condensing section where the vapor becomes superheated and condenses on the aerosol particles greater than 4 nm. The particles grow rapidly to large individual particles that are counted optically. In that respect, the detection principle of the CPC is similar to a cloud chamber aspirating smoke detector (ASD). The CPC combined relative uncertainty is better than ±10 of the reading.

The EAD measures an aerosol concentration referred to as the total aerosol length, equal to the sum of the diameter of all particles in a unit volume. This quantity is also referred to as the first moment of the size distribution (the number concentration is the zero-th moment). In the EAD, particles flow into a charging section where positive ions accumulate on particles to a net charge state proportional to the particle diameter. An aerosol electrometer measures the net charge, which is proportional to the total aerosol length. The combined relative uncertainty in the EAD measurement is typically better than ±10 of the reading.

The TEOM is a direct measure of the mass concentration of an aerosol. The sampled aerosol with a fixed volumetric flow is passed through a vibrating filter that accumulates the aerosol particles. The vibration frequency is proportional to the mass of the filter. The frequency is measured as a function of time, and with the volumetric flow rate, the mass concentration is computed. The TEOM combined standard uncertainty is ±0.5 mg/m^3.

Properties of the size distribution of interest include the first moment of the number distribution with the mean size defined as the arithmetic mean diameter (AMD), given by

$$AMD = \frac{\sum(n_i \cdot d_i)}{N} \tag{B-1}$$

where n_i is the number of particles of size group d_i, and N is the total number of particles. The first moment correlates with the response of the ionization chamber in smoke detectors. Another property of interest is the mass (or volume) distribution, which is a better predictor of the response of light-scattering, photoelectric alarms than the diameter distribution. The third moment of the size distribution can be represented by the total mass, M (or volume) with a mass mean diameter (d_{mm}), given by

$$d_{mm} = \frac{\sum(m_i \cdot d_i)}{M} \tag{B-2}$$

where m_i is the number of particles of size group d_i, and M is the mass of all particles. Comparing these two mean diameters gives a sense of the width of the size distribution. If both AMD and d_{mm} are the same the particles are of a single size (monodisperse) while an increasing difference between the two diameters indicates ever broadening distribution. For log-normally distributed aerosols with an AMD of 0.100 µm and geometric standard deviations (σ_g) of 1.30 and 1.70, the $d_{mm}$is 0.123 µm and 0.233 µm respectively.

The diameter of average mass can be computed if the mass and number concentration are known using equation 3.

$$d_{am} = \left(\frac{6M}{\rho\pi N}\right)^{1/3} \qquad \text{B-3}$$

B.2.1 Instrument Cabinet Experiments

Experiments were conducted using a condensation mono-disperse aerosol generator (CMAG, TSI Model 3475), an instrument that can produce high concentrations of narrow size distribution aerosols from 0.1 µm up to 8 µm in diameter, and a Gemini smoke detector tester aerosol generator, which produces aerosol designed to mimic smolder smokes. The CMAG produces particles from Di-Ethyl-Hexyl-Sebacate (DEHS, density of 0.912 g/cm^3), while the smoke detector tester produces particles from mineral oil (density of 0.85 g/cm^3).

Aerosols from the CMAG or smoke detector tester were introduced into the cabinet from a tube located at the cabinet floor and pointing up. The aerosol was sampled from the ceiling of the instrument cabinet and directed to the ELPI. Experiments were conducted with 9 different settings on the CMAG, and one base setting on the smoke detector tester. Data for the experiments are located in the spreadsheet files labeled {Instrument cabinet CMAG and Gemini exps} and {Test_aerosol_ELPI}. The first file contains the ASD alarm times and the end of test number and mass concentrations, and arithmetic mean diameter and diameter of average mass, while the second file contains the number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time.

The arithmetic mean particle size at the end of the test for the CMAG experiments ranged from 0.12 µm to 0.82 µm, depending on the CMAG settings, and 0.33 µm for the smoke detector tester aerosol. In only one CMAG setting did ASD2 (cloud chamber type) respond at alert or alarm settings, and in fact, only pre-alerted in one other CMAG setting. The light-scattering ASDs tended to respond at all CMAG settings. The smoke detector tester aerosol triggered all light-scattering response levels, while the cloud chamber ASD responded at the level between pre-alert and alert consistently. These results show the response to various concentrations of given particle size distributions, but by themselves do not indicate effectiveness, nor appropriateness for a given application.

An example of the ELPI data is shown below in Figures B2 and B3. The aerosol concentration curves are proportional to each other since the size distribution of the CMAG aerosol does not change much with time. The mean size fluctuates before the arrival of the CMAG aerosol at the sampling port because of the low concentration background (room) aerosol. The mean diameters show a slight growth trend over time, which may be caused by the aerosol generator, or aging of the aerosol at the ceiling of the cabinet.

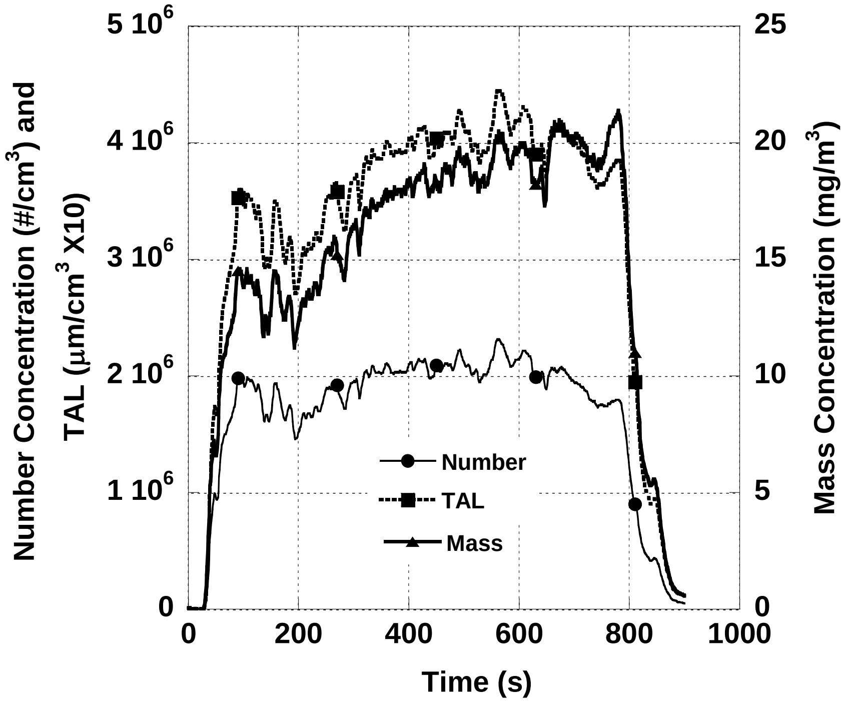


Figure B2. ELPI aerosol concentrations for CMAG experiment 40.

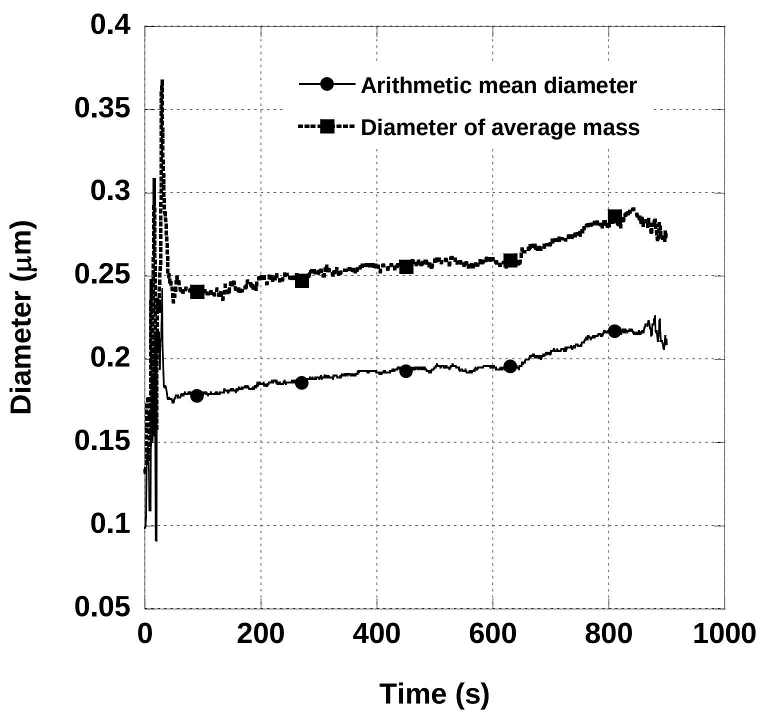


Figure B3. ELPI aerosol diameters for CMAG experiment 40.

B.2.1.2 Degraded materials

Almost all experiments conducted in the instrument cabinet with the degrading materials were monitored with the ELPI. The spreadsheet labeled {Instrument_cabinet_ELPI} contains the ELPI results number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time. Figures B4-B9 show ELPI 60.0 min HRP results for XLPE, PVC(2), and CSPE samples.

Additional experiments were conducted in which the smoke sampled from the aerosol sampling port was directed to the CPC, EAD and TEOM as alternate direct measurements of number concentration, total aerosol length, and mass concentration. The materials examined were limited to XPLE, PVC(2) and CSPE at HRPs of 15.0 min and 60.0 min, and overheated resistors. The spreadsheet labeled {Instrument_cabinet_moments} contains the measurement results and the bus bar heating measurements for those experiments.

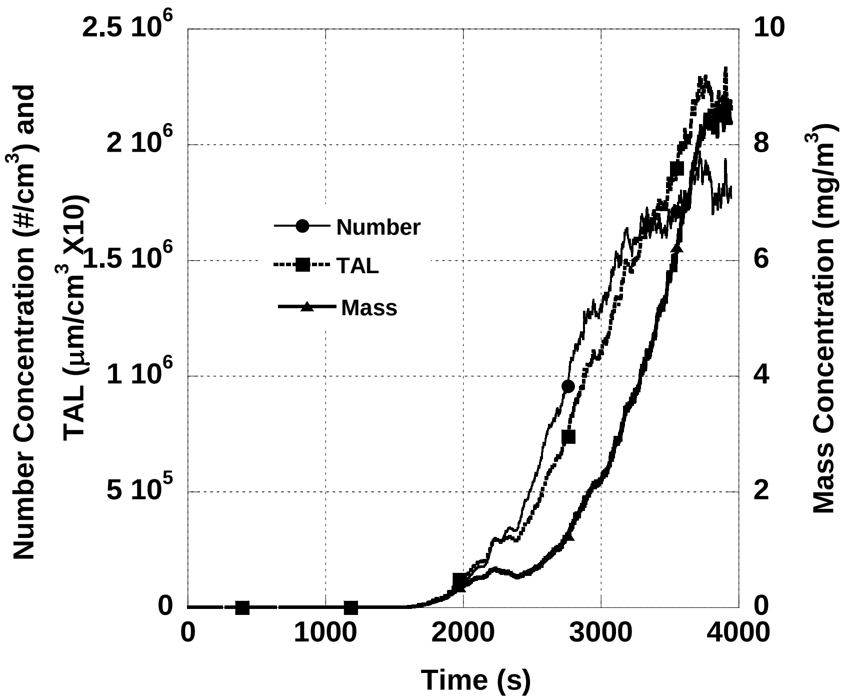


Figure B4. ELPI aerosol concentration for XLPE and 60.0 minute HRP.

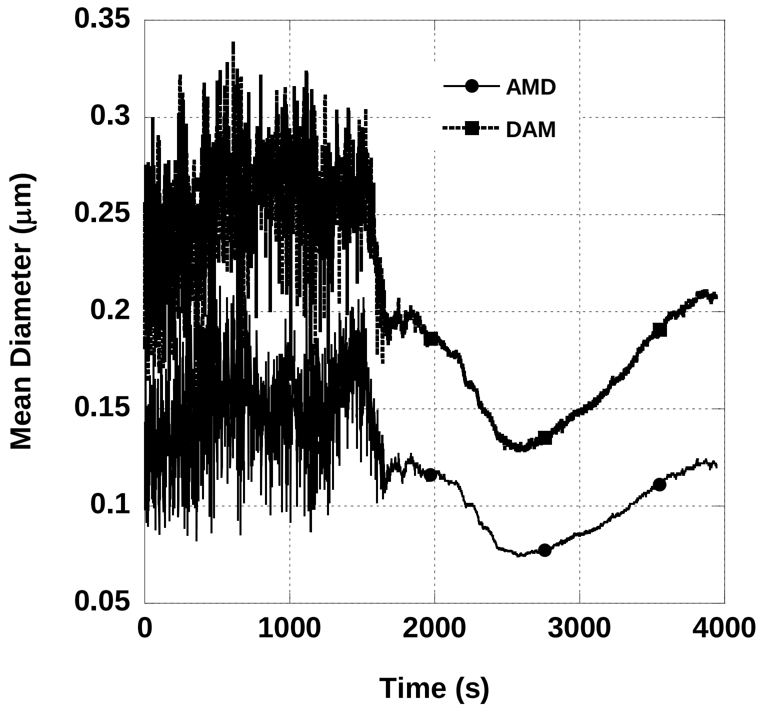


Figure B5. ELPI mean particle diameters for XLPE and 60.0 minute HRP.

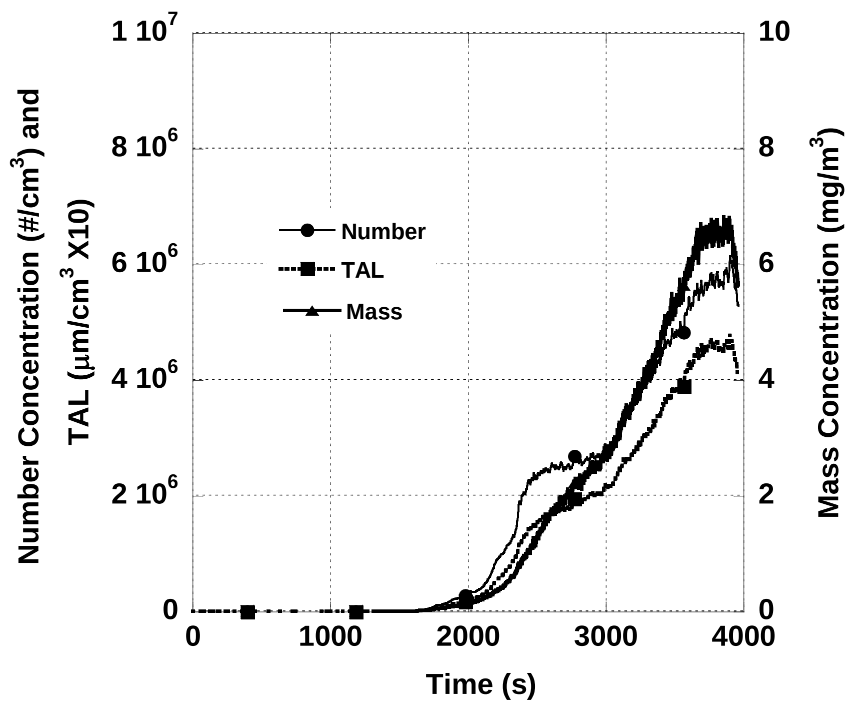


Figure B6. ELPI aerosol concentration for PVC(2) and 60.0 minute HRP.

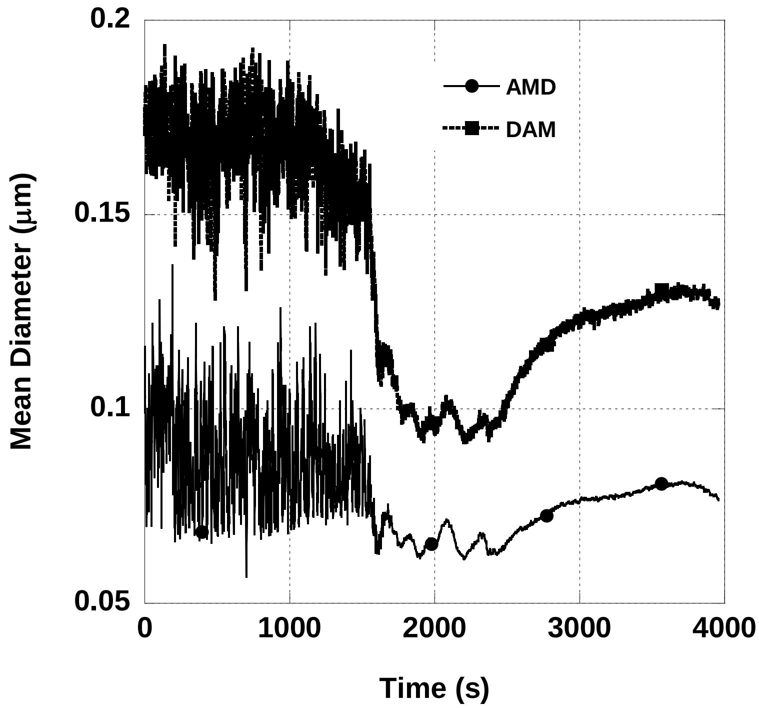


Figure B7. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP

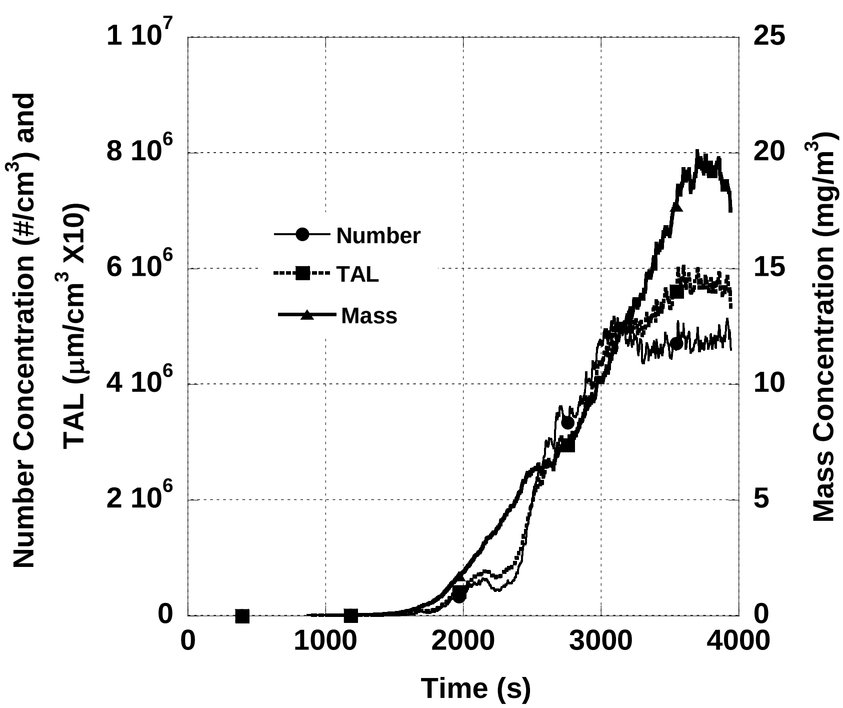


Figure B8. ELPI aerosol concentration for CSPE and 60.0 minute HRP.

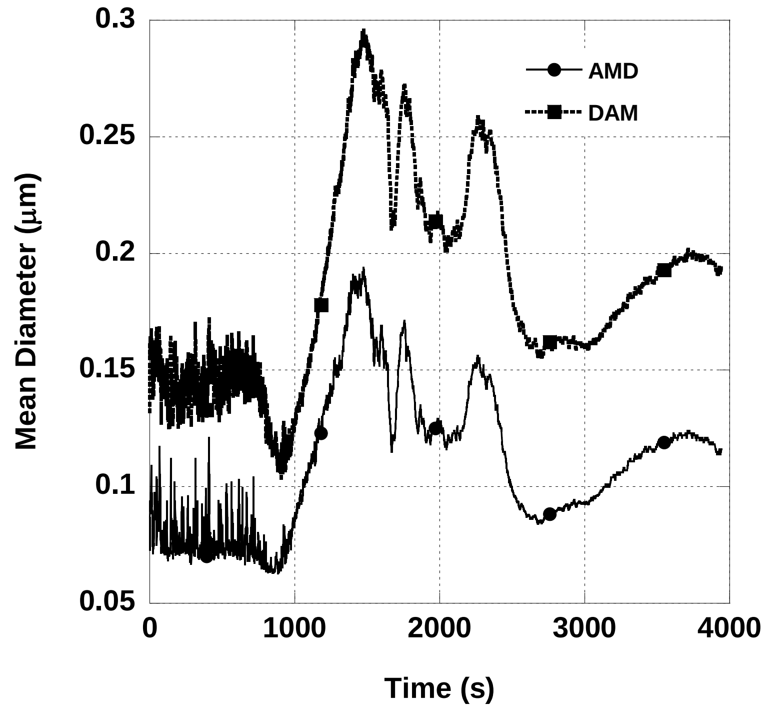


Figure B9. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP

B.2.2 Large Cabinet

During the large cabinet experiments, smoke was sampled from the top of the cabinets and directed to the ELPI. Data was collected for the 16.3 and 65.0 minute HRP experiments for XLPE, PVC(2), CSPE, and PCB materials, and for 260 minute HRP experiments for XLPE and CSPE materials. Experiments were conducted with XLPE and CSPE samples in which the HRP was reduced to achieve a lower bus bar temperature, and the hold time was increased so the EOT times, 21.3 and 70 minutes, were the same. In addition, BS 6266 1 meter wire tests were conducted. The spreadsheet labeled {Large_cabinet_ELPI} contains the ELPI results number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter and diameter of average mass values as functions of time.

Figures B10 – B13 show the aerosol concentration results for naturally ventilated cabinets and XLPE and CSPE experiments, with the normal 16.3 minute HRP and shorter HRPs to set points of 325 degrees C and 225 degrees C, respectively.

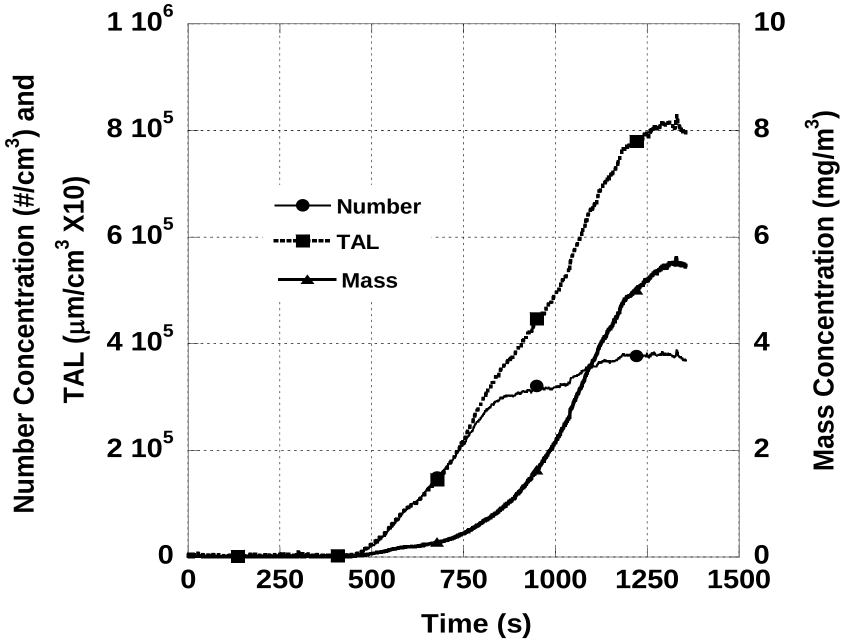


Figure B10. **Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and 16.3 minute HRP.**

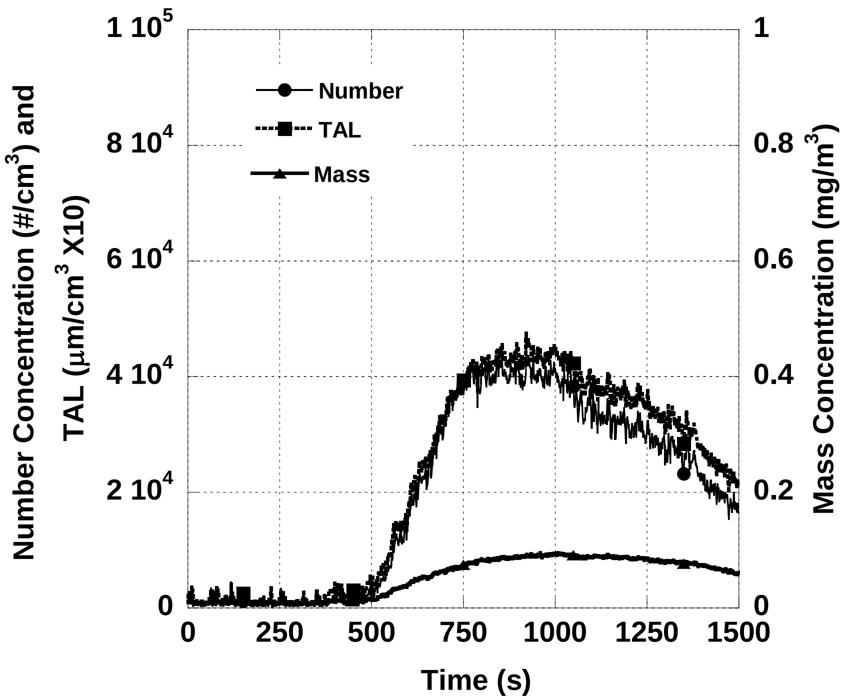


Figure B11. **Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and 10.5 minute HRP to a set point of 325 ˚C and held until 21.3 min.**

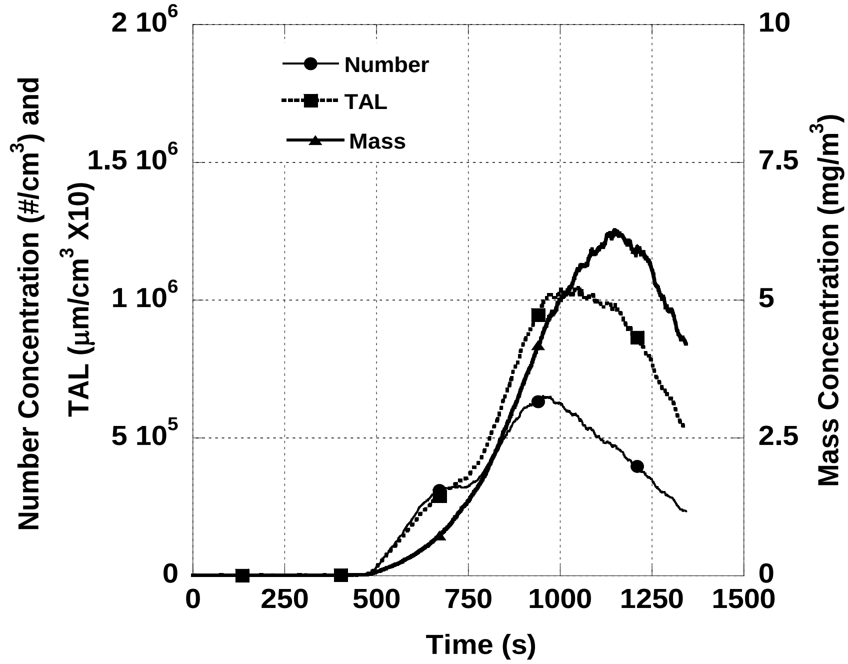


Figure B12. Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE and 16.3 minute HRP.

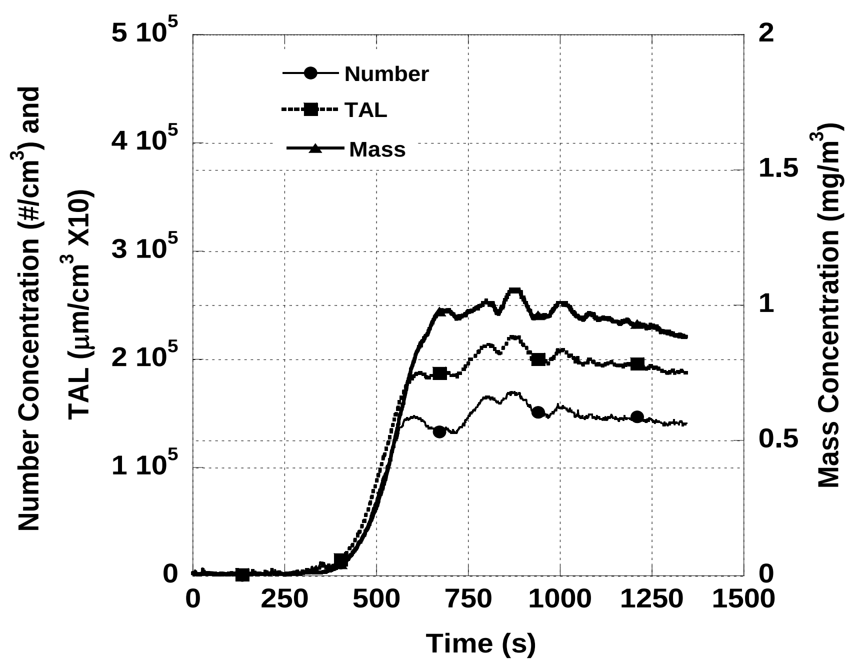


Figure B13. Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE and 7.9 minute HRP to a set point of 250 °C and held until 21.3 min.

B.3 Supplemental Data Supporting Objective E

Figures B-14 and B-15 present the in-cabinet, naturally ventilated data for the 15 minute and 4-hour HRP, respectively. These figures show the detectors' time of response ("alert" for VEWFD systems and "alarm" for conventional spots). This data shows trends similar to the data presented in Figure 5-49.

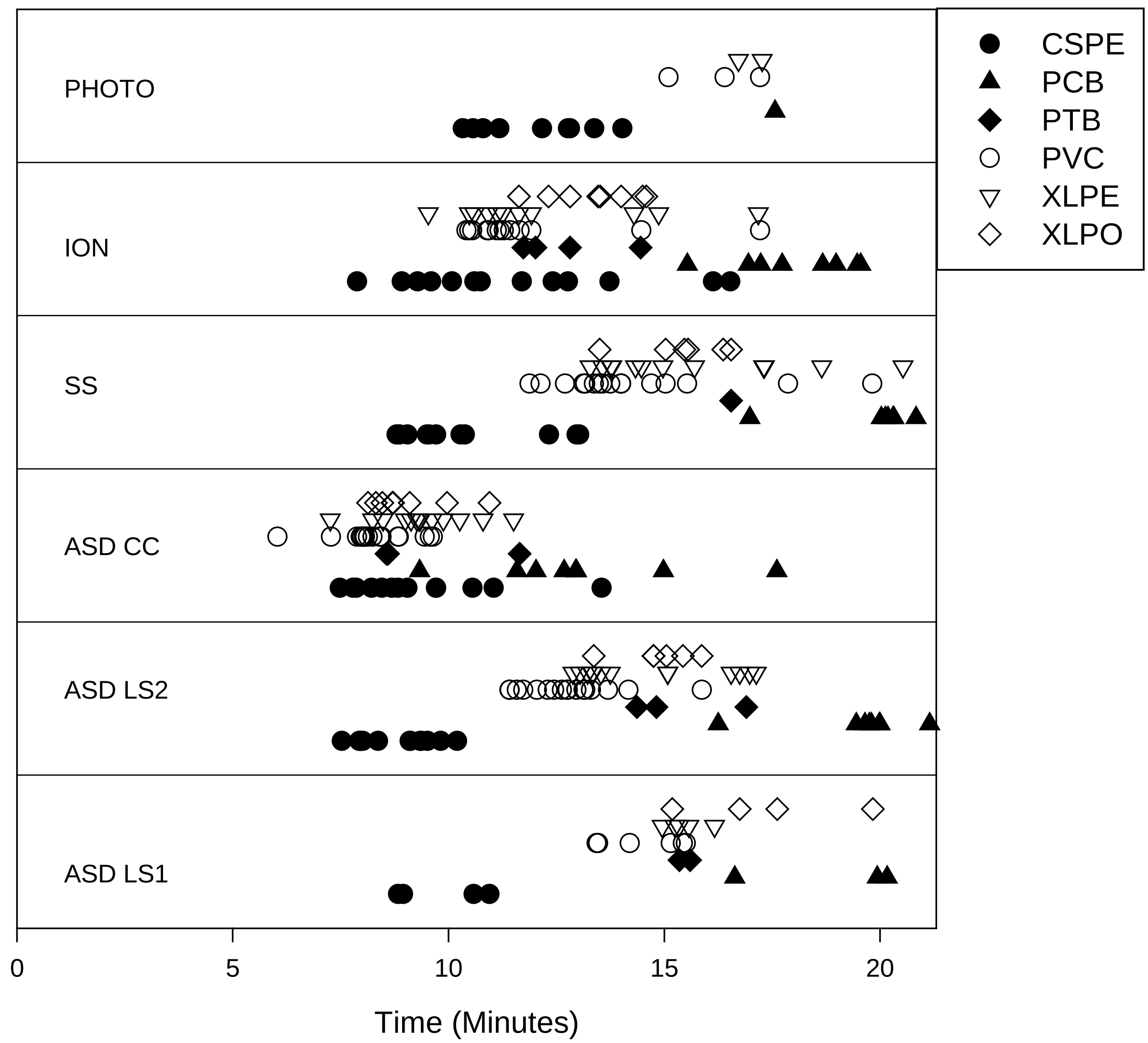


Figure B-14. Detector response to selected materials (15 minute HRP) in-cabinet, natural cabinet ventilation

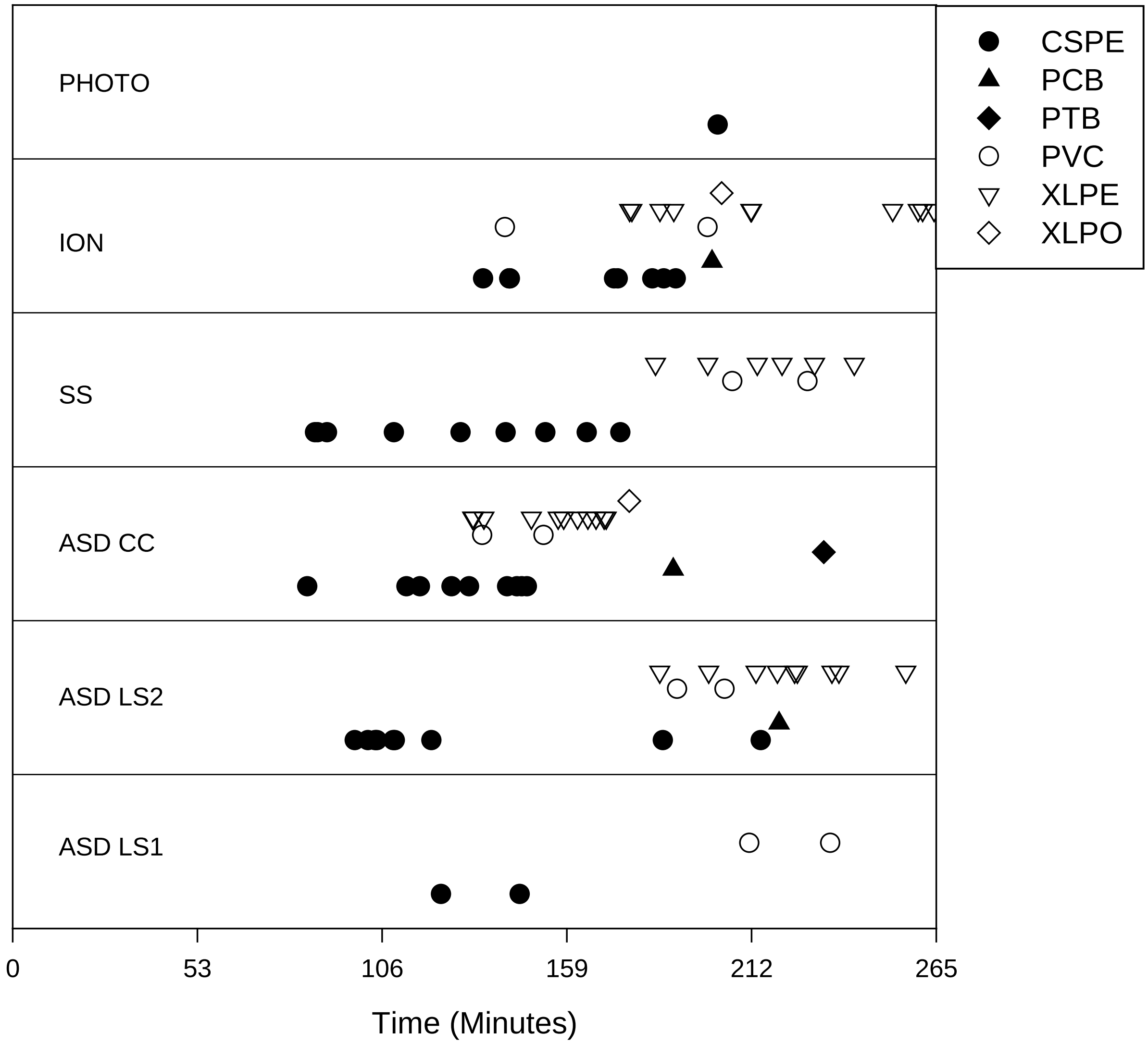


Figure B-15. Detector response to selected materials (4-hour HRP) in-cabinet, natural cabinet ventilation

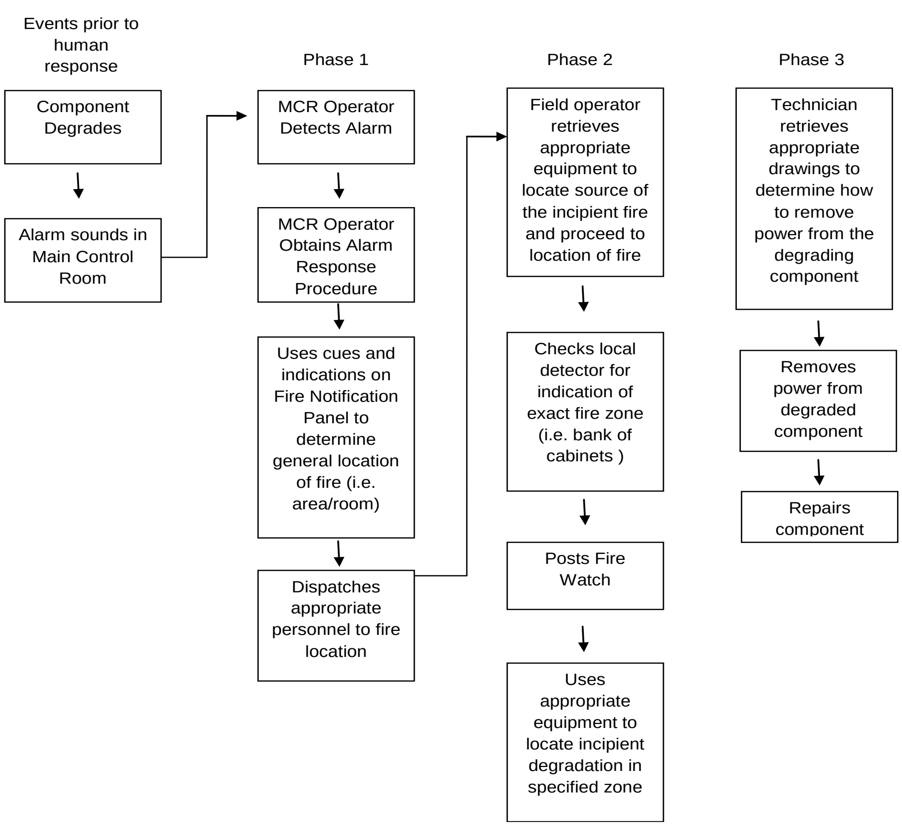
APPENDIX C
SUPPORTING INFORMATION FOR HUMAN PERFORMANCE EVALUATION

C.1 Human Factor/Human Reliability Analysis Evidence Database

This section provides documentation related to questions and answers received during the course of this project. After each entry, an application designator will appear, which are defined as follows:

IC – in-cabinet application
MCR – main control room application
AW – areawide application

C.1.1 Response Operations: Questions and Answers[37]



[37] This set of questions was used to obtain information from 2 NPPs. One NPP provided written responses, the other through a teleconference.

The previous chart (in C.1.1.) depicts an in-cabinet very early warning fire detection system (VEWFDS) alarm response operation. It is not specific to any one plant and represents a generic case. The alarm response operations are represented here in three phases. The authors categorized the responses into three different phases because each phase is completed by different groups of personnel.

The authors recognize that there will be variations in alarm response operations. The aim is to capture examples in which operations may vary from those depicted herein. In addition, some specific questions regarding individual processes are noted below:

Operations Questions

1. Is there immediacy associated with VEWFDS alarm response? In other words, is the alarm treated like any other fire alarm? If not, how is it different?

   Plant X: Yes, if an alert comes in, an operator and instrumentation and control (I&C) tech are sent. If an alarm, the operator and tech are sent along with the fire brigade. If a system trouble annunciator comes in, an operator is sent out. Alarm does not necessarily indicate a flaming fire. The response associated with an incipient alert/alarm is the same as for spot detectors. First, the MCR dispatches an operator, not the fire brigade, as in a VEWFDS alert. If additional signs/signals of fire are detected, then the fire brigade is sent, similar to when a VEWFDS alarm comes in. Regarding immediacy, fire alarms of any kind trump other activities, so a response from operators comes within seconds. Only a reactor trip would trump a fire alarm. (IC)

   Plant Y: Field operator dispatched immediately. (IC)

   a. Are the VEWFDS systems set to have alerts and alarms? If so, how many of each?

      Plant X: Set to have one alert and one alarm (also real-time graphic read-out of sampler) (IC)

      Plant Y: Yes there is an alert and an alarm. Alerts are at 20 percent above background and alarms at 50 percent above. (IC)

   b. Are alerts, alarms and system trouble differentiated on the annunciator panel?

      Plant X: Yes. (IC)

      Plant Y: Yes, three annunciators on front panel. (IC)

   c. If both alerts and alarms are used, how does the response differ?

      Plant X: If an alert comes in an operator and I&C tech are sent. If an alarm, the operator and tech are sent along with the fire brigade.

      Plant Y: No difference in response, field operator will be immediately dispatched to investigate either

2. Where is the alarm located in the control room (e.g. front panel/back panel)?

Plant X: All three annunciators are on the front panel.

Plant Y: Front panel.

3. Where is the fire notification panel located?

Plant X: A computer screen located on shift technical advisor (STA) desk. The screen is separate from other screens and is dedicated to fire. A reactor operator (RO), senior reactor operator (SRO), or STA can look at this. Either SRO will look or he or she will assign someone to look (as STA will not be in MCR when this annunciator goes off).

Plant Y: Close to shift managers desk

4. What personnel are dispatched by MCR operators (e.g. just field operator, field operator and digital instrumentation and controls (DI&C) technician)?

Plant X: Field operator and DI&C technician

Plant Y: Field operator only

a. Are the necessary staff available 24/7? If not, what are the contingency actions (e.g., DI&C tech called in)? How do contingency actions affect the timing of the response?

Plant X: Yes, including I&C tech. One is required at the plant at all times. Probably more than one during the day shift.

Plant Y: Field operator available 24/7.

5. What equipment is used to locate source of incipient fire (e.g. sniffer, thermal imaging camera)?

Plant X: Portable sniffer—tested weekly.

Plant Y: Portable sniffer.

a. If a thermal imaging camera is used, are baseline heat mappings of each cabinet available to compare with current conditions? If so, is comparison done at the scene of incipient fire or is additional analysis involved (e.g., software package needed to compare conditions)?

Plant X: Thermal cameras are not used.

Plant Y: Not applicable.

b. What is the reliability and sensitivity of the sniffer technology?

Plant X: Tested weekly.

Plant Y: Not specifically known, but probably similar to fixed installation as it is the same type of equipment.

6. How many cabinets are typically part of the same zone?

Plant X: It varies, from one to nine cabinets. There are typically sampling ports in each cabinet. The cabinets are partitioned and sealed.

Plant Y: Between 5 and 15 cabinets

7. Is the posted fire watch a permanent or roaming fire watch? If it is roaming, how frequently is the site observed?

Plant Y: Continuous fire watch until event is concluded. Fire watch personnel are prevented from leaving the post; they cannot go through keycard door.

Plant X: Permanent fire watch following alert or alarm until situation resolved.

a. Is the dispatched field operator also considered the initial fire watch? If yes, what training is required to qualify as a fire watch (e.g., ability to use fire extinguisher, fire brigade training)?

Plant X: Yes. All (i.e., 100 percent) AO's have "fire watch incipient" training. About 95 percent of FOs are fire brigade qualified. All FOs are qualified as incipient fire watch; (this was added training, includes fire extinguisher use).

Plant Y: Yes. All operators trained in use of fire extinguishers, fire watch, and most are fire brigade members.

8. What type of training is given to operators for using sniffers and thermal imaging cameras?

Plant X: Training—initial, continuing training cycle every 2 years, sit down instructional and practical at end, about 4-hour training. Practical training includes finding a "smoking" wire; no timing data collected on this aspect of training.

Plant Y: Training not implemented as of yet, but expect that all operators will have specific training (with qualification sign-off) in use of sniffers as part of basic operator training.

9. Are cabinets opened when using the portable sensing equipment, or is it used with the doors closed?

Plant X: It depends on the zone to which personnel are responding. If it is a multi-cabinet zone, personnel start by sniffing the outside of cabinets to determine which specific cabinet it is. The identified cabinet is then opened to find the component. If it is a one-cabinet zone, the cabinet is opened. These actions are training-based.

Plant Y: Yes.

10. Is the stopping point for receiving credit at the point of posting a fire watch, at the point of de-energizing the panel, or at time of repair?

Plant X: Assumption is made that 90 percent of incipient fires will be prevented and, specifically, the fire watch will prevent the incipient fire from having an affect beyond the ignition site.

Plant Y: National Fire Protection Association (NFPA) 805 Fire PRA credits incipient detection as a means of detecting fire before propagation from cabinet. No credit is taken for de-energizing or repairing affected component, or preventing loss of cabinet function.

11. How often are VEWFDS down for service? How often are false alarms experienced?

Plant X: Annual maintenance requires system to be out-of-service for half a day. Overall, Plant X is not seeing many unplanned shutdowns.

False alarms caused by ongoing work. Personnel usually know about this work and can take detector out-of-service and post a fire watch. One detector alarms more often than others; it is not necessarily false-alarm, but rather, a bit too sensitive. The alarm often does not “lock in.” They are correcting this by changing the sensitivity settings. (IC)

Plant Y: No operating experience as yet.

Timing Questions

12. Do you have any information regarding timing from the VEWFDS alarm sounding to a flaming fire?

Plant X: Yes, 2 hours and 42 minutes from alert to flaming fire on August 8, 2013.

Plant Y: No plant specific experience as yet.

13. What is the average time from the alarm sounding in the MCR to the dispatch of field personnel?

Plant X: Immediately. The operator closest to location is dispatched.

Plant Y: Based on normal fire alarm response—Immediate

14. What is the average timing between the field operator receiving the dispatch call and arriving at the fire location?

Plant X: Varies, but typically, 2 to 8 minutes. I&C tech are typically a few minutes behind auxiliary operator (AO).

Plant Y: Usually 3 to 4 minutes for field operator; 15 minutes or less for brigade response.

15. What is the average time for the field tech to locate the degraded component using the portable equipment?

Plant X: No empirical information available. A single cabinet zone would require a few minutes to narrow down which component.

a. How does the zone size affect this timing (three cabinet zone vs. 10 cabinet zone)?

Plant Y: No experience as yet but would estimate 1 minute to sniff one cabinet. Therefore time to identify specific cabinet could be 5 to 15 minutes.

b. If thermal imaging is used, how long does comparison between baseline and current conditions take?

Plant X: Do not currently use thermal imaging.

Plant Y: Not applicable.

16. What is the average time to de-energize a degraded component?

Plant X: Quickly once the component is identified. If whole thing is on fire, they will de-energize the entire cabinet, which takes seconds. It would take minutes for specific breaker. One breaker requires a local action whereas the whole cabinet can be done from the control room. The logic for the cabinet power is already laid out in MCR on control board. No procedures for specific equipment de-energization; this activity is directed by CR supervisor.

Plant Y: Do not anticipate de-energizing component as an immediate response unless absolutely warranted because of the impact on plant operations

17. What is the average time to repair a component?

Plant X: Varies widely.

Plant Y: Long term.

C.1.2 Information from Trip Reports

1. How do operators respond to the various notifications, (e.g. pre-alarm and alarm)?

Response 1: They respond in accordance with APP-044-B39. If detector indicates alarm, investigate for any indication of smoke, charring or overheating components. In addition to visual inspection, other methods such as thermography can be used to locate any overheating components. If an additional alarm on opposite train is received, activate the fire brigade. (MCR)

Response 2: In a pre-alarm condition, operation attempts to clear the pre-alarm, if no success, operation will initiate an operator alert and request ERT personnel assistance. (AW)

Response 3: Pre-alarm: control room call responding organizations, shift emergency response manager; someone checks the panel or visual size-up. Alarm: shift manager. (AW)

2. Has the system false alarmed?

Response 1: Yes. During the initial installation of the VESDA system, multiple spurious alarms were observed. Over the years, some alarm set points have been offset to account for the environmental conditions, as a result, numbers of spurious alarms have reduced. The cause of the spurious alarm ranges from unknown reasons, to airborne charcoal dust from filters, to fumes from floor stripping, to dust bunnies. (AW)

Response 2: Yes. The most common cause is/was other work in protected areas (units not bypassed). During the summers immediately following installation, there were some issues caused by heavy smog or wildfires, causing high ambient background conditions. (AW)

Response 3: Yes, from nitrogen purging, maintenance activities. Protocol to inform CSNC, insurance company, (follow procedure for notification, SERM, duration time, same notifications if it is a real fire. (AW)

Response 4: No. (MCR)

Response 5: Yes, from burning popcorn, hot work in the battery room, and a fan failure. (AW)

3. How would an incipient fire be located and verified (equipment used, sequence of actions taken)?

Response 1: Compensatory measures, thermal imaging (IR), only certified people can use sniffers. (AW)

Response 2: Thermal imaging cameras are used to detect incipient fires. (AW)

Response 3: Cabinet doors would be opened, visual and smell senses would be used. If necessary, a thermal imager would be used. (MCR)

Response 4: Human senses. (AW)

4. What kind of training has been provided to the operators, technicians and fire fighters on the system?

Response 1: Control maintenance technicians were provided with a one week comprehensive training on the EST 3 and the VESDA system at Edwards. They were trained on the operation of the software and detection panel. (AW)

Response 2: Operations were provided with classroom and hands-on training for operation of the Fireworks and Cirrus-Pro software. Operators were required to show proficiency in Fireworks and Cirrus-Pro to gain qualification. Technicians were provided initial classroom training on the Cirrus-Pro detectors and the FireWorks and Cirrus Pro software which satisfied vendor qualification requirements for plant techs to work on the

Cirrus Pro detectors. A training aid that simulated the detector/fire panel/software interconnection was provided to the training department for further instruction. (IC)

Response 3: No specific training implemented, the unit is straightforward. (MCR)

5. Are the operators trained on calibrating the system using proprietary software, if applicable?

Response 1: The control maintenance technicians are trained on the manipulation of the system and the use of the applicable software. Yes. Control Maintenance technicians have been trained by the product vendor in the use of system configuration software. This is required to enable the technicians to conduct proper maintenance, testing and troubleshooting of devices. (AW)

Response 2: Operators are trained and qualified to use Fireworks and Cirrus-Pro packages. (IC)

Response 3: No. (MCR)

6. Where is the detector located relative to the detection zone and why?

Response 1: The detector is located outside the RGTB cabinets, but approximately 5 feet from the nearest RGTB cabinet, because of space limitations. Tech manual recommends locating the detector within the protected space. (MCR)

Response 2: Aspirating detector is located remote to the cabinets being monitored and air sample is piped from the cabinets being monitored to the detectors. Each detector has four zones. (IC)

Response 4: The detectors are typically located in the protected zone. This approach acts to minimize any adverse effects caused by pressure differentials within different areas of the station. It also serves to ensure that sampled air is discharged to the same area from which it originated, eliminating opportunities for the spread of smoke or airborne radioactive particles from one area to another (AW).

Response 5: In a different room. Both detectors are on the same wall next to each other. (AW)

7. Are there any drawbacks specific to the VEWFDS?

Response 1: Maintenance requires quarterly and annual surveillance which is time consuming and expensive. System is somewhat complicated, requiring a significant vendor interface.

Response 2: A spare unit is recommended. MCR)

8. What compensatory measures do you use when the system is out-of-service?

Response 1: Continuous fire watch. (AW)

Response 2: None. This detector is just one in a detection circuit made up of other spot detectors. The rest of the detector circuit remained operable. The detection circuit is located in the constantly manned control room. (MCR)

Response 3: Continuous fire watch. Also used when the fire source can't be located and alarm will not clear. (IC)

Response 4: Continuous fire watch, restricted work activities. (AW)

1

APPENDIX D
EVALUATION OF OPERATING EXPERIENCE DATA

D.1 Evaluation of Fraction of Fire That Have Detectable Incipient Stages

This appendix documents the review of *potentially challenging or greater fires* from the fire events database. The results are summarized in Table D-1, which contains several fields described below.

Fire ID	Record number from EPRI Fire Events database
Fire Cause	Identifies apparent cause of event
Detected by	Identifies how the event was detected
Cabinet Type	Identifies the type of cabinet where the event occurred
Ignition Component	Identifies the component which ignited
Description	Provides summary of event
Incipient stage	Identifies if the event involved an incipient failure mode. Possible classifications are Yes, No, and Undetermined. Definitions are provided below.

Table D-1. Evaluation and Description of Bin 15 Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Incipient stage (Y/N/U) Reviewer 1	Incipient stage (Y/N/U) Reviewer 2
29	Stab misalignment	Control Room instrumen-tation / annunciator	MCC	MCCB	Failure on demand. Following start of the main turbine turning gear motor a fire occurred in the 480V Engineered Safety Features (ESF) Motor Control Center (MCC) 2B64. Cause is attributed to design of breaker cubicle allowed misalignment when installing the breaker without providing a method of verifying proper breaker position.	PC	N	N
38	Run Contactor Short damaged CPT	Control Room instrumen-tation / annunciator	MG set Breaker	CPT	Failure During Test. During a bus undervoltage and ECSS integrated functional test for Units 2/3 Diesel Generator, a short in the run contactor coil to the 3A RPS MG Set Drive Motor Breaker caused excessive current flow through the control power transformer, which caught fire. This resulted in a loss of power on 3B RPS bus (because of the Reserve RPS Power Supply being out of service for a modification), a half scram and an unplanned Engineered Safety Feature (ESF) actuation.	CH	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
41	Stab misalignment	Fire Alarm	MCC	Breaker	Failure on demand. Immediately following start of the 'D' River Water Supply (RSW) pump, a fire alarm was received. Investigation identified fit between breaker primary disconnects and the associated breaker cubicle stabs was inadequate. Poor fit resulted in arcing in the breaker cubicle and subsequent fire. Breaker had been recently replaced as part of a design modification package and insufficient inhouse review of the breaker interface design specification is the apparent root cause.	PC	N	N
45	Undetermined	Control Room Instrumen-tation / Annunciator	MCC	MCC	Electrical fire in intake structure affecting 2 MCCs. Unite 1 Circ. Water MOVs and Lube Oil Cooling Water Pumps affected, and Unit 2 Circ. Water Pump Motor Bearings affected. Insufficient information to determine cause of failure or component that failed.	PC	U	U
69	Overheating wire	Control Room Instrumen-tation / Annunciator	Control Cabinet	Electrical cable insulation	Breaker self-closing caused by breakdown of insulation in breaker control cabinet. Breakdown caused by insulation contact with protruding tap of a wire wound power resistor, associated heat from resistor and deterioration caused by water intrusion (cabinet located in switchyard). Failure is a result of accumulated effects of 25 years of deterioration.	U (NC-PC)	Y	Y

Table D-1. Evaluation and Description of Bin 15 Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Incipient stage (Y/N/U) Reviewer 1	Reviewer 2
83.1	Ground Fault	Plant Personnel	Power	Essential Lighting UPS / Distribution Panel	Smoke was discovered in the back boards area of the control room by a security officer performing an hourly fire watch tour. Smoke was emanating from the Emergency Lighting Uninterruptible Power Supply and the Essential Lighting Distribution Panel. Cause was short circuit current in plant ground system because of inadequate grounding procedures. Fire was self-extinguished by removal of power by opening AC breaker in ELDP.	PC	Y	Y
83.2	Ground Fault	Plant Personnel	Power	Essential Lighting Isolation Transformer	Following event 83.1, AO was surveying duty area and found smoke and fire in Train B DC equipment room (different room and elevation from event 83.1). Fire was contained to essential lighting isolation transformer. Fire required removal of 480V power from ELIT by manually opening circuit breaker, and application of carbon dioxide extinguisher by AO and Fire Brigade.	PC	Y	Y
89	CPT & Relay Failure	Unknown	MCC	CPT & HGA Relay	Internal short in the control power transformer, which caused the failure of the HGA control relay. Root cause of CPT failure not reported. Failure of these two components prohibited the proper operation and automatic transfer of the EDG room ventilation system from Unit 3 busses to Unit 2.	PC	Y	Y

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
98	Undetermined	Plant Personnel & Fire Alarm	Control Cabinet	Undetermined	During a 24-hr post-maintenance run of emergency diesel generator an operator noticed heavy smoke coming from the EDG control panel. Initiation component and cause of event was not identified.	PC	U	U
131	Undetermined	Plant Personnel	Undeter mined	Undetermined	Non available, fire was in turbine building	CH	U	U
144	Stab Misalignment / Ground Fault	Control Room / Plant Personnel	MCC	Breaker stabs	Failure on Demand. Concurrent with attempted start of containment cooling fan (closing of breaker), supply circuit breakers for 480VAC MCC tripped as a result of a bus to ground electrical fault. Responding operators discovered a small fire in the MCC. Root cause identified inadequate design resulted in improper placement of circuit breaker in MCC. One stab didn't make up to its associated bus bar correctly, resulting in a high resistance connection.	PC	N	N
146	Breaker to Bus Stab High Resistance	Control Room / Plant Personnel	Load Center	Breaker stabs	Failure on demand. Breaker failure following placing breaker in-service after restoration steps from a test of the automatic start feature of an isophase bus cooling fan. Failure because of high resistance connection between bus bar stabs and breaker assembly.	PC	N	N

Table D-1. Evaluation and Description of Bin 15 Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Incipient stage (Y/N/U) Reviewer 1	Incipient stage (Y/N/U) Reviewer 2
152	Breaker to Bus Stab High Resistance	Fire Alarm	MCC	Breaker stabs	Failure on demand following maintenance MCC failure concurrent with charging pump starting. Root cause identified high resistance connection at the stab/bus interface likely because of less than adequate preventative maintenance and original design inadequacy.	PC	N	N
161	Undetermined	Plant Personnel	MCC	Undetermined	'D' control rod drive mechanism (CRDM) fan (1-HV-F-37D) tripped. Approximately 30 minutes later operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed.	PC	Y	Y
175	Undetermined	Undeter-mined	7.2kV Switchgear	Undetermined	Fire in the non-safety 7.2kV switchgear room.	CH	U	U
187	Undetermined	Plant Personnel	Control Cabinet	Undetermined	Smoke from Unit 3 condensate demineralizer control panel. Power supply in the panel was unplugged to extinguish the fire.	PC	U	U
188	Lightning Strike	Plant Personnel	Power Control Cabinet	Undetermined	Lightning strike caused a fire in a power control center. De-energizing bus supplying power extinguished the in the power control center.	PC	N	N
203	Undetermined	Plant Personnel	MCC	Undetermined	Two MCCs burned	CH	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
206	Missing Component	Plant Personnel	Breaker	Breaker	Fire in recirculation motor generator field breaker caused by missing extension piece for the center phase shorting bus. This allowed the field to be continuously shorted during operation.	PC	U	U
211	Undetermined	Plant Personnel	MCC	CPT	Control Power Transformer failure in MCC	U (NC-PC)	Y	Y
219	Undetermined	Roving Fire Watch	MCC	CPT	Control Power Transformer failure in MCC	PC	Y	Y
224	Human Error	Plant Personnel	MCC	Undetermined	Electrical fault in 480V MCC cubicle caused by human error during maintenance/cleaning	U (NC-PC)	N	N
253	Breaker Failure	Plant Personnel	Switchgear	Trip Coil	Breaker failed to open causing excessive current in trip coil.	U (NC-PC)	N	N
254	Undetermined	Plant Personnel	MCC	Undetermined	MCC electrical overload	U (NC-PC)	U	U
303	High Resistance	Plant Personnel	Control Cabinet	Fuse Disconnect	Plant heater boiler control cabinet on fire caused by high resistance connection in the 60 amp fuse disconnect. Cabinet doors were found open with flames coming out of the cabinet and paint burning off of the top.	PC	Y	Y
320	Breaker Failure	Plant Personnel	MCC	Breaker	Feeder breaker tripped when operator attempted to start 'B' main chill water pump. Local breaker was observed to be on fire and had not tripped.	PC	N	N
381	Breaker cooling fan failure	Control room Instrumentation / annunciator	MCC	Cooling fan	Aux cooling equipment fan motor shorted out with fan motor assembly on fire.	PC	U	U
411	Water intrusion	Plant personnel	Breaker box	Breaker	Breaker box failure caused by water intrusion	U (PC-CH)	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
517	Transformer fault	Control room annunciator & Smoke Alarm	UPS	Transformer	Fire in ERFDADS computer uninterruptable power supply. Apparent cause was a turn to turn fault in the top winding. Vibration, temperature, and age are contributing factors to this failure.	CH	Y	Y
520	Inverter fault	Control room annunciator & Smoke Alarm	UPS	Unknown	Fire in ERFDADS Inverter	PC	U	U
588	Ground fault	Control room annunciator & smoke alarm	Switchge ar	Unknown	Ground fault on 480V SWGR	CH	U	U
10338	Breaker fault	Plant Personnel	MCC	Breaker	Failure on Demand. During start of pump, breaker flashed and resulted in small fire in cubicle with door forced open.	PC	U	Y
20264	MCC Coil fault	Plant personnel	MCC	Coil	Smoke observed coming out of MCC. Hold in coil overheated.	U (NC-PC)	U	U
20267	Breaker fault	Plant Personnel	MCC	Undetermined	Breaker malfunction	U (NC-PC)	U	U
20268	Overheated component	Plant Personnel	MCC	CPT	Control Power Transformer overheated	U (NC-PC)	Y	Y
20269	Undetermined	Plant Personnel	Electrical Lighting Panel	Undetermined	Electrical Lighting Panel Failure	U (NC-PC)	U	U
20270	Transformer Failure	Fire Watch	MCC	Transformer	MCC Breaker Transformer failure	U (NC-PC)	Y	Y
20272	Relay failure	Plant Personnel	Electrical Panel	Relay	Electrical Panel Relay	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
20273	Trip coil failure	Plant Personnel	Switch-gear	Breaker trip coil	Heavy smoke was observed in the Train 'A' switchgear room caused by a faulted trip coil.	U (NC-PC)	N	N
20275	Overheat	Plant Personnel	MCC	CPT	Control power transformer burned up causing the diesel generator lube oil heater MCC to smoke.	U (NC-PC)	Y	Y
20276	Breaker	Plant Personnel	Switch-gear	Undetermined	RCP breaker cubicle	U (PC-CH)	U	U
20282	Overheat	Plant Personnel	MCC	CPT	Operator saw smoke coming from an MCC for the MISV hydraulic pump; transformer fault.	U (NC-PC)	Y	Y
20287	Overheat	Roving Fire Watch	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20295	Overheat	Plant Personnel	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20302	Ground fault	Plant Personnel	MCC	Undetermined	Ground fault on main and/or reserve feed breakers cause fire	U (NC-PC)	U	U
20312	Switch	Smoke alarm	Switch-gear	Switch	EDG roto test switch damaged and failed causing a fire	U (NC-PC)	U	U
20325	Chemical Spill	Plant Personnel	Heat trace wiring	Heat trace wiring	Acid spill on heat trace wiring	U (NC-PC)	Y	Y
20328	Undetermined	Smoke alarm	Electrical Distri-bution	Undetermined	Sudden electrical distribution panel failure with smoke.	U (NC-PC)	U	U
20329	Relay fault	Plant personnel	Switch-gear	Relay	Relay stuck in intermediate position	U (NC-PC)	U	Y
20334	Breaker	Plant Personnel	MCC	Breaker	MCC Breaker	U (NC-PC)	U	U
20346	Breaker	Plant Personnel	MCC	Breaker	Breaker in 4kV room	CH	U	U
20356	Internal Short	Plant Personnel	MCC	Light bulb	Short in light bulb	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
20357	Human Interaction, Improper Maintenance	Plant Personnel	MCC	MCC internals fell on power phase	Ground fault inside a nonsafety-related MCC caused by improperly equipment restored to service. Internal plane cover not properly secured and fell during investigations and caused ground fault.	U (PC-CH)	N	N
20362	High Resistance	Other Equipment Failure	MCC	Insulation / fuse block	Insulation burned off of one lead to motor starter contactor and fuse block severely melted. Termination screw loose on starting input terminals.	U (NC-PC)	Y	Y
20382	Undetermined	Plant Personnel	Switch-gear	Undetermined	Switchgear failure	U (NC-PC)	U	U
30276	PCB fault	Plant Personnel	Emer-gency Lighting	Power transformer	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell.	PC	N	N
30281	Procedure Error	Plant Personnel	Control Panel	Insulation	During testing of synch switches for Main Xfmr, Emergency Aux Xfmrs and Main generator, insulation failed because of excessive applied voltage (230,000volts applied to a 120V synch bus).	CH	N	N
30338	Inadequate PM	Control Room Instru-mentation / Annun-ciation	Control Panel	Panel Blower	Panel blower (fan) failure. Blower found to be full of dust and dirt.	PC	Y	Y
30478	Relay failure	Plant Personnel	Control	Relay	Condensate demin panel fire and smoke from affected relays (3).	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Incipient stage (Y/N/U) Reviewer 1	Incipient stage (Y/N/U) Reviewer 2
30513	Overheat	Fire Alarm	Control	CVT	Constant Voltage Transformer inside rod action control cabinet in back panels of MCR ignited combustible materials located inside transformer housing	PC	Y	Y
30522	Undetermined	Fire Alarm	Control	Undetermined	RBCCW cathodic protection cabinet fire.	PC	U	U
30578	Undetermined	Plant Personnel	Power Supply	Undetermined	Fire reported in electrical box associated with power supply for the cask handling crane. Damage limited to heat shrink tubing on a connector.	PC	U	U
50467	Breaker fault	Plant Personnel	Switch-gear	Closing Coil	Breaker found to be smoking. Breaker removed and found closing coil was frozen in the close position.	U (NC-PC)	N	N
50473	Water intrusion	Equipment trouble alarm	Electrical Panel	Relay	Small fire discovered in electrical panel while investigating burning odor while responding to alarm from same electrical panel. Flames and smoke were observed emanating from relay. Failure was a result of water intrusion from HVAC condensate drain line.	PC	Y	Y
50784	Relay misalignment	Plant Personnel	Control Cabinet	Relay	During relay testing, the relay began to smoke. During de-energization activates, the relay caught fire. Fuses were pulled and CO_2 was used to extinguish. Suspected cause was a slight misalignment of the relay and contact structure.	PC	N	N
50811	Relay failure	Control Room Instrumen-tation / Annunciator	Control Cabinet	HFX relay	Received numerous alarms in control room related to FP filter low-flow alarm. Found FP pump tripped and pressure drop. Smoke observed in room. Investigation found HFX relay burning. Extinguished with portable.	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	**Fire Cause**	**Detected by**	**Cabinet Type**	**Ignition Component**	**Description**	**Severity Class**	**Reviewer 1**	**Reviewer 2**
50874	Breaker failure	Plant personnel	Switchgear	Trip Coil	During shutdown of Recirc MG set the field breaker failed to open. Trip coil smoking and on fire. Fire extinguished and fuses pulled.	PC	N	N

D.2 Quantification of the Time Available for Operator Response

As shown in Figure 2-2, the fire growth profile is made up of several stages. Of importance is the early stage of the fire referred to as the "Incipient" stage. Although many fires exhibit this incipient stage, it is not typically modeled in performance-based design, primarily because of the variability of its duration. This variability is caused by several reasons; including deviations in material properties, ignition source, and configuration, just to name a few. Additionally, for fires which do display an incipient stage, testing has shown that aspirating smoke detecting systems configured to provide very early warning fire detection (VEWFD) do not detect the component degradation at its onset, but sometime after the first quartile. Thus, to quantify the time available for operator response, operating experience was reviewed to identify quantitative information to support a better understanding of either the incipient stage duration, or time available between ASD VEWFD alert and fire conditions. To focus this study, several assumptions must be made.

The assumptions used for the characterization of the available time estimates in this project are as follows:

1. Limited to electrical enclosures found in nuclear power plants
    a. Excluded equipment includes components such as, motors, pumps, MG sets, diesel generators, air compressors.
        i. These components are excluded, not because they do not have the potential to exhibit an incipient stage, but because of the limited scope and resources to develop an understanding of the failure modes and their associated duration, which can contribute to risk significant fire scenarios.

2. Limited to component fires that have a sufficiently long duration (incipient stage) such that operator response has the potential for enhanced warning and thus enhanced suppression capabilities.
    a. The duration curve developed DOES NOT model the incipient duration for all fires, just those fires that exhibit an incipient duration greater than approximately30 minutes[38].

It should be noted that the current state of knowledge related to understanding the duration of component degradation and associated fire signature from such degradation, is limited. One of the primary reasons for said limitation is because of the fact that, in many instances, the early degradation phases do not affect circuit or system functionality. As such, the early degradation conditions are not explicitly explored, with the exception of those plants that have a periodic inspection process which employs the use of thermal imaging cameras or similar technologies. Even so, these technologies and the frequency of inspection may not be completely successful in identifying these early degradations with such finality that corrective actions can be taken to remedy the potential failure of the component(s).

Given the assumptions and limitations, an attempt was made to quantify the duration of the incipient stage as discussed above. Because of the lack of information, it would have been ideal to conduct a formal expert elicitation process, where by a group of experienced experts

[38] The 30-minute minimum was chosen based on a factor of 2 based on the maximum use of 15 minutes for plant personnel (fire brigade) response to fire locations. The factor of 2 was based on the assumption that the incipient fire location may be more difficult to locate because of the nature of the fire signature exhibiting low amounts of smoke and possibly invisible smoke.

with diverse backgrounds and knowledge provides the expert judgment for use in quantifying the incipient stage duration. Unfortunately, this need was not identified in the initial project planning phase and so resources were not made available to support such an effort. Consequently, to acquire this type of information, an informal ad hoc approach was used in which several knowledgeable individuals from the NRC and Sandia National Laboratories were asked to quantify the incipient duration using available information.

Even with the pivotal role that quantifying the duration of the incipient stage plays with regard to determining successful operator action, limited responses were provided to the request. Thus, the estimate provided below represents an evaluation of available operating experience, and as such, likely does not represent the informed technical community's viewpoint. This evaluation is purely based on data, and no engineering judgment has been used to adjust the estimate.

<u>Operating Experience</u>

The Updated EPRI Fire Events Database was reviewed for Bin 15 "Electrical Cabinets" Fire Events. A summary of those events that contribute to the fire ignition frequency are presented above in Section D.1. Of those events, only a limited number are associated with low-voltage (<250V) equipment, with the majority of the events (approximately 80 percent) involving low-voltage switchgear, load control centers, or distribution panels, etc.

In reviewing all the low-voltage (<250V) Electrical Panel events classified as "Challenging," "Potentially Challenging," and for "Undetermined," <u>zero events</u> were identified as non-power distribution-type equipment in scenarios for which timing information associated with the duration of the incipient stage was provided.

When the review was expanded to include all Electrical Panel equipment types, which are classified as "Challenging," "Potentially Challenging," or "Undetermined," <u>only</u> <u>one event</u> was identified in which timing information associated with the duration of the incipient stage was presented. This event was FID 161 and indicated that approximately 30 minutes elapsed between time of breaker trip and operations finding a small flame within the enclosure. The event description is presented as follows:

> 'D' control rod drive mechanism (CRDM) fan tripped. Approximately 30 minutes later, operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed.

Although the event report is unclear regarding what caused the initial tripping of the CRDM fan and how long before the breaker trip the failing component had been degrading, it does suggest an approximately 30 minute reference point between an initiating event and detection (by plant personnel) of a small fire.

One event out of the ~70 events used to determine the fire ignition frequency for electrical panel provides a very weak basis with large uncertainty for quantifying the duration of the incipient stage generically for all of the varieties, vintages, and combinations of electrical components found in operating NPPs. Thus, in an attempt to develop a generic prediction of the duration of NPP electrical cabinets, other sources of information were sought.

The first source included reviewing the "Non-Challenging" events from the EPRI fire events database. Although use of this information is not ideal because these events are not used to

quantify risk, they may provide some insight into the quantification effort. Upon this review, two events were identified as having timing information associated with the duration of the incipient stage. The first “Non-Challenging” event was FID 10647, which indicated that a fire occurred in a control cabinet for a reactor building chiller that, because of high outside air temperature, ran under a full-load condition over the course of an afternoon. The following three apparent fire causes and contributing factors were identified:

1) Power cable was inadequately sized to 208 Amp service while the minimum electrical circuit load ampacity for this load was 403.2 Amp.

2) Breaker failed to trip during high current conditions

3) Experienced poor power-block phase connection (high resistance).

Although the event description does not provide a specific time frame during which the chiller unit was operating at full-load, or in excess of the ampacity limits of a 4/0 AWG power cable conductor, it did specify that the failure occurred over an afternoon. Webster’s Dictionary defines an afternoon as “the day from noon until sunset”(Webster's II New College Dictionary, 3rd Ed., 2005). Thus, depending on the time of year and location within a time zone, the definition of an afternoon could vary from 5 to 9 hours. So, for this example, the average afternoon length was assumed to be 7 hours.

The second “Non-Challenging” event was FID 50836, and identified a computer inverter fire. In this event, detailed timing information was provided as follows. At 0500, the Unit 2 computer inverter was started up per operating procedures, with normal startup and loading indications. At 0555, a fire alarm was received. At 0558, the operator reported smoke and fire emitting from a U2 computer inverter. Loss of power to the computer bus resulted in the loss of most MCR U2 trending displays. Consequently, this event shows that in less than 58 minutes the equipment transitioned into flaming conditions.

The second source of information included the assumptions made in previous incipient fire detection risk quantification efforts, namely, the EPRI Fire PRA Enhancements and the NRC FAQ 08-0046 interim staff position. In EPRI Report 1016735, when determining the preemptive response effectiveness “P,” an assumption is made that “IFD systems will alarm up to an hour or more before ignition occurs (based on manufacturers’ claims, NFPA 76 objectives, and technical discussion in Appendix C of the EPRI report).” Although that report indicates that a technical discussion supporting the assumption is provided in Appendix C, a review of that appendix didn’t produce substantial evidence to support this estimate. In the published, final version of the NRC Staff interim position, the one-hour assumption was also made with little to no basis. Regardless of the validity of the one-hour estimate, it can be considered a quasi-consensus because numerous individuals were responsible for the development, review and approval of these documents. Hence, the one-hour time frame available following ASD VEWFD detection at an alert condition will be retained; however, it should be noted that this hour corresponds to the time from ASD detection to ignition, and not the start of component degradation to ignition.

The last source sought for insights was well-documented, recent U.S. NPP events in which ASD systems were in the area. These events, which occurred in 2013 and 2014, included ones captured in the fire events database.

2013 event: On August 7, 2013m, at 23:30, an operator was dispatched to Aux Bus E to

investigate an equipment trouble alarm. Four minutes later the operator identifies that there is a ground fault on the 6.9kV/480V Aux Bux E. At 23:38, an IFD zone located in an electrical cabinet 20 feet way notifies an alert condition. Two hours and forty-two minutes later an explosion occurs involving the Aux Bus 1E2. Therefore, the IFD provided 2.7 hours of advanced warning before ignition; in this case ignition is considered to be the occurrence of the explosion. Information from this event was taken from the following source, Beasley, K., 08-08-2012 HNP Fire Event on 1E2 Bus. Retrieved July 29, 2014 from Fire Protection Information Forum Archives: http://www.nei.org/Conferences/Conference-Archives/Fire-Protection-Information-Forum-Archives.

2014 event: The event occurred because of an internal fault in the 480V load center station service transformer 1D2. The event started at 07:51, with the MCR receiving electrical equipment trouble alarms associated with 1D2. At 08:32, it was confirmed that grounds were present on both sides of the transformer. At 09:00 a single zone of the IFD notified an alert condition, and at 09:02, the same IFD zone indicated an alarm condition. At 09:29, the resistor associated with the ground relay was glowing red, and at 09:31 it was determined to de-energize 1D2. At 10:07, local plant personnel identified smoke emanating from the 1D2 transformer cubicle and a determination was made to trip the reactor, which was at 75 percent power. At 10:24, a confirmation was made that no more smoke was emanating from the 1D2 transformer. Report never identified if flaming conditions occurred.

Regardless of the severity classification of this event, it provided timing information associated with the time between ASD response and fire, if it is assumed that when the plant was shut down a fire was eminent. Because of the limited amount of data, it was decided to keep this event data. So, given the IFD notified the MCR of an alert condition at 09:00, if we assume that ignition occurred at 10:07, there was approximately 1.12 hours of advanced warning before assumed flaming conditions.

This completes the available quantitative information regarding the length of the incipient stage for electrical components found in U.S. NPPs through operating experience. However, other sources of for timing information were sought, including NASA, Canada NPPs, National Laboratories, and the NAVY. One event was provided by a National Laboratory where resistors overheated in two isolation chassis drawers of a 125Vdc power supply rack for a Particle Beam Fusion Lab Z shot machine. The system uses software to control hardware (programmable logic controller). During an experiment in 2011, the shot was aborted, however an error in the software failed to shut down the power supply to two of the charging capacitor circuitry. This resulted in overheating of the resistor network to ground. From time of test abort to identification of overheating resistors was 59 minutes. Visible thermal damage was observed on the exterior of the electrical enclosure (discolored paint, soot deposits) and the resistor drawers were a complete loss.

Table D-2 provides a summary of this available operating experience duration information. The “Time Available” estimates are based off of the incipient stage operating experience and adjusted using the data from the NIST testing. The basis for this adjustment is presented in Section 8.1.2. The resulting exponential distribution fit to the “Time Available” data is shown in Figure D-1 and Table D-3.

Table D-2. Summary of Incipient Stage Duration and Time Available for Operator Response

Event	Incipient stage (Hours)	Time Available for Operator Response (Hours)			
		CC	LS-SS	ION	PHOTO
EPRI FEDB 161	0.5	0.26*	0.13*	0.17*	0.04*
EPRI FEDB 50836	0.9	0.47*	0.23*	0.31*	0.07*
SNL z-machine	0.98	0.51*	0.26*	0.33*	0.08*
EPRI / NRC FAQ		1.00	1.00	1.00ᵻ	N/A
2014 Event		1.12	0.56*	0.73*	0.17*
2013 Event		2.75	1.38*	1.80*	0.42*
EPRI FEDB 10647	7	3.64*	1.82*	2.38*	0.56*
Lambda		*0.7*	*1.3*	*1.0*	*4.5*

* estimate based on operating experience adjusted with experimental results (mean time to detection) and assumption of linear component degradation

ᵻ used EPRI/NRC FAQ estimate for non-VEWFD system since data indicates that ION spot-type detectors performed equivalently or better than LS ASD VEWFD which those documents cover.

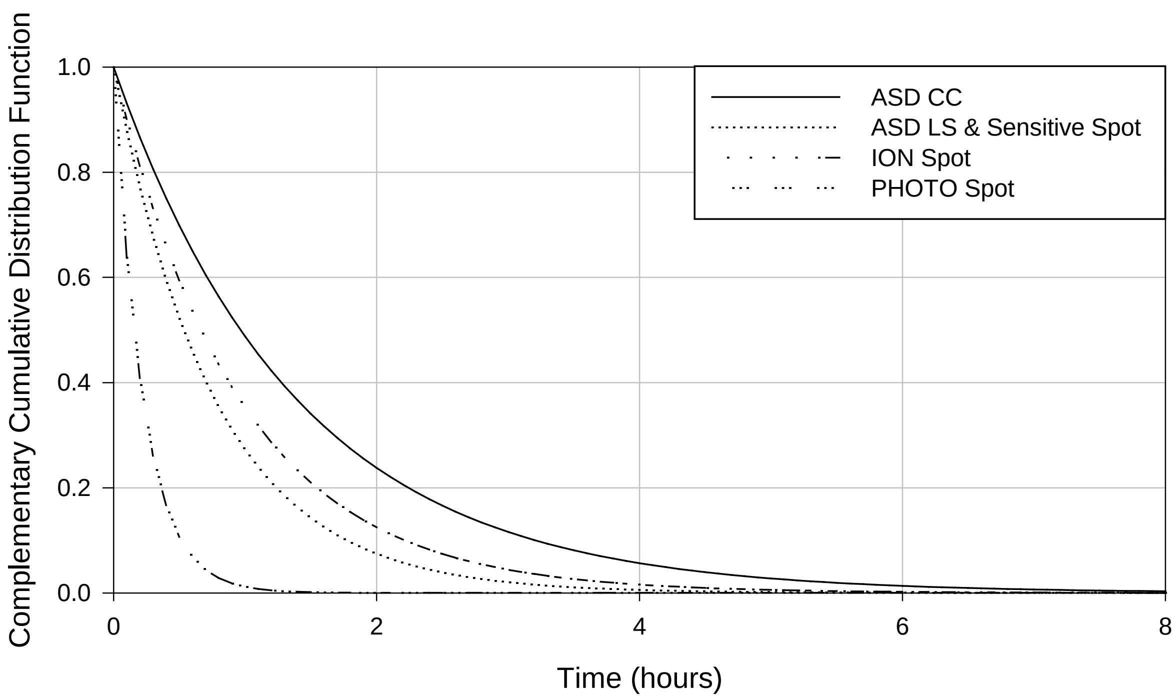


Figure D-1. Exponential distributions fit to data for the time available for operator response following an ASD alert for different detection technologies tested

Table D-3. Exponential Distribution Values for Time Available for Operator Response by Smoke Detection Systems

Time (Minutes)	Complementary Cumulative Distribution Function			
	ASD CC	ION Spot	ASD LS and SS	PHOTO Spot
0	1	1	1	1
1	0.99	0.98	0.98	0.93
2	0.98	0.97	0.96	0.86
3	0.96	0.95	0.94	0.80
4	0.95	0.93	0.92	0.74
5	0.94	0.92	**0.90**	0.69
6	0.93	**0.90**	0.88	0.64
7	0.92	0.89	0.86	0.59
8	0.91	0.87	0.84	0.55
9	**0.90**	0.86	0.82	0.51
10	0.89	0.84	0.81	0.47
. . .	. . .	. . .	. . .	. . .
30	0.70	0.58	0.52	0.11
. . .	. . .	. . .	. . .	. . .
60	0.49	0.35	0.27	0.01
Lambda	0.72	1.04	1.30	4.48

D.3 Evaluation of Enhanced Fire Suppression Fire Events

This section documents the review of fire events from the fire events database where an operator was present in the room of origin when a flaming condition began. These results were used to develop a new suppression curve. The results are summarized in Table D-3, which contains several fields described below.

Fire ID	Record number from EPRI Fire Events database
Fire Cause	Identifies apparent cause of event
Detected by	Identifies how the event was detected
Cabinet Type	Identifies the type of cabinet where the event occurred
Description	Provides summary of event

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
83.1	Ground Fault	Plant Personnel	Power	Smoke was discovered in the back boards area of the control room by a security officer performing an hourly fire watch tour. Smoke was emanating from the Emergency Lighting Uninterruptible Power Supply and the Essential Lighting Distribution Panel. Cause was short circuit current in plant ground system because of inadequate grounding procedures. Fire was self-extinguished by removal of power by opening AC breaker in ELDP.	9
161	Undetermined	Plant Personnel	MCC	‘D’ control rod drive mechanism (CRDM) fan (1-HV-F-37D) tripped. Approximately 30 minutes later operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a “6-inch flame” was observed. At the time of fire discovery the Operations fire brigade members were in the area. When the source was found the fire was immediately extinguished and reflash watch set	5

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
253	Breaker Failure	Plant Personnel	Switchgear	Breaker failed to open causing excessive current in trip coil. Operations crew were present within room during failure.	10
20270	Transformer Failure	Fire Watch	MCC	MCC Breaker Transformer failure detected by fire watch	1
20272	Relay failure	Plant Personnel	Electrical Panel	Electrical panel relay fire. Detected by security guards within the fire area.	4
30276	PCB fault	Plant Personnel	Emergency Lighting	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell. An indication existed of the smell of smoke in the Control Room. Upon investigation found Emergency Lighting Battery Box # E7-12 on the East Wall of the Control Room, behind 1C614, with smoke coming out.	2

APPENDIX E
LITERATURE REVIEW

This appendix provides a summary of literature reviewed in support of this project. All summaries are from publically available documents. The literature is from a variety of sources, including the National Fire Protection Research Foundation, academia, vendors, conference proceedings, and journal articles. The summaries are provided in chronological order. At the end of this section, additional reading material that was reviewed is identified, but not summarized below.

E.1 Custer, R.L.P., Bright, R.G., "Fire Detection: The State-of-the-Art," U.S. Department of Commerce, National Bureau of Standards, June 1974.

> This report, although dated, provides a substantial amount of information related to fire detection technologies with consideration of fire signatures, detection modes, test methods, performance requirements, and code requirements. For those with limited-to-no knowledge of fire detection systems operations, review of the report is strongly recommended.
>
> Important concepts gathered from this report, applicable to the current study include a description of submicrometer particle counting detectors; ambient condition effects on detector response; and an emphasis on the importance of detector maintenance. Relevant information is communicated in the main body of this report.

E.2 Meacham, B.J., "Factors Affecting the Early Detection of Fire in Electronic Equipment and Cable Installations," May 1992.

> This article provides an overview of the factors that influence fire detection, such as fuel characteristics; compartment configuration; environmental configurations; and maximum allowable fire size at time of detection; and guidance on selecting appropriate devices. The focus is on telecommunication facilities. The first factor discussed is the fuel and fire characteristics, which consist of circuit, component, or interconnecting wiring, which can produce considerable combustion products, but have a relatively low-energy output, and may never transition to a flaming fire. Loss history has shown that small, low-energy fires are a serious problem and make early detection difficult because of weak plume strength. Weak plumes and low ambient temperatures can cause insufficient smoke transport to the uppermost level of a ceiling-height enclosure.

E.3 Gottuk, D.T., McKenna, L.A., "Response Time Comparison of Spot vs. Aspirated Laser Smoke Detection," September 1999.

> Hughes Associates, Inc. performed 56 full-scale tests for Pittway Systems Technology Group, comparing the response time of laser-based Notifier VIEW spot detection systems to Vision Systems laser aspirating smoke detectors (ASDs), which were exposed to a variety of smoke sources and ventilation conditions within a telecommunications facility.

An operating Bell Canada switch center was selected as the test site (100 ft. wide, 180 ft. long [18,000 sq.ft.], 15.5 ft. high. Five smoke sources were evaluated, including BSI 6266 wire; Bell Canada wire; BSI 6266 chemical smoke test; internal printed wire board; and conductive heating of EPDM cable insulation. The sources were evaluated at ten different locations with variable source heights and two different ventilation conditions. Normal ventilation conditions consisted of three recirculation air conditioning units, operating at a combined 25844 cubic feet per minute (cfm), serving the DMS switching center, and a general HVAC unit serving the larger toll/frame area at 12,618 cfm. Reduction ventilation conditions consisted of shutting down two of the three recirculation air conditioning units. Several variations of detector configuration were also used to evaluate any performance differences. The VIEW spot detectors were arranged in two redundant loops. One loop used detector spacing at 200 ft^2 while the other loop spaced the detectors at 400 ft^2. VIEW detectors were also placed on the return air grills, and detector-mounting angles were varied among tests to evaluate the effect on system response. Two laser ASDs were installed in the ceiling areawide configuration, and one laser ASD was installed on the return air grills of the recirculation system.

Several key insights were identified from this testing, namely the following:

- Comparable performance between the laser ASD and 200 ft^2 VIEW systems was demonstrated, while the 400 ft^2 VIEW system showed decreased performance compared to either the 200 ft^2 VIEW or laser ASD systems.

- Return air grill detection showed no clear difference between the laser ASD and the spot VIEW detectors. For the VIEW system, the return air grill configuration responded to fewer sources than the 200 ft2 system and was slower to respond; however, the returns did detect 3 additional fires not detected by the areawide VIEW system.

- Considerable variability existed in the alarm times from a given detector system because of changes in source type and location. Even for tests in which conditions were the same, response time varied.

- ASD configured to both ceiling areawide and return air grills were unable to detect most of the BSI wire tests (13 of 19 tests undetected). Additionally, the majority of the Bell wire tests were undetectable by both ASD and VIEW systems.

- Air flow monitoring tests showed that the ASD system didn’t issue a supervisory alarm until 66 percent to 76 percent of the sampling holes were blocked, while the vendor default settings for low airflow warning were determined or found to occur at 30 percent reduction in normal airflow. Thus, air flow reduction doesn’t correlate to sampling hole blockage for the particular ASD system tested.

E.4 Geiman, J., Gottuk, D., "Alarm Thresholds for Smoke Detector Modeling," Fire Safety Science Proceedings of the Seventh International Symposium, 2002.

This paper illustrates an evaluation of the use of smoke optical densities outside a detector as a criterion for predicting smoke detector response. The Temperature Rise Method was not evaluated because of the highly questionable accuracy. The study applied three full-scale experimental data sets that used optical density meters located in close proximity to some of the detectors (ion and photo). This paper concludes that determining the precise alarm times is not currently possible with the large number of variables that not only exist, but influence smoke detector response. Using nominal detector sensitivities as an alarm threshold, leads to only about 20 percent of the alarm predictions corresponding to actual detector alarms. In most cases, the use of the nominal sensitivity will result in predicting alarms before they actually occur. One exception is ionization detector response to flaming fire conditions, which corresponded with predicted alarm conditions 50 percent of the time. Using an alarm threshold of 0.14OD/m (9.4 %/ft obscuration) provides a relatively high level of confidence in predicting detector alarms, but will typically predict alarm response times that are potentially longer than would actually occur.

E.5 Nicholson, J., "Looking Up: NFPA 805, Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," NFPA Journal, May/June 2003.

This article provides a high-level overview of how performance-based fire protection application of NFPA standards have improved safety at Canadian nuclear power plants (NPPs). The use of performance-based, over prescriptive requirements, facilitates the use of (their) equivalencies in making more realistic analyses of Bruce Power Plants safe shutdown capability. The Bruce implementation of performance-based initiatives was deemed to be equivalent to the Canadian Standards Association N-293. As part of the plant upgrades, Vesda Air Aspiration Systems were installed.

E.6 Tieppo, Eddie, "Very Early Warning Aspirated Smoke Detection in Nuclear Power Facilities," October 2003.

This paper provides a high-level overview of design and benefits of VEWFD systems over conventional spot-type detectors. Maintenance considerations for ASD systems are also presented with discussion of detector unit, filter, and pipe network maintenance concerns. This paper concludes with a discussion of several applications used in Canadian NPPs in areas such as the main control room, equipment rooms, cable tunnels, and generators halls.

E.7 Vision Systems, "White Paper: Using Air Sampling Smoke Detection to Protect Mission-Critical Facilities from Fire," 2004.

This paper provides a high-level overview of the importance of protecting mission-critical facilities, such as essential financial installations, from the effects of smoke damage on their electronic computer systems. More and more, the risks associated with data center fires are caused by increased energy consumption from modern computers, and the need to use high-ventilation, flow rate air conditioning to cool the computer electronics. Consequently, such high air flow environments, using conventional spot-type detectors becomes ineffective. However, it is not only

potential fire damage from which the data centers need to be protected. Smoke contamination of electronic equipment, even as small as 16 micrograms per square centimeter, can cause corrosion and long term effects and 30 microgram per square centimeter can result in short-term effects.

The paper also provides an overview of how ASD systems work; common application in typical data center environments; ASD system design characteristics that are important to consider in ensuring the EW or VEW detection; coverage area; and sensitivities. The paper also establishes that in-cabinet and integrated-equipment detection enable an excellent VEWFD solution for the following reasons:

1. Sampling is performed closest to the source.

2. Addressability is enhanced as compared to ceiling or air return type detection.

3. Likelihood of smoke/fire damage to other equipment is minimized.

4. Background noise (dust/smoke) within enclosures is relatively consistent.

5. Numerous detector set points made a staged response replicable/possible.

E.8 Vision Fire & Security, "Development of Performance Equivalency Methodology for Detection and Suppression System Integration," 2006.

Vision Fire & Security Pty Ltd. developed a detection equivalency method, which resulted in development of an "application tool" to allow ASD systems to be specified as an alternative to the conventional spot-type detection design for applications in which detection is used for suppression system actuation. The study focused on the use of ASD systems in challenging environments, such as areas with high airflow, very low or non-thermal energy fire hazards, and dense equipment layout as a solution for risk management and business continuity. The Fire Dynamics Simulator (FDS), a fire modeling computational fluid dynamic tool developed by NIST, was used to determine the appropriate ASD alarm level to establish an equivalent or better level of performance as compared to the benchmark for conventional spot-detection.

This work identified that, for an equivalent performance, ASD requires higher sensitivity settings in rooms where (1) the airflow is higher, (2) the room size is increased, and (3) the ceiling height is increased. For the application using an ASD system to supplement or replace conventional spot-type detectors, the report concludes that with proper alarm settings (based on airflow characteristics and room physical dimensions), detection performance can be enhanced, and more consistent fire size at time of suppression can be achieved. The report doesn't appear to take into consideration the uncertainness associated with the FDS modeling, nor does it explicitly describe the basis equivalency calculation method.

E.9 Fabin, T.Z., Gandhi, P.D., "Smoke Characterization Project," April 2007.

The Fire Protection Research Foundation, along with the Underwriters Laboratories, undertook a smoke characterization study to more fully characterize the products of flaming and non-flaming combustion for materials found in common residential settings. Small-scale cone calorimeter, intermediate scale calorimeter and UL 217/268-type fire room tests were conducted to evaluate smoke characteristics for natural, synthetic, and multi-component materials in both flaming and non-flaming combustion modes. Quantities such as mass-loss rates; heat and smoke release rates; smoke particle size and count distribution; effluent gas composition; combustion mode effects; smoke alarm response; and smoke stratification were characterized. Although the report provides a thorough evaluation for the combustion modes and materials tested, most of the materials are not commonly found in NPP applications, making the application of these results uncertain.

E.10 Collier, P.C.R, Whiting, P.N., "Timeline for Incipient Fire Development: Study Report No. 194," 2008.

The Building Research Levy funded work to evaluate incipient fire development of furniture fires with regard to the modeling of the incipient stage in performance-based design fires. Using test data, and literature and statistical evaluations, the researcher noted that the incipient fire development period is variable and its duration was dependent on intensity and location of the ignition source. Because of the variability in the incipient stage, the report recommends no allowance for incipient fire development in performance-based applications. Although furniture fires are not realistic surrogates for electrical cabinet fires, the variability of the duration of the incipient stage is a characteristic likely applicable to electrical cabinet fires.

E.11 Milke, J.A., et al., "Validation of a Smoke Detection Performance Prediction Methodology," Volumes 1-4, October 2008.

The Fire Protection Research Foundation sponsored a research project to evaluate the current capabilities of the computational fluid dynamic (CFD) code FDS to predict smoke detector activation in response to relatively low energy incipient fire sources. This work was performed by the University of Maryland and Underwriter Laboratories, and is documented in a four-volume report titled, "Validation of a Smoke Detection Performance Prediction Methodology(Milke, Mowrer, Brookman, & Gandhi, 2008)." Volume 1 documents the characterization of the heat and smoke release of eight incipient fire sources that were selected for the project; Volume 2 provides a detailed description of the large-scale room fire tests. Volume 3 evaluates the smoke detector response, and Volume 4 compares the experimental results with the predictions of FDS simulations.

Modeling of smoke detector response typically uses one of three methods, namely, temperature rise, critical velocity, or optical density. However, these methods do not address the operational principles of the detectors resulting in uncertainty in the detector response modeling approximations. Eight smoke sources were characterized by performing small-scale tests using the IMO intermediate scale calorimeter at UL in Northbrook, IL. The smoke sources used include: shredded office paper, polyurethane (PU) foam with micro-fiber fabric, printed circuit board, and an ABS plastic computer case, which was used to create flaming smoke sources, while PU foam with micro-fiber fabric, ponderosa pine sticks, cotton lined fabric, and polyvinyl chloride (PVC)-insulated wire were used for smoldering smoke

sources. The primary smoke signature of interest was the obscuration of visible light, but particle count density, mean particle diameter, CO and CO2 production data were also collected.

The interesting results from this small-scale testing, as it relates to NPP smoke sources, are the characterization of the PVC-insulated wire test. The PVC test followed the procedure outlined in Annex B, "Performance Test Procedure for Very Early Warning and Early Warning Fire Detection Systems" of NFPA 76, using the North American Wire Test outlined in Table B.2.1 of that standard. However, the UL test deviated from the Annex procedure in that the test duration lasted 60 seconds, instead of the standard specified 30 second duration. The results indicated that the average maximum smoke release rate of 0.10 m^2/s occurred just after 60 seconds; the maximum mean particle diameter of 0.135 micron occurred just before 120 seconds; and the average maximum particle count density of 200,000/cc occurred at approximately the same time.

The large-scale testing included unventilated and ventilated conditions. The 24 unventilated tests were conducted in the UL 217/268 room, measuring 10.8 m by 6.6 m and 3.0 m tall. The rooms were instrumented with photocell/lamp assemblies; measurement ionization chamber units; spot-type smoke detectors (both ionization and photoelectric types); thermocouples; thermocouple trees and velocity probes. The 64 ventilated large-scale tests were conducted in different room measuring 7.2 m wide, 7.2 m long (51.8 m^2) by 9.0 m high. This enclosure was equipped with an injection-type mechanical ventilation system, with two ceiling air injector diffusers, and four transfer grills providing air exhaust to the plenum space above the ventilated test room. The ventilated room experiments consisted of testing three ventilation rates, namely 0, 6, or 12 air changes per hour (ACH). The ventilated room tests included the same instrumentation as the unventilated tests, with the addition of three ASD single-zone systems, having three sampling ports per zone (two sampling ports within the test room, one port sampling from outside the test room). The intent of including the ADS systems was to collect information to evaluate the prediction capabilities of FDS. Unfortunately, the data files associated with the ASD system could not be synchronized with the other data files.

Evaluation of the data/feedback indicates that the point type "smoke detector response(s) appear to be strongly dependent on the specific characteristics of the smoke and, in some cases, on the detector technology." The researchers then evaluated the detector response based on the 80th percentile values of obscuration and suggested nominal guidelines for detector response, depending upon the ventilation conditions, fire characteristics, (flaming vs. smoldering) and in some cases, detector technology.

Table E1. 80th Percentile Obscuration Level at Detector Response

Smoke Source	Ventilation	Detector Type	
		Photoelectric	Ionization
Flaming	With	5%/ft	8%/ft
	Without	8%/ft	
Non-Flaming	With	1 – 2.5%/ft	
	Without	10%/ft	12%/ft

The report classified the smoke sources as “incipient fire sources,” considering that half the sources used produced their smoke signatures during flaming combustion; the basis for classifying these smoke sources as “incipient fire sources,” is questionable given that all were identified as either smoldering or flaming. In addition, no clear distinction was made as to the portion of the overall smoke release rate profile that corresponds to the incipient stage. Although these tests provided useful data for characterizing the effluent from the various fire sources and for evaluating the smoke prediction capabilities of FDS, because the results were not reported for the ASD system tested, little can be drawn from these results regarding the response of an ASD VEWFD system.

E.12 Xtralis, “IT/Server Room Fire Test Demonstrations – VESDA & photoelectric conventional point detectors, Technical Report,” October 2008.

Xtralis provides a case study from demonstration tests conducted at their Test Facility IT/Server room. Smoke tests were conducted in various locations within the room to demonstrate an ASD smoke detector’s early warning (EW) and very early warning fire detection (VEWFD) capability. The ASD applications tested included ceiling, return air grill, air duct, and cabinet configurations. The ASD system results were compared to conventional spot-type detectors that were included in the tests.

The test facility measured 11.0 m wide x 6.5 m deep x 3.0 m high for a total floor surface area of 71.5 m^2. The room ventilation conditions were representative of those found in telecommunication facilities, namely, clean, cool air is introduced through the floor, and exhaust via the air return grill located on a wall.

Individual Xtralis VLC detectors were used for cabinet, ceiling, air return grill and duct detection with conventional photoelectric spot-type detectors set to 1.4 %/m obscuration (Mode 1) located adjacent to the ASD sampling points, except for the cabinet applications. An alarm control panel was used to log all detectors’ alarm times. Fire/smoke tests included overheated PVC wire, overheated resistor, and smoldering smoke pellet tests were also conducted. The duration of the overheated cases did not exceed 10 seconds. Seven different locations throughout the facility were used to locate the fire/smoke generation specimens.

Results indicated that for the short-duration fire/smoke sources tested and the locations of the EW and VEWFD systems, performed better than the conventional spot-type detectors. These tests did not provide any information on system performance for slowly degrading electrical components or timing information for operator response to such incipient stages.

E.13 Xtralis, “Warehouse Fire Detection Test Results - ASD vs Point (spot-type) vs Beam Detectors, Case Study,” April 2008.

Case study presents results from a series of demonstration tests conducted in Victoria University’s Warehouse. Three small fire tests were conducted to illustrate the benefits of EW and VEW detection capabilities. Comparisons were drawn between ASD EW and ASD VEW, as well as conventional spot-type and beam detectors.

The warehouse was 43 m long, 12 m wide for a gross floor area of 516 m^2, and had a ceiling height of 8.5 m at the central pitch. A single ASD pipe was installed along the ceiling ventilated ridge and contained six sampling holes spaced 7.2 meters apart. Several alarm thresholds were used for the ASD system, however only the Alert (~0.1 %/ft obscuration [0.3 percent per meter obscuration]) and Fire 1 (~0.37 %/ft obscuration [1.2 percent per meter obscuration]) alarm times were reported. Thus the Alert threshold was twice as sensitive and the Fire 1 threshold was almost ½ as sensitive as the minimum sensitivity for an alert per NFPA 76. Six optical spot-type detectors were also placed along the ceiling ridge vent adjacent to each ASD sampling point. The spot-type detectors had a sensitivity of 1.4 %/m obscuration. Smoke sources included liquid heptanes (100 ml), timber, and smoke pellets and were all located in the same area under the center line of the sloped ceiling, between the farthest two sampling points of the ASD system, and directly below the projected beam detector line of sight; positioning of the warehouse rollup door(s) also varied.

The results indicated that the ASD system performed better than the conventional and projected beam. For tests in which conventional spot-type detectors responded, the ASD system responded on average 52.2 seconds before the spot-type detector. Of the 21 tests conducted, the ASD systems responded with an alert 19 times, while the spot-type responded only 4 times, and the beam detector only responded in one test. The report concludes that the ASD system performed better than the other systems compared and supports the use of ASD systems in challenging warehouse type environments that promote smoke dilution because of high ceiling heights, stratification and natural ventilation conditions. However, it should be noted that, unless the report contains a typographical error, the 4.6 %/ft obscuration [1.4 %/ft obscuration] sensitivity of the spot-type detector is outside the bounds of UL 268 (0.5-4.0 %/ft obscuration) and would not be cited on the listing.

E.14 Milke, J., et al., “Guidelines for Estimating Smoke Detector Response,” Suppression and Detection Research and Applications Symposium (SUPDET 2009), Orlando, FL

This paper summarizes the work completed in Volume 3 of the “Validation of a Smoke Detection Performance Prediction Methodology,” sponsored by The Fire Protection Research Foundation. See Section E.11 for a full description of this work.

E.15 Miller, J., “Analyzing Photo-electric smoke detector response based on aspirated smoke detector obscuration,” Masters of Science Thesis, University of Maryland 2010.

Following the completion of the fire protection research foundation work, the data was analyzed by a student at the University of Maryland to improve the obscuration-level response accuracy of spot-type photoelectric smoke detectors. This work is documented in a Master of Science thesis titled, “Analyzing Photo-Electric Smoke Detector Response Based on Aspirated Smoke Detector Obscuration” (Miller, 2010). In this work, the ASD data files were analyzed against the other light obscuration measurements made during the testing, such that the data files could be synchronized. Then, the spot-type detector response was compared to the obscuration measurements made by the ASD system. The results concur with the conclusions made in the original test program, with the exception of non-flaming fires without ventilation; in this case, the student’s analysis indicated that the photoelectric detector performed better (responded at lower obscuration values) than the original report suggested (range of 0.4 to 5 %/ft obscuration).

Although the results compare well with the conclusions from the original report, uncertainties associated with averaging the ASD system response, unknown system offset time, filter effects, and smoke transport lag, were not explicitly quantified, and complicated the analysis. Even so, the results of this work parallel the conclusions from the original report suggesting a relatively large deviation in the expected obscuration level of 2.5 percent at photoelectric detector response. Unfortunately, because the ASD system was used as a measurement device, rather than setup as a detector, little can be drawn from this work regarding its performance. However, the underlying conclusion re-enforces the basic fire detection principles that are applicable to ASD detectors, which state that smoke characteristics, smoke transport, and detector characteristics directly impact the performance of a detectors response compared to its listing.

E.16 Zaworski, J., Laramee, S., O'Conner, D.J., "Comparative Testing of Various Detection Technologies," Schirmer Engineering Corporation, 2010.

Schirmer Engineering witnessed and reported the results of a series of fire tests conducted in a warehouse environment for axonX. The work was commissioned by axonX to evaluate the relative performance of their video image fire and smoke detection (VID) against numerous flame and smoke detection technologies. The test series consisted of 21 different fire scenarios which were repeated three times each for a total of 63 tests using five technologies (ASDs, projected beam smoke detection, spot-type ionization and photoelectric, and VID).

An ASD sampling pipe was located near the ceiling (~18ft) and ran the length of the room with three sampling ports spaced approximately 20ft from each other. The default ASD detector sensitivities were used with the "Fire 1" and "Fire 2" set points used for comparison (~0.18 %/ft obscuration and 1.2 %/ft obscuration, respectively, at each sampling point). Seven different fire sources ranging from smoldering to flaming fires, were used. Of interest to the NRC/NIST project was the overheated smoldering wire source, which consisted of a bundle of Type NM-B 14/3 cables wrapped around a heating element energized for 20 minutes per test. The fire sources were placed in three different locations within the room.

Results from this test series indicated that, in general, for warehouse type applications, the VID response fastest form most fire sources typically followed by the ASD and Ion spot detectors. For the low-energy overheated wire and smoldering wood tests, the VID responded in the 298 – 455 second range, while the ASD, beam, and Ion detectors responded in the 805 – 1016 second range. Given the sensitivity settings for the ASD systems, physical arrangement, and fire source characteristics, these results are reasonable.

E.17 Gottuk, D., et al., "Validation of Modeling Tools for Detection Design in High Air Flow Environments, Final Phase I Report," The Fire Protection Research Foundation, August 2012.

The Fire Protection Research Foundation sponsored an effort to examine the applicability of using computer modeling tools for modeling smoke detection system designs in high airflow rate environments. This report documents the identification of modeling requirements, potential computer models, gaps in knowledge, and

development of a research program to address these gaps. Seventeen model requirements and eight models were identified. The gap analysis identified the following four gaps:

1) Specification of the fire and smoke input

   Specification of the rate of smoke production for incipient fires and the smoke production and heat release for flaming fires is considered a modeling gap. Two aspects for this gap include existence of applicable measured data, and the methodology for specifying the inputs. The capability to predict the ignition and growth of fires of real world objects remains the subject of academic research.

2) Smoke transport

   Soot deposition upon walls and equipment is a known challenge related to smoke detection system design and modeling. Deposition of soot reduces the concentration of soot in the air, and acts to delay detection response. Soot deposition is primarily caused by thermophoresis (thermal gradients), electrophoresis (electric fields), and impactation (sharp turns in air streams near obstructions). This all suggests deposition is more significant inside electrical equipment than outside.

3) Smoke detection performance

   The ability to correlate conditions predicted by a model at a smoke detector/ASD sampling port to an alarm condition within the detector is a significant gap. There are no established correlations for predicting alarm response for ASD systems at either low or high air flow environments. ASD test data indicates that correlations will be highly dependent upon the specific detector model.

4) Large-scale integral test data set

   Limited data exists for HVAC flows and cooling effectiveness of IT/telecom facilities. An IT/telecom facility-specific set of large-scale tests would serve as a validation benchmark for determining the suitability of a specific model.

In the development of a test plan to address these gaps in knowledge, the authors identified the following issues, which are applicable to NPP fire scenarios in electrical equipment enclosures:

- The duration and amount of smoke released from electrical equipment will be dependent upon the size of the heat source, the orientation of the material with respect to the heat source, and the amount of material exposed.

- Significant fire development occurs when pyrolysis/smoldering combustion transitions to flaming. Although it is generally a goal to detect fires before flaming conditions, there are practical issues that can prevent successful intervention at the early stage. These include smoke levels not visible to site personnel, resulting in a source being difficult to find, and fires that occur because of energetic events, and result in relatively fast fire growth.

- Smoke production from an incipient circuit board fire may impact several other circuit boards and pieces of electrical equipment, before being enveloped into the primary air flow. In this scenario, soot deposition on the impacted equipment may reduce the overall smoke concentration that is transported to a detection site, compared to the same source in the open.

- Given the range of cabinet and ventilation configurations, it may be necessary to evaluate several potential configurations with sources at different locations within a cabinet. Total soot deposition may be significantly different for source in the bottom of a cabinet that has continuous vertical ventilation openings exposed to external ventilation conditions (smoke flows out of the cabinet), compared to a source at the bottom of the cabinet with exhaust openings at the top of the cabinet (smoke must flow up through the cabinet.

- Several detection devices used complex algorithms that continuously monitor ambient conditions and adjust detection levels accordingly.
  An understanding of the operation of such software, the optional and default settings, and the manufacturers recommendations are needed to ensure that the device meets performance goals.

Additional Readings:

i. Litton, C.D., “Laboratory Evaluation of smoke detectors for use in underground mines,” Fire Safety Journal, pp. 387-393, Vol. 44, 2009.

ii. Xtralis, “Designing & Deploying Aspirating Smoke Detection in Harsh Environments,” SFPE Webinar, http://magazine.sfpe.org/webinar/designing-and-deploying-aspirating-smoke-detection-asd-harsh-environments.

iii. Gallucci, R.H.V., Iqbal, N., Frumkin, D., Metzger, D., Barrett, H., “Credit for Very Early Warning Fire Detection in Fire Probabilistic Risk Assessment,” ANS Risk Management, 2009.

iv. Ludewig, F.A., “Application of Cloud Chamber Techniques to Fire Detection,” Environment One Corporation, Schenectady, NY.

v. Schifilti, R.P., “Applications of Fire Detection, Alarm and Signaling Systems in Industrial Occupancies,” Fire Protection Engineering Magazine, http://magazine.spfe.org/content/applications-fire-detectoin-alarm-and-signaling-systems-industrial-occupancies, 2013.

vi. Gottuk, D.T., McKenna, L.A., “Spot and Aspirated Laser Smoke Detection in Telecommunications Facilities,” Fire Technology, pgs. 147-178, Vol. 38, 2002; Proceedings, AUBE ’01, 12th International Conference on Automatic Fire Detection, 2001.

vii. AirSense Technology, Ltd., “Aspirating Smoke Detection, A Brief Guide for the Designer,” 1999.

viii. Xtralis, Dinaburg, J., Meikle, P., Vayeda N., “Testing & Verification of ASD Technology in Different Environments,” SPFE Webinar, 2012.

ix. NRC, “NUREG/CR-1798, Acceptance and Verification for Early Warning Fire Detection Systems – Interim Guide,” 1980.

x. Fissan, H., Otto, E., Dixkens, J., “Particle Transport in Sampling Lines used in Fire Detection Systems,” Fire Safety Journal, pgs. 205-215, Vol. 29, 1997.

xi. Xtralis, “Validation of NIST FDS Model with VESDA Detector Smoke Measurement,” Doc. 11124-01, 2013.

xii. Xtralis, White Paper, “Very Early Warning Aspirating Smoke Detection in Nuclear Facilities,” Doc. 18434-02.

xiii. Xtralis, White Paper, “The Complementary Application of Very Early Warning Fire Detection and Reliable Gas Monitoring in Diverse Environments,” Doc.18620_01.

xiv. Air Intelligence, “Industry Applications, High Ceilings,” 2009.

xv. FireTEC, “A Comparison of Aspirated Smoke Detectors, Honeywell FAAST Detectors and Xtralis VESDA VLF (laserfocus) Conducted by Packer Engineering, Inc. and the Fire Testing and Evaluation Center at The University of Maryland,” College Park, MD.

xvi. Parks, L.L., Kushler, B.D., Scrapiglia, M.J., McKenna, L.A., Budnick, E.K., Watts, J.M., “Fire Risk Assessment for Telecommunications Central Office,” Fire Technology, Vol. 34, No. 2, 1998.

xvii. Floyd, J., Overholt, K., Ezekoye, O., “Soot Deposition and Gravitational Settling Modeling and the Impact of Particle Size and Agglomeration,” Proceedings of the Eleventh International Symposium, Fire Safety Science, 2014.

xviii. Gottuk, D., Mealy, C., Floyd, J., “Smoke Transport and FDS Validation,” Proceedings of the Ninth International Symposium, pp., 129-140, International Association for Fire Safety Science.

xix. Tinsley, A., Gorbett, G., Hanks, C., “Comparative Assessment of VLC-505 & FAAST 8100, Return Air Duct and Warehouse Testing,” Eastern Kentucky University, 2011.

xx. Vision Systems, “Cabinet Detection Aspirating Smoke Detection,” 2000.

xxi. NRC, “NUREG/CR-0488, Nuclear Power Plant Fire Protection Fire Detection (Subsystems Study Task 2),” 1979.

xxii. Brookman, M.J., “Smoke Characterization of Incipient Fire Sources for FDS Modeling,” Master of Science Thesis, University of Maryland, College Park, MD 2008.

xxiii. Johnson, P., “Very Early Warning Fire Detection for High Tech/High Value Facilities,” SFPE Symposium, Fire Protection and Suppression, 1987.

NRC FORM 335 (12-2010) NRCMD 3.7 — U.S. NUCLEAR REGULATORY COMMISSION **BIBLIOGRAPHIC DATA SHEET** *(See instructions on the reverse)*	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG-2180
2. TITLE AND SUBTITLE Determining the Effectiveness, Limitations, and Operator Response for Very Early Warning Fire Detection Systems in Nuclear Facilities (DELORES-VEWFIRE) DRAFT for Comment	3. DATE REPORT PUBLISHED MONTH: June — YEAR: 2015 4. FIN OR GRANT NUMBER JCN N6903
5. AUTHOR(S) Gabriel Taylor, Susan Cooper, Amy D'Agostino, NRC Office of Nuclear Regulatory Research Thomas Cleary, National Institute of Standards and Technology	6. TYPE OF REPORT 7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Division of Risk Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

National Institute of Standards and Technology
Engineering Laboratory
Fire Research Division
Gaithersburg, MD 20899

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Risk Analysis
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

G. Taylor, NRC Project Manager

11. ABSTRACT (200 words or less)

Aspirated smoke detection (ASD) systems have been available on the commercial market for more than four decades as an alternative technology to spot-type smoke detection for detecting products of combustion. Recently, these systems have been installed as very early warning fire detection (VEWFD) systems to support licensees transitioning to a performance-based fire protection program. In many, but not all cases, the choice to install these systems is based on the expectation that these systems may reduce the estimated fire risk in a fire probabilistic risk assessment (PRA). The lack of data evaluating the performance of these systems has limited the acceptance of their use.

This report documents research conducted by the Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), and the National Institute of Standards and Technology (NIST) to evaluate the performance of both ASD and conventional smoke detection systems in common nuclear power plant applications. A literature search, multiple scales of testing, and a risk-scoping study provide a comprehensive evaluation of the response of several smoke detection systems the incipient stage of fires.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)	13. AVAILABILITY STATEMENT
Smoke Detection	unlimited
Very Early Warning Fire Detection System	14 SECURITY CLASSIFICATION
Aspirated Smoke Detection	*(This Page)* unclassified
NFPA 805	*(This Report)* unclassified
Fire Probabilistic Risk Assessment	15. NUMBER OF PAGES
Fire Protection	16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

@NRCgov

NUREG-2180
Draft

Determining the Effectiveness, Limitations, and Operator Response for Very Early Warning Fire Detection Systems in Nuclear Facilities (DELORES-VEWFIRE)

June 2015