Final (PRE-PUBLICATION) Report

NUREG-2180

United States Nuclear Regulatory Commission

Protecting People and the Environment

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

Final (Pre-Publication) Report

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 Public Electronic Reading Room at http://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 Printing Office
   Mail Stop SSOP
   Washington, DC 20402-0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161-0002
   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: Office of the Chief Information Officer,
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301-415-2289

Some publications in the NUREG series that are posted at NRC's Web site address http://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, and 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 NRC regulatory process are maintained at:
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 contractor-prepared publications in this series are not necessarily those of 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-VEWFIRES)

Final (Pre-Publication) Report

Manuscript Completed: September 2016
Date Published:

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

[1]NRC, Office of Nuclear Regulatory Research
[2]National Institute of Standards and Technology

Office of Nuclear Regulatory Research

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 have or 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 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 area-wide 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 area-wide applications in non-continuously occupied NPP areas.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

Figure **Page**

Figure **Page**

LIST OF TABLES

<u>**Table**</u> <u>**Page**</u>

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). The fire PRAs are primarily being developed to support 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 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 area-wide 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 a 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 were also evaluated. 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 area-wide detector response in 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 area-wide 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 area-wide 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 to protected equipment that could generate products of combustion during an incipient stage. Phenomena such as dilution and stratification are minimized as compared to area-wide 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 area-wide 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 area-wide 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 influence the performance of ceiling versus air return ASD VEWFD application effectiveness.

Contrasting the performance of conventional spot-type smoke 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 area-wide 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 naturally ventilated 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. area-wide).

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, reduces 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, on average, 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 systems. 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 type of in-cabinet smoke detection system used.

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., not 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.

The reliability and availability was evaluated for ASD systems. Data from the Electric Power Research Institute (EPRI) report EPRI 1016735 “Fire PRA Methods Enhancements: Additions, Clarification, and Refinements to EPRI 1019189,” literature on German NPP operating experience, information collected during site visits, and reliability estimates as part of smoke detector listings were used to estimate unreliability estimates for ASDs. 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 area-wide 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 targets outside of the electrical cabinet. Area-wide 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;

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

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. Jake Stefanick developed the early versions of the calculation tools included in the back of this report, and his support is greatly appreciated.

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. A special thanks to Anita Aikins-Afful at the NRC for her technical editing support.

Internal and external stakeholders provide comments and suggestions on the draft of this report when it was published in the Federal Register (80 FR 38755) on July 7, 2015. Those stakeholders who commented are listed and acknowledged below.

Victoria K. Anderson *(Nuclear Energy Institute)*
Jeffery Ertman *(Duke Energy)*
David T. Gudger *(Exelon Generation)*
Meghan Housewright *(National Fire Protection Association)*
Stuart Lewis *(Electric Power Research Institute)*
Ron Robertson *(Safe Fire Detection)*
Dwight Wills *(Building Reports)*

A public workshop was held on April 26, 2016 at the NRC Headquarters Offices located in Rockville, Maryland, and simultaneously presented via a webinar. During this all-day workshop, participants provided valuable insights and feedback. The authors would like to acknowledge those who participated, including:

Victoria Anderson
(Nuclear Energy Institute)
Dennis Andrukat, *(U.S. NRC)*
Harold Barrett, *(U.S. NRC)*
Paul Bemis, *(Pacific Gas and Electric)*
Michael Birnkrant,
(United Technologies Research Center)
Harrison Brown,
(TVA Brown's Ferry Nuclear Plant)
Greg Casto, *(U.S. NRC)*
Stan Chingo, *(Duke Energy)*
Daniel Davidson, *(Southern Nuclear)*
Joelle DeJoseph, *(Jensen Hughes)*
Josh Dinaburg, *(Jensen Hughes)*
Robert Dukes, *(Enercon)*
Jeffery Ertman, *(Duke Energy)*
Stephen Fleger, *(U.S. NRC)*
Daniel Frumkin, *(U.S. NRC)*
Nick Gomez, *(System Sensor)*
James Gregerson,
(Pacific Gas and Electric)
Scott Groesbeck, *(DP Engineering)*
Kenneth Hamburger, *(U.S. NRC)*
Naiv Hughes, *(U.S. NRC)*
Mark Hulet, *(APS)*
JS Hyslop, *(U.S. NRC)*
Boemhee Jeong, *(Southern Company)*
Brian Krystek,
(Engineering Planning and Management)
Greg Kvamme, *(Xcel Energy)*
Sawyer Lance, *(Pacific Gas and Electric)*
Ashley Lindeman,
(Electric Power Research Institute)
James Lloyd, *(Safe Fire Detection, Inc.)*
Christopher Lord,
(FENOC Beaver Valley Power Station)
Laroy Martin, (Dominion)
Shivani Mehta, *(U.S. NRC)*
Stephanie Morrow, *(U.S. NRC)*
Charles Moulton, *(U.S. NRC)*
Victor Ontiveros, *(Jensen Hughes)*
JongSeuk Park, *(KINS, Korea)*
Andrew Ratchford, *(Jensen Hughes)*
Robert Robertson, *(Safe Fire Detection, Inc.)*
Scot Robertson, *(Safe Fire Detection, Inc.)*
Frederick Ross, *(TVA)*
Mark Henry Salley, *(U.S. NRC)*
Thomas Shudak,
(Nebraska Public Power District)
Brenda Simril, *(TVA)*
Philip Smith, *(U.S. NRC)*
Joseph Soscia, *(Enercon)*
Susumu Tsuchino, *(JNRA)*
Travis Weber
(Engineering Planning and Management)
Stephanie Weimer *(Entergy)*
Keith Williams *(Duke Energy)*
Mark Wishart *(Jensen Hughes)*
Boyee Wong *(Pacific Gas and Electric)*
Mark Wright,
(Defense Nuclear Facilities Safety Board)
Joel Yurkosky, *(Enercon)*
Kiang Zee, *(Jensen Hughes)*

A public meeting was held on September 20, 2016 at the NRC Headquarters Offices located in Rockville, Maryland. During this meeting the NRC staff provided feedback on a tabletop pilot exercise of NUREG-2180 performed by industry and additional concerns raised on the completeness, benefit to plant safety, need for an expert elicitation and removal of single component damage end state from the draft report. The authors would like to acknowledge those who participated, including:

Victoria Anderson
(Nuclear Energy Institute)
Harold Barrett *(U.S. NRC)*
Jana Bergman *(Curtiss-Wright)*
Pamela Burns *(Southern Nuclear)*
Greg Casto *(U.S. NRC)*
Thomas Collopy *(FENOC)*
Richard Correia *(U.S. NRC)*
Joelle DeJoseph *(Jensen Hughes)*
Jeffery Ertman *(Duke Energy)*
Jason Floyd *(Jensen Hughes)*
Michael Gartman *(U.S. NRC)*
John Giddens *(Southern Nuclear)*
Joseph Giitter *(U.S. NRC)*
Kenneth Hamburger *(U.S. NRC)*
JS Hyslop *(U.S. NRC)*
Boemhee Jeong *(Southern Company)*
Francisco Joglar *(Jensen Hughes)*
Robert Krsek *(U.S. NRC)*
Brian Krystek
(Engineering Planning and Management)
Greg Kvamme *(Xcel Energy)*
Ashley Lindeman
(Electric Power Research Institute)
Sara Lyons *(U.S. NRC)*
David Miskiewicz
(Engineering Planning and Management)
Marty Murphy *(Xcel Energy)*
Joe Pollock *(Nuclear Energy Institute)*
Andrew Ratchford *(Jensen Hughes)*
Robert Rishel *(Duke Energy)*
Joseph Reed, *(Nuclear Energy Institute)*
Eric Ruesch, *(U.S. NRC)*
Mark Henry Salley, *(U.S. NRC)*
Harold Stiles, *(Duke Energy)*
David Stroup, *(U.S. NRC)*
Mike Testa, *(FENOC)*
Keith Vincent, *(NextEra Energy)*
Travis Weber,
(Engineering Planning and Management)
Mark Wishart, *(Jensen Hughes)*
Kiang Zee, *(Jensen Hughes)*

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	area-wide
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

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 spot-type 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 as part of a fire risk scoping study.

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 (including assumptions and limitations), 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 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 1016735 titled, “Fire PRA Methods Enhancements (Additions, Clarifications, and Refinements to EPRI 1011989),” in December 2008. The EPRI report presented an interim methodology and guidance for fire

1 Definitions are presented in Section 16.

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.

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 the 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 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

   - This includes an evaluation of in-cabinet and area-wide 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 ASD 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 area-wide

- 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 General Approach and Project History

To achieve the stated purpose and objectives, this confirmatory research project was broken down into three distinct areas: review of literature, operating experience, and testing. Each area has its own subtasks, as shown in Figure 1-1. These three areas support the risk scoping study, as well as providing input to the human performance evaluation.

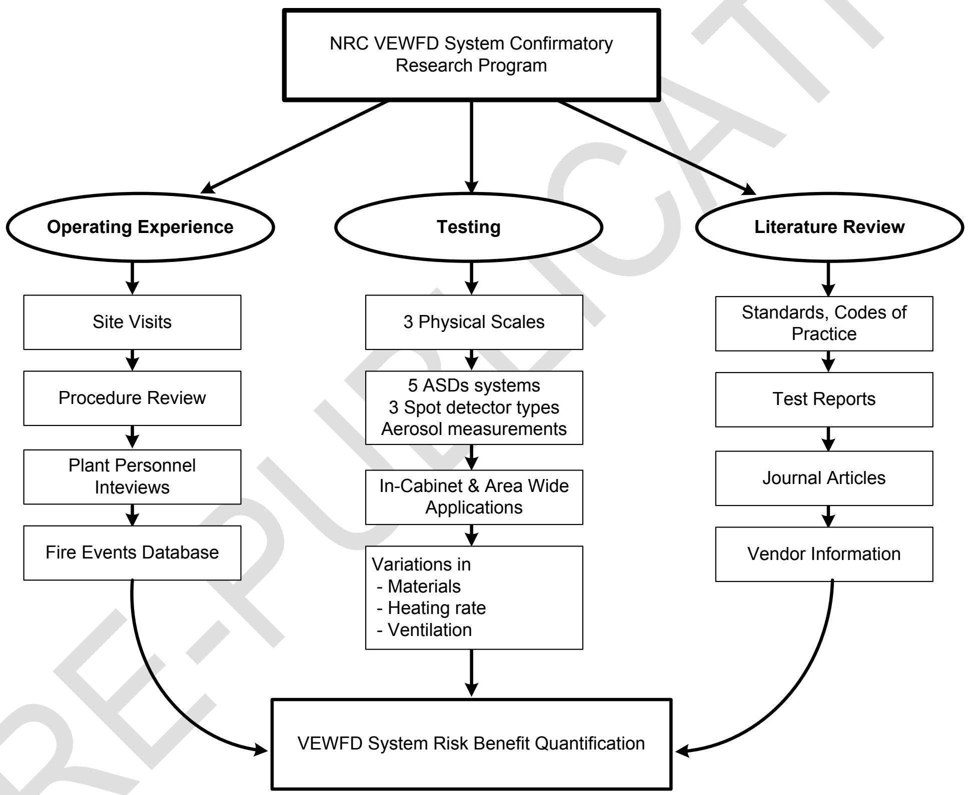


Figure 1-1. Illustration of VEWFD System Confirmatory Research Project

Early in the project, staff from NIST reviewed available literature on ASD VEWFD systems to support development of a test plan. 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. Upon finalizing the test plan, systems and materials were procured and testing commenced.

Once the literature, test data, operator response characteristics, and operating experience were understood, a risk scoping study was completed to evaluate the performance of these systems.

Project History

This project took over five years to complete. To help understand the elements, complexity, and interactions of this project, a short history is provided.

The need for this work developed out of the initial NFPA 805 pilot plant application and the desire to characterize the benefit of having VEWFD systems and their effect on the fire PRA quantification. In 2008, frequently asked question (FAQ) 08-0046 was proposed by the Nuclear Energy Institute (NEI), through its NFPA 805 Task Force to seek additional guidance on modeling the use of VEWFD systems in fire PRAs. Later that same year, EPRI 1016735 titled, "Fire PRA Methods Enhancements (Additions, Clarifications, and Refinements to EPRI 1011989)," was issued. Based on this industry report, discussions between NRC staff and industry, and the beliefs at the time of these systems performance, an interim staff position was issued in 2009 (see FAQ 08-0046 closure memo). The interim guidance was based on vendor expectation and consensus standard performance objectives. A lack of applicable data was apparent. In 2010, a user need request was transmitted from the Office of Nuclear Reactor Regulation requesting confirmatory research in this area. The Office of Nuclear Regulatory Research (RES) contracted with NIST in 2011 to perform testing to support addressing several of the user need request objectives. That same year, NPP sites that have VEWFD systems installed were identified and site visits were planned, including the development of a list of questions that was reviewed and commented on by the user need office.

Early in 2012, several USA and Canadian NPP sites and a National Aeronatutic and Space Administration (NASA) site were visited to understand how these systems were being used and to obtain operating experience to support the objectives of this project. 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)

By the middle of 2012 a draft test plan was shared with the user need office and comments were received and incorporated as appropriate. The small-scale laboratory and small room testing were completed by the end of the year.

In 2013, the preliminary results from the testing indicated that for in-cabinet applications, there were little performance differences between spot-type detection (ionization) and ASD VEWFD systems. This preliminary information was communicated to the NRC stakeholders during a public teleconference held on March 21, 2013 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML13080A166). After the exchange of preliminary information, the user need office requested larger scale testing and testing of multi-zone ASD VEWFD systems. It also was requested that RES engage the ASD vendors and EPRI to better understand the test program and the results. Two meetings were held with these 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 user need office staff was in attendance during both meetings. The NRC presentations are available electronically (ADAMS, Accession No ML14356A581). The test plan was shared with the user need office and EPRI for review and comment. Those comments were incorporated as appropriate and testing commenced in the fall of 2013, however a delay of approximately 6 weeks was experienced because of a lack of appropriations (i.e., government shutdown). The larger room testing finished in early 2014.

In March 2014, the data from all testing was received, and the NRC staff began data processing and analysis tasks to support the risk scoping study documented in Part II of this report. In May, a high-level description of the risk scoping study approach was presented during a routine user need meeting. A question related to this research was asked during a June Commission meeting on NFPA 805 and staff from the user need office responded. A follow-on briefing for Commissioner Magwood was requested and provided, with other Commissioner staff in attendance. The first draft of the report was transmitted to the user need office on August 1, with a two part presentation of the reported provided to the user need office that same month. High level comments on the first draft were provided to RES staff by the end of August and a revised version of the report was returned to the user need office on November 2. In late November 2014 UNR office comments were received on the second draft report and a request to have senior staff meet to thoroughly review the data that were used to estimate one of the parameters in the risk scoping study approach. A consensus on the disposition of the low-voltage control operating experience was reached in December and the intent to publish memo was routed before the end of the year.

In early 2015, the user need office requested that the draft report be sent to EPRI for review and comment. EPRI comments were received January 21. After a January 29 FAQ call, it was clarified that the user need office sought an extended EPRI review; however, RES disagreed because publishing this report as a draft document for public comment served the same purpose. As a compromise, RES agreed to transmit to EPRI the questions that were included in the *Federal Register* (80 FR 38755) and have EPRI seek for responses from the industry to provide additional operating experience to better inform the report prior to issuance for public comment. The questions were transmitted to EPRI in February and by the end of March, no responses were provided. The draft report was issued for a 60-day public comment on July 7, 2015.

The public comment period closed on September 8, 2015 and approximately 200 comments on the report were received. In addition to the public comments, additional comments from the user need office and its contractor were received. By early November most of the comments were resolved and communicated to the user need office. In addition, NEI identified in its cover letter that "…industry has some very recent operating experience with these systems that could provide useful input to this report. Once a complete report on the operating experience is available, the industry will provide this to the NRC for consideration in the final version of this NUREG." In mid-October operating experience from Shearon Harris was provided. Upon reviewing the information and after discussions with the user need request office, it was determined that the information provided was not complete and a site visit could facilitate a better understanding of this recent operating experience for incorporation into the final report. The site visit occurred on January 13, 2016 and the draft-final version of this report started the publication process in early February 2016.

Subsequent discussions with the user need office indicated that holding a public workshop to communicate the final results from this work, discussing changes to the report between the draft and final versions, and presenting the event tree non-suppression probability estimation tool would be of value. A public workshop was held on April 26, 2016, with 55 participants in attendance. In June of 2016, NEI requested that a tabletop pilot of the risk quantification approach be performed prior. Those results were provided to the NRC in July and a public meeting was held on September 20, 2016 to communicate the NRC feedback on the tabletop pilot along with the staffs' response to additional comments provided by NEI. The following provides a high level milestone timeline of this project.

2010
- User need request (June)

2011
- NIST contract in place (July)

2012
- Site visits conducted (March – May)
- Small scale testing (summer)
- Full scale testing (November – December)
  NRR/EPRI observe testing at Montgomery County Police Training Academy

2013
- Preliminary results presented during Fire PRA Methods and FAQ call with NEI.
- Meeting with ASD venders (May)
- Meeting with EPRI (July)
- Requested to test multi-zone ASD
- Government shutdown
- Full scale testing multi-zone (November – December)
  NRR/EPRI observe testing at Hughes Associates Inc.

2014
- Data received from NIST (March)
- Commission meeting on NFPA 805 (June)
- First draft report to user need office (August)
- Second draft report to user need office (November)
- All NRC staff comments resolved and draft report finalized for issuance (December)

2015
- User need office requests EPRI be provided opportunity to review and comment (January)
- EPRI comments received (January)
- User need office requests additional feedback from EPRI (January)
- Report formally issued draft for public comment (80 FR 38755, July)
- Comment period closed (September)
- NEI provided additional operating experience received (October)
- User need office requests site visit to better understand recent operating experience
- Public comments resolved (November)

2016

- Site visit conducted (January)
- Data collection standardization sheet developed (January)
- Report finalized for final issuance (February)
- NEI requests tabletop pilot exercise be performed (June)
- Tabletop results provided to NRC (July)
- Public meeting to provide NRC feedback on tabletop results and response to additional NEI comments

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 does not represent any determination that these are the only fire detection methods suitable for NPP applications. Additionally, this report does not 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 incipient stage 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 an approach 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, inspection, 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.

- **Section 13** presents assumptions and limitations of the risk scoping study.

PART III

- **Section 14** presents a summary from the findings of this project and conclusions.

- **Section 15** identifies recommendations for future research

- **Section 16** provides definitions for terms commonly used in report

- **Section 17** provides a list of references

- **Appendices A–H** contain supporting information including; view graphs from meetings with vendors, experimental data, human performance, operating experience, literature reviewed, quick reference for risk scoping study parameters, VEWFD data collection sheet, and user guides for the event tree non-suppression probability estimation tool.

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) 76, “Standard for 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 area-wide 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.

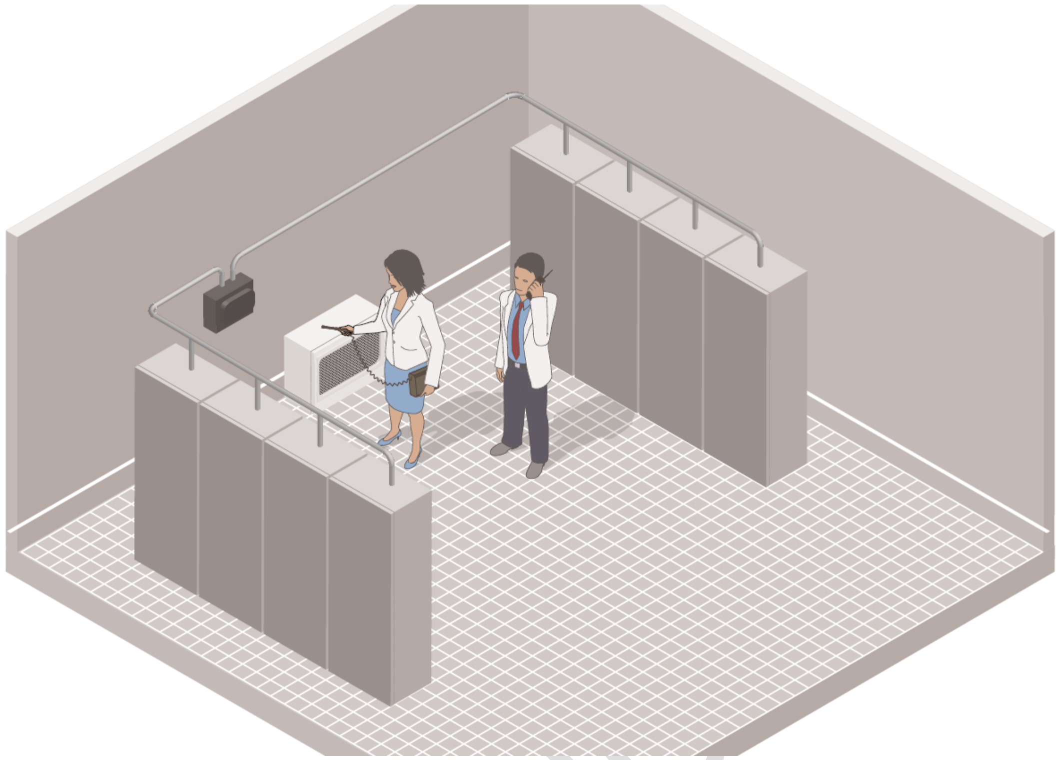


Figure 2-1. Illustration of ASD system in an in-cabinet application

ASD VEWFD systems have been used at several U.S. NPPs (e.g., Three Mile Island Nuclear Station, H.B. Robinson Steam Electric Plant, Clinton Power Station) 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 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. Operating experience has also indicated that the benefit from using these systems may extend beyond fire risk reductions. In some instances, these systems may be capable of detection component failures that if left unattended could result in extended system or plant down time.

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.[1] Because of the lack of information and test data, the 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 (NUREG-0050). 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 <u>Dynamics of Fire Stages</u>

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 2-2 (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

[1] 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.

incipient stage and transition point as it relates to performance-based methods, is paramount to the research performed under this project.

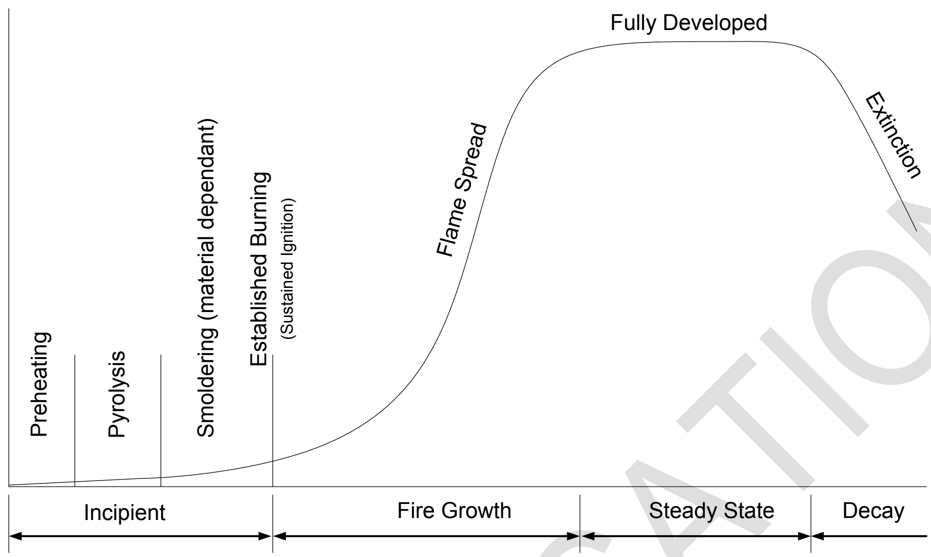


Figure 2-2. Fire stages

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. Alternatively, component degradation could begin 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 understanding 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).

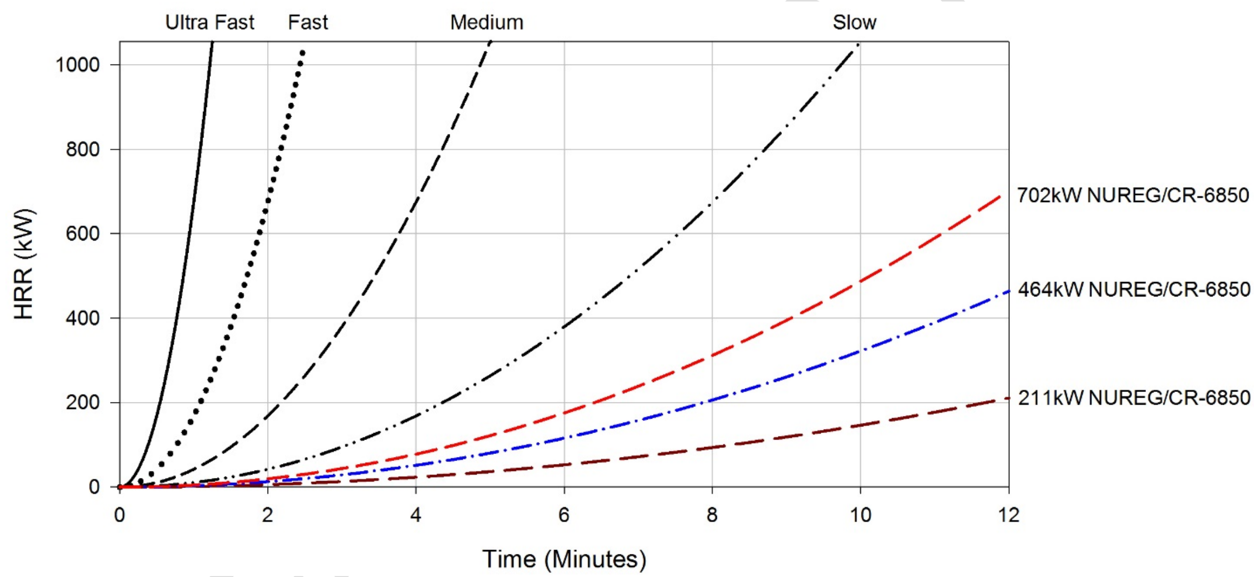


Figure 2-3. Illustration of several performance-based t-squared fire growth profiles (Note: incipient, steady-state, and decay stages not shown)

<u>Alternative definitions</u>

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^{-04} 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 than 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 initially produces (through pyrolysis) submicron particles ranging in size from 5×10^{-04} to 1×10^{-03} micrometers[2] (Ref. 11). 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 combustion[3] 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 This range is representative of the typical particle sizes observed during the early stages of pyrolysis. Larger particles sizes outside of this range are likely and dependent on materials and/or smoldering combustion.

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

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:

$$I = I_0 \cdot \exp(-\kappa C d)$$

where: I = intensity of transmitted monochromatic light over pathlength d, (cd)
I_0 = initial intensity of monochromatic light (cd)
κ = extinction coefficient, (m^2/g)
C = mass concentration of smoke particles, (g/m^3) and
d = 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 (OD) per unit length (meter or foot),

$$OD = \frac{1}{d} log_{10}\left(\frac{I_0}{I}\right) = \frac{\kappa C}{2.303}$$

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

$$\frac{I_0 - I}{I_0} \cdot 100$$

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., %/m obscuration or %/ft 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 area-wide application, respectively. These figures show the detector unit, smooth bore pipe network with two zone and sample ports.

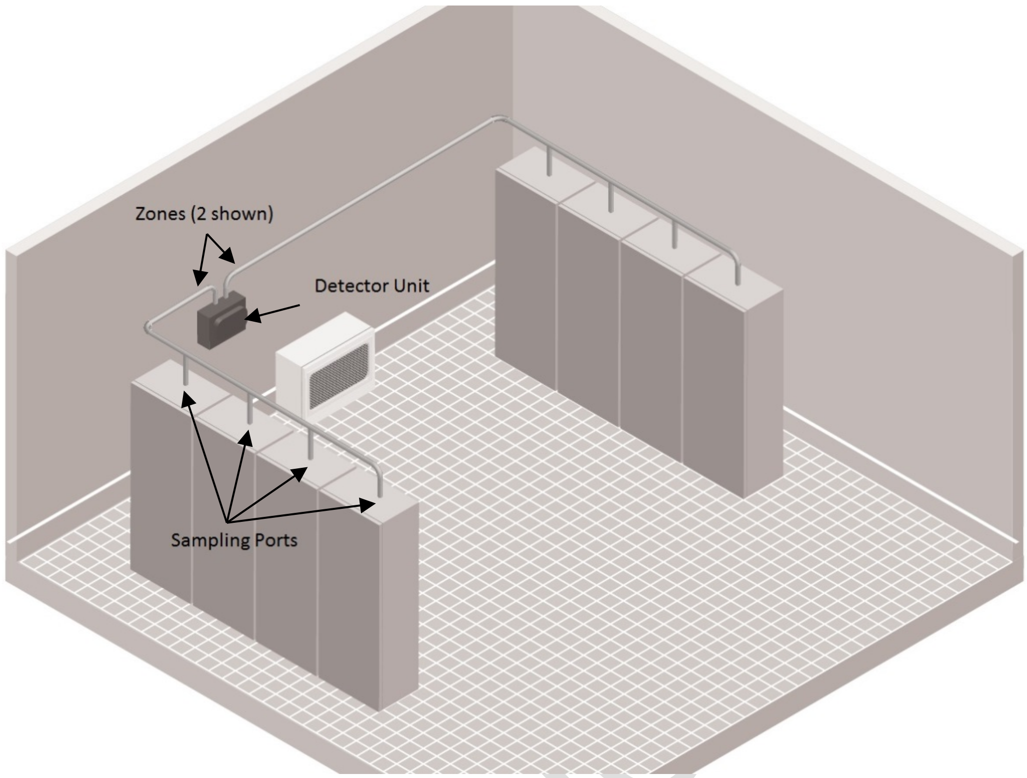


Figure 2-5. Illustration of ASD in-cabinet application

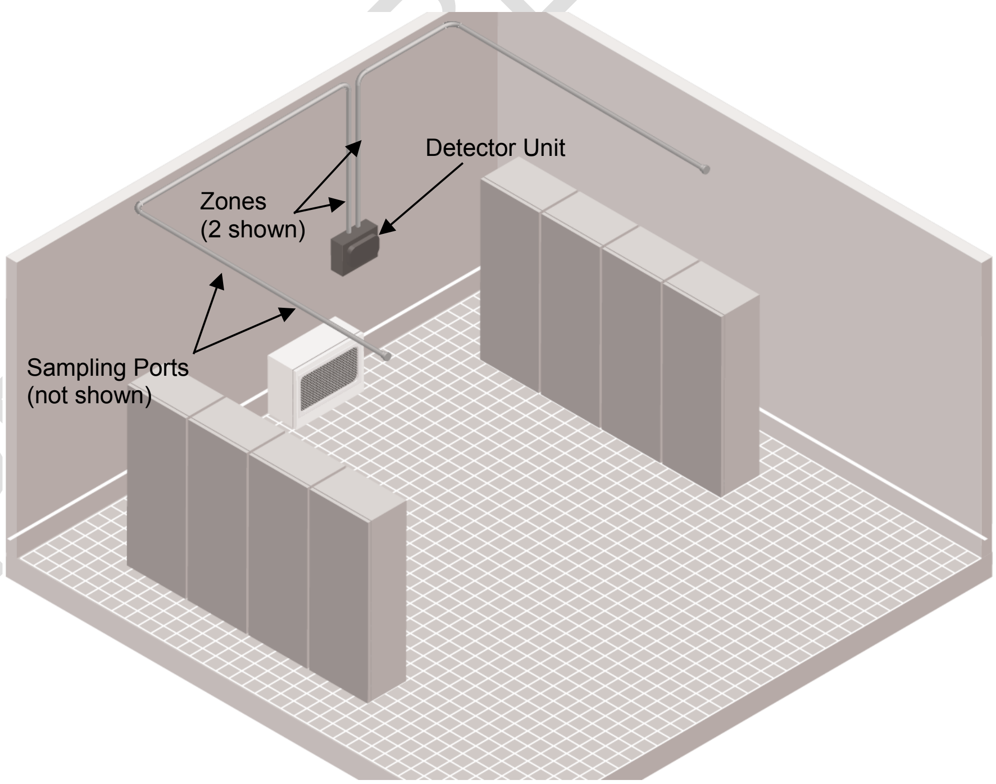


Figure 2-6. Illustration of an ASD area-wide application

Two types of detector unit technology are commonly used in ASDs; 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 minimum 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 shall not exceed 60 seconds.

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 area-wide 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 area-wide 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. Detector/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 when designing the detection system layout. Depending on the detector location and type, these conditions may result in delayed detection for very early warning applications. Areas of high air flow can have an effect on smoke dilution as well. The detection technology best suited for such applications should be carefully considered.
  - 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.
  - Humidity and ambient conditions can also result in condensation being trapped within the smooth bore air sampling piping, if not properly designed and installed to prevent water accumulation in low points. The use of moisture traps and drains in the piping system may be necessary is some applications.

- 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.

Test and Test Control

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.

Records

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[4], 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[5].

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

5 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."

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 *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). 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 frequency.

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, most 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). U.S. NPP 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 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 environmental conditions, 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 area-wide ceiling-mounted ASD type application could degrade the systems performance, the blockage in sampling point(s) 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 any unintentional pipe openings.

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 algorithm 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.

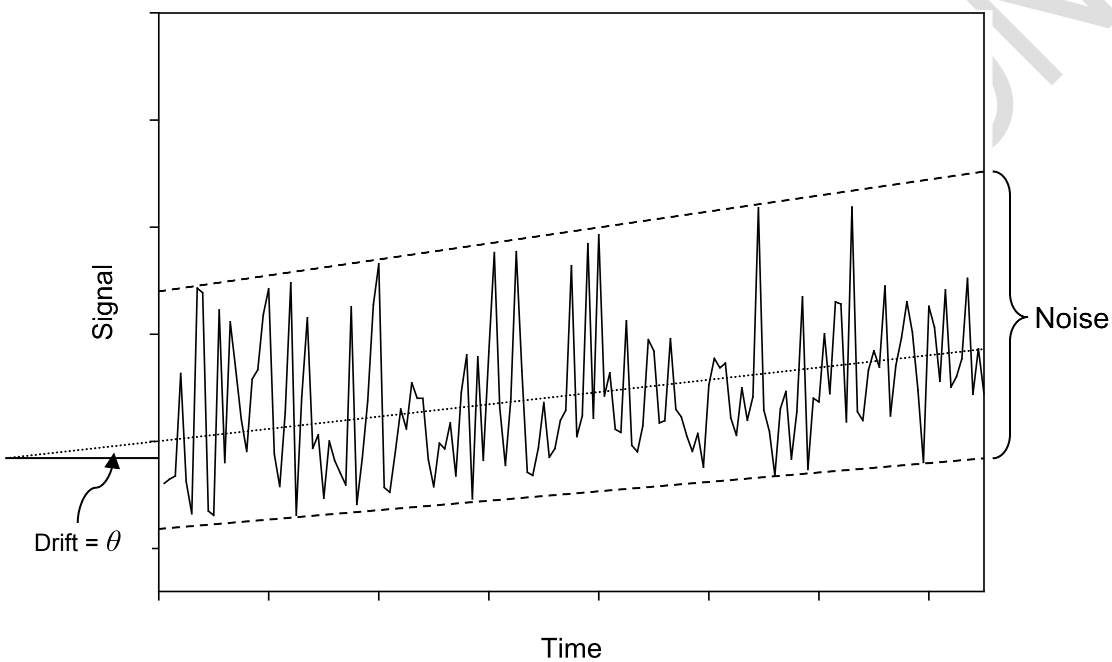


Figure 2-7. Illustration of detector signal background noise and drift

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 prescriptive-based applications requires installation, testing and maintenance in accordance with NFPA 72 (Ref. 22). Some licensees using these systems have committed to the requirements of NFPA 72 associated with inspection, testing, and maintenance. 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 to support 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.

Subsequently, the project team coordinated several site visits and expanded the team with human reliability and human factor experts. The site visits fostered a general understanding of the installation and response to the VEWFD systems. This supported development of a test plan that represented NPP applications to the extent possible given certain laboratory limitations. Teleconferences were held with licensees who have VEWFD systems installed to allow the HRA and human factors experts to understand how the plant operators and staff respond to these systems and any actions taken. This information allowed the team to identify assumptions and place bounds on the analysis developed on Part II of the report. This more detailed operational information is discussed in greater detail in Sections 9, 10, and Appendix C.

This section summarizes the information received through site visits to gain a better understanding of these systems applications, support development of a testing approach, estimation of system unreliability and unavailability, along with understanding general operating experience. Operating experience documented in the EPRI fire events database was also reviewed and used to support Part II of this report. However, that operating experience information is described in Sections 7, 8, and Appendix D along with how it is used to support the objectives of this report.

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 and plant operator /technician response to system notifications 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. The Shearon Harris site was visited a second time in early 2016. The purpose of this visit was to better understand recent operating experience that was provided during the public comment on the draft version of this report. 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.

<u>Deterministic Applications</u>
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 transient combustible control zones. In this instance, an ASD system was used in area-wide 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, documentation of these events was not readily retrievable.

<u>Risk Applications</u>
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 a risk metric from Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis."

In an IPEEE case, the licensee postulated a fire scenario in a control room reactor turbine generator board contributing to a core damage frequency (CDF) of 4.5×10^{-05} 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 6.9×10^{-06} 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 risk reduction 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 area-wide 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[1] 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

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

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). This site used the 30 percent set point to represent the “alert” response, while the 50 percent set point represented the “alarm” response.[2] 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
    - NFPA 76 Annex B/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
- 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.

Acceptance testing is an important process to ensure that ASD systems are properly installed and functional. Feedback from one of the sites visited, indicated that the installation instruction did not contain a critical step from the design requirements to include opening all sampling ports. Bacause of the cabinet configuration, acceptance testing did not verify the ASD systems response to a smoke source at each sampling port. Thus, the system was non-functional from commissioning until the installation error was identified by plant personnel performing period testing on the system.

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. Revisit to the plant in early 2016 determined that set points were changed after commissioning for one of the 10 systems installed. In this instance, the detector was experiencing significantly more nuisance alarms (alerts) than the other VEWFD systems installed in similar applications. As such an engineering evaluation was performed and the detector unit was decreased in sensitivity. Instrumentation and control technicians maintain and repair the systems with vendor

[2] These detector gain and % of gain settings are vendor specific. Sampling point (i.e., port) sensitivity is dependent on the number of sampling points per zone along with the detector sensitivity setting. The identification of these gain settings DO NOT imply an equivalency to the NFPA 76 minimum sensitivity requirements for VEWFD systems.

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.

Appendix D.2 of this report describes a limited number of events where VEWFD systems detected pre-flaming conditions (incipient stage). Several other cases were observed 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 very similar, with some slightly different between facilities.

For several sites, 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.

At one site an ASD VEWFD system is installed in the reactor turbine generator board 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 reactor turbine generator board 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 does not 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.

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 area-wide 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.[3] 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 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.

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

When an “alert” (pre-alarm) notification is received, operators attempt to clear the pre-alarm. The purpose of this action is to help support a determination of a continuous, intermittent, or nuisance system response. 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 sounds 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.

<u>System Performance</u>
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 in use when the site visits occurred were of the laser-based technology. Cloud chamber type systems were initially used for a short period of time, but none remain. The decision to discontinue the use of the cloud chamber systems were partially due to the large number of systems planed and maintenance of the systems water supply. 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 is 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 occurred than when spot detectors were installed.

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

Conference Proceedings

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 (time of discover 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

Telecommunications

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. 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 does not 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 sensitivity.

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 follow-up 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 area-wide arrangements and low-energy (incipient stage) 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 area-wide). 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 area-wide 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. These are the minimum allowable levels to meet the definition of VEWFD system. If set to these levels (at each hole location), then it may be considered to meet the minimum sensitivity requirements of NFPA 76 for VEWFD. For area-wide detection, the added benefit of the active air sample would likely improve ASD performance, but in cabinets with very little airflow there may be little to no difference. The primary benefit of ASD is that you can set them to alert at much more sensitive levels, whereas the 0.2 %/ft obscuration is about the limit for most high sensitive spot detectors. 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, 2013 Edition, 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 vendor's process involved initially setting the detector to a gain setting commonly used for the application. Then the background signal is observed of a period of time to ensure remains below a specific reading to reduce the likelihood of nuisance alarms. If it does (as it did for our testing) that set point is maintained. Since this process differs from how the light scattering based detectors were configured, direct comparison between the two technologies is not strait forward.

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 area-wide applications, there is no consensus opinion characterizing the duration and failure mechanisms of a 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 area-wide 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 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 tabulated values are shown in Table 4-2 below. The classes in the table represent a range of electrical insulation materials.

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 °C, for scoping experiments conducted in the laboratory at NIST, and subsequently raised to 485 °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 area-wide experiments; and a standardized source to assess area-wide system design. Experiments with these sources were included as reference sources and were not considered in any analysis of VEWFDS effectiveness in this report.

The materials used in the in-cabinet and area-wide 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 the flame propagation- test of IEEE 383-1974, "IEEE Standard for Type Test of Class 1E Electric Cables, Field Splices and Connections for Nuclear Power Generating Stations."

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.

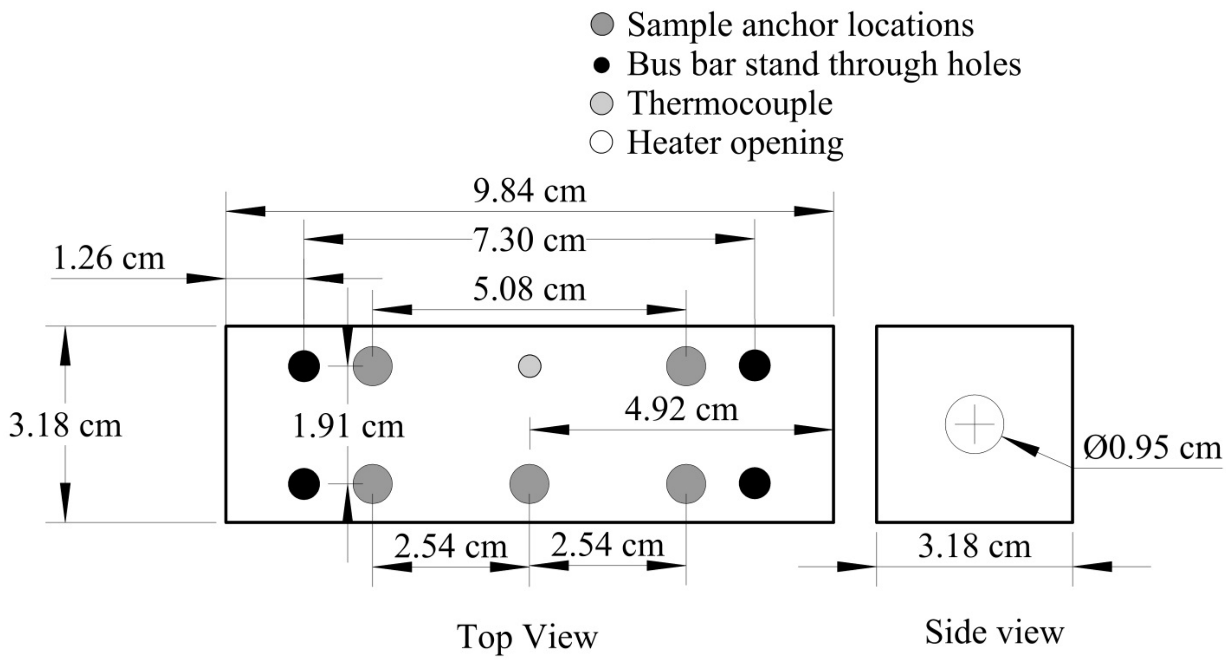


Figure 4-1. Schematic of the bus bar

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.)

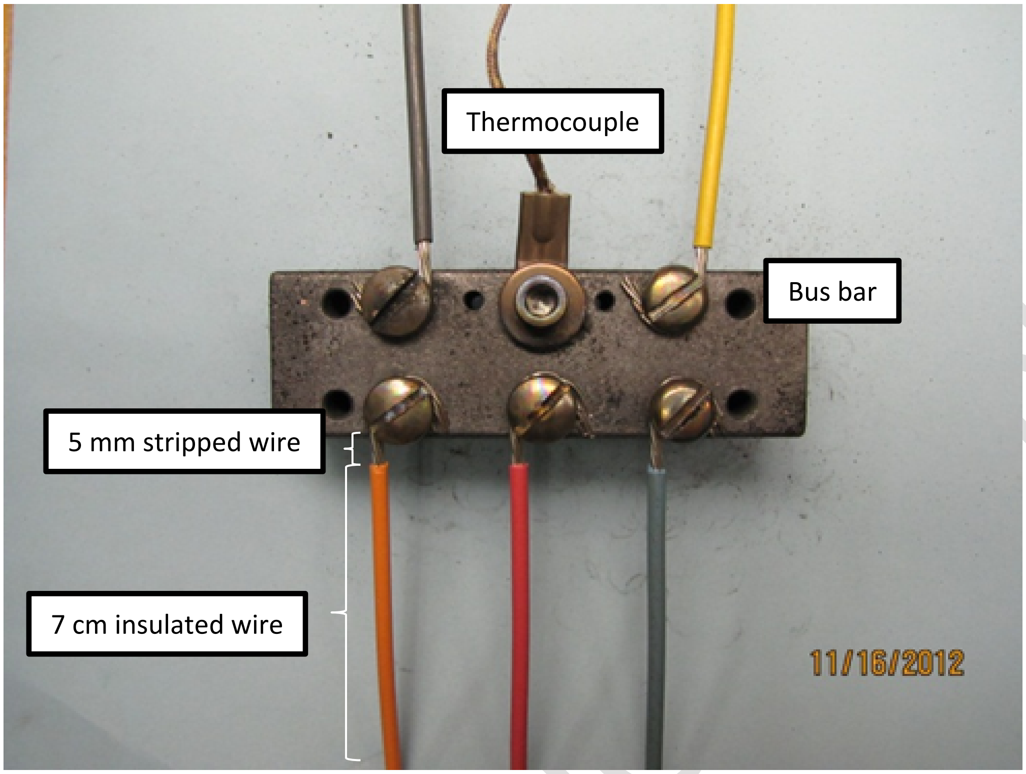


Figure 4-2. XLPO2 wire mounted to the bus bar

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 area-wide 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.

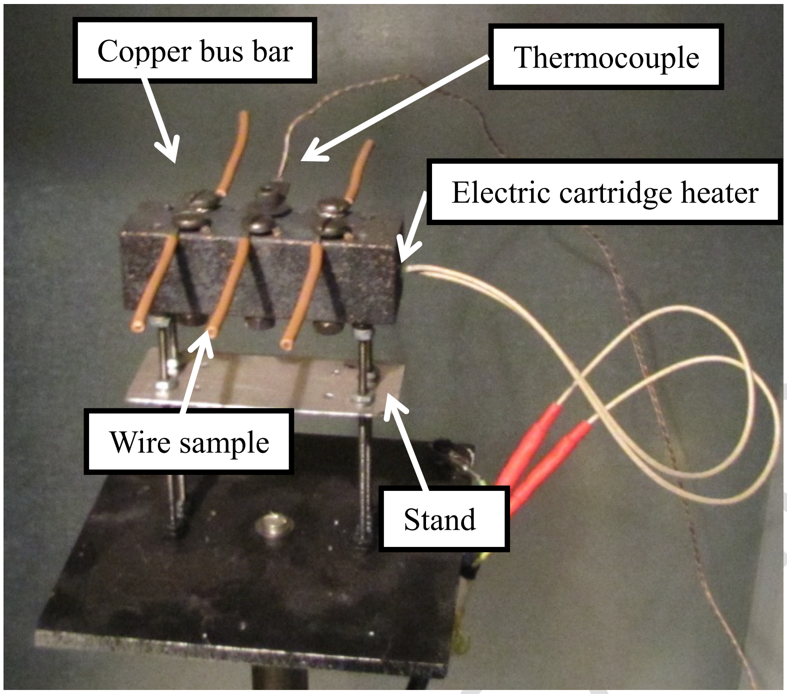


Figure 4-3. The bus bar mounted on the stand inside a cabinet

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 °C after 1 hour. The three linear ramp slopes are bound by the logarithmic profile from 265 °C to 412 °C, and the exponential profile from 41 °C to 446 °C which covers a temperature range where degradation is detectable by the ASDs.

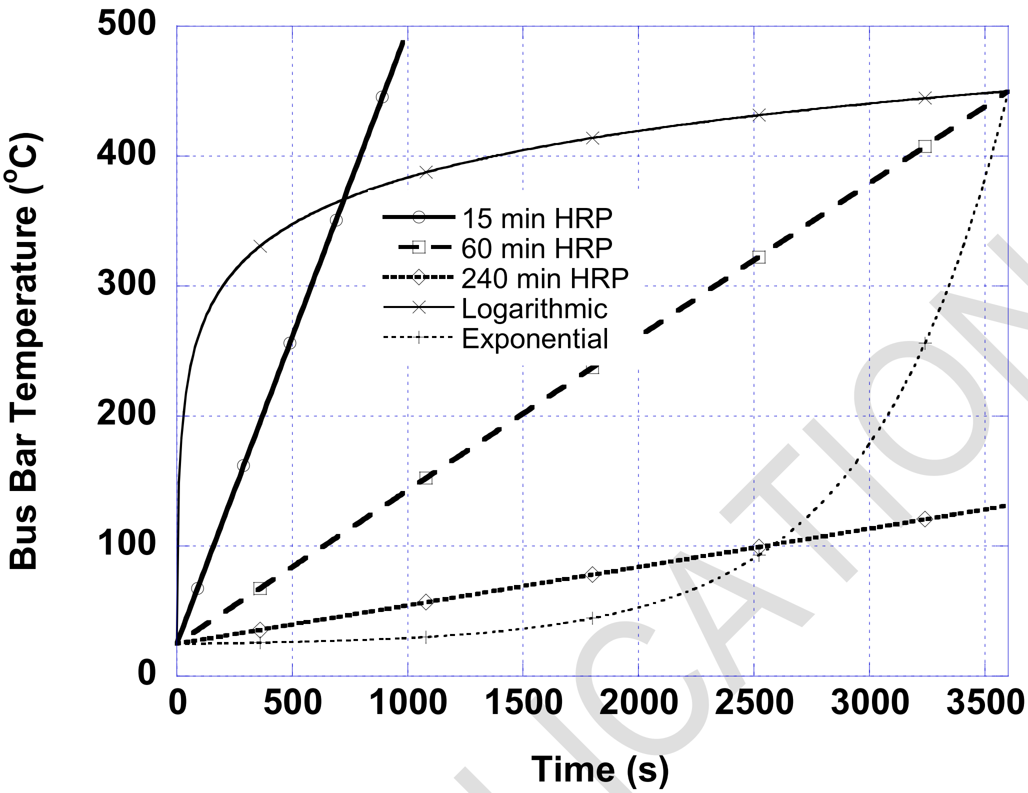


Figure 4-4. Heating ramp profiles for 15, 60, and 240 minute HRPs, with logarithmic and exponential bounding profiles that reach 485 °C in 60 minutes

A load cell was used to weigh 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.

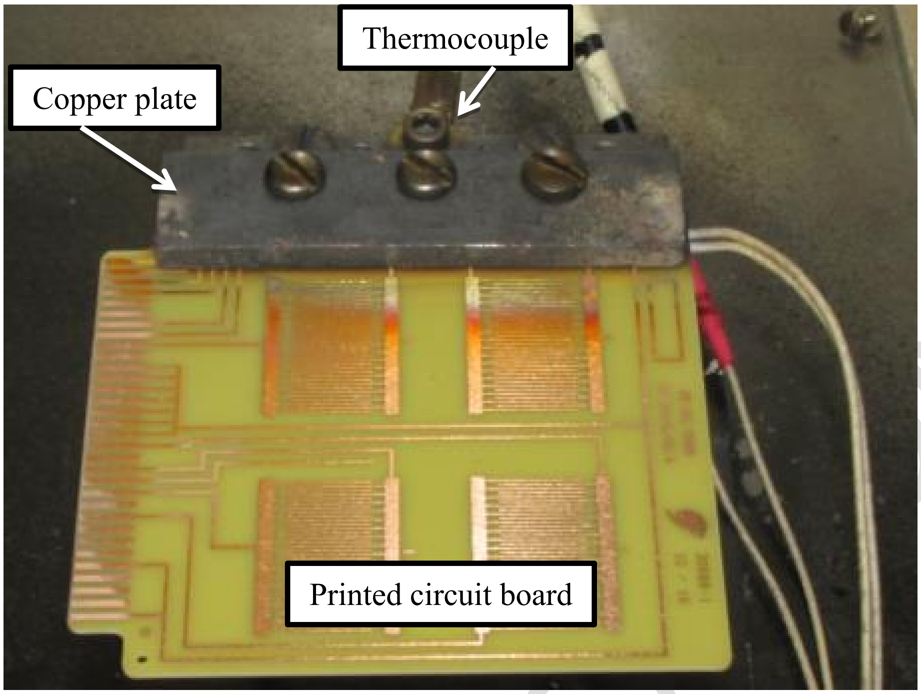


Figure 4-5. Printed circuit board (PCB) mounted to the bus bar

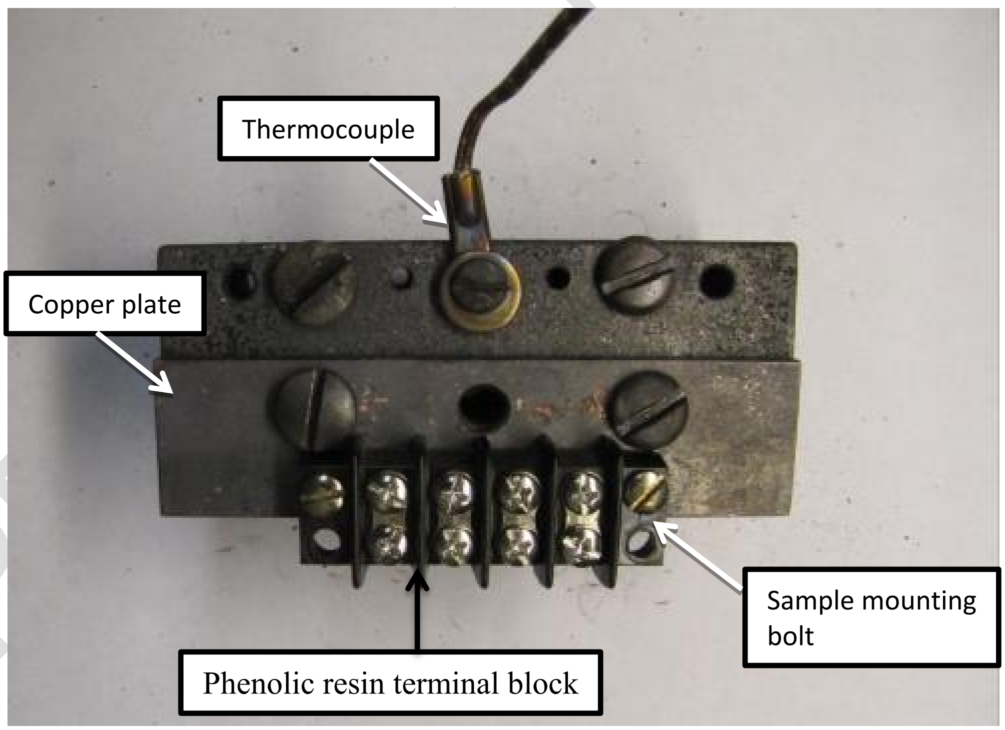


Figure 4-6. Terminal block (TB) mounted to the bus bar

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 °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.

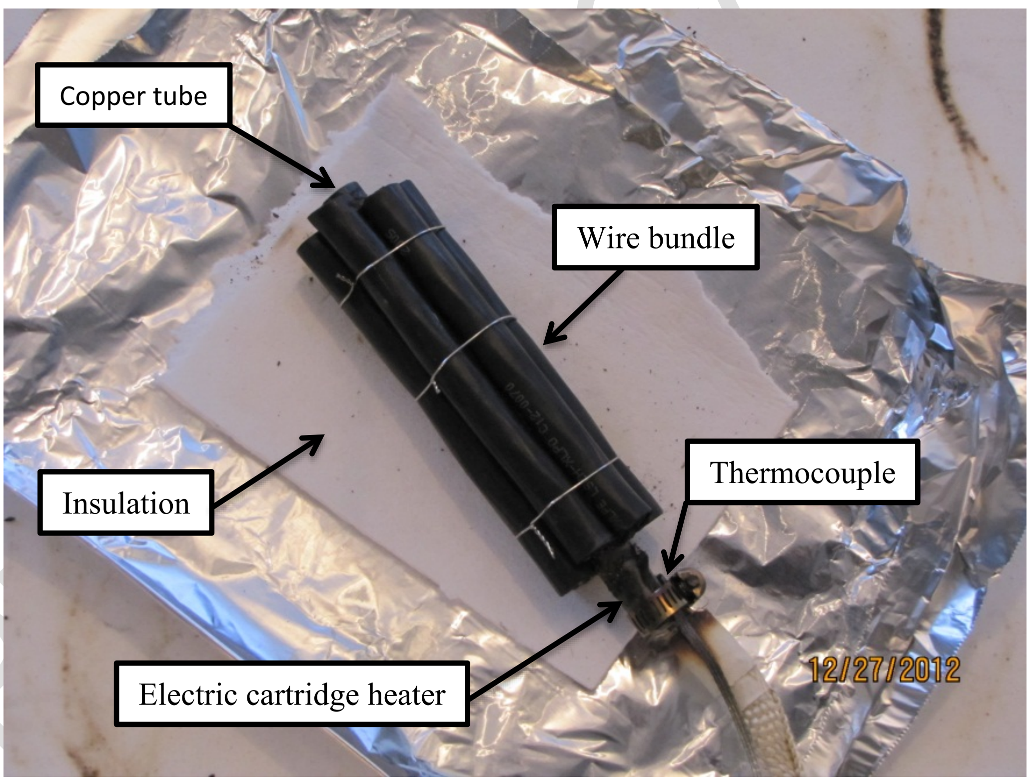


Figure 4-7. The cable bundle sample

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. For these tests, any alarm verification or time delay features were disabled. 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.

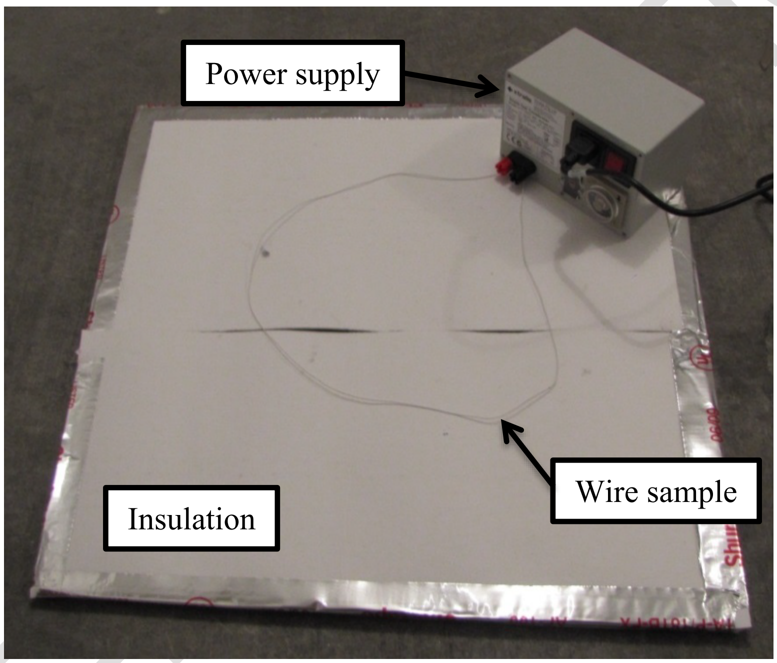


Figure 4-8. A single wire test was setup following the British Standard 6266

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.

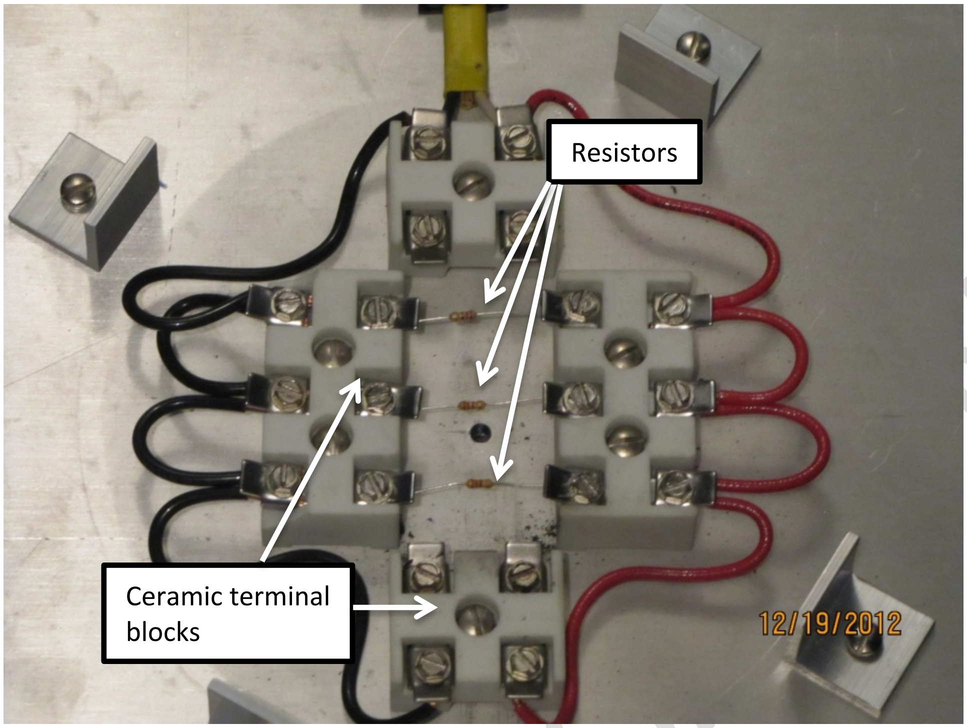


Figure 4-9. A set of three resistors wired in parallel.

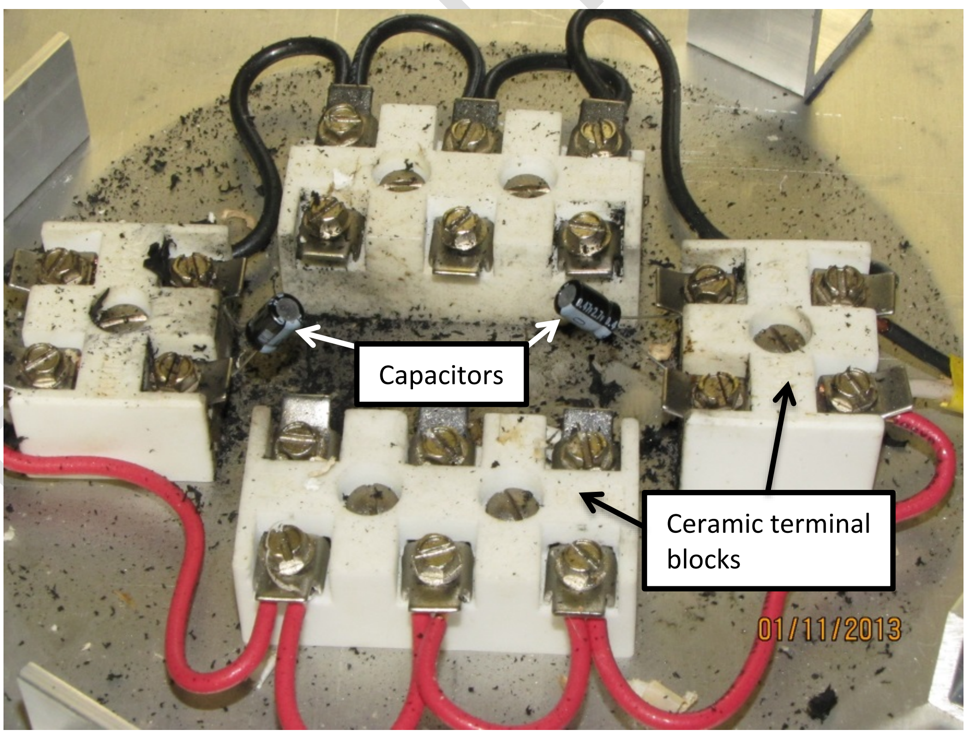


Figure 4-10. A pair of capacitors wired in parallel

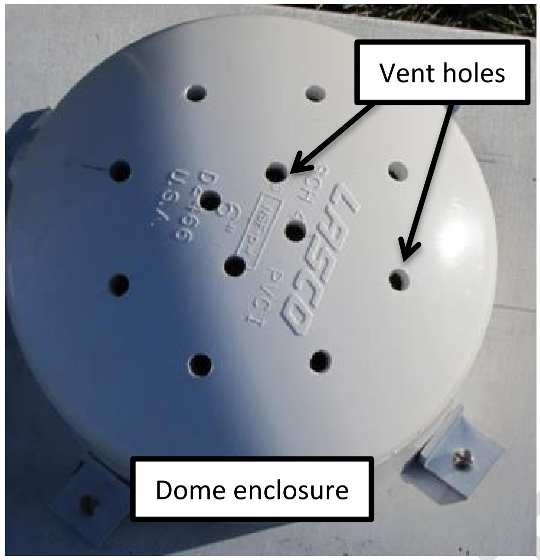


Figure 4-11. Dome enclosure for the resistor and capacitor tests

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.

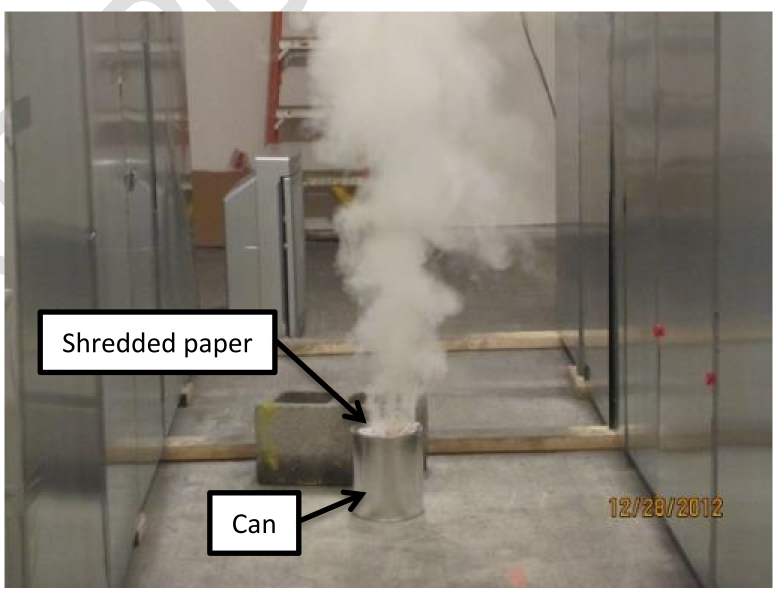


Figure 4-12. Shredded paper test

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, area-wide 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 370^{o}C. 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.

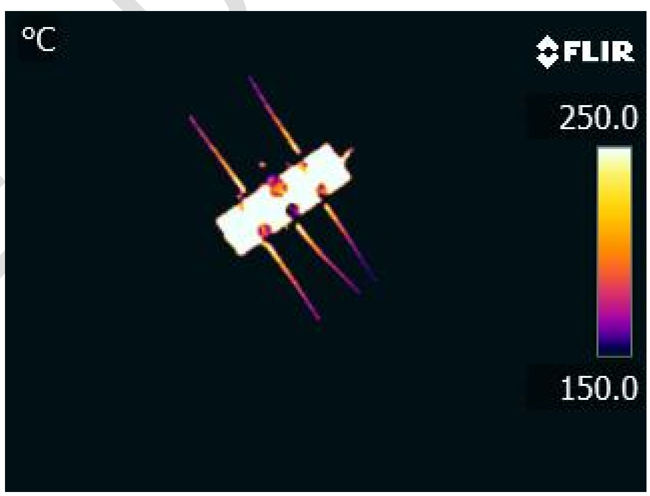
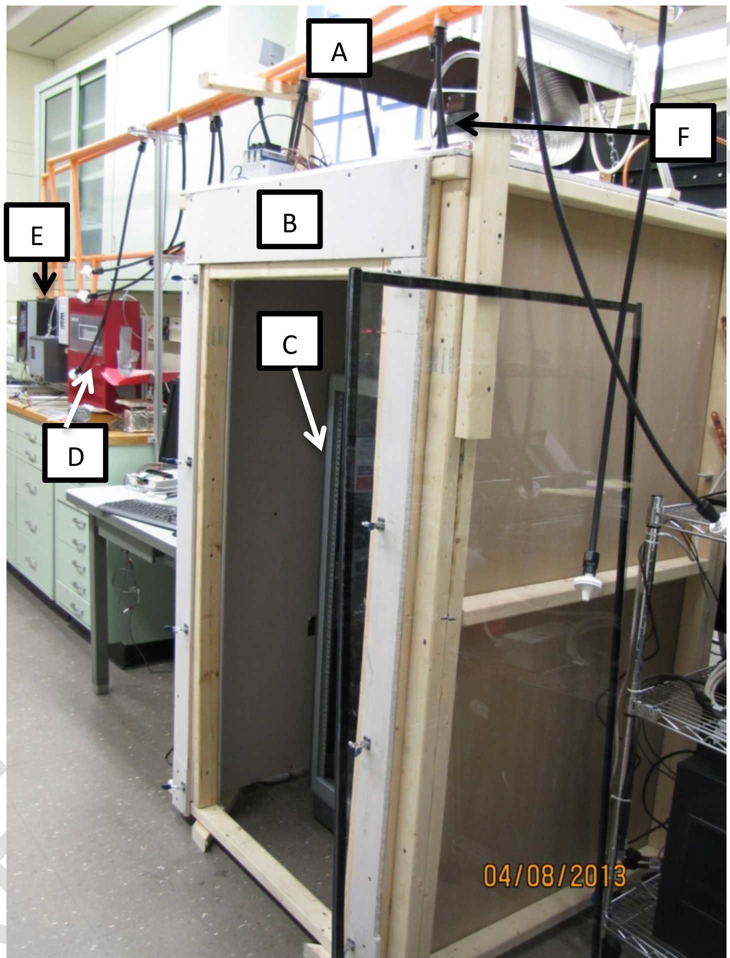


Figure 4-13. Thermal image of XLPE wires following a 60.0 minute heating ramp and a 5.0 minute soak period

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
B: Ventilated enclosure
C: Instrument cabinet
D: Fire alarm control panel
E: ASD systems
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.

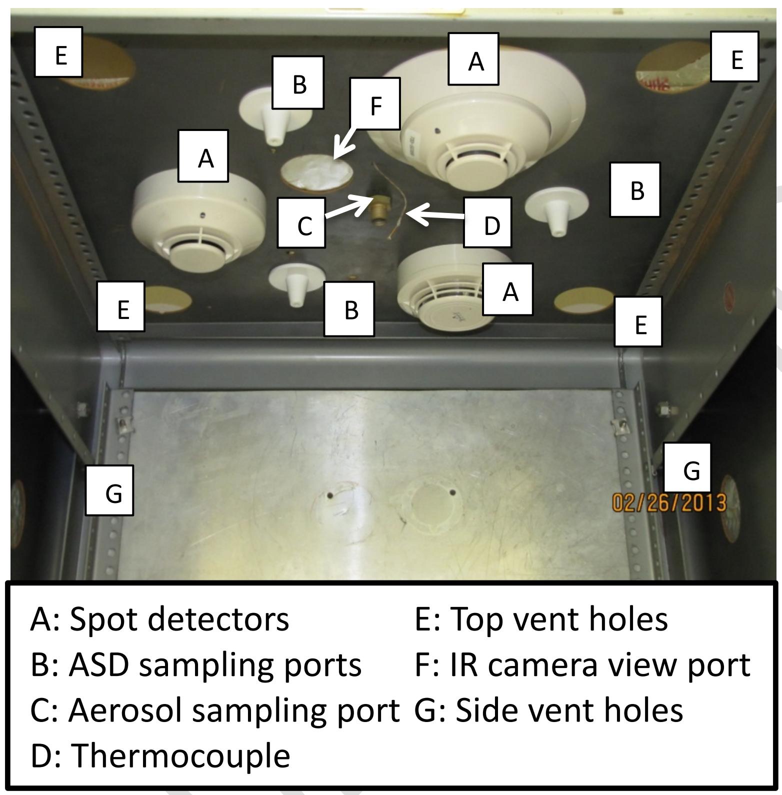


Figure 4-15. Instrument cabinet ceiling view

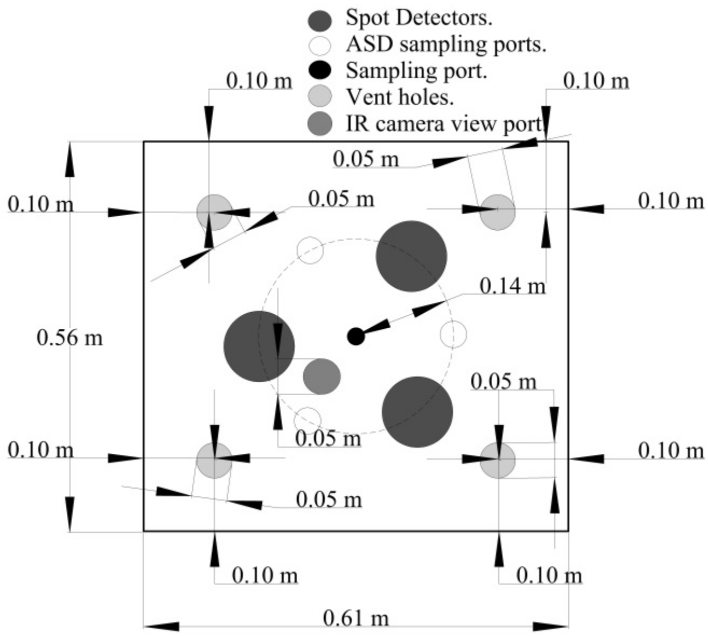


Figure 4-16. Instrument cabinet top plate hole pattern

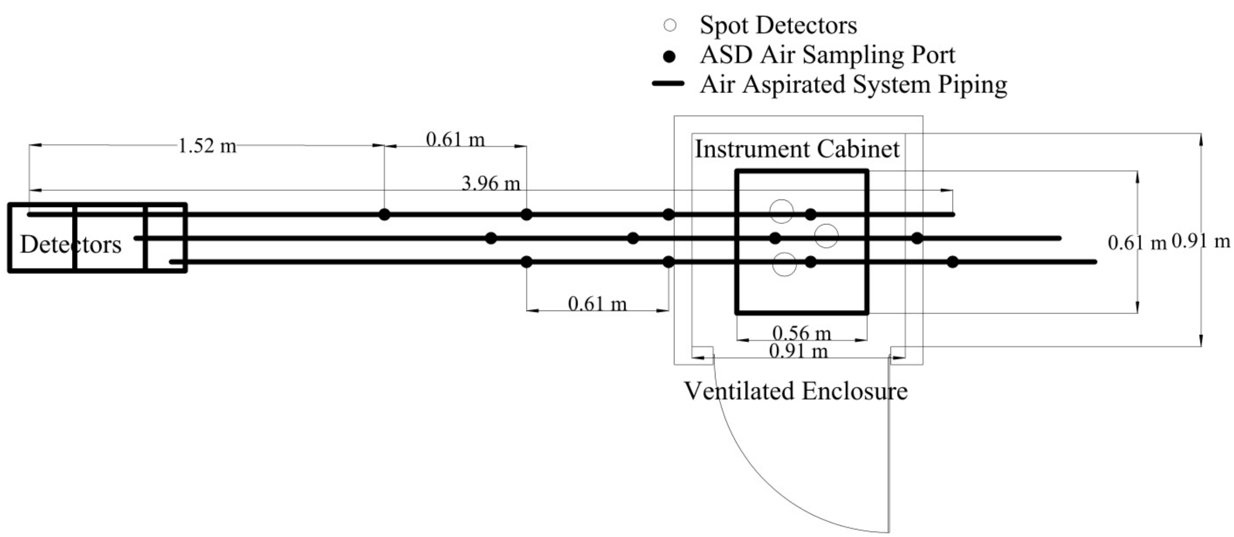


Figure 4-17. ASD pipe layout for the instrument cabinet experimental setup

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.

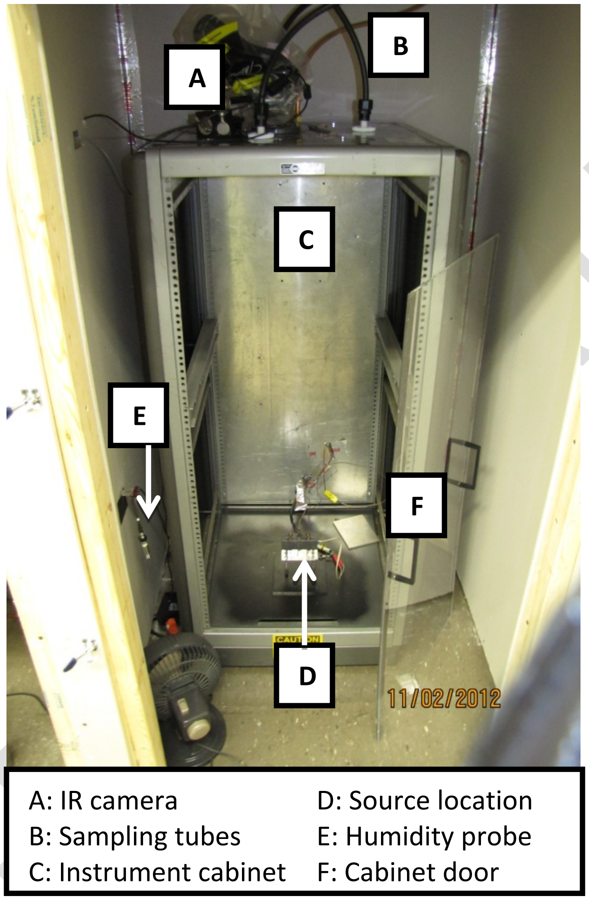
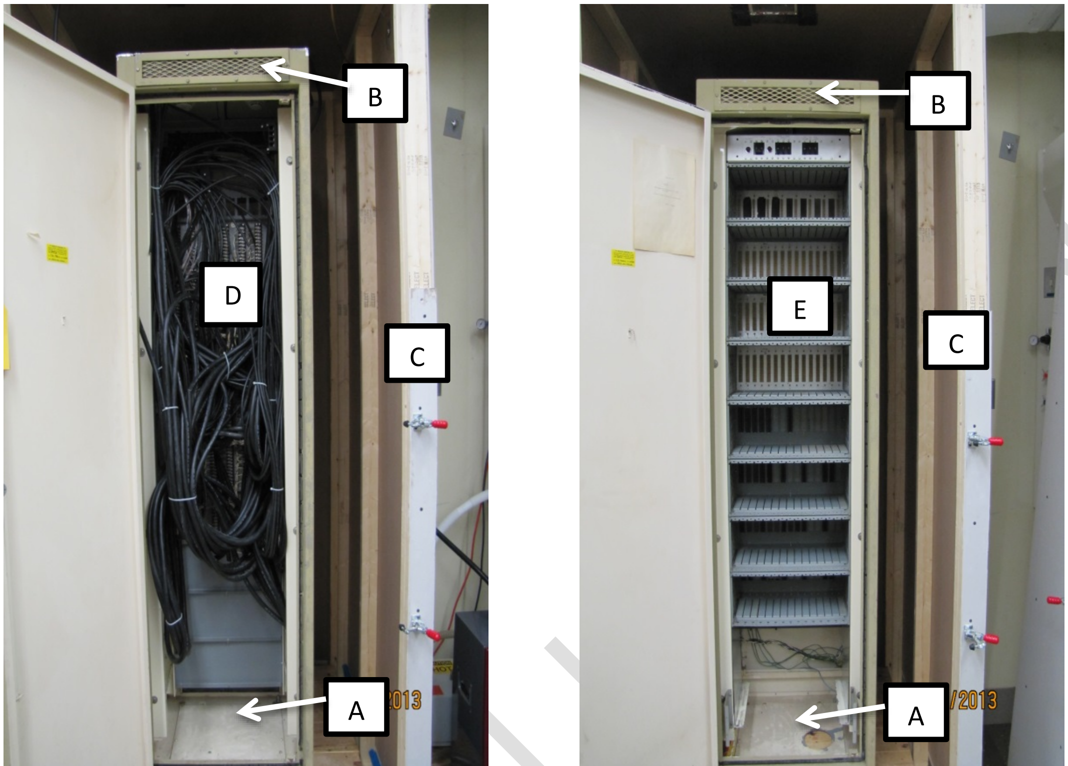


Figure 4-18. Instrument cabinet inside NIST laboratory

4.4.2 Laboratory, large NPP cabinet configurations

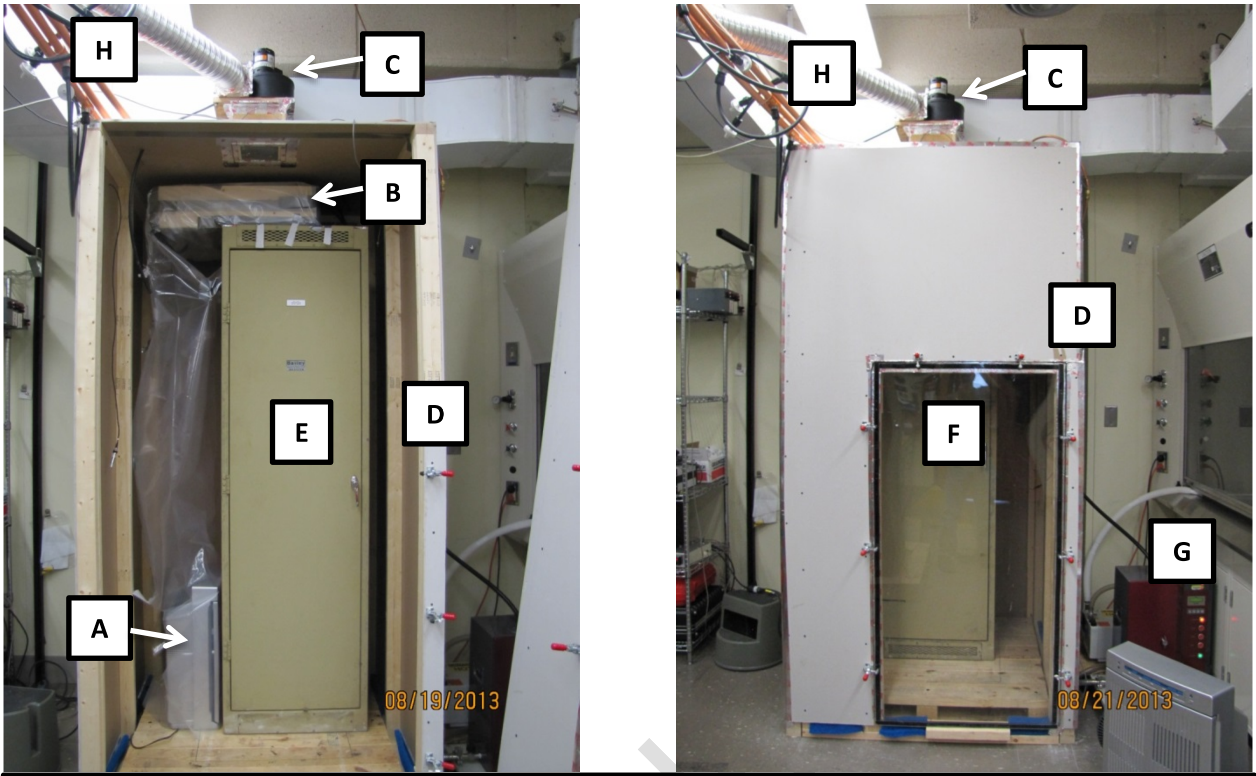
These experiments used two surplus NPP electrical cabinets, which can be seen in Figure 4-19. The cabinets were 0.61 m by 0.61 m by 2.13 m tall. The cabinet on the left (Cabinet 1) had cable bundles hanging from the back wall and was naturally ventilated. The cabinet on the right (Cabinet 2) was a compartment 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.



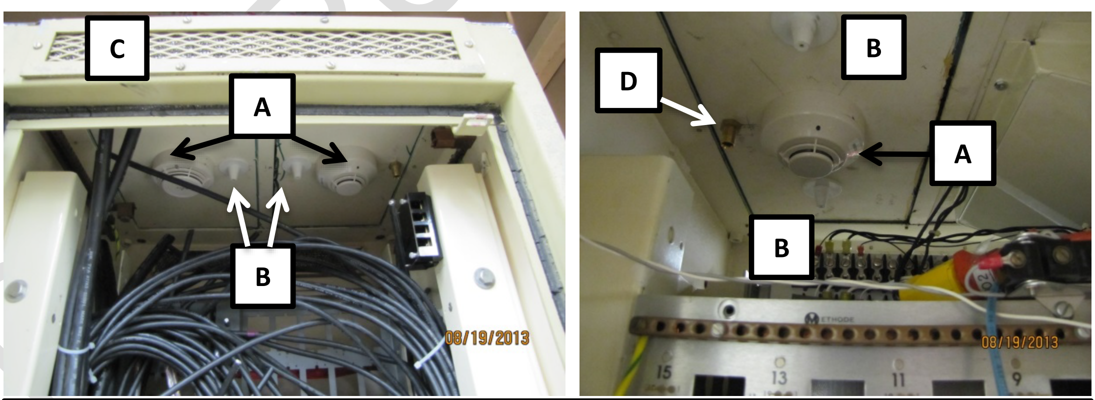
A: Source location
B: Air vents
C: Cabinet enclosure
D: Naturally ventilated cabinet
E: Force ventilated cabinet

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 HEPA-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.

A: Cabinet Air inlet
B: Blower
C: Blower enclosure
D: Force ventilated cabinet
E: Cabinet enclosure

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 by 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.

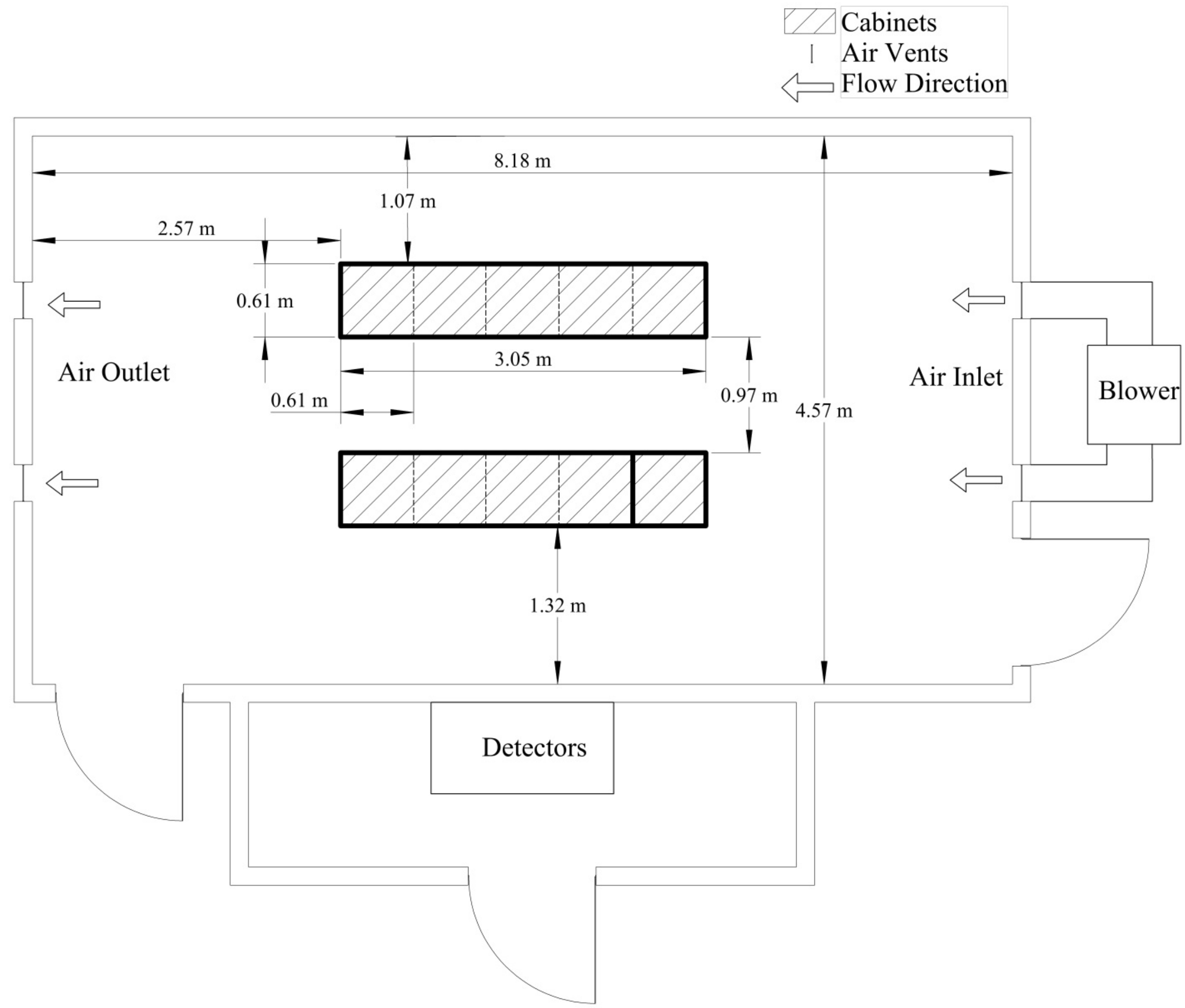
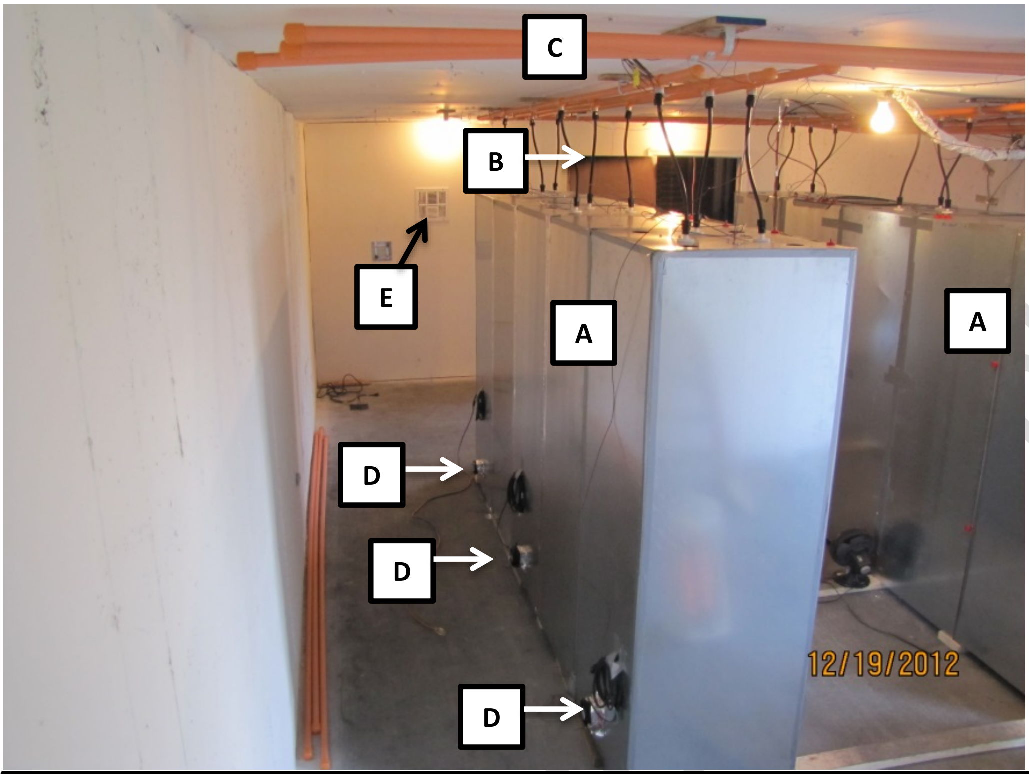


Figure 4-23. Small room full-scale experiment space layout



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

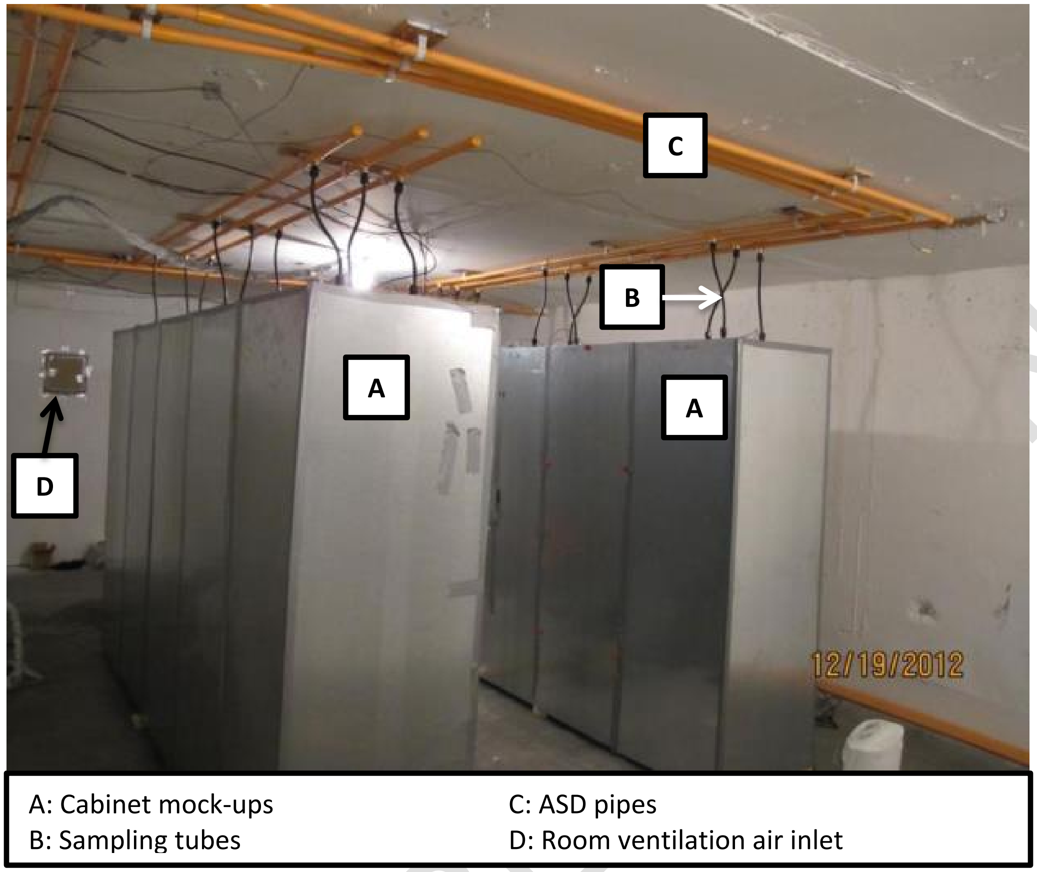
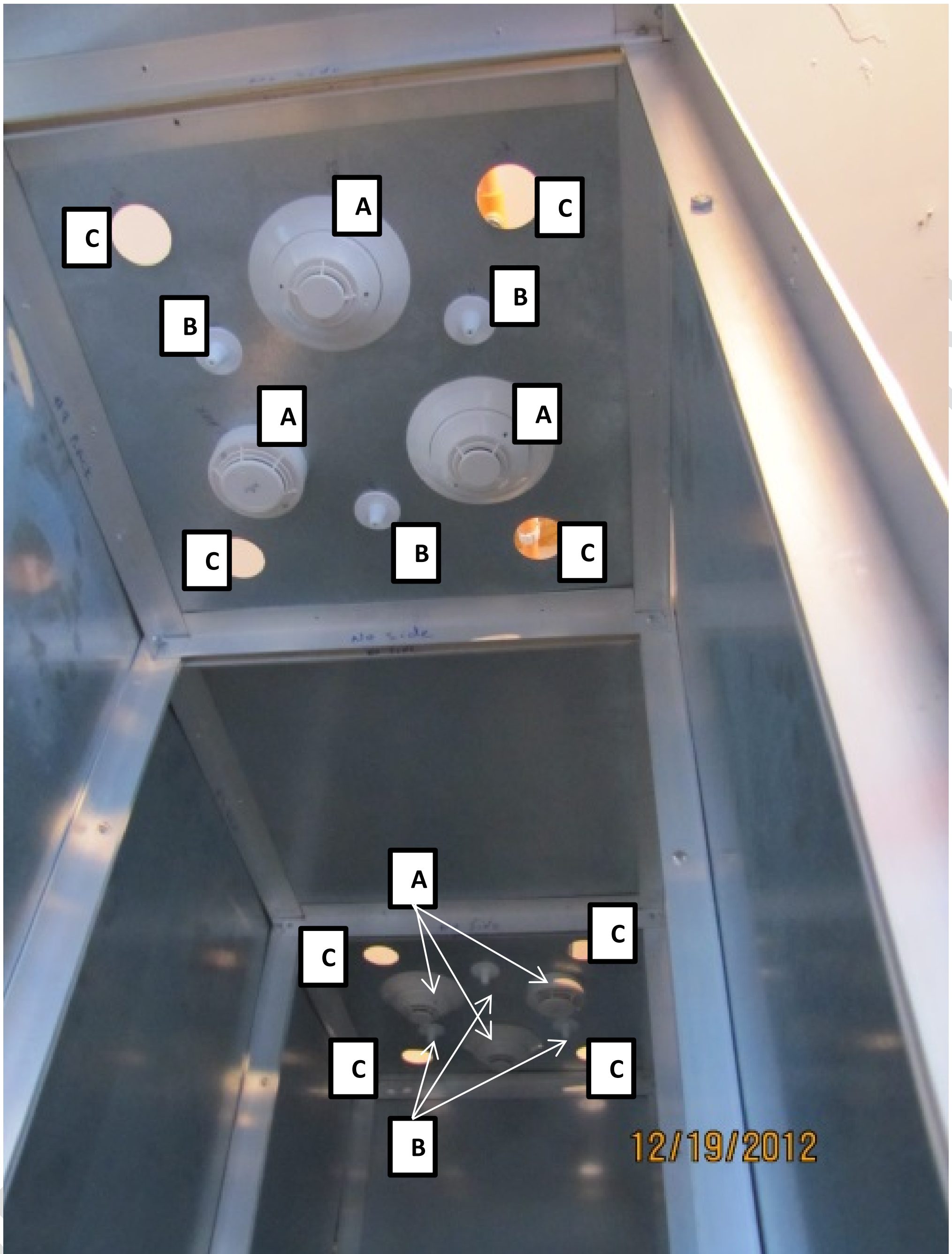


Figure 4-25. View of the small room full-scale experimental space ceiling

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.



A: Spot detectors
B: ASD sampling ports
C: Vent holes

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.

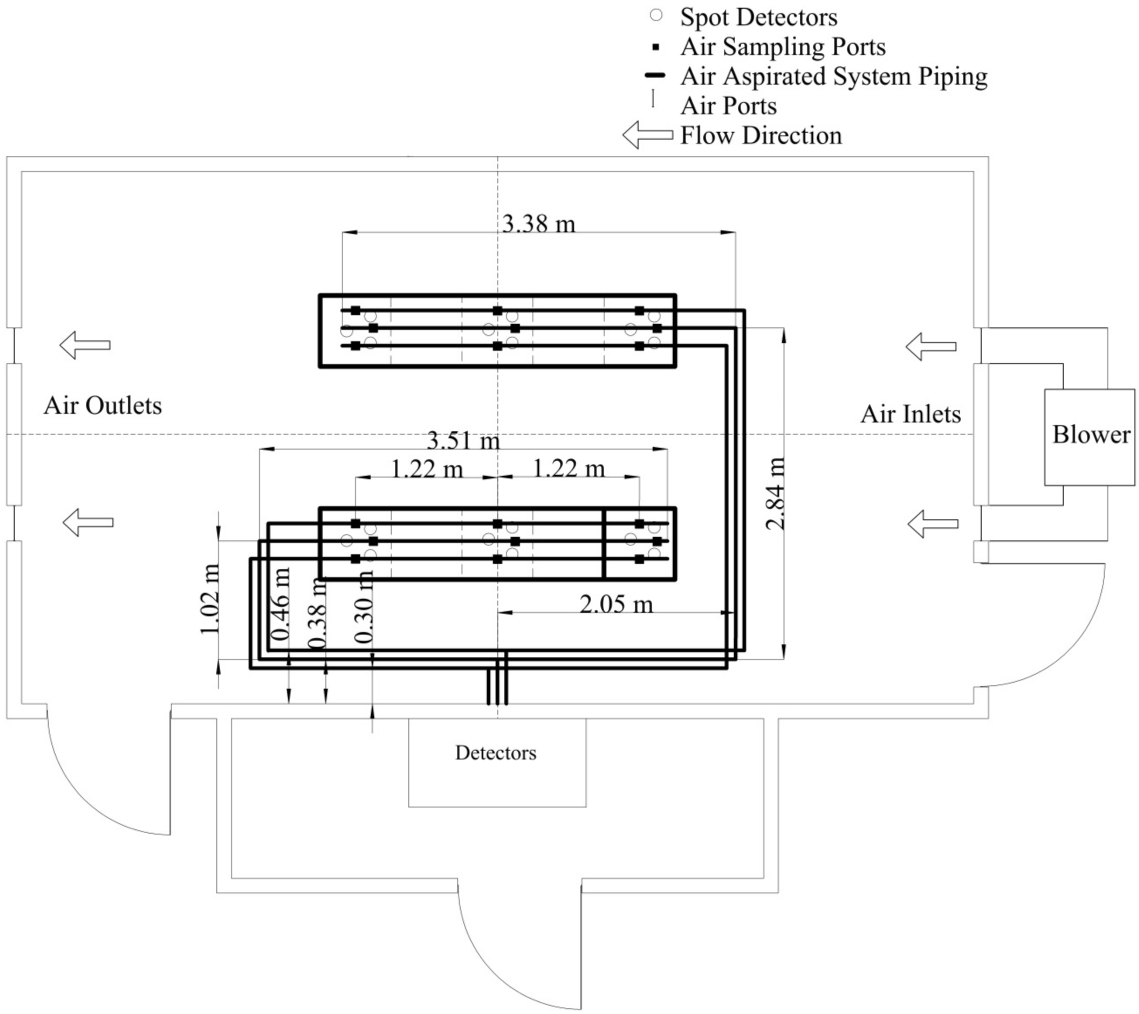


Figure 4-27. In-cabinet ASD pipe layout

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 area-wide 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 area-wide ASD experiments, the samples were placed in either cabinet 7, the center of the room or one of the room quadrants.

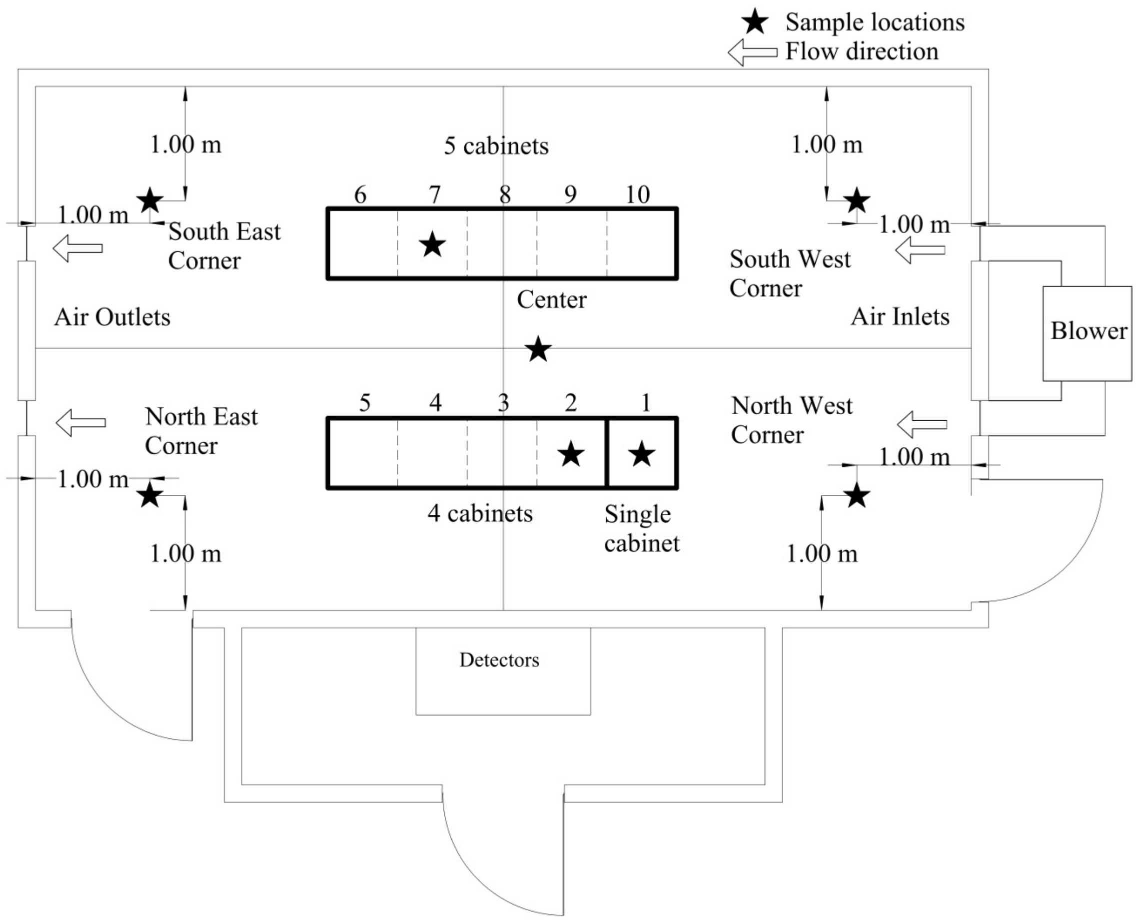


Figure 4-28. Smoke source sample locations

4.4.4 Area-wide, small room configuration

The area-wide ASD configuration had spot detectors on the ceiling of the room. The piping system for the aspirated smoke detectors was modified for this configuration. Area-wide piping and detector locations can be seen in Figure 4-29. The area-wide 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.

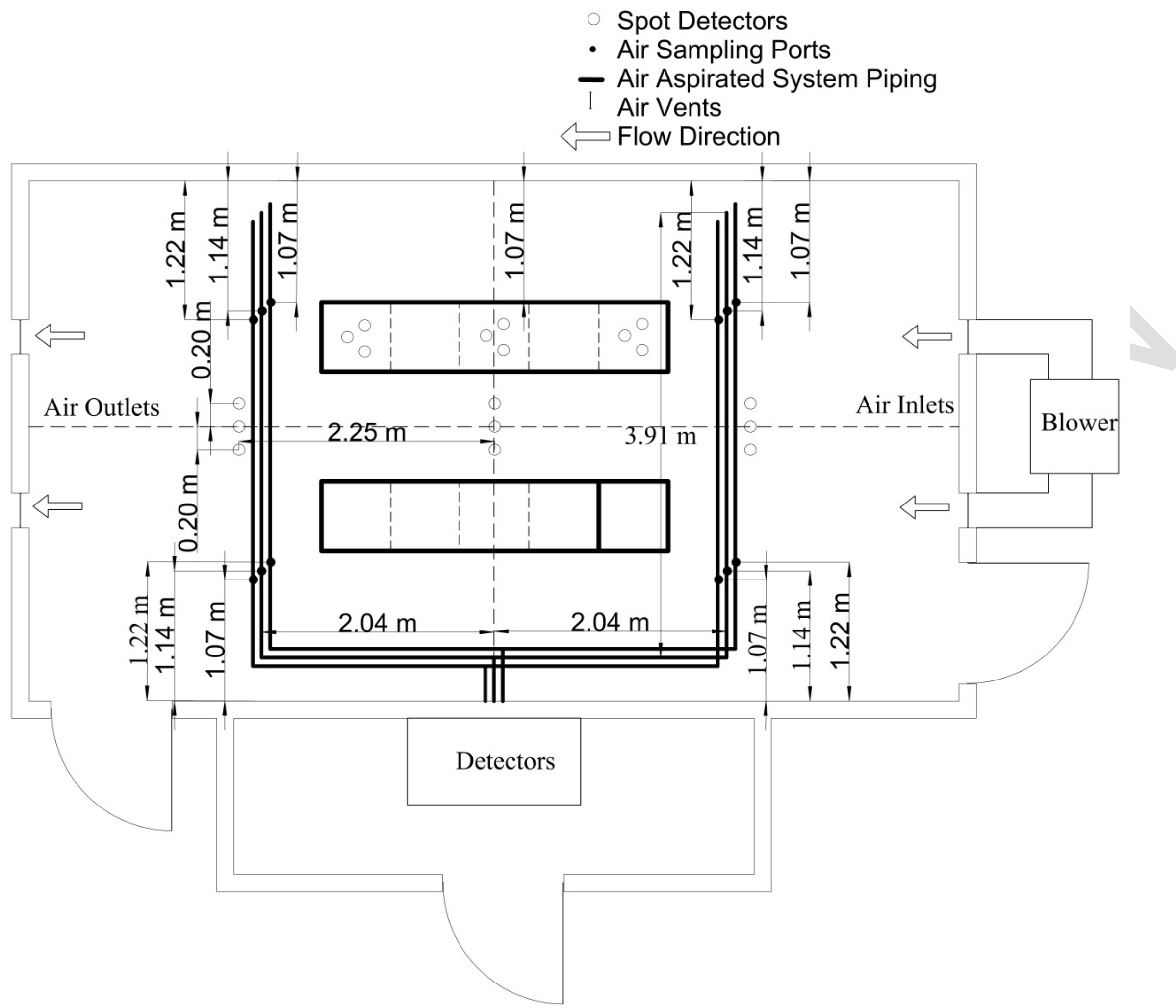


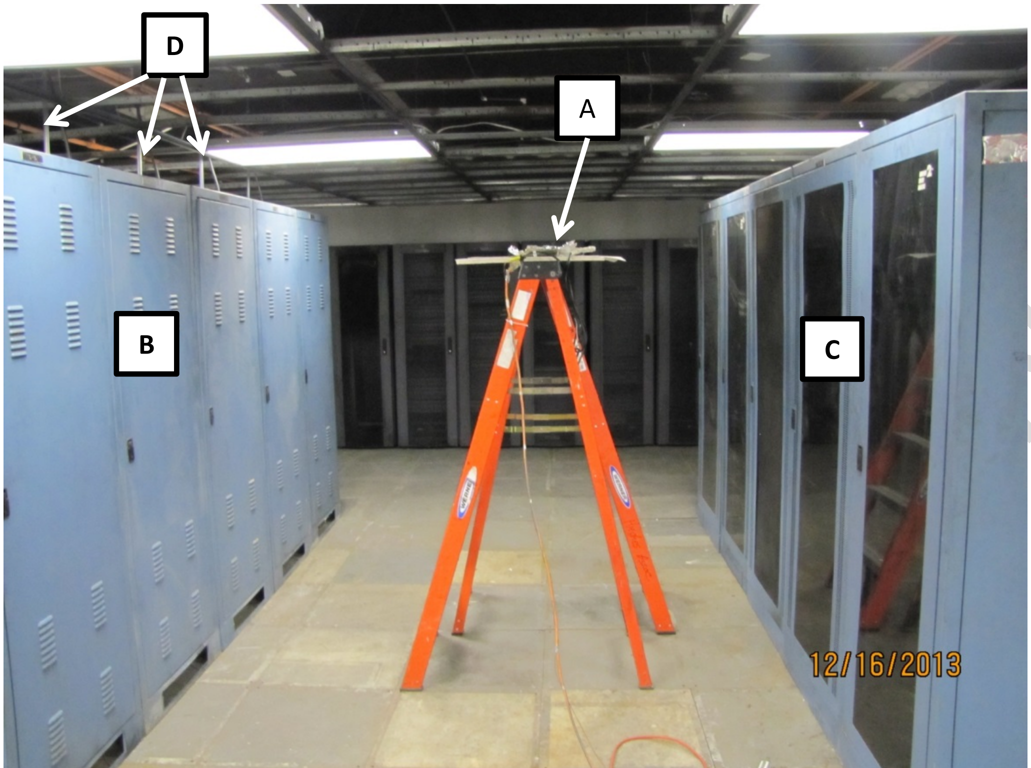
Figure 4-29. Area-wide ASD pipe layout

4.4.5 In-cabinet, large room, electrical cabinet configurations

The experimental space for the large-room, full-scale experiments was 10 m by 10 m by 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
B: Test Cabinets, Instrumented
C: Test Cabinets, Not instrumented
D: In-Cabinet ASD Sampling Lines
E: Areawide ASD piping
F: Areawide sampling port

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



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

Figure 4-31. Front view of the 100 m^2 facility

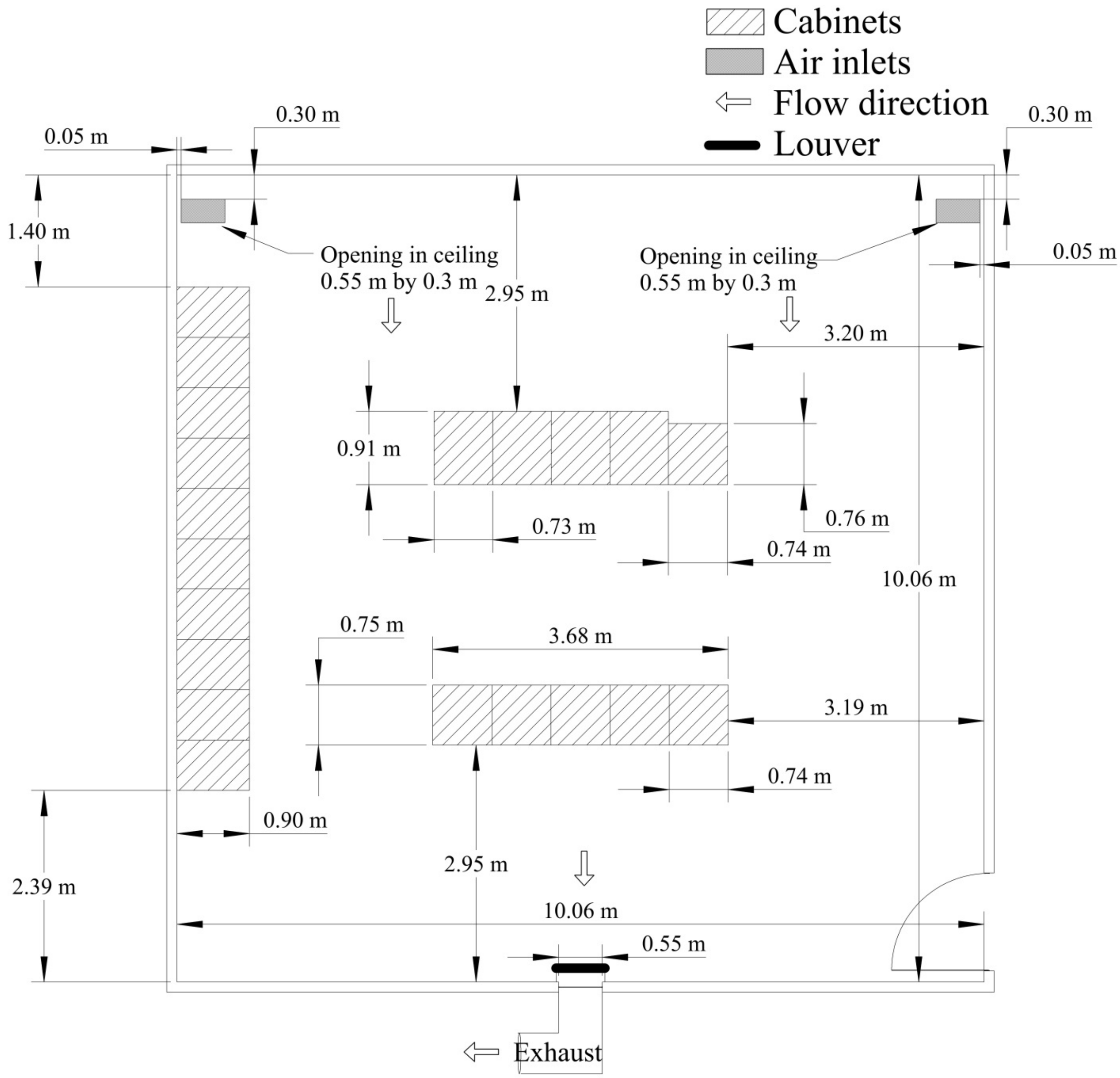


Figure 4-32. Large room testing facility layout

Experiments were conducted with single-port ASD VEWFD systems for in-cabinet coverage and multi-port ASD VEWFD systems for in-cabinet and area-wide 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.

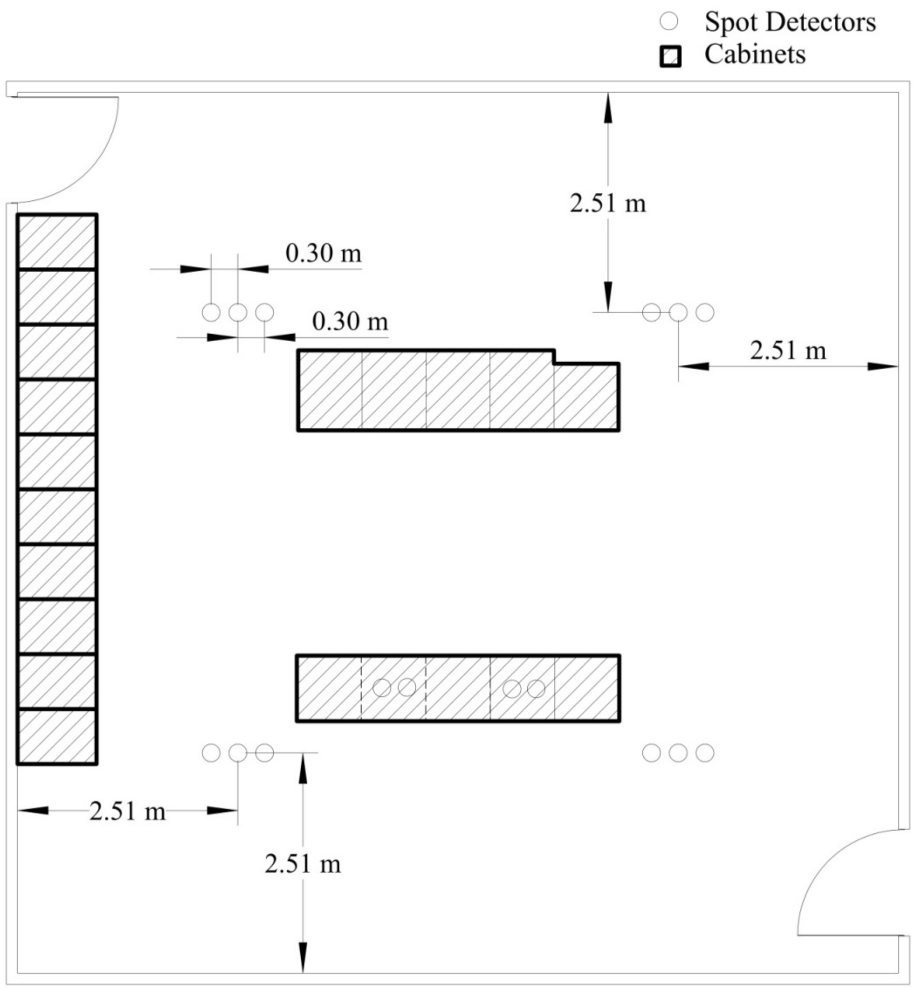
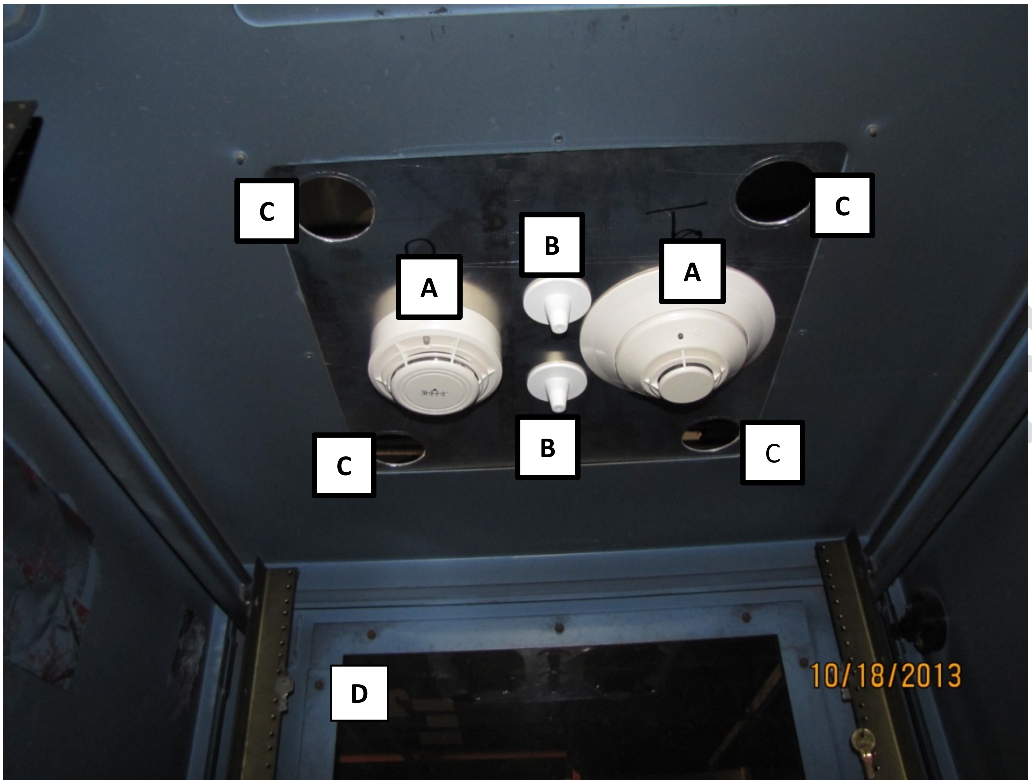


Figure 4-33. Spot detectors layout inside 100 m² facility



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

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

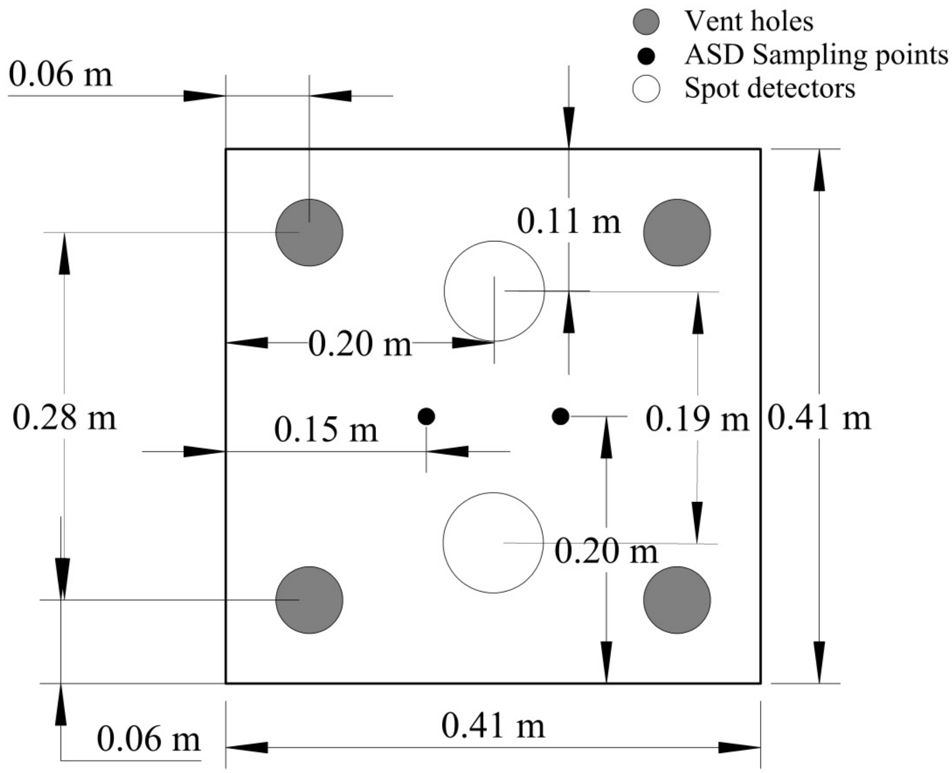
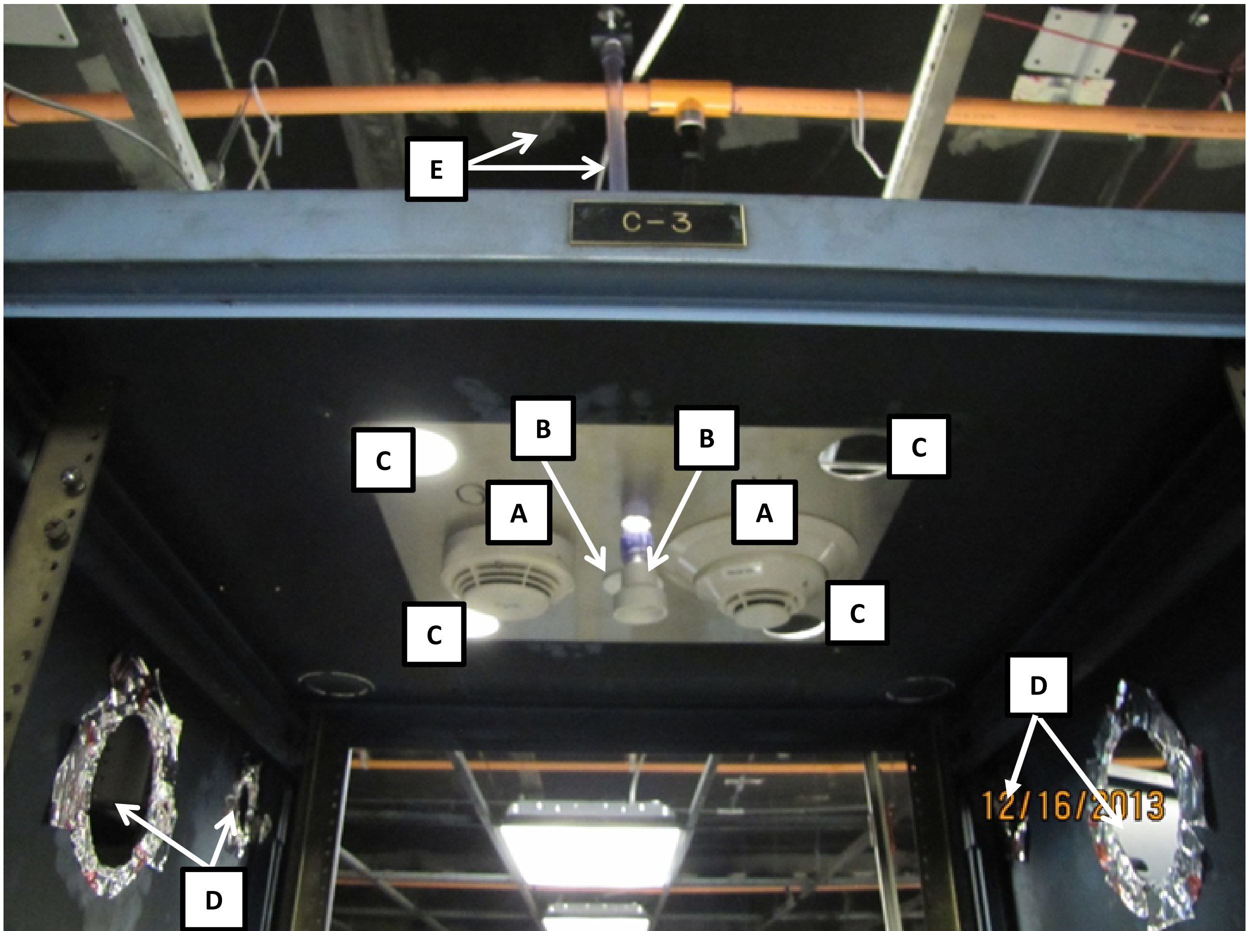


Figure 4-35. Detectors, sampling ports, and vent hole locations for in-cabinet experiments



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.

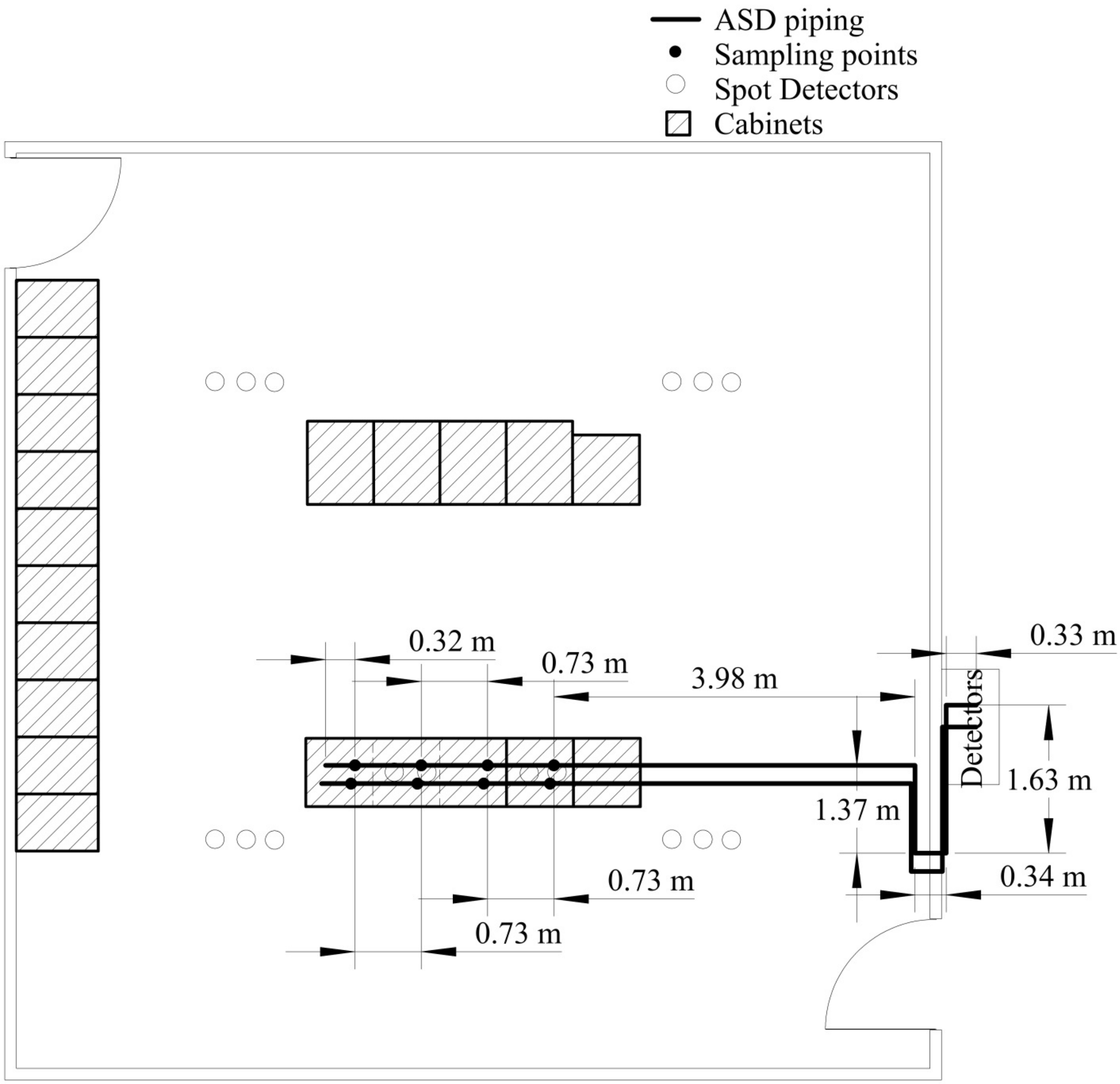


Figure 4-37. Single zone piping configuration for ASD2 and ASD3

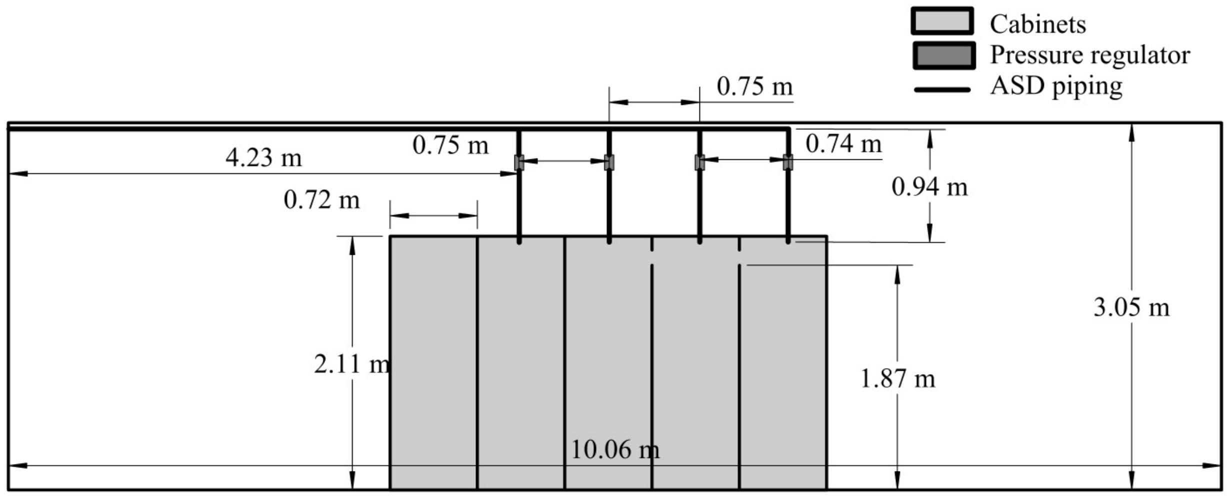


Figure 4-38. Front view of the ASD4 piping setup for the in-cabinet sampling

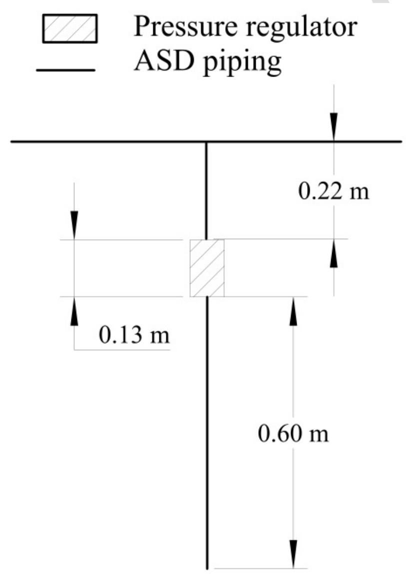


Figure 4-39. Pressure regulator located above each sampling port for ASD4

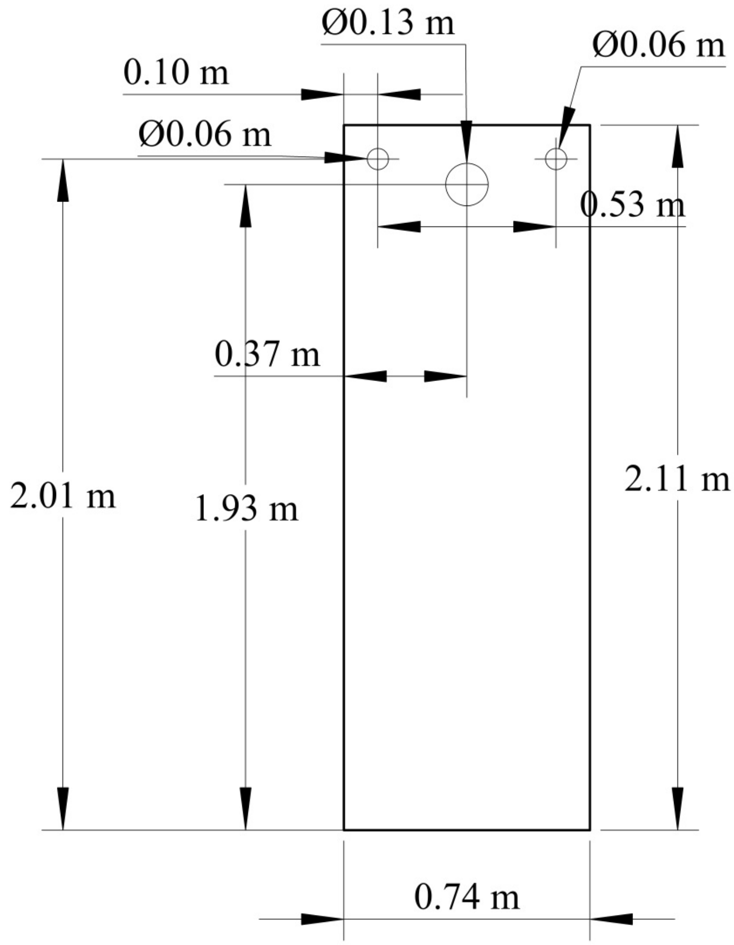


Figure 4-40. Side view of a cabinet, showing the location of the side vents

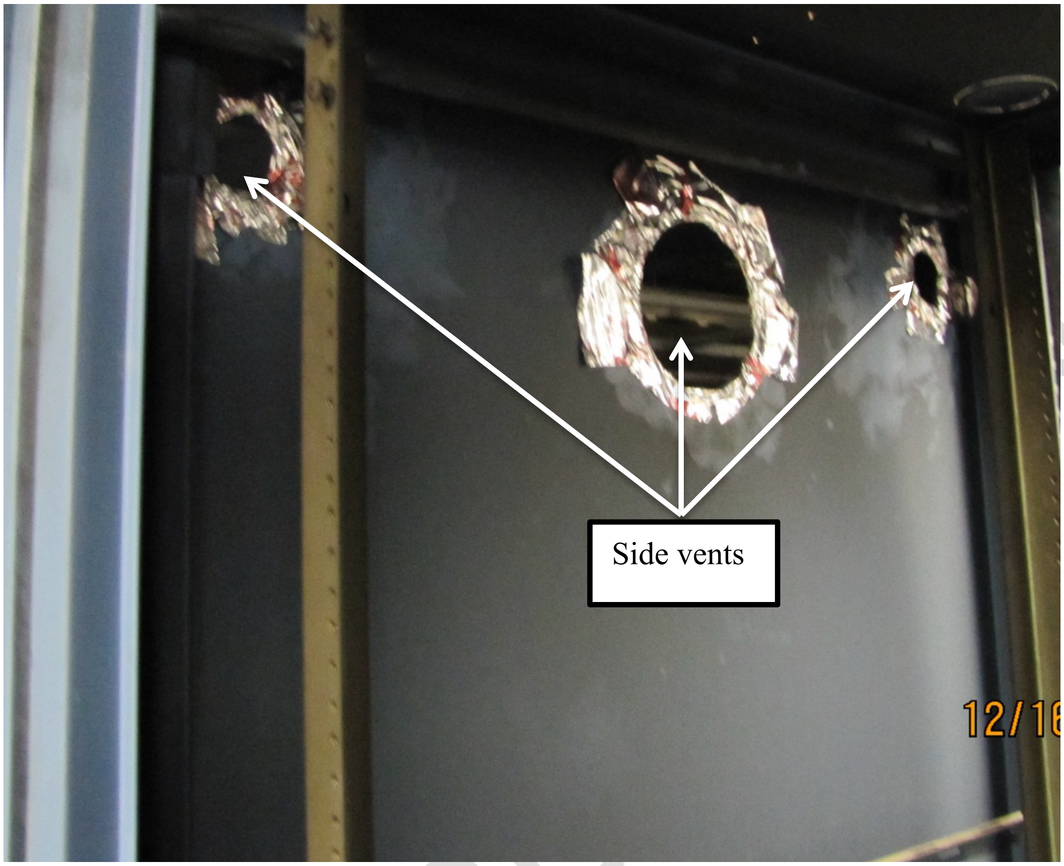


Figure 4-41. Side vents allowing flow between three cabinets with ASD sampling

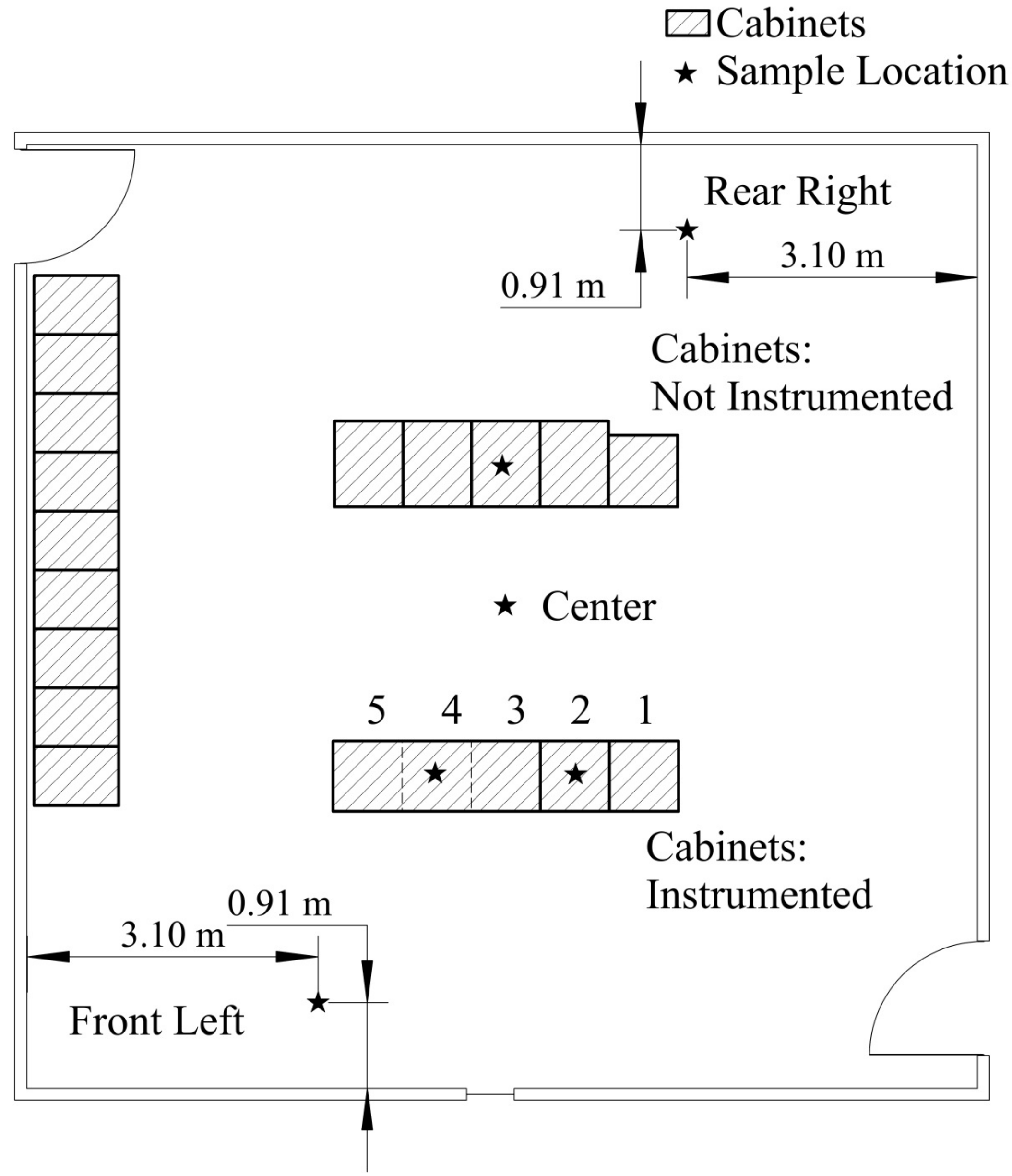


Figure 4-42. Sample locations in the experiments performed

4.4.6 Area-wide, large room configurations

In the multi-zone ASD VEWFD experiments, two area-wide 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 area-wide ceiling ASD piping networks. The piping network design was supplied by the system vendor, and also met the intent of

NFPA 76. For conventional detection, per NFPA 72, no return air monitoring is required. Duct detectors were not able to be installed at the facility where the testing was being performed.

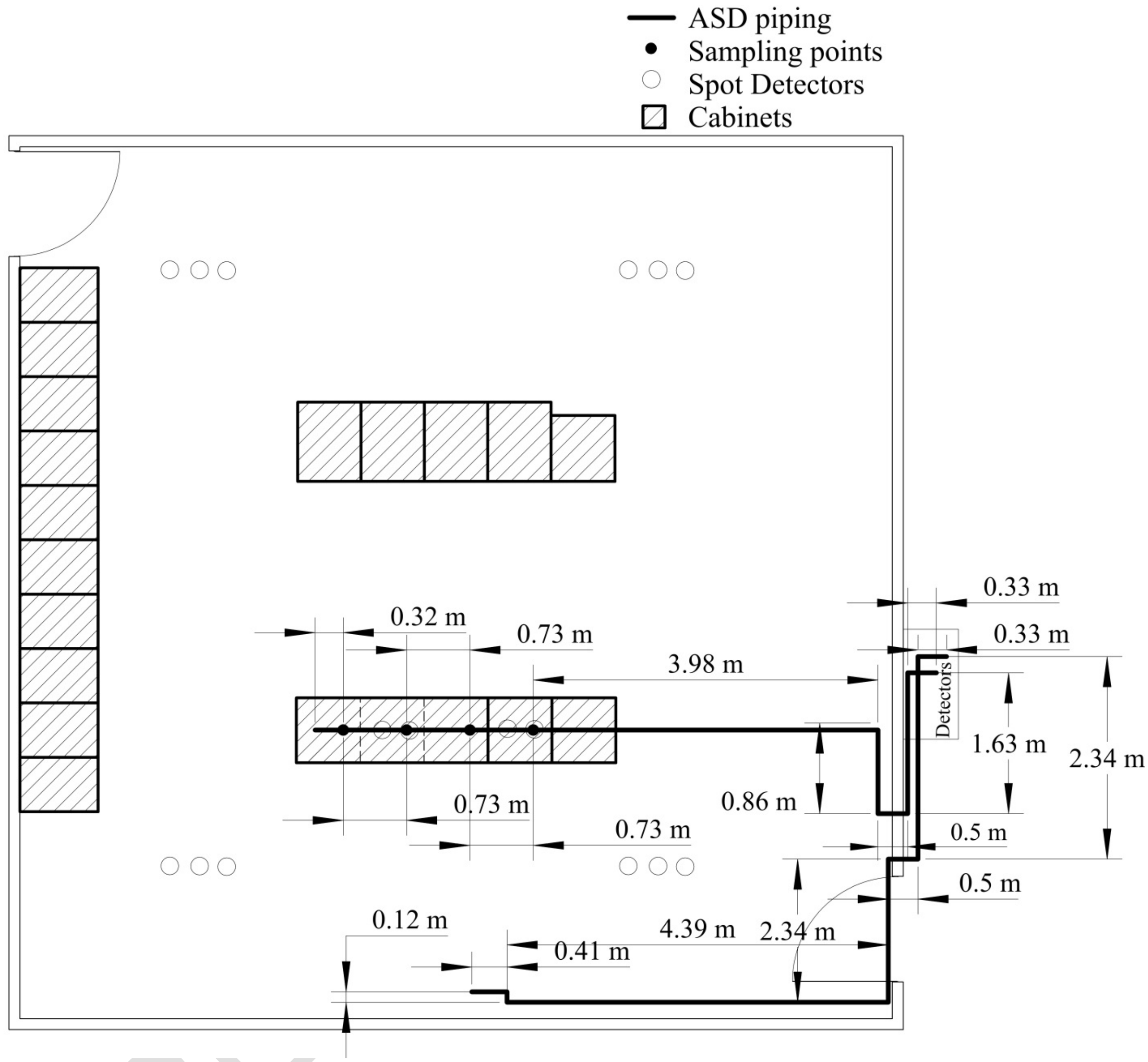


Figure 4-43. ASD4 piping layout for the in-cabinet and HVAC inlet sampling

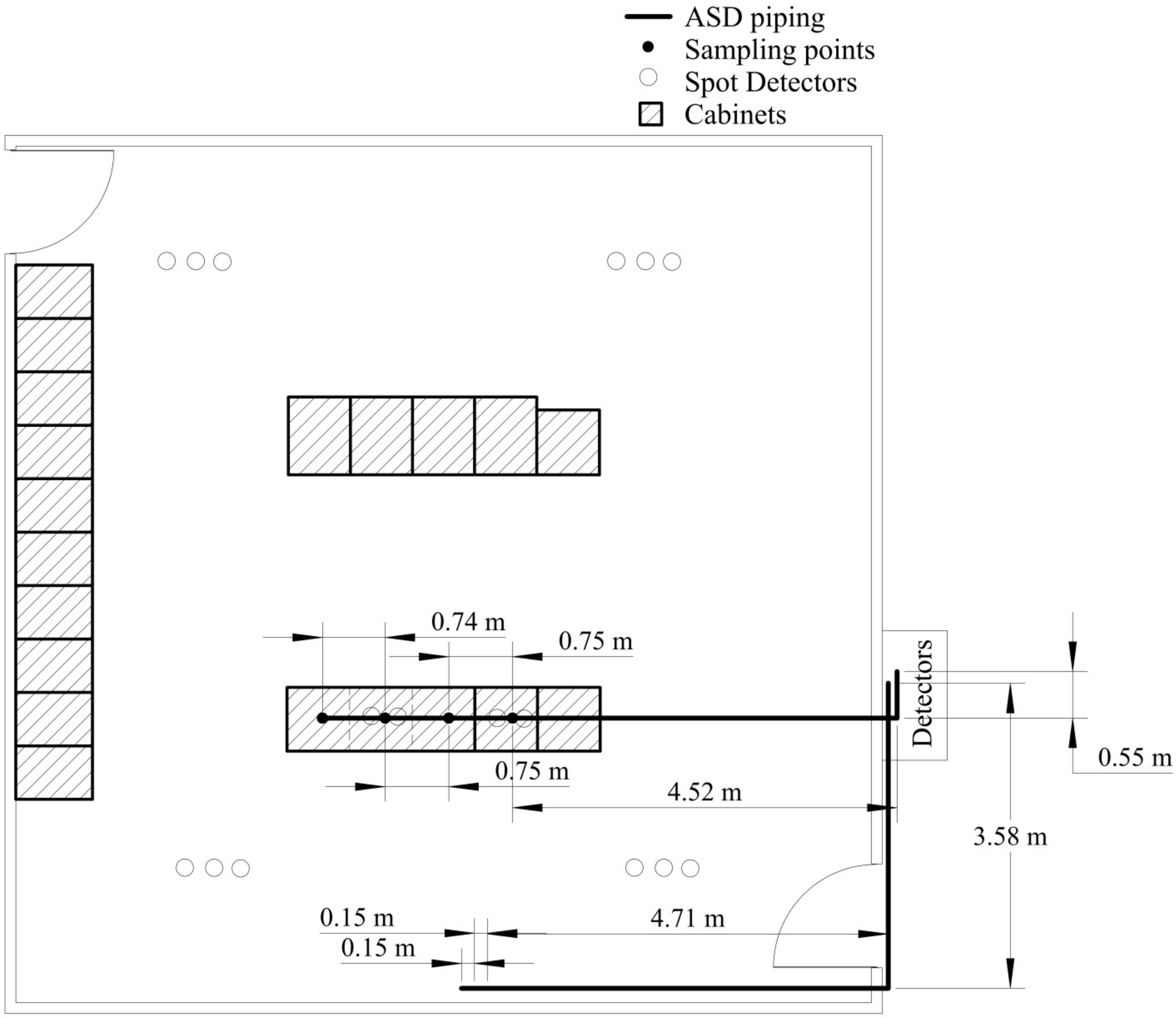


Figure 4-44. ASD5 piping layout for the in-cabinet and HVAC inlet sampling

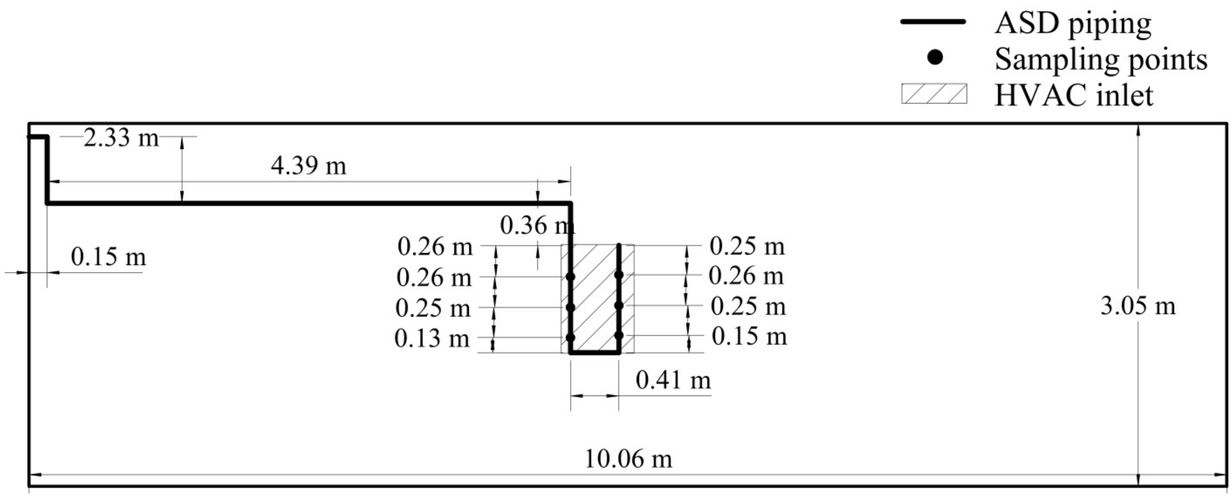


Figure 4-45. ASD5 piping layout, with sampling locations located at the HVAC exhaust

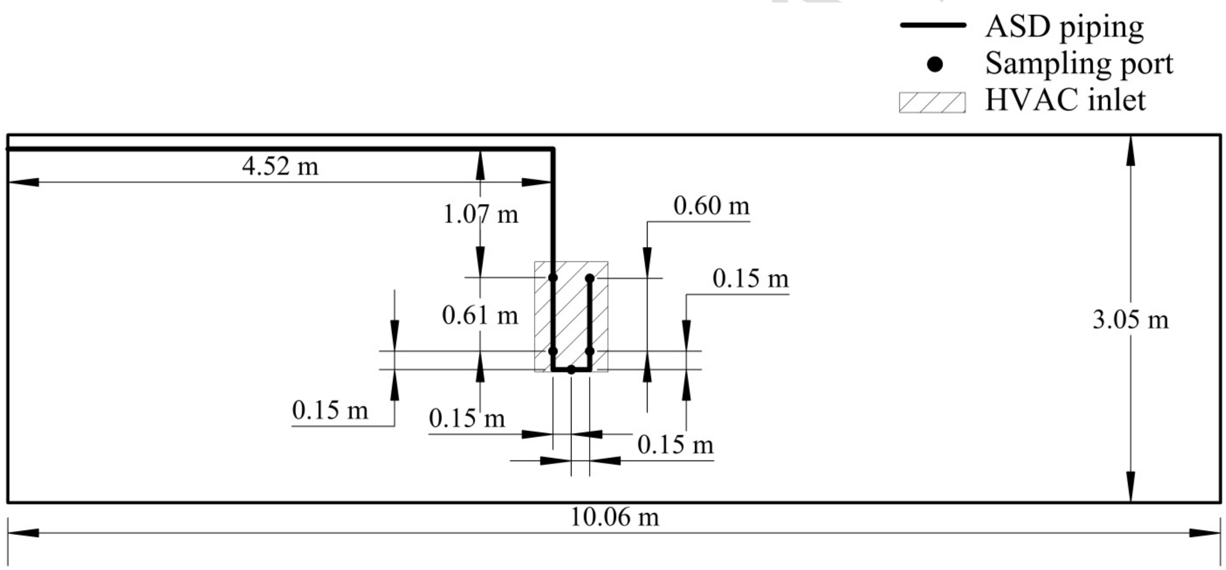


Figure 4-46. ASD4 piping layout, with sampling location located at the HVAC exhaust

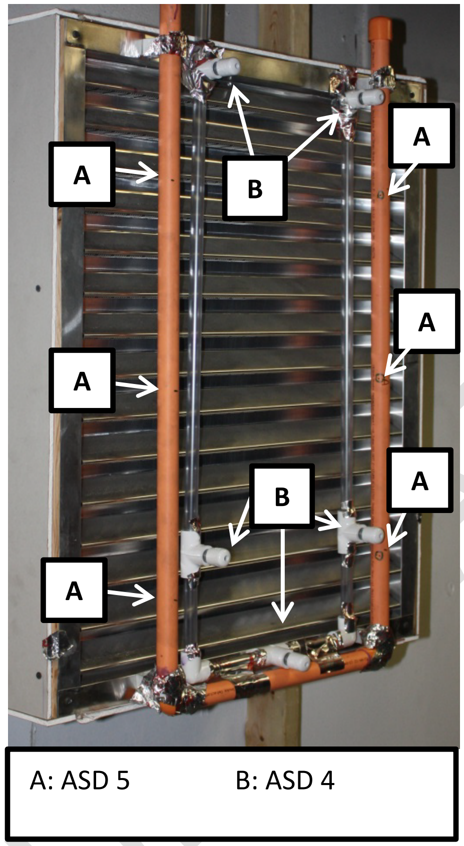


Figure 4-47. Return air grill protected with ASD piping

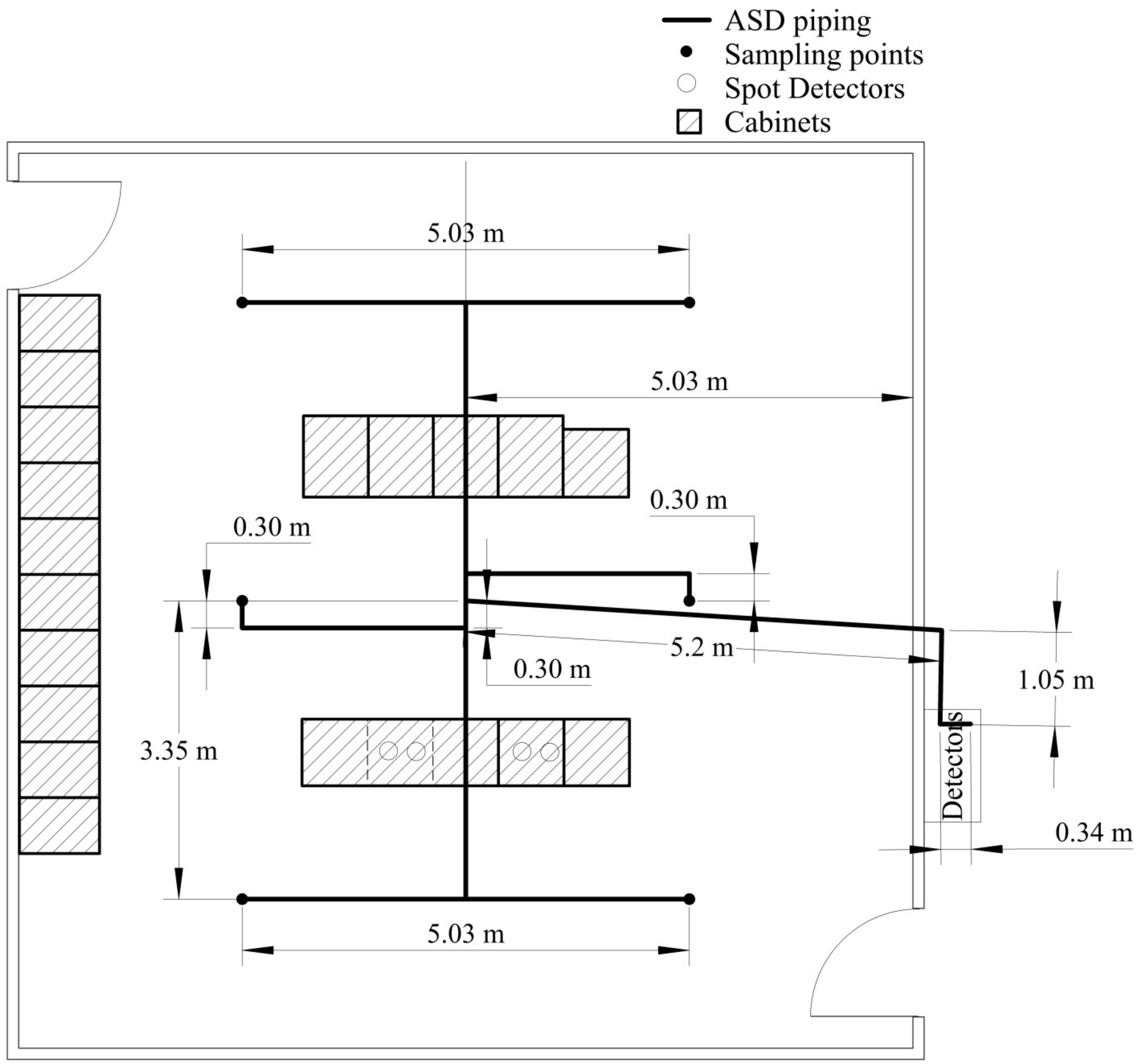


Figure 4-48. Area-wide ASD4, piping layout

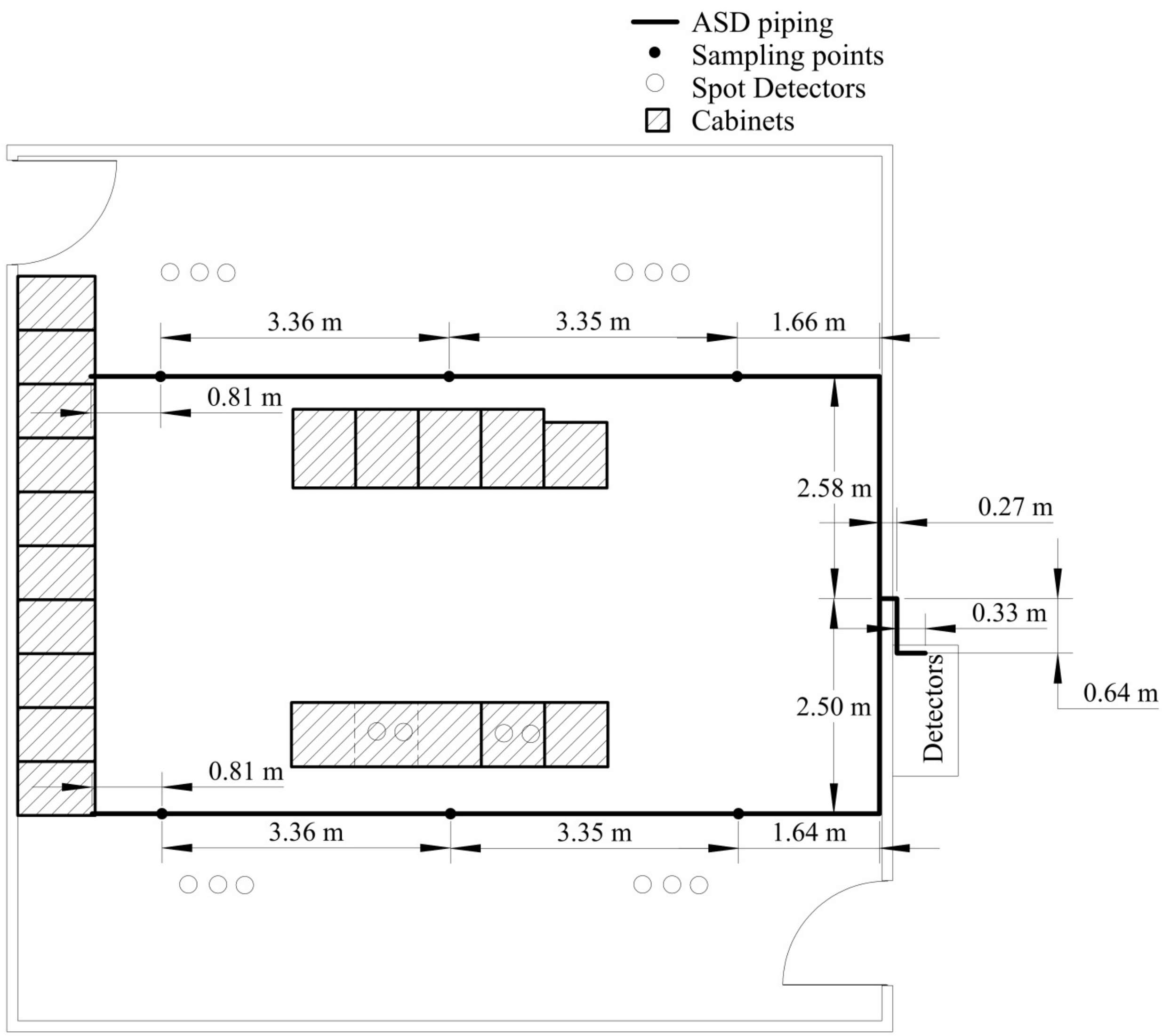


Figure 4-49. Area-wide ASD5, piping layout

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. Either heated wire test per NPFA 76 Annex B.2 or vendor recommended performance tests were conducted before each series of tests.

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 12^{o}C. 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 1^{o}C.

The suction pressures for the six in-cabinet sampling ports for the three ASDs were 0.12 kPa, 0.07 kPa, and 0.08 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 area-wide experiments

The small-room, area-wide 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 0.07 kPa for the first two sampling ports (closest to the detector), and 0.06 kPa for the last two sampling ports. For ASD3, the suction pressures were 0.09 kPa for the first two sampling ports, and 0.08 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, area-wide 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 area-wide experiments

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

4.6 <u>Experimental Design</u>

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 presents the test matrix for the Laboratory Instrument Cabinet experiments using single-zone detectors.

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 presents the test matrix for the Laboratory Large Cabinet experiments using single-zone detectors. Table 4-6 presents the test matrix for the limited number of Laboratory Large Cabinet experiments using a reduced HRP.

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

Table 4-5. Laboratory Large-Cabinet Experiments (Continued)

Configuration Number	Experimental Configuration			Experiments Conducted
	Material	Heating Ramp Period (min)	Cabinet Ventilation	
22	PCB	65.0	Natural	1
23	PCB	65.0	Forced	1
24	BS 6266	-	Natural	6

Table 4-6. Large Cabinet Experiments with Reduced 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

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

Configuration Number	Experimental Configuration					Experiments Conducted
	HRP (min)	Source Cabinet	Source Elevation (m)	Cabinet Ventilation (ACH)	Room Ventilation (ACH)	
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, Area-wide 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[1]	Source Elevation	Room Ventilation (ACH)	
1	CSPE	65.0	2	0	0	1
2	CSPE	65.0	2	0	6.5	1
3	CSPE	65.0	4	0	0	1
4	CSPE	65.0	4	0	6.5	1
5	CSPE	65.0	4	0	14	1
6	CSPE	260.0	4	0	0	1
7	CSPE	260.0	4	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	2	0	0	2
16	XLPE	65.0	2	0	6.5	1

[1] Refer to Figure 4-42 for a graphical representation of the various source locations. Numbers represent the cabinet that the source was located in the bank of instrumented cabinets.

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	2	0	7.4	1
18	XLPE	65.0	4	0	0	2
19	XLPE	65.0	4	0	6.5	1
20	XLPE	65.0	4	0	7.4	1
21	XLPE	65.0	4	0	14	1
22	XLPE	260.0	4	0	0	2
23	XLPE	260.0	4	0	6.5	1
24	XLPE	260.0	4	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	Cabinets not instrumented	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	Cabinets not instrumented	0	0	1
36	Cable Bundle	65.0	Cabinets not instrumented	0	6.5	1
37	Cable Bundle	65.0	Cabinets not instrumented	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 area-wide 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 and within the range of the materials auto ignition temperature. Given the measured wire temperature profile and thermal imaging camera images, this 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. It may also be worth noting that the final block temperatures are above the generic critical temperature thresholds to estimate functionality failures of cables, namely 205 and 330°C.

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 area-wide 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 °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 HRP of 60.0 minutes to a final set point of 450 °C, followed by a 5.0 minute period heating period at the final set point, for a 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	5.1×10^5 / 2.0×10^6	0.025 / 0.10	-	-	-
VEWFDS Alert	0.05 / 0.20	1.2×10^6 / 4.8×10^6	0.05 / 0.20	0.20	-	-
VEWFDS Alarm	0.25 / 1.00	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 5-1 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.

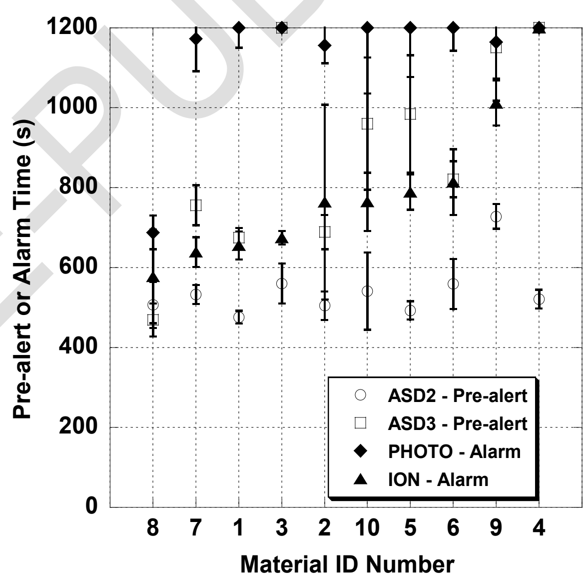


Figure 5-1. VEWFD pre-alert and conventional alarm times for the 15 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)

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.

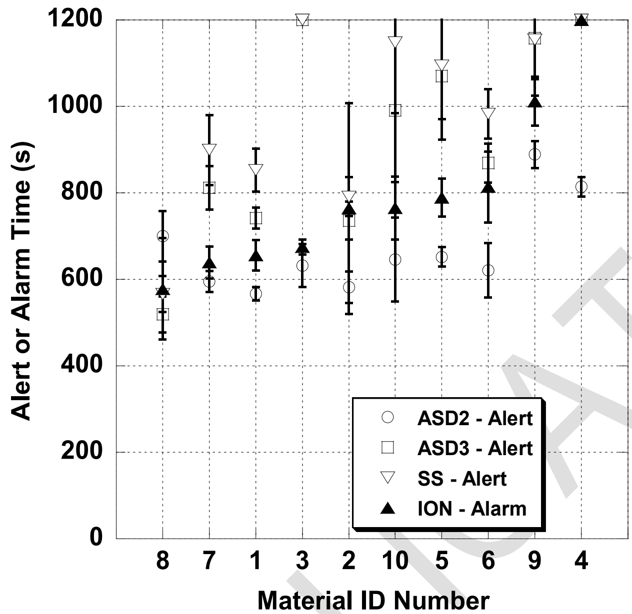


Figure 5-2. VEWFD alert and ION alarm times for the 15 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)

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.

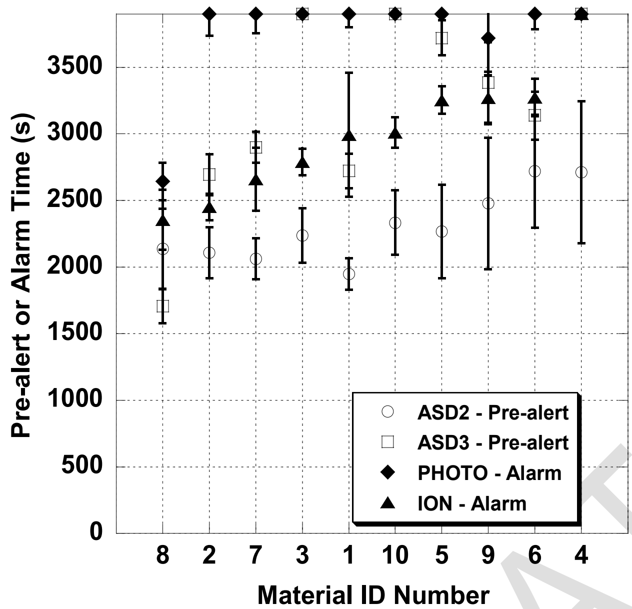


Figure 5-3. **VEWFD pre-alert and conventional alarm times for the 60 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)**

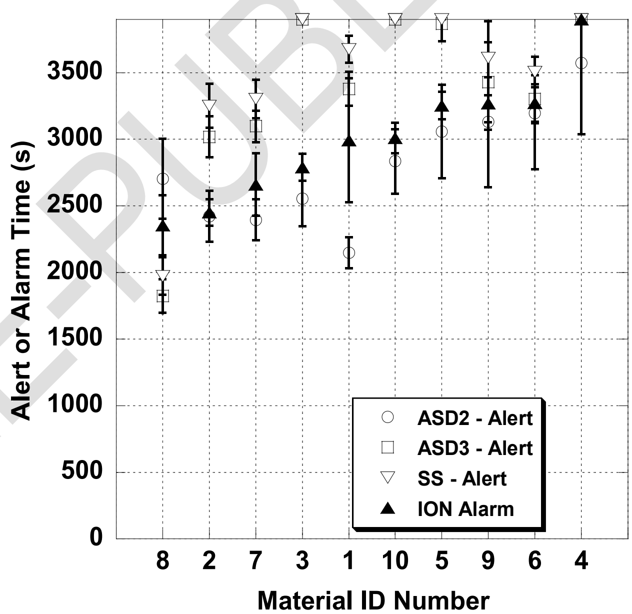


Figure 5-4. **VEWFD alert and ION alarm times for the 60 minute HRP instrument cabinet experiments. (Error bars represent ± one standard deviation for repeated tests)**

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. The one exception to this pattern is Material 8, in which case the ASD3 alerted first, followed by the ASD2, ION, and PHOTO.

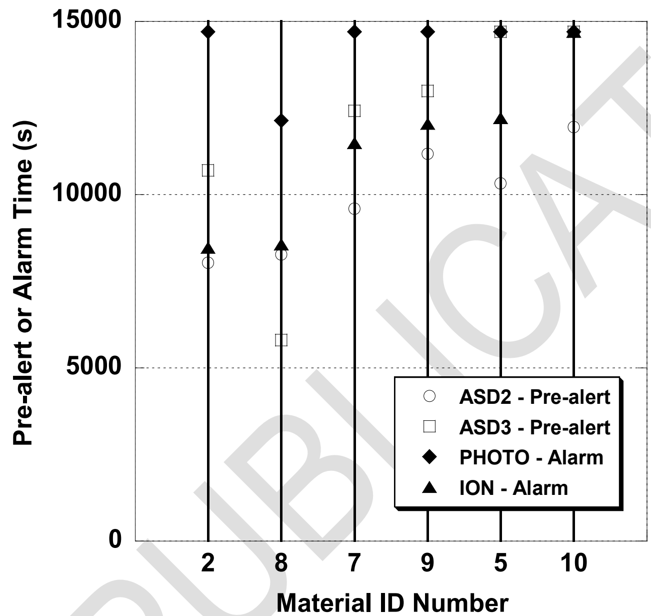


**Figure 5-5.	VEWFD pre-alert and conventional alarm times for the 240 minute HRP instrument cabinet experiments**

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.

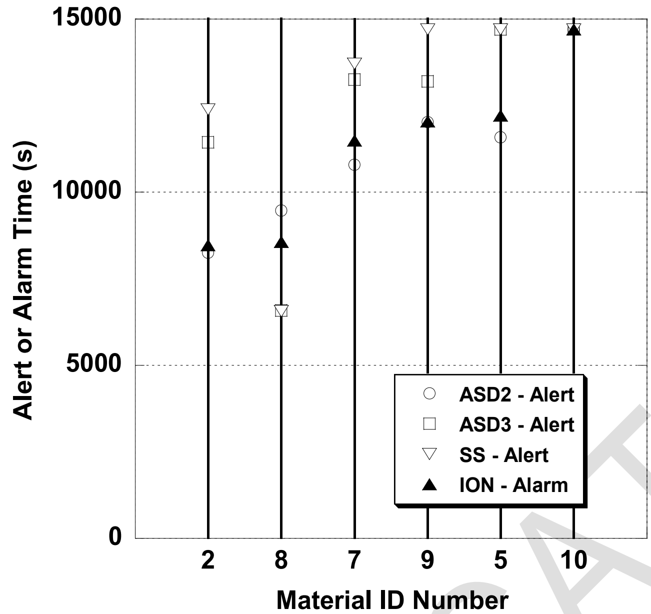


Figure 5-6. VEWFD alert and ION alarm times for the 240 minute HRP instrument cabinet experiments

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
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[1] 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

[1] The “block temperature” is the surface temperature measured by the thermocouple attached to the surface of the copper bus bar block. Refer to Section 4.2.1 for details.

increased, while ASD3 responded at lower block temperatures. The magnitude of the temperature difference was not large, thus the practical implications may be minor.

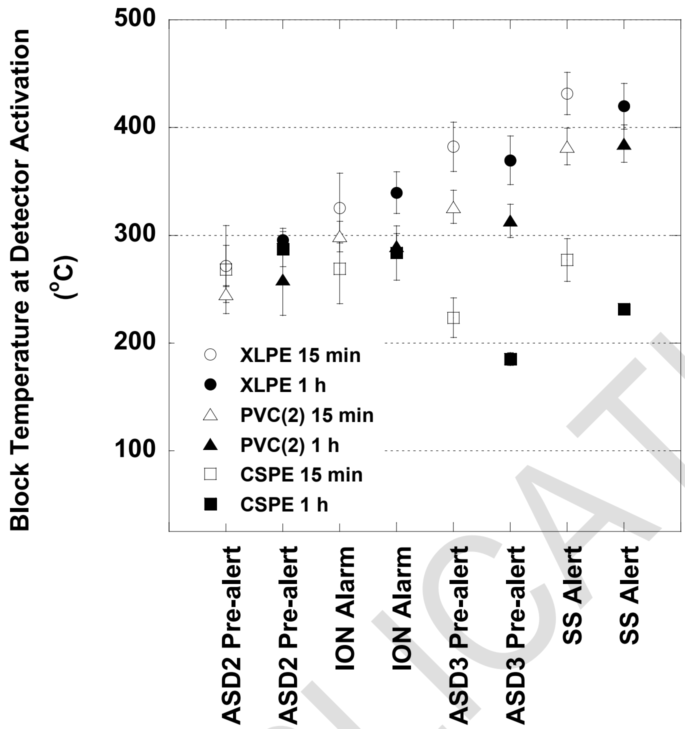


Figure 5-7. Block temperature at pre-alert, alert or alarm time for various detectors. (Error bars represent +/- one standard deviation for repeated tests)

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.

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 °C. The slope of the set point ramp remained the same as the 450 °C final set point experiments, but the duration of the ramp period was increased to 16.3, 65, and 460 minutes for the new HRPs. The 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	$3.8\times10^4/1.5\times10^5$	0.0063/0.025	-	-
VEWFD Alert	$1.4\times10^5/5.5\times10^5$	0.05/0.20	0.20	-
VEWFD Alarm	$6.4\times10^5/2.6\times10^6$	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.

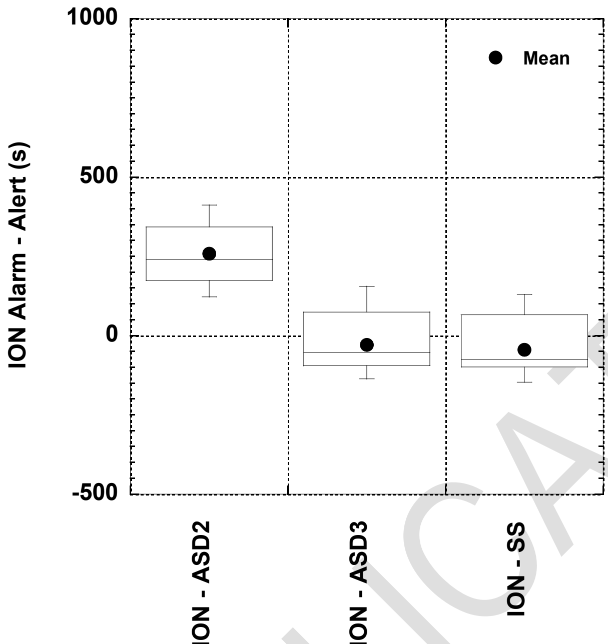


**Figure 5-8.	Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 16.3 minute HRP experiments**

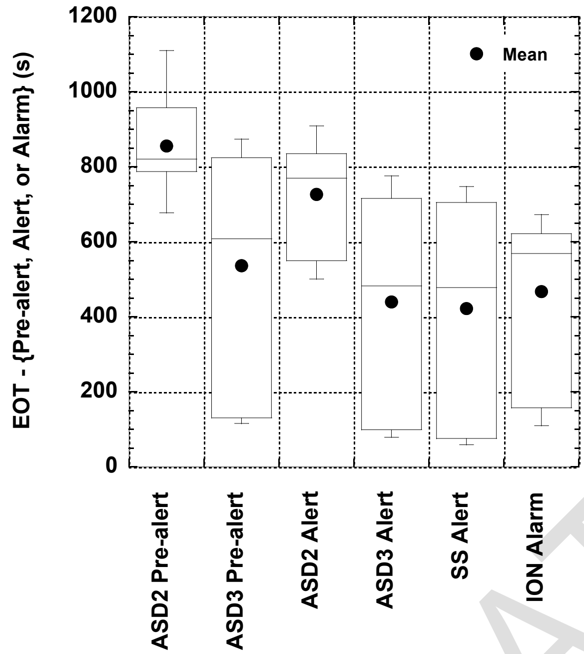


Figure 5-9. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 16.3 minute HRP experiments

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.

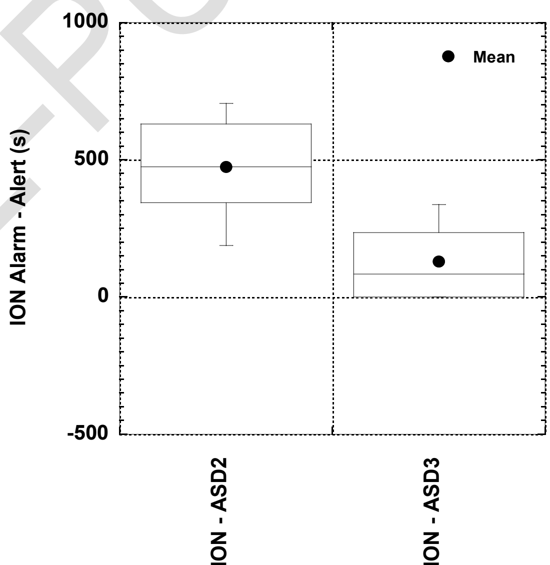


Figure 5-10. Time difference between ION alarm time and the ASD alert time for large cabinet, forced ventilation, 16.3 minute HRP experiments

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.

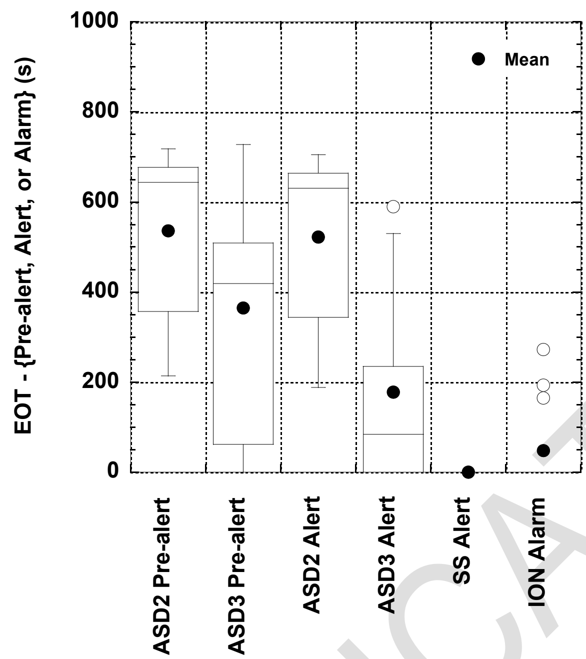


Figure 5-11. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation, 16.3 minute HRP experiments

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.

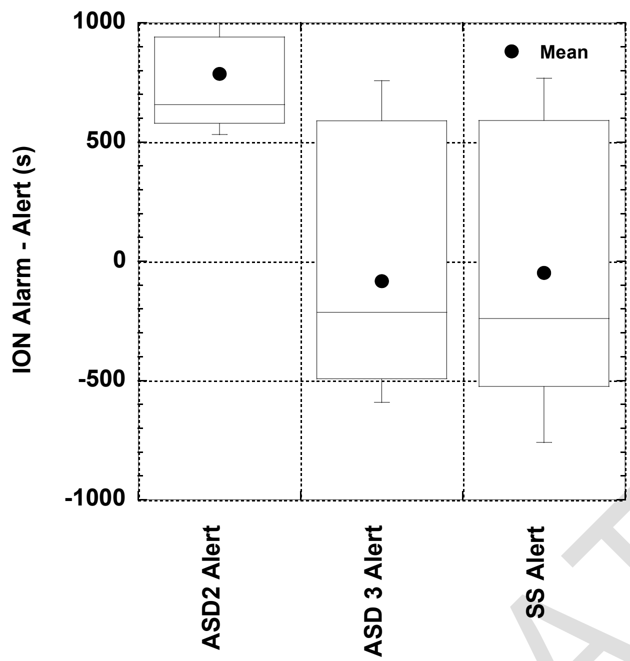


Figure 5-12. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 65.0 minute HRP experiments

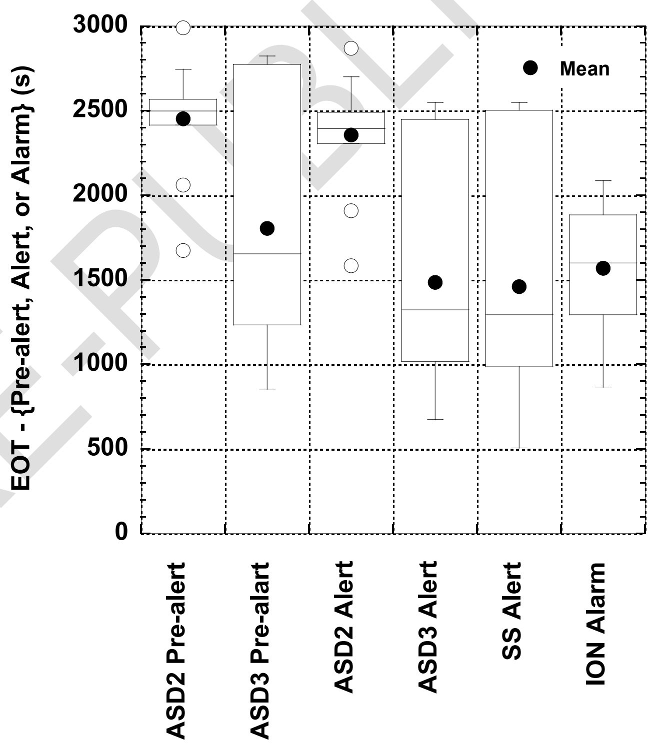


Figure 5-13. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 65.0 minute HRP experiments

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.

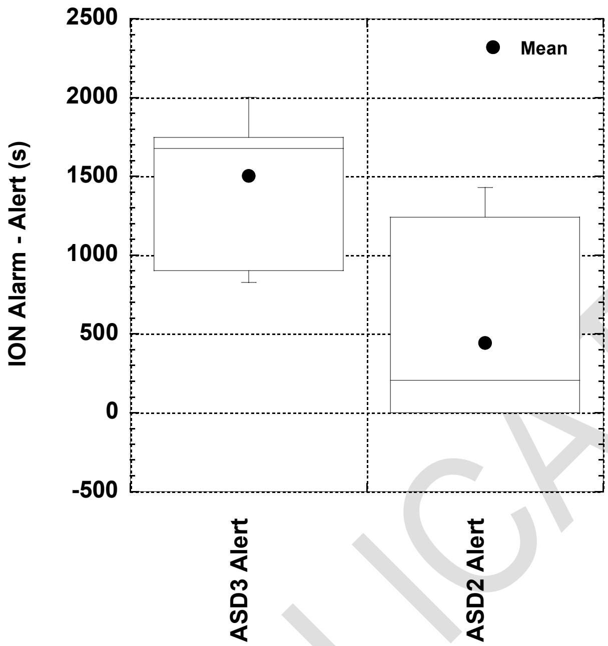


Figure 5-14. Time difference between ION alarm time and the ASD alerts times for large cabinet, forced ventilation, 65.0 minute HRP experiments

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.

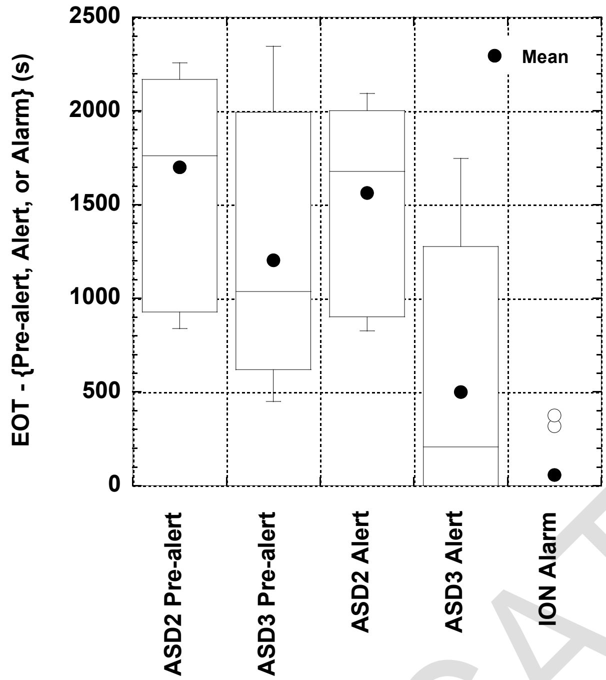


Figure 5-15. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation, 65.0 minute HRP experiments

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.

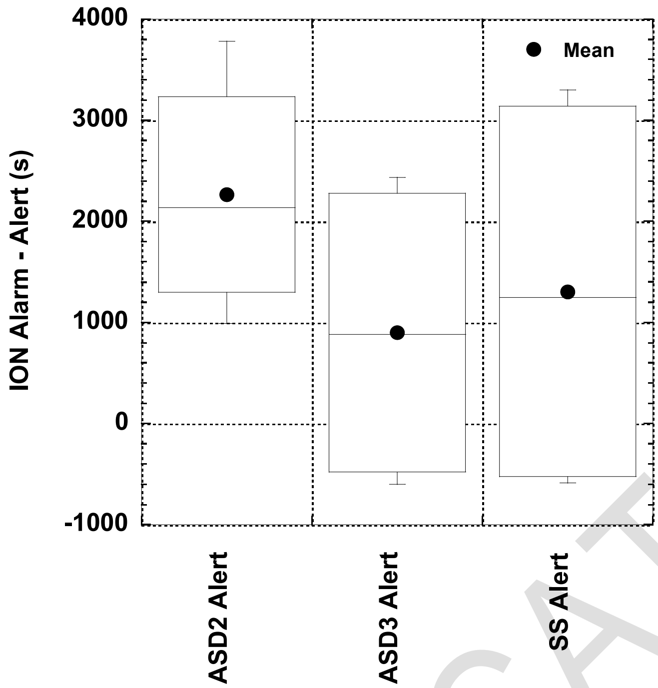


Figure 5-16. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 260.0 minute HRP experiments

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.

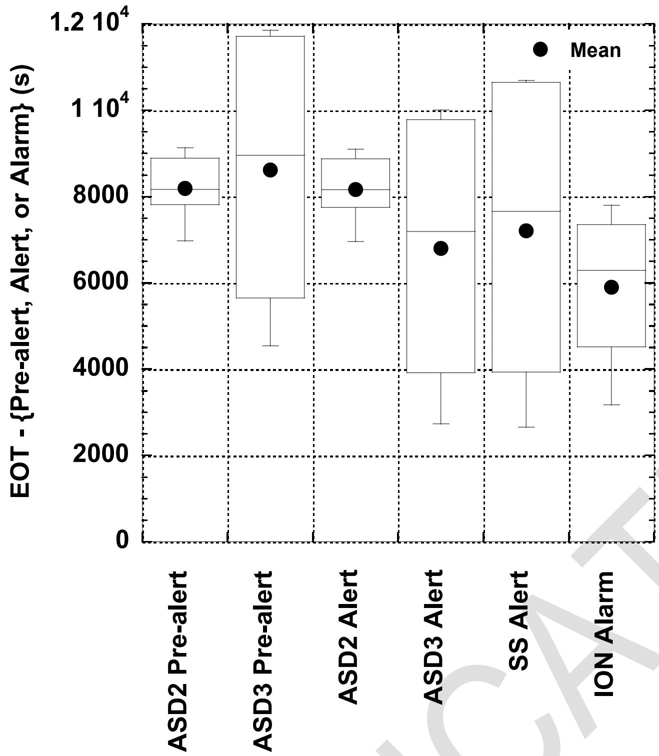


Figure 5-17. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 260.0 minute HRP experiments

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	1.2×10^6 / 7.2×10^6	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 first data set 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.

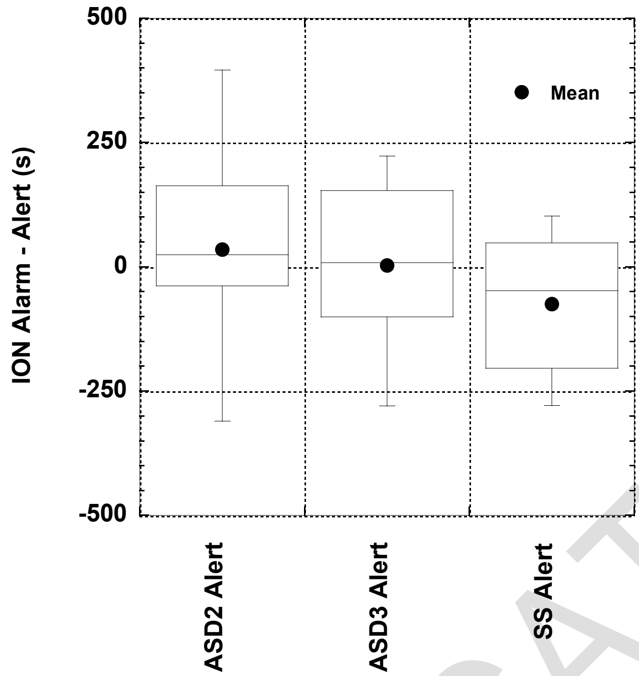


Figure 5-18. Time difference between ION alarm times and the ASD alerts and SS alert for small room, cabinet mock-up, 16.3 minute HRP experiments

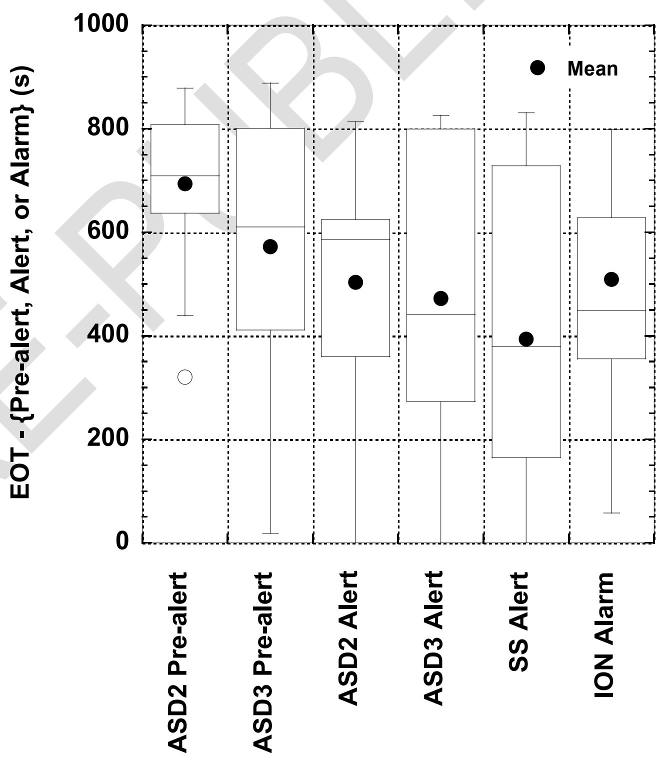


Figure 5-19. Time difference between the end of test (EOT) time (1278 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 16.3 minute HRP experiments

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.

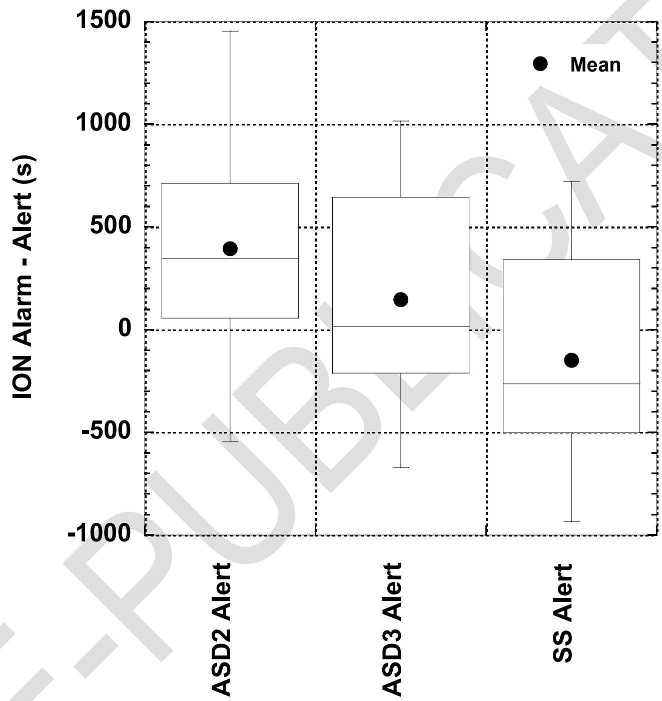


Figure 5-20. Time difference between ION alarm time and the ASD alerts and SS alert for small room, cabinet mock-up, 65.0 minute HRP experiments

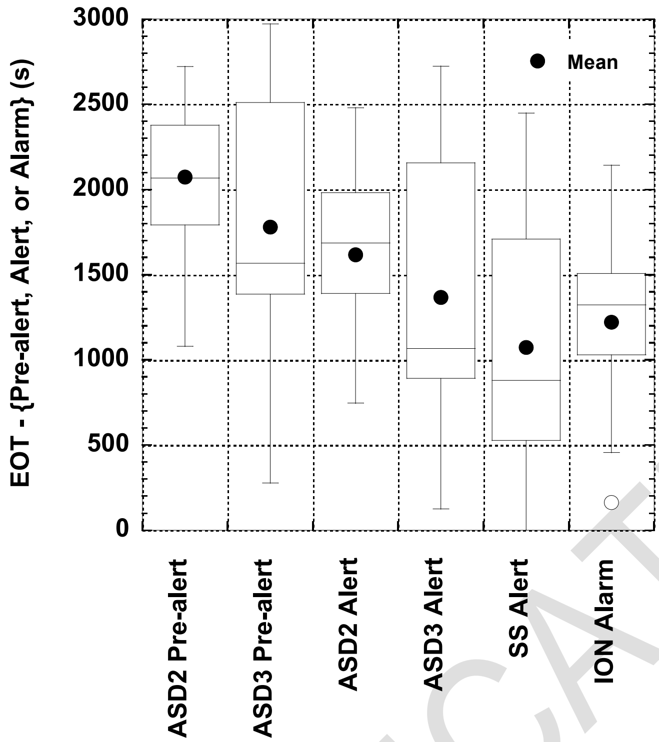


Figure 5-21. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 65.0 minute HRP experiments

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.

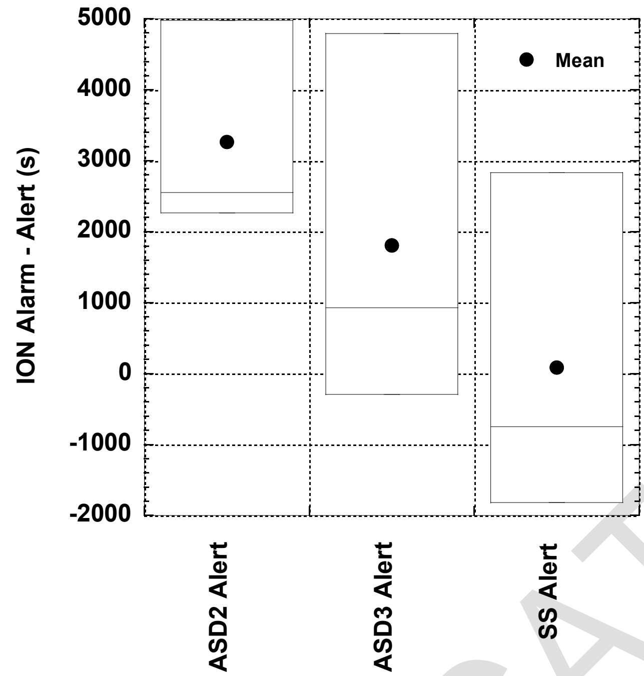


Figure 5-22. Time difference between ION alarm times and the ASD alerts and SS alert for small room, cabinet mock-up, 260.0 minute HRP experiments

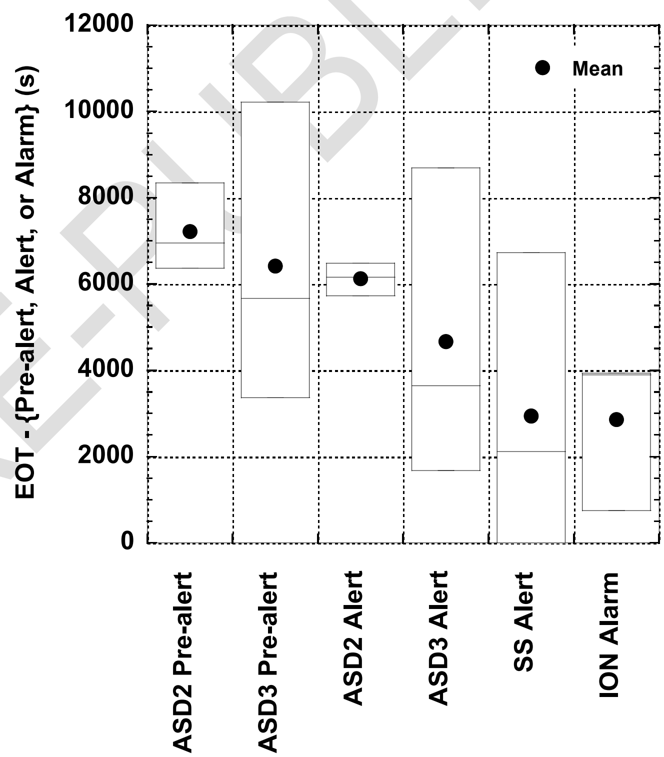


Figure 5-23. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-up, 260.0 minute HRP experiments

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).

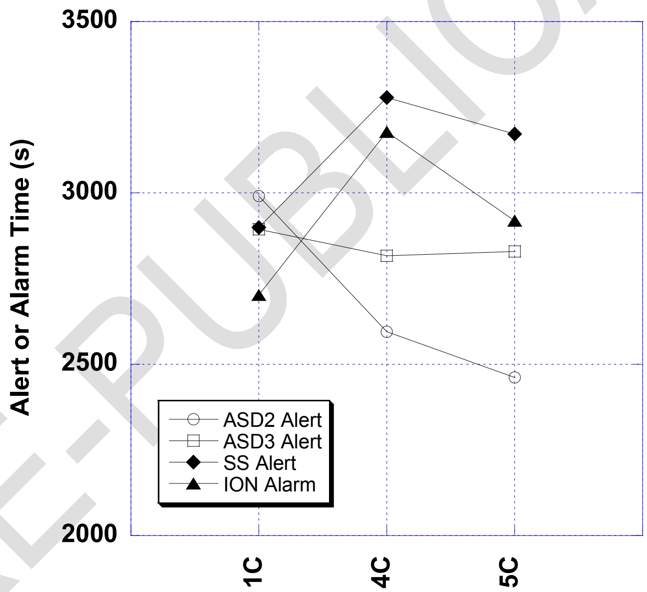


Figure 5-24. Mean alert or alarm times for small room, 1, 4, and 5-cabinet mock-up configurations, 65.0 minute HRP experiments

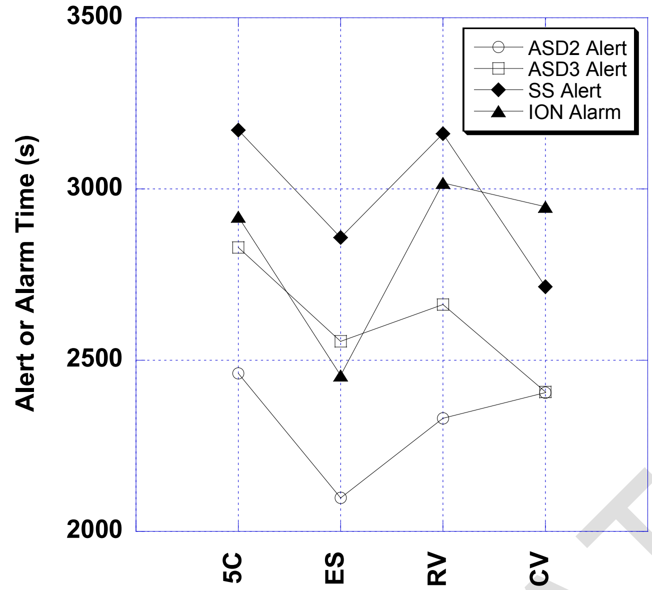


Figure 5-25. Mean alert or alarm times for small room, 5-cabinet mock-up configurations, 65.0 minute HRP experiments

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.

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	3.8×10^4 / 1.5×10^5	0.0063 / 0.025	-	-
VEWFD Alert	1.4×10^5 / 5.5×10^5	0.05 / 0.20	0.20	-
VEWFD Alarm	6.4×10^5 / 2.6×10^6	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 ION alarm for the three-cabinet arrangement suggesting some cooperative ASD sampling from adjacent cabinets.

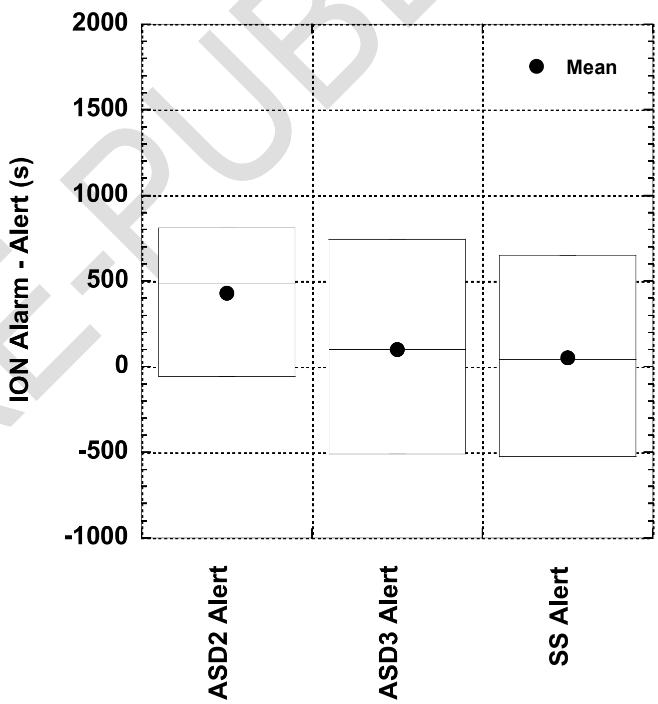


Figure 5-26. Time difference between ION alarm times and the ASD alerts and SS alert for large room, single-zone single-cabinet, 65.0 minute HRP experiments

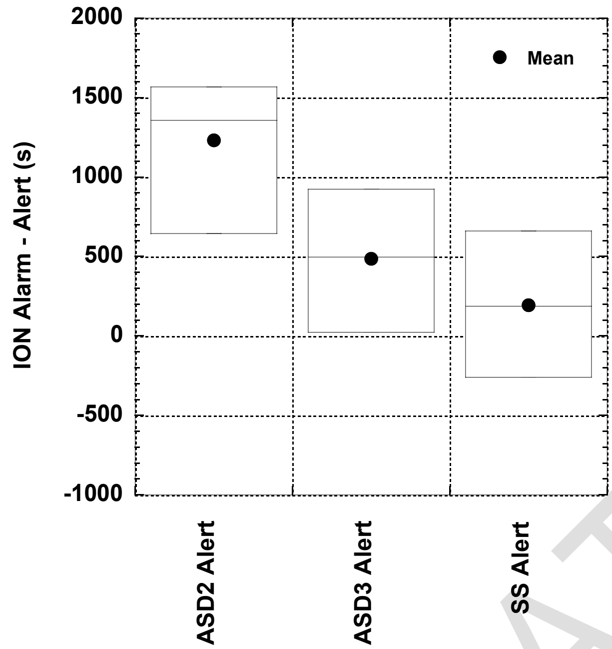


Figure 5-27. Time difference between ION alarm times and the ASD alerts and SS alert for large room, single-zone, three-cabinet configuration, 65.0 minute HRP experiments

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

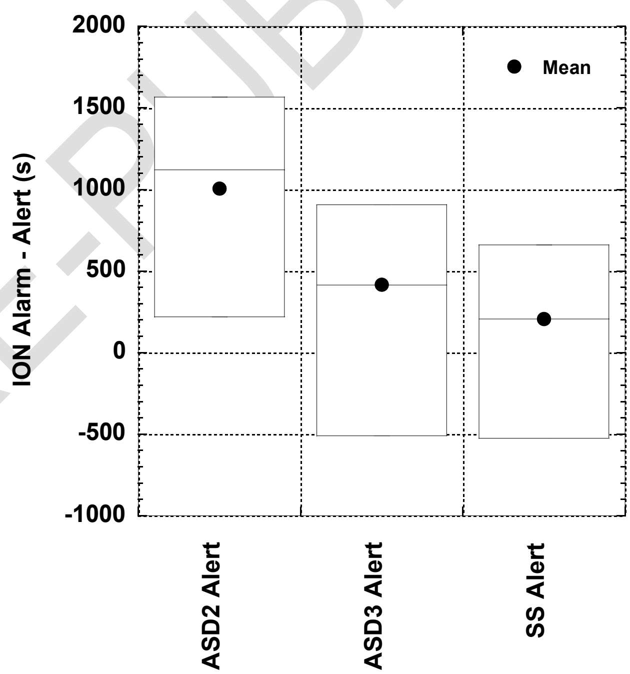


Figure 5-28. Time difference between ION alarm times and the ASD alerts and SS alert for large room, single-zone, no ventilation, in-cabinet, 65.0 minute HRP experiments

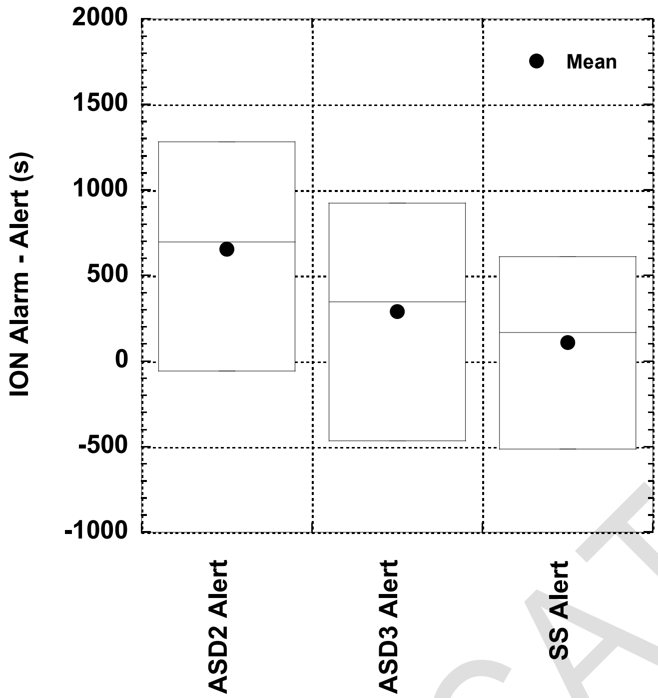


Figure 5-29. Time difference between ION alarm times and the ASD alerts and SS alert for Large room, single-zone, 7.4 ACH room ventilation, in-cabinet, 65.0 minute HRP experiments

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, and SS pre-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.

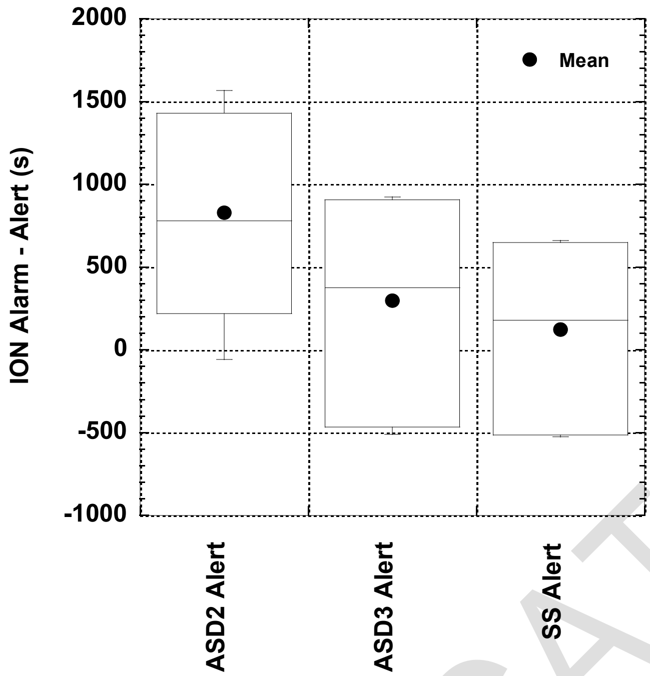


Figure 5-30. Time difference between ION alarm times and the ASD alerts and SS alert for large room, single-zone, in-cabinet, 65.0 minute HRP experiments

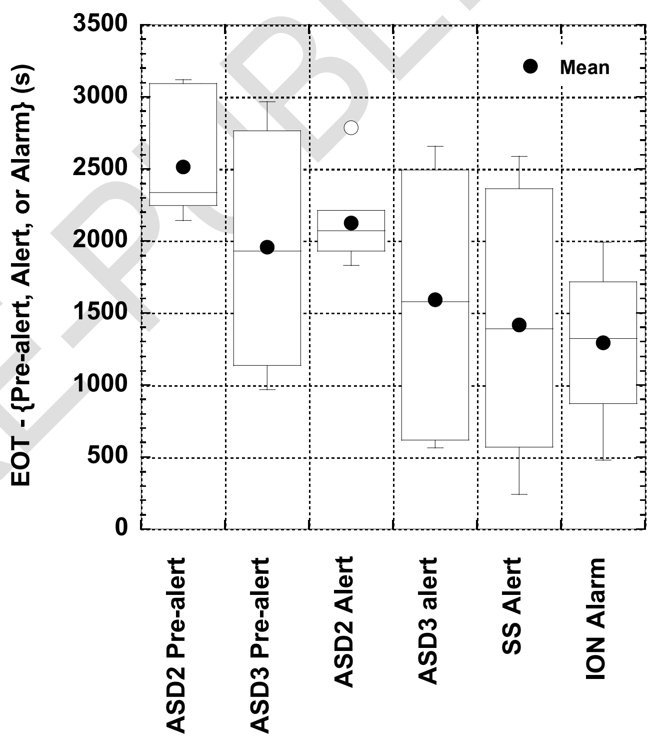


Figure 5-31. Time difference between the end of test (EOT) time (4200 s) and ASD Pre-alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet, 65.0 minute HRP experiments

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, and SS pre-alarm time. The decreasing mean time difference trend was ASD2 alert, SS alert, ASD3 alert and ION alarm.

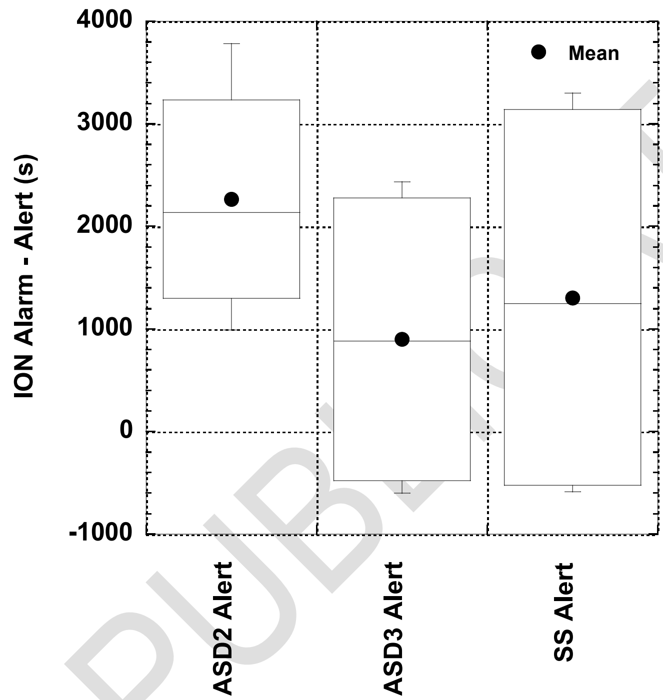


Figure 5-32. Time difference between ION alarm times and the ASD alerts and SS alert for large room, single-zone, in-cabinet, 260.0 minute HRP experiments

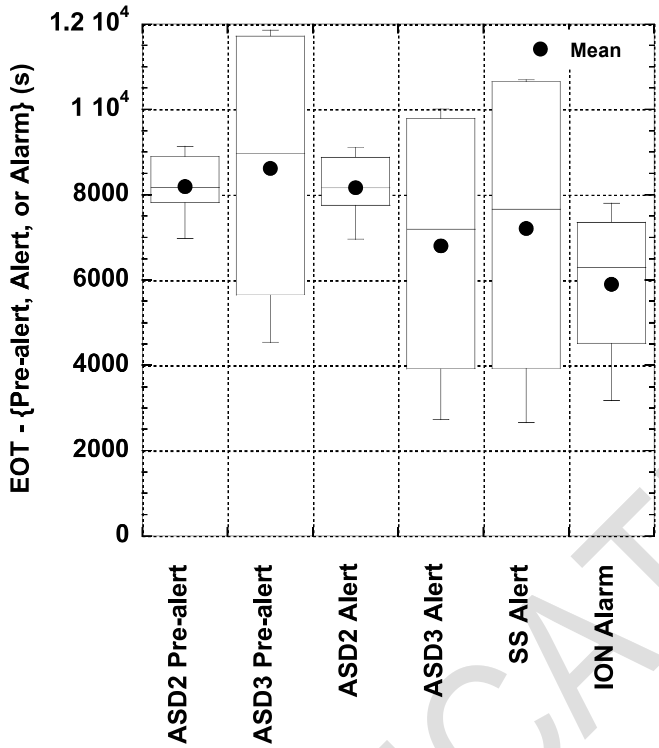


Figure 5-33. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet, 260.0 minute HRP experiments

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

1. The time difference between the ION 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 ION 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. ASD4 (cloud chamber) sensitivity setting were vendor-specified.

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), and ION alarm.

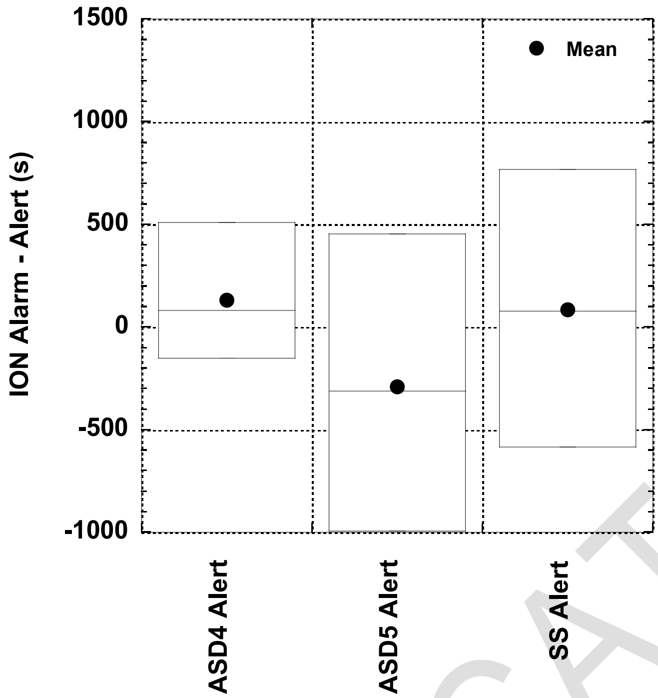


Figure 5-34. Time difference between ION alarm times and the ASD alerts and SS alert for large room, multi-zone, single-cabinet, 65.0 minute HRP experiments.

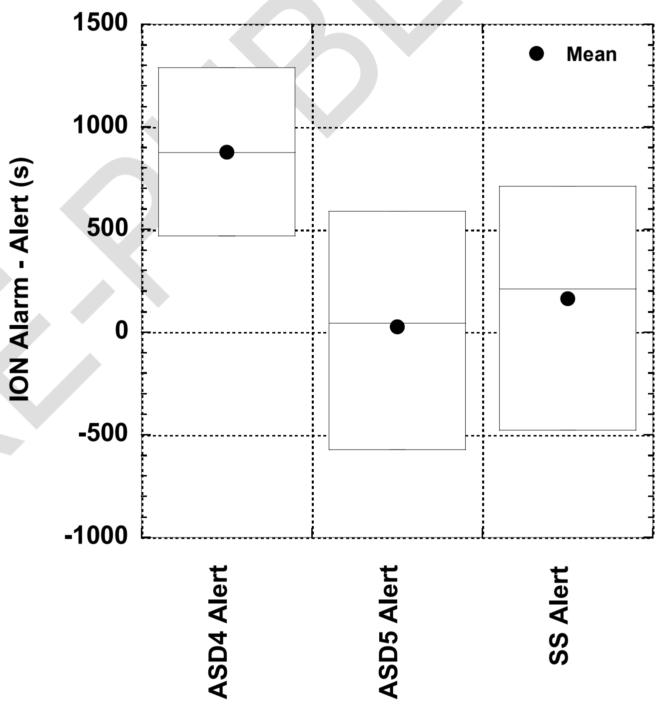


Figure 5-35. Time difference between ION alarm times and the ASD alerts and SS alert for large room, multi-zone, three cabinet configuration, 65.0 minute HRP experiments

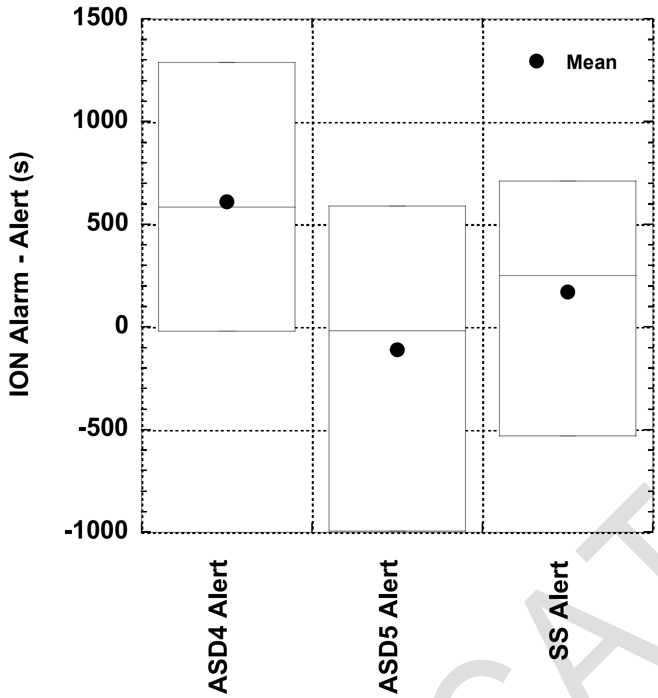


Figure 5-36. Time difference between ION alarm times and the ASD alerts and SS alert for large room, multi-zone, no ventilation, 65.0 minute HRP experiments

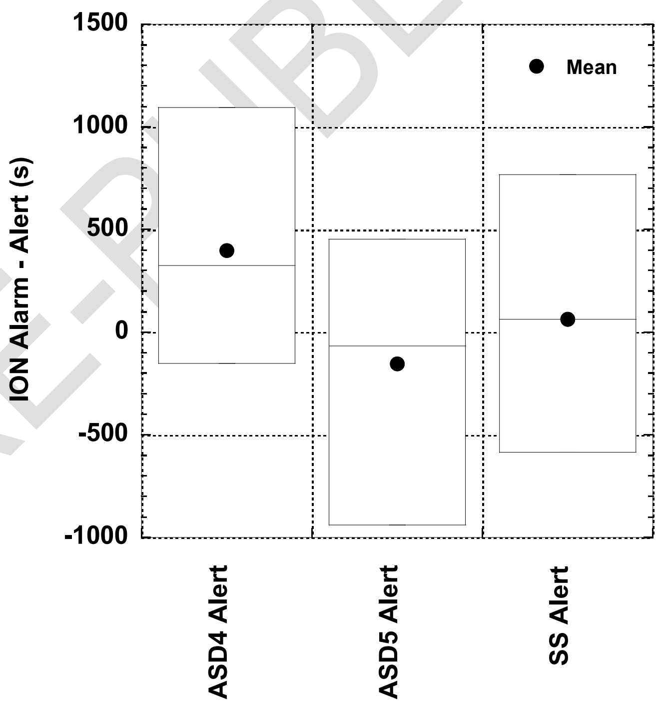


Figure 5-37. Time difference between ION alarm times and the ASD alerts and SS alert for large room, multi-zone, 7.4 ACH room ventilation, 65.0 minute HRP experiments

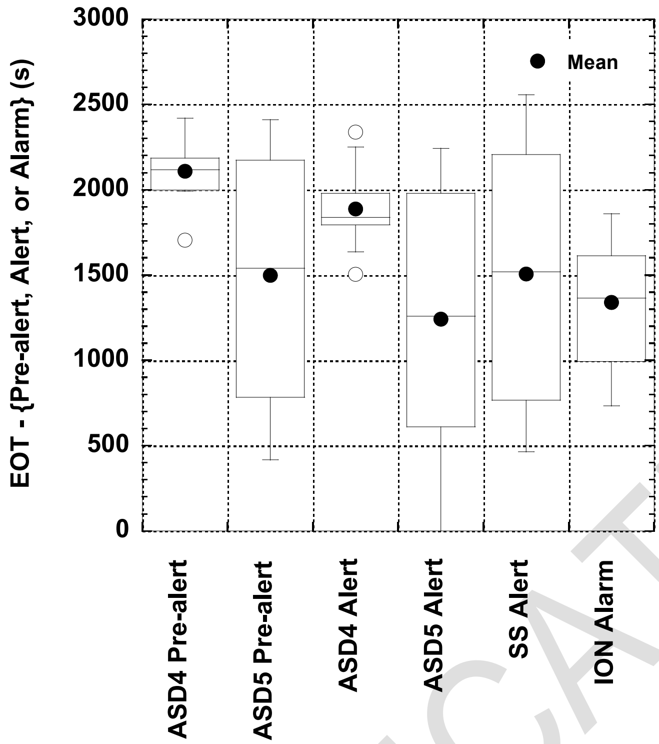


Figure 5-38. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, multi-zone in-cabinet, 65 minute HRP experiments

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.

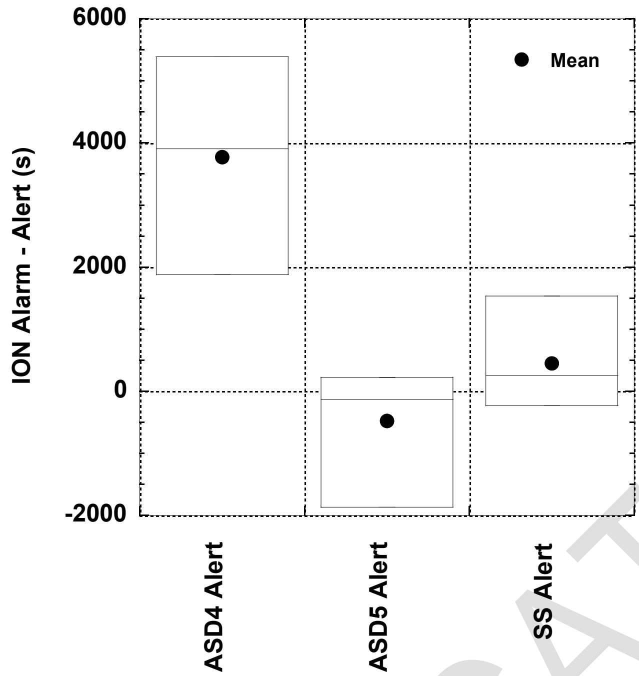


Figure 5-39. Time difference between ION alarm times and the ASD alerts and SS alert for large room, multi-zone, in-cabinet, 260.0 minute HRP experiments

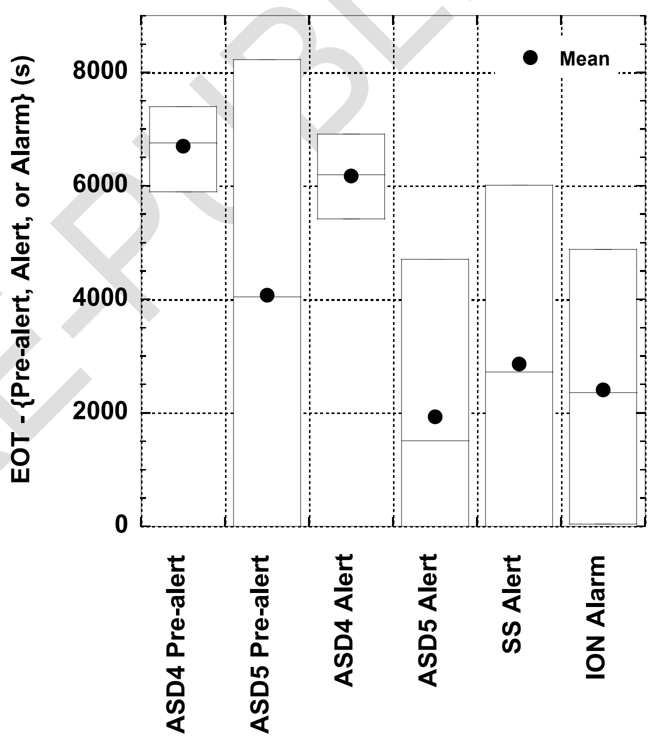


Figure 5-40. Time difference between the end of test (EOT) time (15900 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large room, multi-zone in-cabinet, 260.0 minute HRP experiments

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

1. ASD4 responded before the conventional ION 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, Area-wide 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, Area-wide 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	8.5×10^5 / 3.4×10^6	0.05 / 0.20	0.20	-	-
VEWFD Alarm	0.25 / 1.00	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.

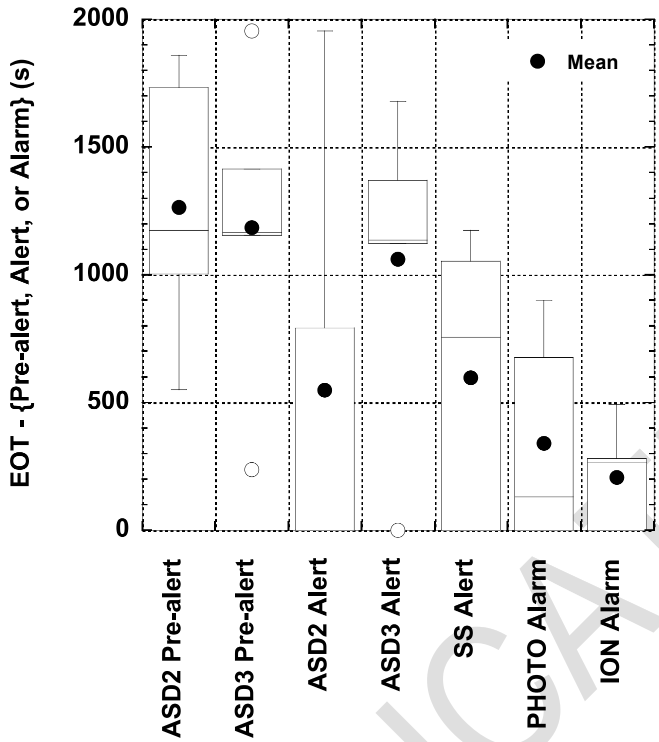


Figure 5-41. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts, PHOTO and ION alarm time for small room, area-wide, 65.0 minute HRP experiments

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 Area-wide Experiments

The large-room, multi-zone, area-wide experiments included in-cabinet, return air grill, and area-wide 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. Area-wide and return air grill locations are referred to as AW and RA, respectively.

Table 5-9. Nominal Detector Sensitivities for Large Room, Multi-Zone, Area-wide 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	1.5×10^5 / 9.0×10^5 / 7.5×10^5	0.0159 / 0.10	-	-	-
VEWFD Alert	2.5×10^5 / 1.5×10^6 / 1.3×10^6	0.0334 / 0.20	0.20	-	-
VEWFD Alarm	4.5×10^5 / 2.7×10^6 / 2.3×10^6	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 area-wide experiments with ventilation air flow.

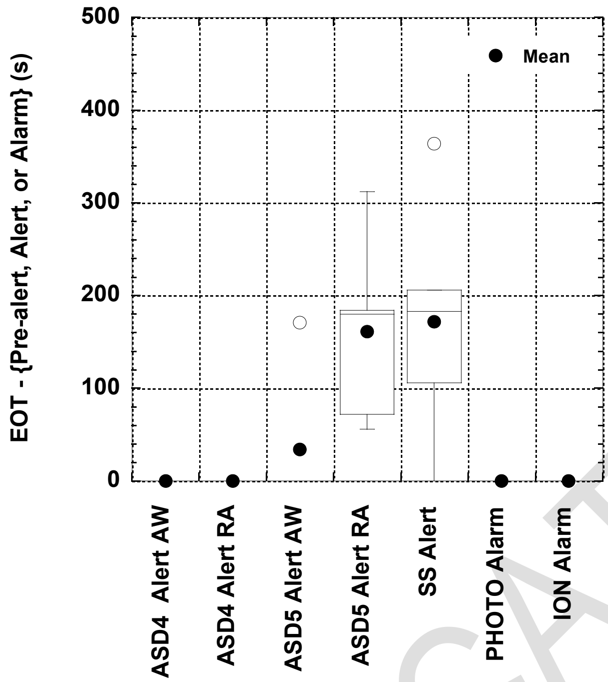


Figure 5-42. Time difference between the end of test (EOT) time (1278 s) and ASD alerts, SS alerts, PHOTO and ION alarm time for large room, area-wide, 16.3 minute HRP experiments

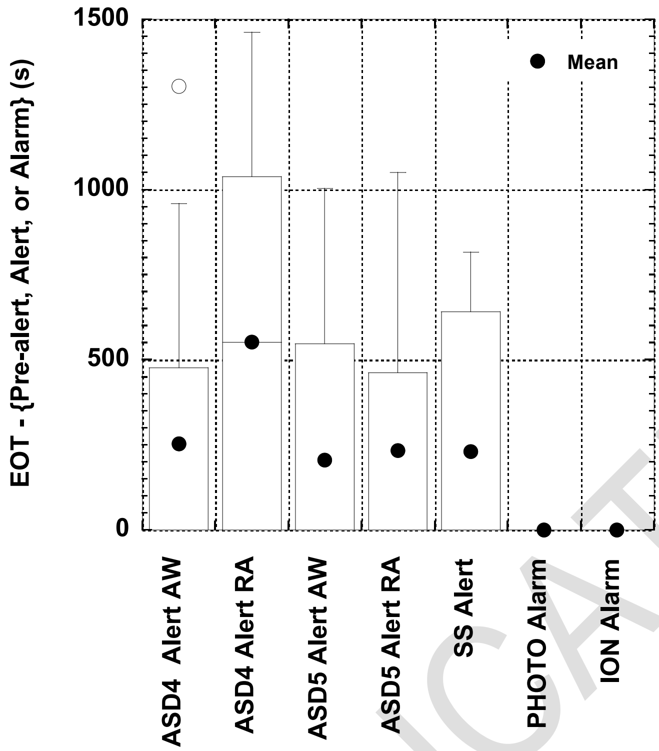


Figure 5-43. Time difference between the end of test (EOT) time (4200 s) and ASD alerts, SS alerts, PHOTO and ION alarm time for large room, area-wide, 65.0 minute HRP experiments

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 area-wide outperformed the ASD5 return air zone and the ASD5 area-wide.

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 area-wide 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).

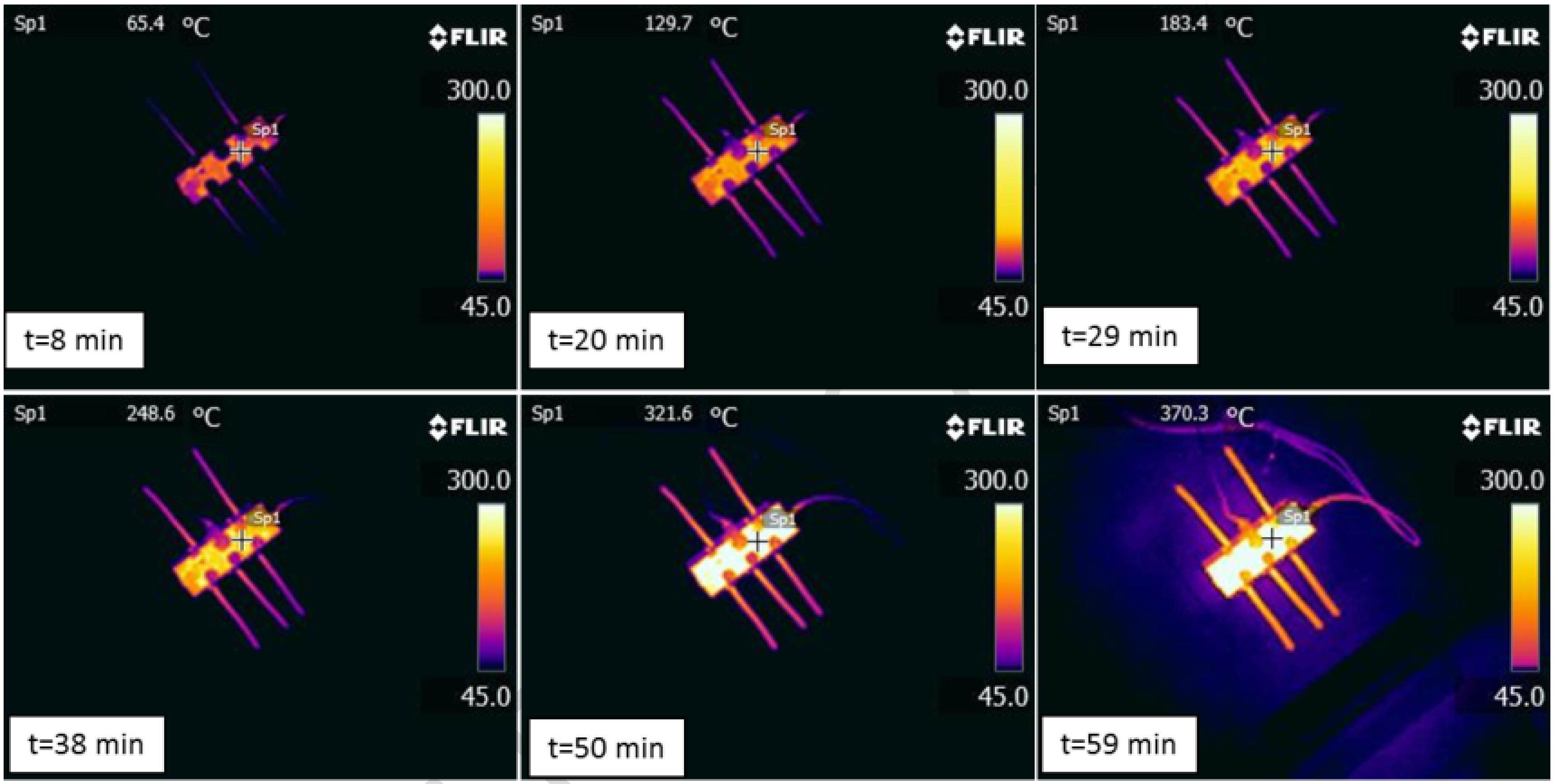


Figure 5-44. Heating profiles for 12 AWG XLPE wires at various times during the heating process. The temperature of the block can be seen in the top left corner in each image.

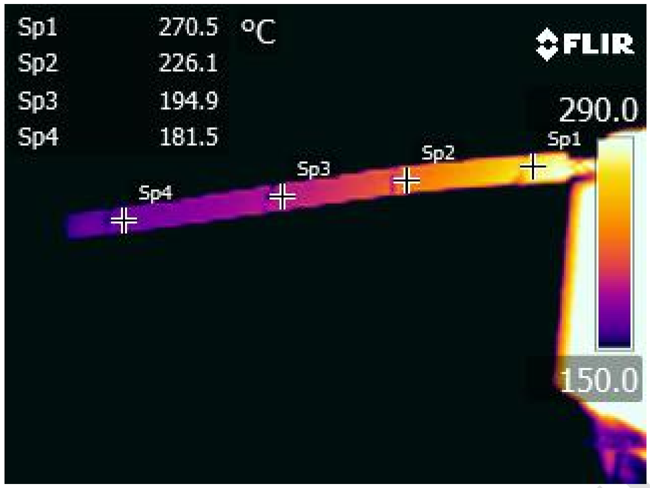


Figure 5-45. Temperature profile for a 12 AWG XLPE wire. The image was taken at the end of a 60.0+ minute HRP and a 5.0 minute set point hold at 450 °C. The bus bar temperature was 446 °C.

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.

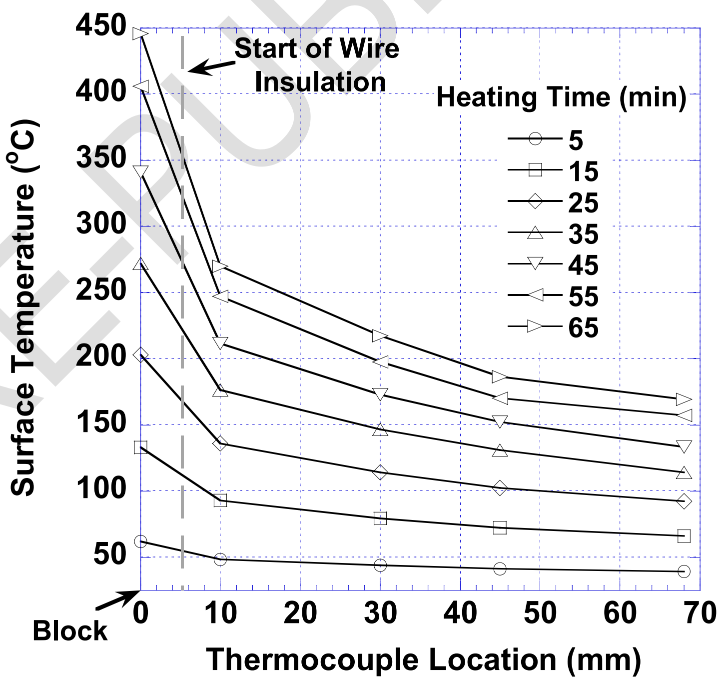


Figure 5-46. Wire surface temperature as a function of time for a 60.0 minute HRP followed by a 5.0 minute hold (± 2 ºC). Thermocouples were located along the insulated surface of a 12 AWG XLPE sample

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 °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 °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 °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 °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 °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.

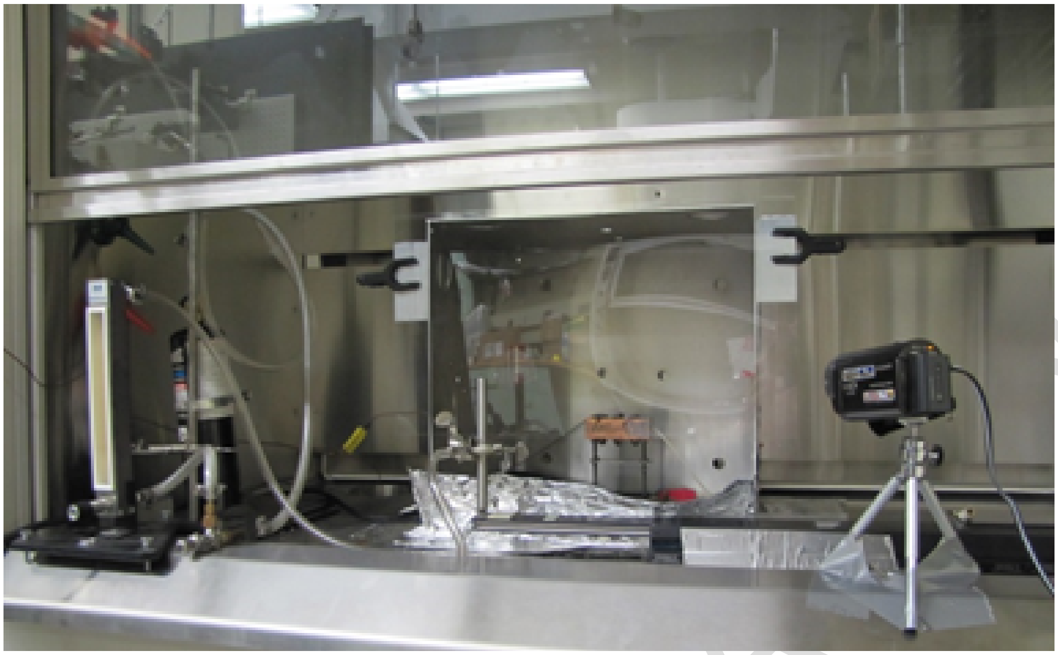


Figure 5-47. Experimental setup

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. Refer to Section 4.2 for more detail on the design and intended purpose of the incipient fire source.

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, and supporting the risk scoping study presented in Part II.

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 area-wide 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)[1], while the "alert" response for the ASD CC is the vendor recommended sensitivity. Since the latter does not 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

[1] 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.

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.

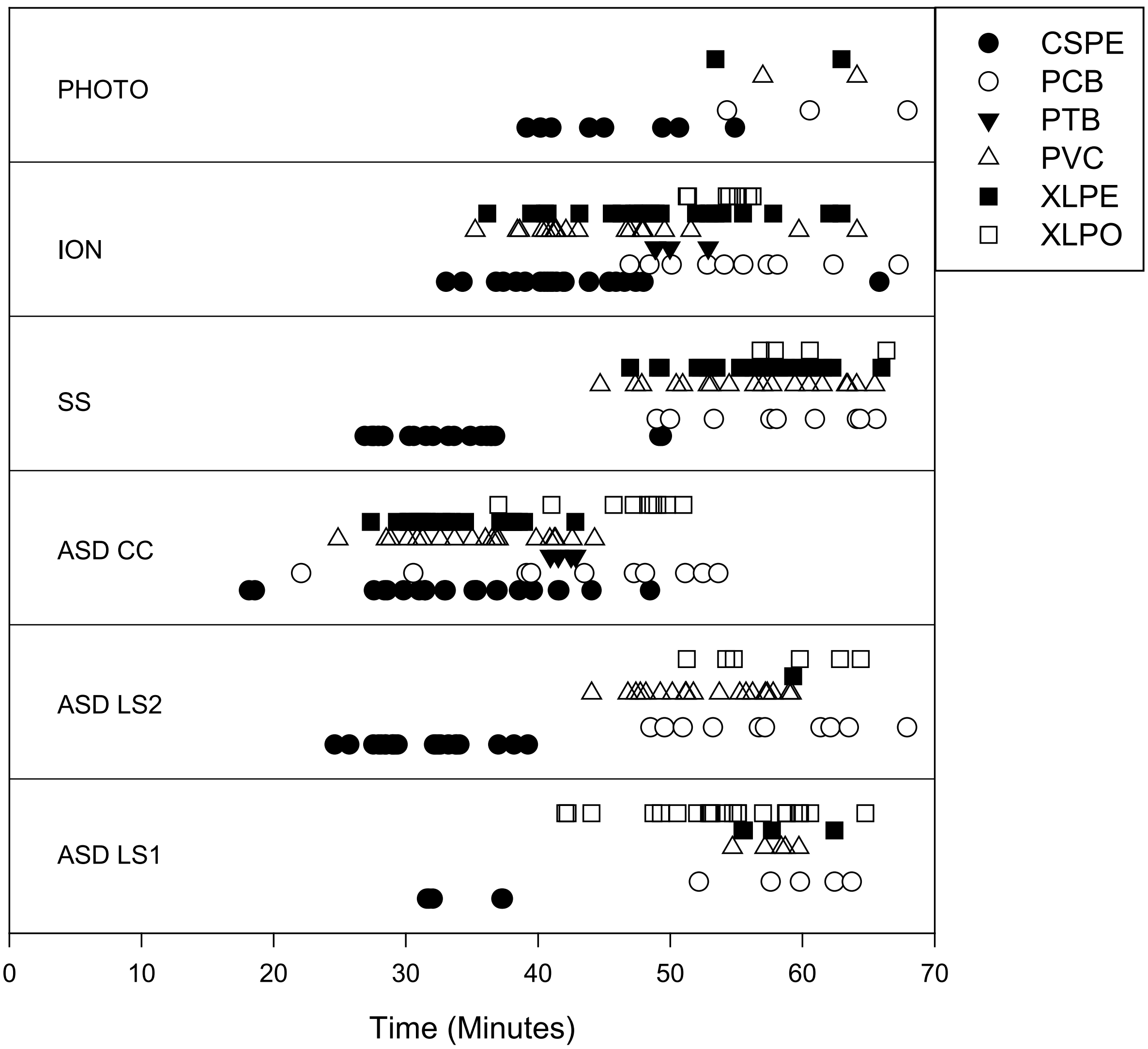


Figure 5-49. Detector response to selected materials (1-hour HRP)

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.

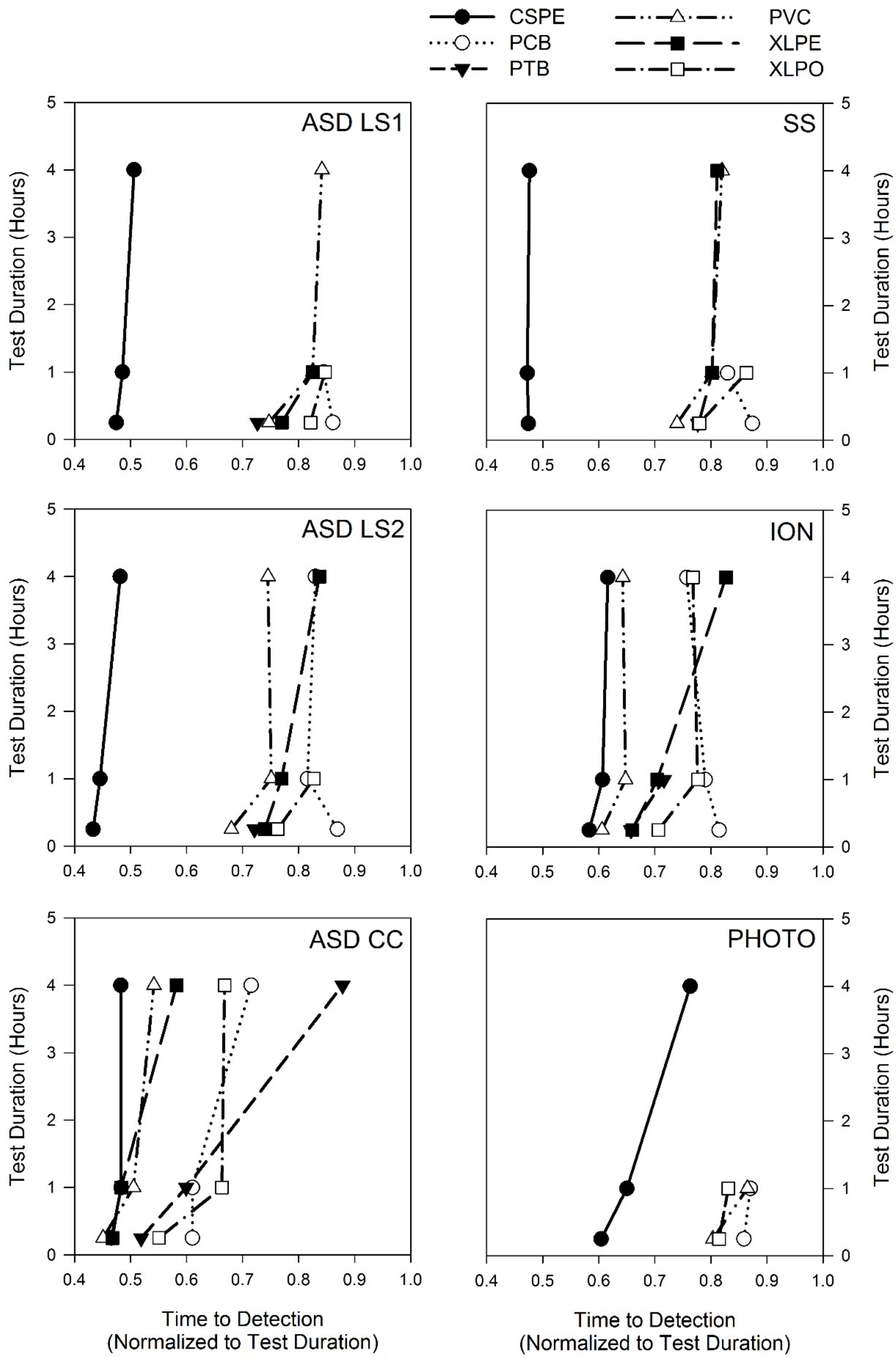


Figure 5-50. Time to detection, by detector

The insights from the data presented in Section 5.9.1 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. The normalization of the test durations in Figure 5-50 also indicates that the mean detection range between the three HRP is narrow on the order of 1/10th of the test duration. This observation is used to support the timing analysis discussed in Section 8.

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 low-energy (incipient stage) fire 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.

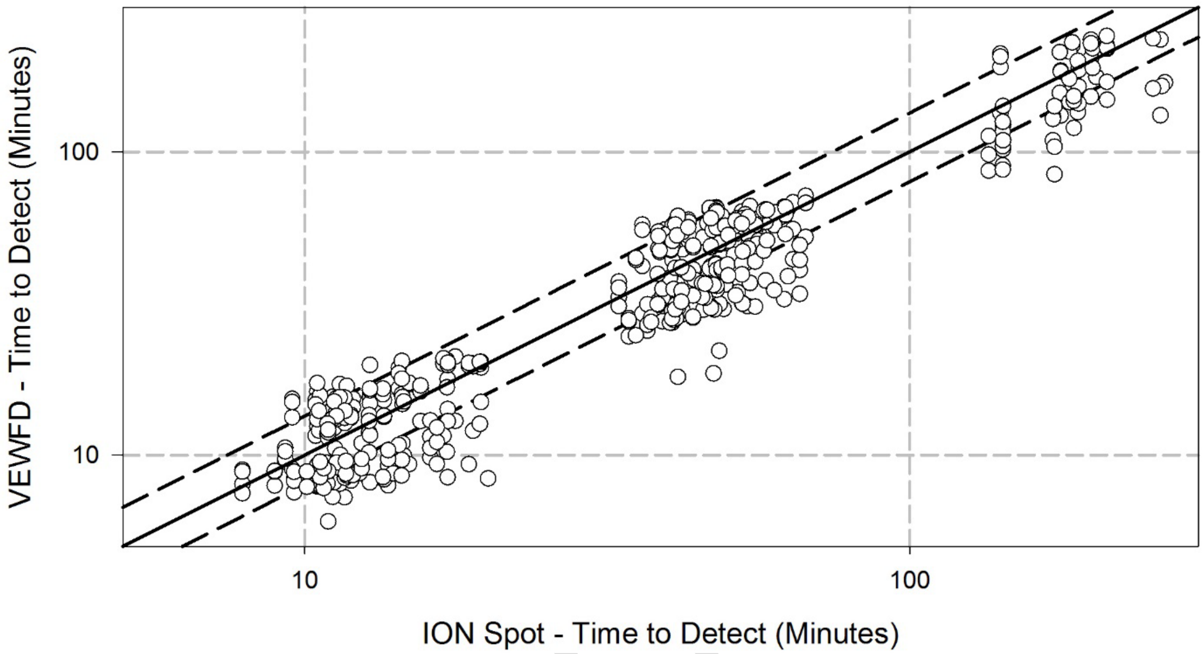


Figure 5-51. Summary plot – ION alarm versus VEWFD alert (in-cabinet, natural ventilation)

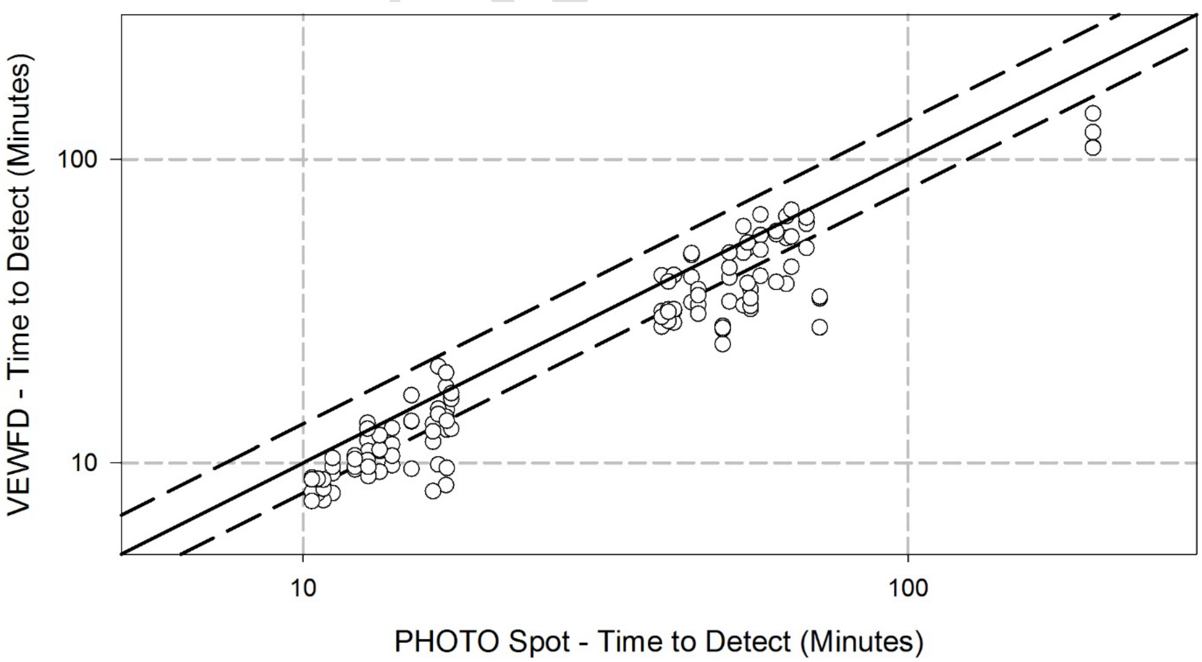


Figure 5-52. Summary plot – PHOTO versus VEWFD (in-cabinet, natural ventilation)

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	$5^{th}/95^{th}$ Percentile	Mean	$5^{th}/95^{th}$ 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.

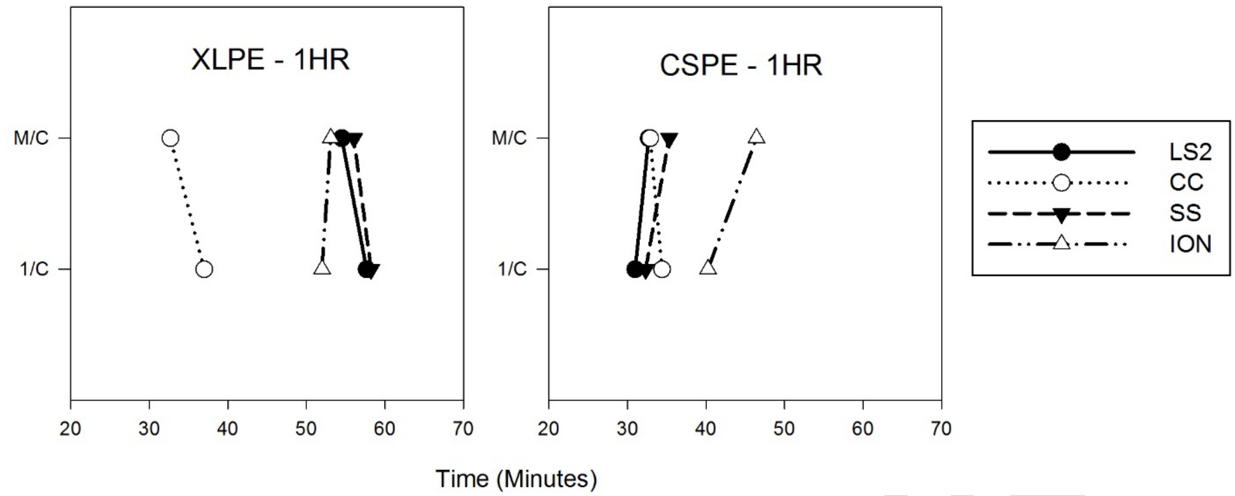


Figure 5-53. Detector response versus number of sampling ports in cabinet space

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.

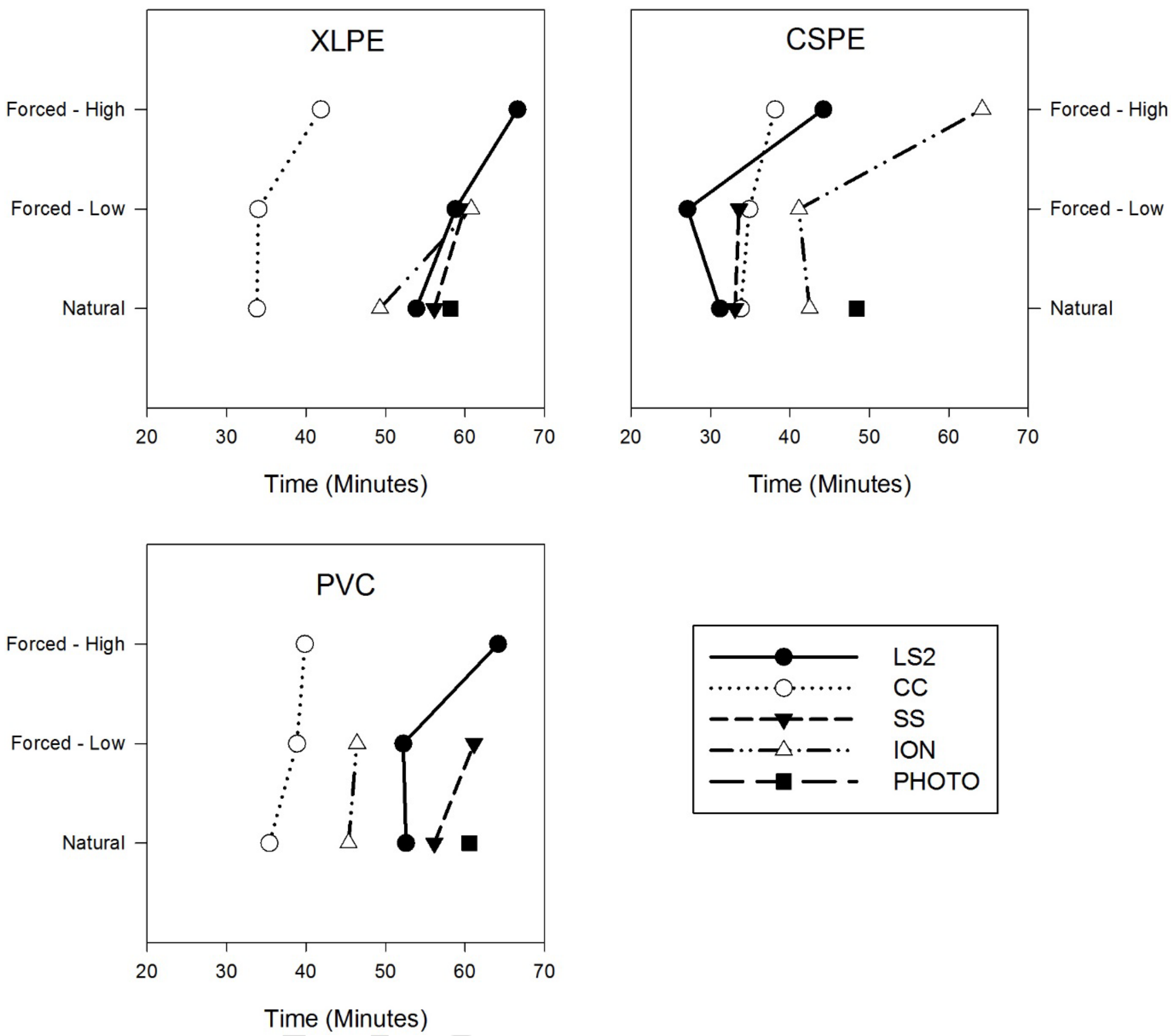


Figure 5-54. Effect of cabinet ventilation on in-cabinet detector response

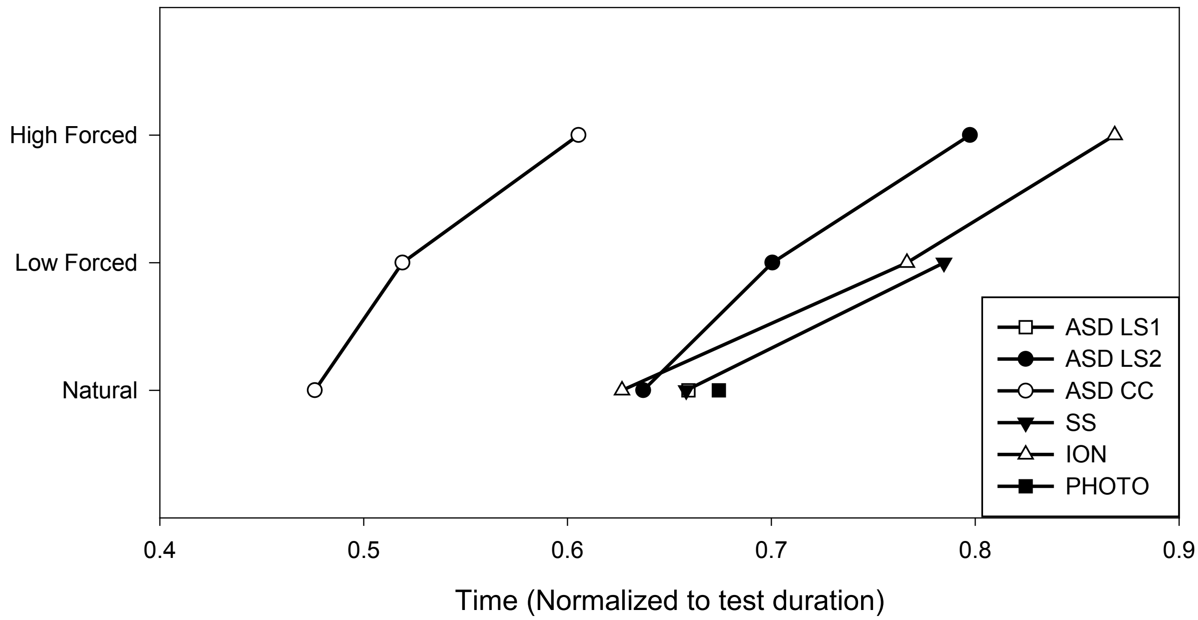


Figure 5-55. Effect of cabinet ventilation on in-cabinet detector response for all materials and all HRPs.

5.9.4 Effectiveness of in-cabinet and area-wide 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) stage 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 area-wide 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 mean 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). The data showed a large difference between the two cases, with regard to system effectiveness. 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 cases. Further evaluation of the differences between cabinet design and testing conditions identified several parameters that are likely influencing these results. Photographs and descriptions of these cabinet configurations are shown in Sections 4.4.2 and 4.4.3.

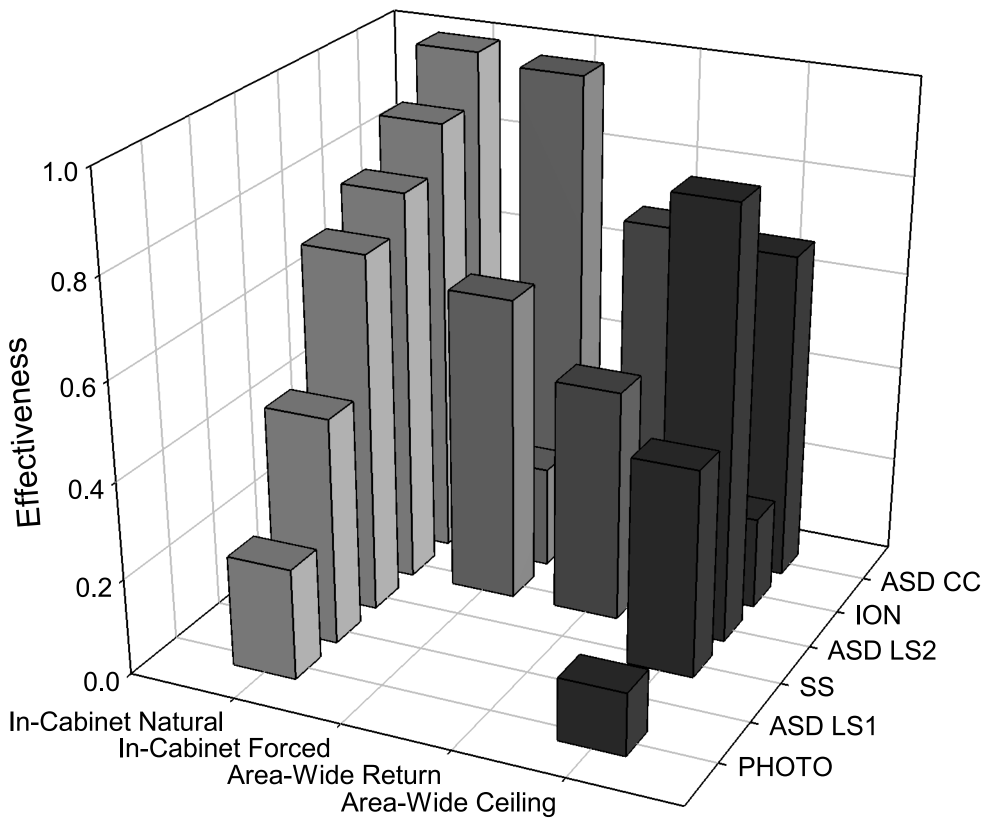


Figure 5-56. System effectiveness by detector and application (Note: no data for ION area-wide return)

<u>Cabinet Design Influence</u>
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 ability 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.

<u>Ventilation rate</u>
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 360 cabinet air changes per hour. The results indicated that, in general, as the ventilation rate increased, the effectiveness of any smoke detector technology in detecting the incipient source decreased and the time to detection increase. For light scattering ASDs VEWFD systems and SS detectors, the low flow rate data indicates a slight improvement in detector effectiveness compared to the naturally ventilated case. 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 7-5. These estimates support the risk scoping study presented in Part II. The system effectiveness estimates are all based on test data from this program.

5.9.5 Area-wide 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.

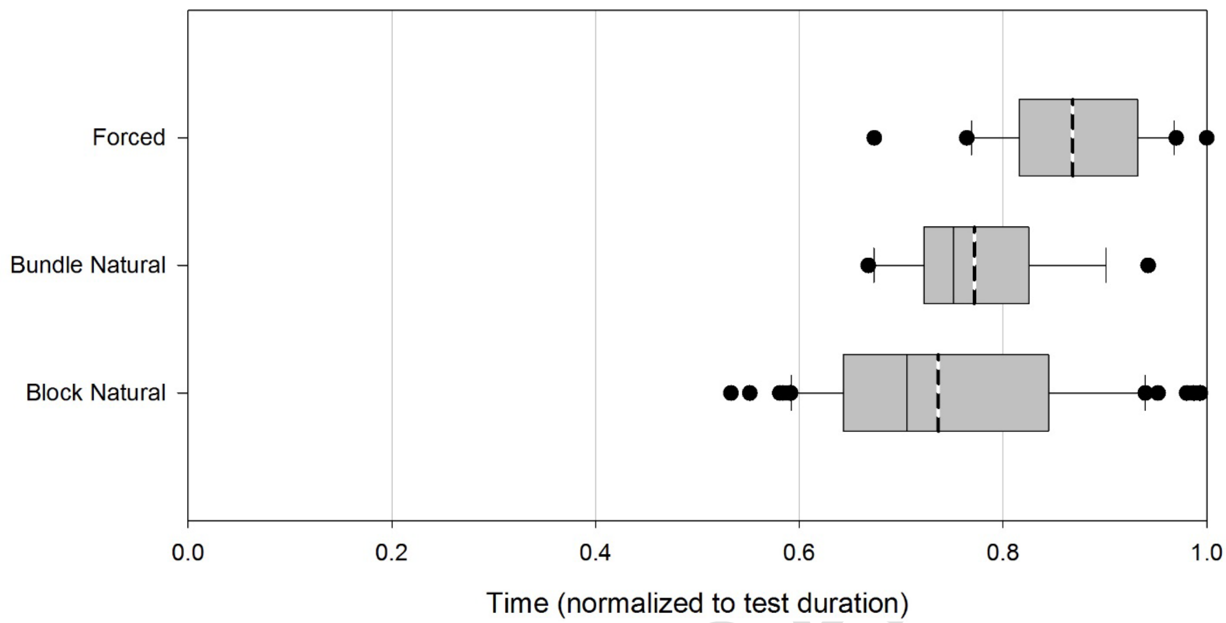


Figure 5-57. ASD time to detect area-wide ceiling configurations

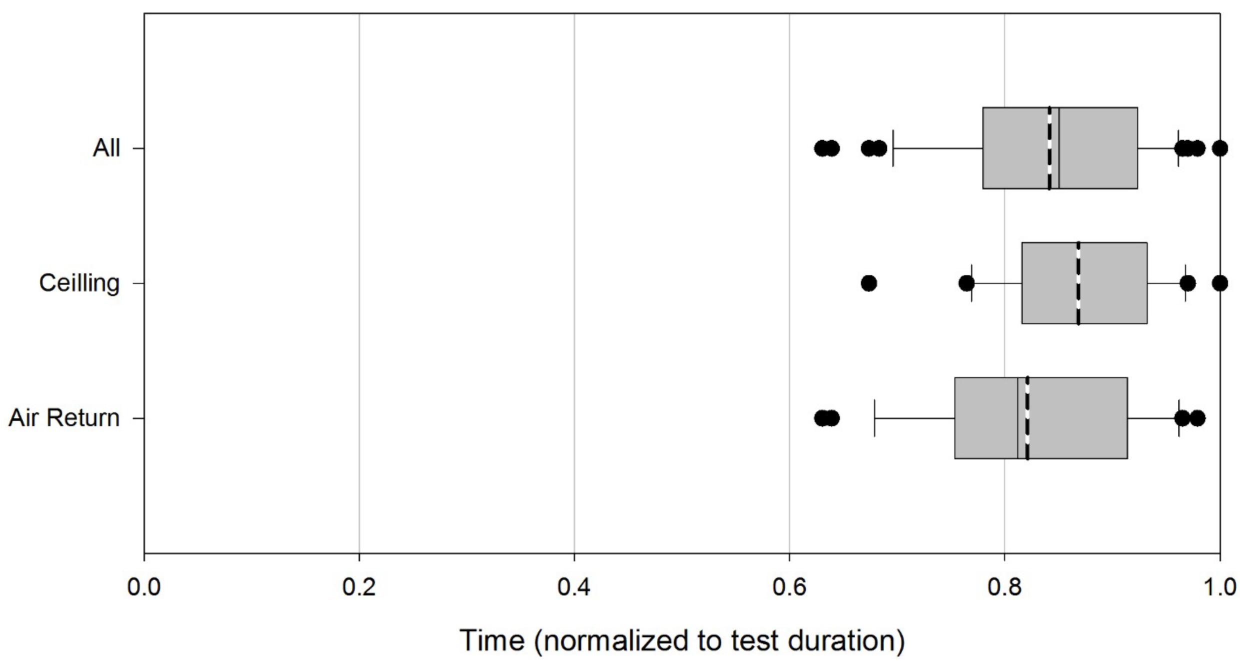


Figure 5-58. ASD time to detect area-wide forced ventilation air return and ceiling pooled

The last comparison of the area-wide 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 area-wide application is better at detecting the bundle source.

5.9.6 ASD comparison: In-cabinet versus area-wide

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.

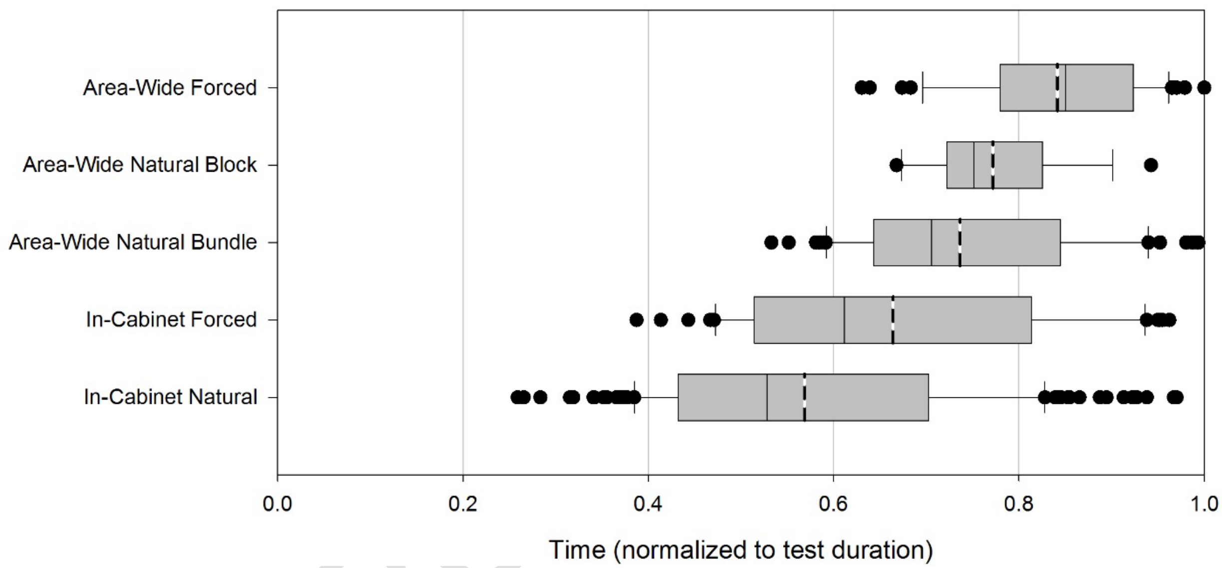


Figure 5-59.   ASD time to detect low-energy incipient sources

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 approach 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 and develop risk insights. 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:

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

Where λ_i Frequency of fire scenario i

$P_{ed,j|i}$ Conditional probability of damage to critical equipment set (“target set”) j given 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

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 probability of equipment damage is decomposed into two parts:

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

Where $SF_{j|i}$ severity factor for damage to target set j given fire source i

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

6.1.1 Application of VEWFD System Probability of Non-Suppression: P_{ns}

Specific care must be taken when applying the probability of non-suppression (P_{ns}) for very early warning fire detection (VEWFD) systems. The probability of non-suppression is only applicable to target damage sets located outside of the electrical cabinet. That is, the VEWFD system **ONLY** affects the adverse consequences related to cabinet fires resulting in fire growth outside the initiating electrical cabinet which could damage secondary combustibles and targets. The fire ignition source is assumed to be damaged given any fire involving itself as the source. The probability of non-suppression represents the probabilistic outcome that the fire will damage critical secondary equipment before some means of fire suppression can be achieved. As a result, the analyst should characterize both the initial fire source and those combustible materials to which the fire might spread.

When a fire scenario contains several target sets, the scenario CDF equation can be written as follows, where the quantities in the square brackets represent the target set (j) contributions:

$$CDF_i = \lambda_i \times \left[\sum_j SF_{j|i} \times P_{ns,j|i} \left(\sum_k p_{CD,k|i,j} \right) \right]$$

Where

λ_i	Frequency of fire scenario i
$SF_{j\|i}$	severity factor for fire scenario i
$P_{ns,j\|i}$	probability of non-suppression before damage to enclosure *(target j)* given 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 scenario targets sets (j) can be within the electrical enclosure and external to the electrical enclosure.

<u>Target sets within initiating electrical enclosure:</u>

Under a suppression strategy $P_{ns,j|i}$ is assumed to be 1. This is done due to the difficulty in assessing the likelihood of successful prevention. This approach is intended to take credit for the fire suppression capability and assumes that the cabinet will be damaged. To be effective, the licensee needs to establish procedures that require appropriately trained personnel to be in place until the problem has been successfully resolved. Success in this approach is ultimately judged based on the ability to suppress the fire rather than prevent it.

Under a de-energization strategy, the suppression event trees presented in Section 6.4 could be modified as illustrated in Figure 6-6 to estimate $P_{ns,j|i}$. A de-energization strategy is considered one in which the end state is achieved by removing power from the affected cabinet (or part of the cabinet) and repairing the degraded component (i.e., this is a prevention strategy/approach). Section 9.2 provides a generic description of a tabletop analysis performed for a de-energization strategy. Section 10.6.4 provides human failure event quantification items for a de-energization strategy that should be considered when performing the detailed human reliability analysis (Section 10) to support a scenario-specific de-energization approach and quantification of scenario-specific human error probabilities. Fire scenario and human response information,

including timing and feasibility analysis, would be needed to support estimation of the human error probabilities via a detailed Human Reliability Analysis. Pre-planning the steps to de-energize the cabinets would be needed to ensure power is removed in a timely manner thus insuring the prevention of flaming conditions. The estimates developed in Section 10 and 11 are for suppression capability only and as such do not apply to a de-energization strategy, which requires detailed scenario-specific information. The process outlined in Section 10, for suppression capability, could be modified with alternative timing assumptions to quantify the parameter $\xi_{de\text{-}ss}$. Using the parameter $\xi_{de\text{-}ss}$, it is possible to quantify the modified in-cabinet event tree for a de-energizations strategy, as shown in Figure 6-6. In the de-energization strategy the initiating enclosure term $P_{ns,j|i}$ is calculated as the summation of all "*cabinet damage*" and "*fire damage outside cabinet*" end states as illustrated in Figure 6-6.

<u>Target sets external to the initiating electrical enclosure:</u>

Under a suppression strategy, $P_{ns,j|i}$ is calculated as the summation of all "*fire damage outside cabinet*" end states as illustrated in the in-cabinet event tree (Figure 6-4) or the area-wide event tree (Figure 6-5) depending on the scenario application. This approach is intended to take credit for the fire suppression capability and assumes that the cabinet will be damaged. To be effective, the licensee needs to establish procedures that require appropriately trained personnel to be in place until the problem has been successfully resolved. Success in this approach is ultimately judged based on the ability to suppress the fire rather than prevent it.

Under a de-energization strategy, $P_{ns,j|i}$ is calculated as the summation of all "*fire damage outside cabinet*" end states as illustrated in Figure 6-6.

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.

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

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 maximum reduction of 0.39 from the non-suppression probability, excluding the timing contributions from the t_{dam} and t_{det}.

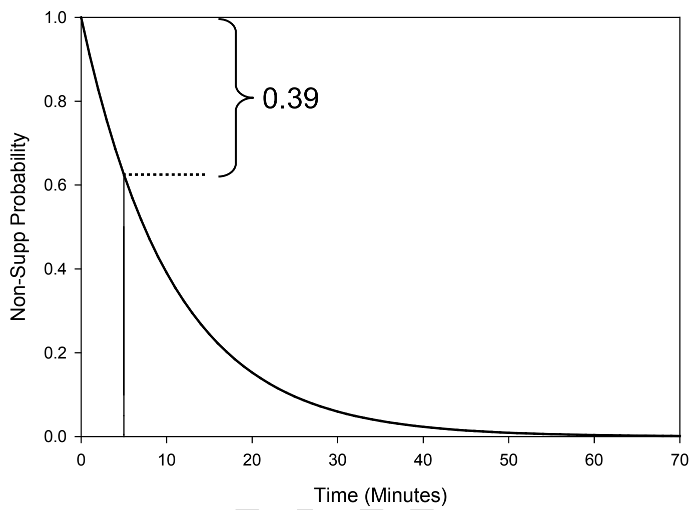


Figure 6-1. Electrical fires suppression curve showing 5 minute in-cabinet detection reduction

The NUREG/CR-6850 (EPRI 1011989) approach does not 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 $T_{fb\text{-}s}$ and $T_{fb\text{-}t}$ 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.

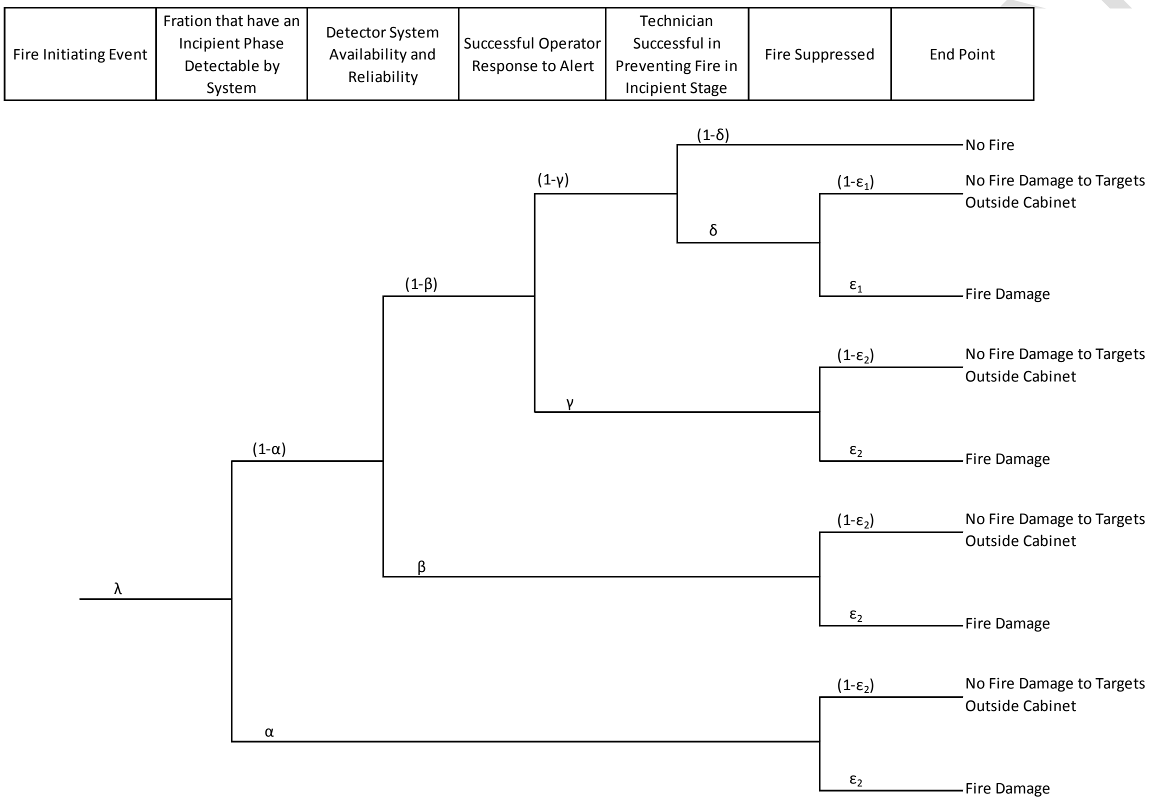


Figure 6-2. FAQ 08-0046 proposed event tree for assessing fire risk for installed VEWFDS in-cabinet

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 parameter's (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 ($1-\lambda$), the personnel staged at the cabinet associated with the ASD VEWFD system 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.

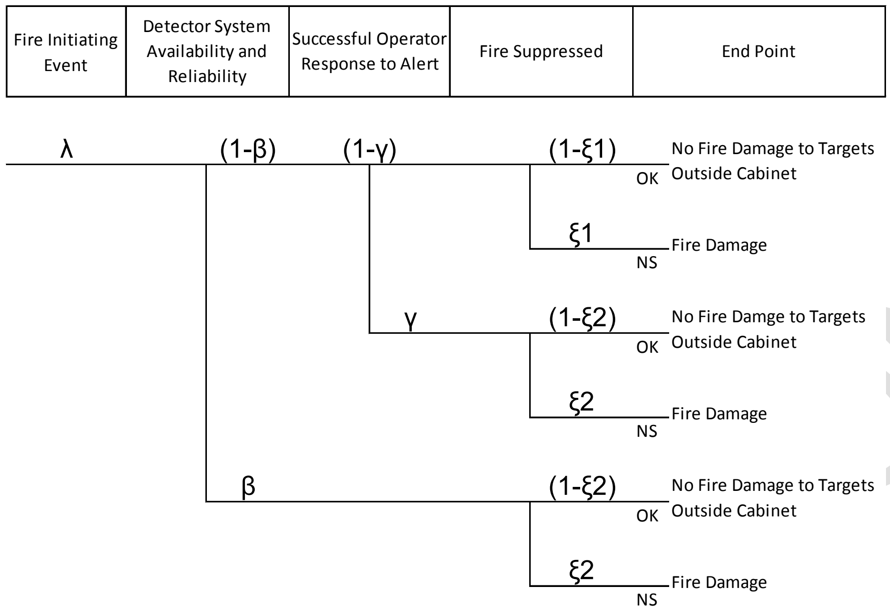


Figure 6-3. FAQ 08-0046 simplified event tree for assessing fire risk for installed VEWFDS in-cabinet

6.3 Approaches to Quantifying Smoke Detection Performance

There are several methods that could be applied to evaluate the non-suppression conditional probability estimate associated with smoke detection systems. Examples include simulation, decision trees, and expert judgment. Some past quantification efforts[1] have used event trees to quantify risk reductions. 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). Typically, event trees are used to evaluate different end states (e.g., fire causes damage to 1. initiating component, 2. secondary targets, 3. room, etc.) and the risk reduction of any detection or suppression system.

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 area-wide type applications. The event trees presented in Figure 6-4 and Figure 6-5 provide a structure to estimate the non-

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

suppression probability for fire scenarios where smoke detection systems are used to protect electrical cabinet ignition sources. Figure 6-6 provides an illustration of how the event tree could be modified to credit a de-energization strategy. However, use of the de-energization event tree requires scenario-specific information and as such, cannot be performed under a generic approach. As such the HEP probabilities developed in Section 10 of this report do not apply to the de-energization event tree shown in Figure 6-6.

The non-suppression probability event trees (Figures 6-4 and 6-5) have two end states (1) cabinet damage and (2) fire damage outside cabinet. These end states are defined as follows:

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, “Detector System Availability, Reliability” quantifies the systems operational performance (Section 7.2). 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 event, “Fractions that have an incipient phase” separates events that exhibit rapidly developing fires from those that exhibit longer incipient stages (Section 7.1). The next branch “Effectiveness,” evaluates the system’s ability to detect low-energy (pre-flaming) fires for a specific installed application (Section 7.2). 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 (Section 10.6). 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 (Section 10.6). Success in the enhanced suppression event represents the probability that any potential fire is suppressed before fire damage to targets of concern (Section 11.1). The last event “Conventional Detection/Suppression” estimates the probability of successfully suppressing a fire given a failure of one of the earlier events (Section 11.2). To estimate the success of these branches, the suppression/detection event tree from NUREG/CR-6850 (EPRI 1011989) can be solved.

A Microsoft Excel® based tool has been developed and included with this report to support a consistent and automated process for solving the event trees presented in Figures 6-4 and 6-5. Appendix H to this report provides a user guide for these VEWFD event tree non-suppression probability calculation tools.

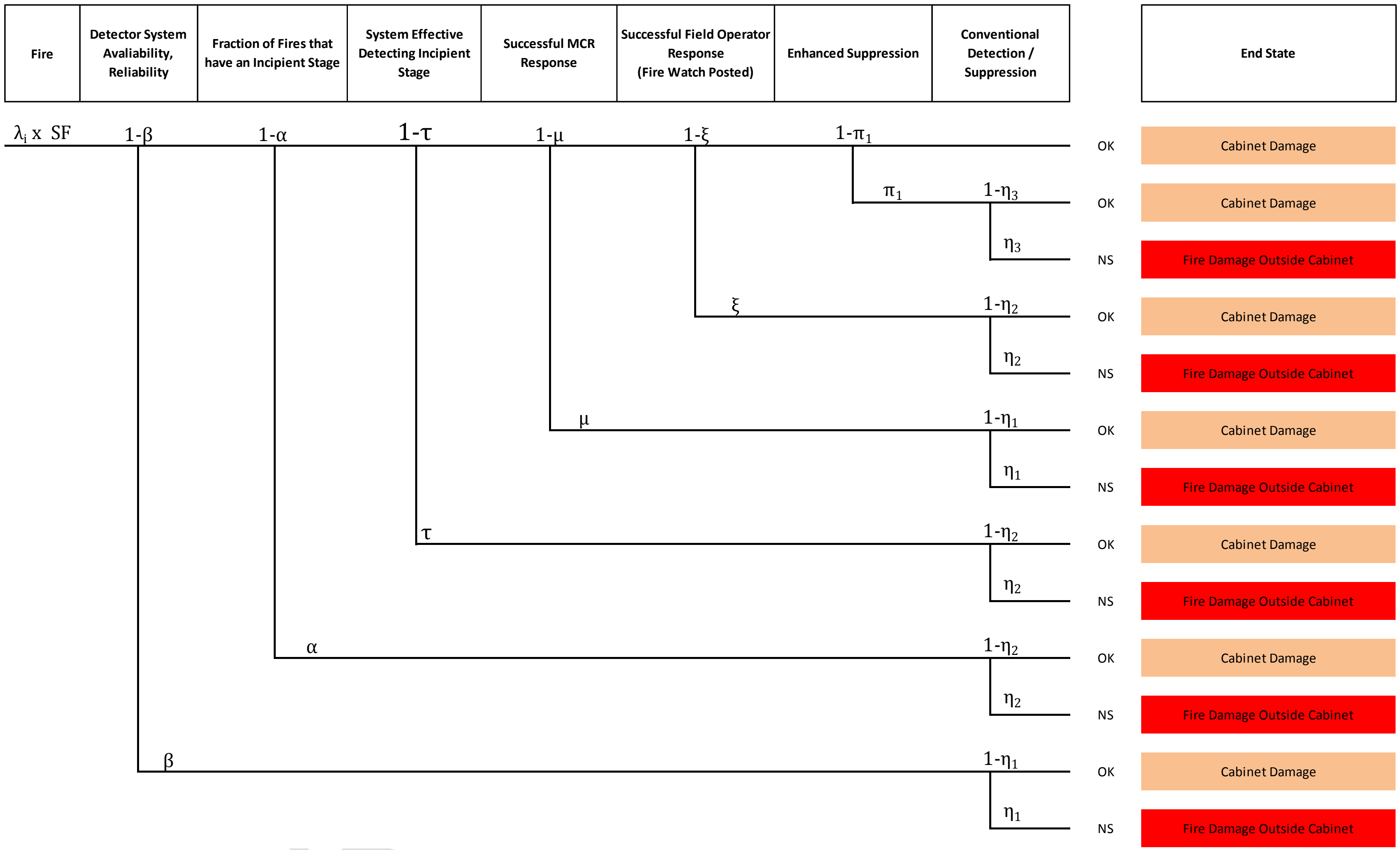


Figure 6-4. Basic event tree for in-cabinet smoke detection non-suppression probability estimation

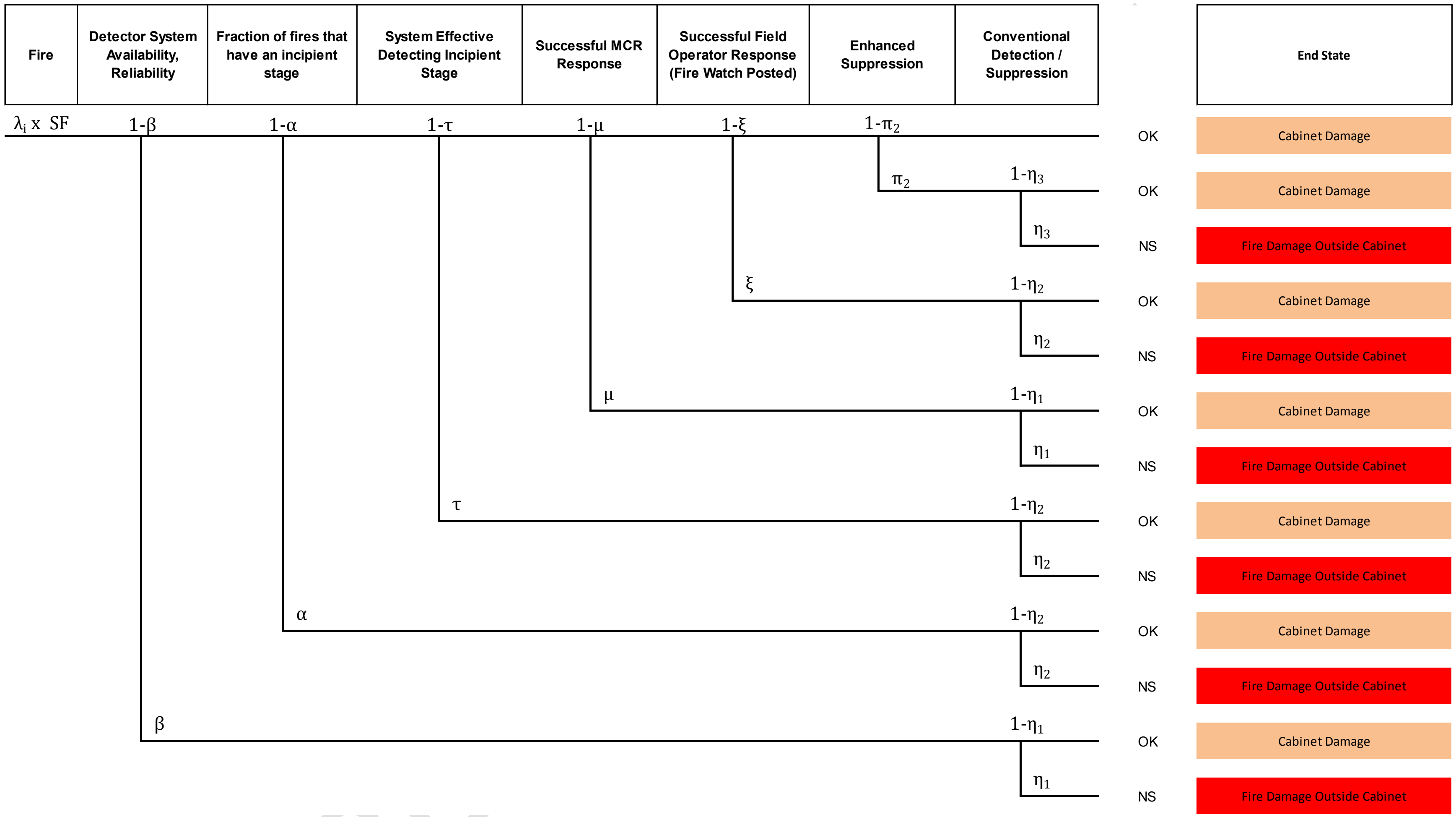


Figure 6-5. Basic event tree for area-wide smoke detection non-suppression probability estimation

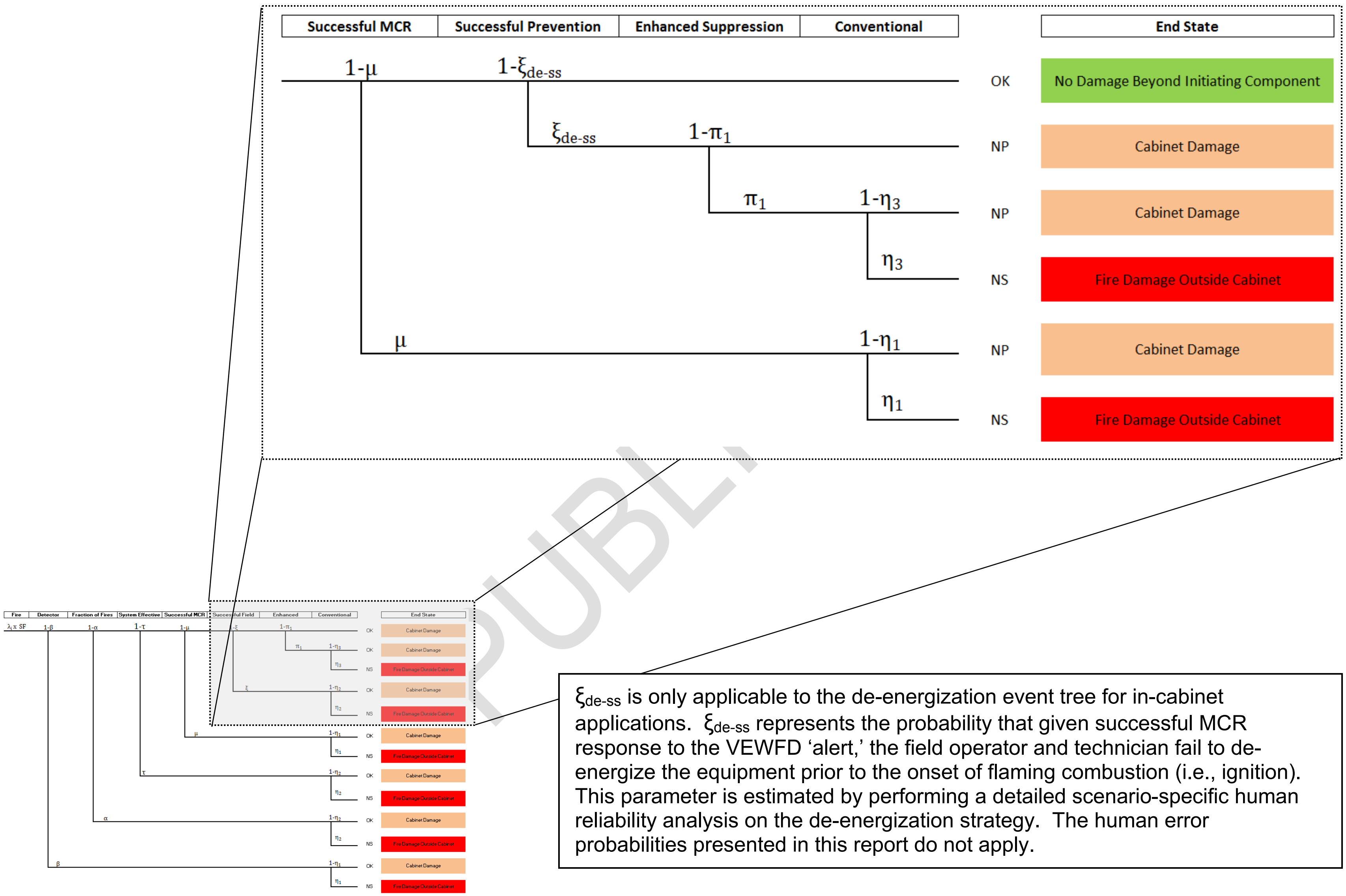


Figure 6-6. Illustration of change to in-cabinet event tree for de-energization strategy

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.*[1] The failure branch of this event is represented "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[2] that occur in a nuclear power plant (NPP) and are considered *potentially challenging or greater fires* have an incipient stage (Ref. 37). *Potentially challenging 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

---

1 The basis for the 30 minutes criterion is presented later in this section.
2 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. The results are based on the independent review of events by two NRC staff members. 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. The process involved developing ground rules and definitions to support the classification (discussed below). Next the reviewers independently reviewed and classified the events per the definitions. Following the initial review, the staff members compared their classifications and discussed events where their classifications differed. Based on this discussion the reviewers may or may not have changed their classification. There was not attempt to force a consensus. In addition, the classification made by these two staff members, the events classified as low-voltage control cases were studied by NRR staff and thoroughly discussed until agreement was achieved and prior to the issuance of the draft version of this report in July 2015.

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 does not 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 does not provide direct information regarding the time frame for component degradation but can be inferred from other information presented.

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

A nominal <u>minimum threshold of 30 minutes</u> should be used to classify as being of "sufficient duration." The 30 minute threshold is based on an assumed maximum 15 minute response time for plant personnel to arrive at the scene and the test data that shows detector response typically occurring half-way through the test duration (assuming test duration represents incipient stage duration). A 30 minute incipient stage duration represents a detector response at approximately 15 minutes ($^1/_2$ of incipient stage (test) duration) and a maximum assumed operator response of 15 minutes.

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. This 30 minute threshold is not intended to indicate that fires only exhibit incipient stages that are greater than 30 minutes, but to model the fraction of fires that do have a shorter incipient stage and would be more difficult for an operator to respond to the ignition source prior to flaming conditions. Lastly, this 30 minute quantity is used for screening events into categories to support quantification of the "fraction of fires that have an incipient stage," and does not, nor should it be used to quantify the actual incipient stage duration as discussed in Section 11 of this report.

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 brackets. These estimates are calculated excluding the "Undetermined" category and using a Jeffery's non-informed method to estimate the uncertainty.

The two bins presented in Table 7-1 represent a demarcation in the fundamental assumption that voltage is an influencing parameter in the duration of the incipient. Stated differently, an assumption is being made that higher voltage equipment such as medium voltage switchgear are more likely to experience a short incipient stage than a low voltage control cabinet. The results presented in Table 7-1 tend to confirm this belief. For instance, the power cabinet class of equipment tend to have a 50% chance of experience an incipient stage of sufficient duration to support early intervention. While the low voltage control cabinets have a higher likelihood of experiencing an incipient stage of sufficient duration. The footnote to Table 7-1 provides examples of the types of equipment that is intended to be classified as "Power Cabinets." The "low voltage control cabinets" classification is intended to cover those cabinets that only have

low voltage control equipment of voltages less than 250V. For equipment that has both power and low voltage control components, such as a motor control center, that equipment should be classified as power cabinets for this evaluation.

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	**0.28** [0.08 / 0.54]

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

This current methodology differs from that provided in FAQ 08-0046. No visible inspection of “low voltage” cabinets needs to be performed to take credit for the provided alpha factor. The presence of fast-acting components such as electrical/electronic circuit boards that contain electrolytic capacitors, chart recorder drives, cooling fan motors, mechanical timers driven by electric motors, etc. was incorporated into the underlying analysis and creation of the alpha factor. The lack of these types of components was not seen to influence the tendency for fast acting fires to occur.

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 fast 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 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 do not adequately represent the failure modes and associated duration 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)

This section quantifies the smoke detection system performance measures of availability, reliability, and effectiveness; system effectiveness (τ) is represented separately. The parameter "β" represents the combined unavailability and unreliability of a smoke detection system to perform its intended design function. The success branch (1-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 should also be explained or justified and included in the unreliability/unavailability estimate.

7.2.1 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. The surveillance test interval is assumed to be semi-annual (4380 hours).

Germany NPPs
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 9.86×10^{-4} based on a semi-annual surveillance.

U.S. NPPs
U.S. NPP unreliability estimates are based on information collected during the site visits (see Sections 3.1, Table 7-3, and Appendix C.1) and information obtained from the EPRI report 1016735. Information on 181 system years shows four system failures. This results in a mean failure rate of 2.84×10^{-6}/hr, with 5^{th} and 95^{th} percentiles of 1.05×10^{-6}/hr and 5.34×10^{-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]

3.5 failures per million hours

4×10^{-6} mean

Unreliability of 8.76×10^{-3}

b. Per UL268 full parts 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 is shown in Table 7-2,of 1.6×10^{-3} is estimated based on a semi-annual surveillance period (4,380 hours) and equal weighting of these three sources of data. The 5th and 95th percentiles are 9.7×10^{-4}, 2.3×10^{-3}, respectively.[4] This generic estimate was developed using a multi-stage Bayesian update using all three data sets. Note that this is a generic estimate. Site (or fleet) specific data could be used to develop and justify site specific unreliability estimates.

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.

Table 7-2. Generic ASD Unreliability Estimate per detector per year

Parameter	Mean	5th percentile	95th percentile
ASD Unreliability	1.6×10^{-3}	9.7×10^{-4}	2.3×10^{-3}

[3] UL 268 simplified part count estimates are not used in the generic unreliability estimates developed below as the full part stress analysis provides a bounding estimate. A sensitivity showed that the difference was on the order of 5×10^{-5}, almost two orders of magnitude below the generic estimate.

[4] Mean expected failure rate of 7.2×10^{-7}, modeled as a gamma distribution with alpha = 15, beta = $20.9\times10^{+6}$ hours

Table 7-3. 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 6-8hrs/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

7.2.2 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:

$$U = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

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

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. With a limited set of data, a frequentist summary approach was taken to estimate the unavailability. This approach is described in NUREG/CR-6823, "Handbook of Parameter Estimation for Probabilistic Risk Assessment," in Section 6.7.2.2. Following this approach, a generic unavailability is shown in Table 7-4. A plant-specific (or fleet-specific) unavailability estimate could be used instead of this generic estimate, if sufficient data is available to support/justify such an estimate.

Table 7-4. Generic ASD Unavailability Estimate per Detector per Year

Parameter	Mean	5th percentile	95th percentile
ASD Unavailability	2.0×10^{-3}	3.0×10^{-4}	3.7×10^{-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.

7.2.3 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 area-wide 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) modeled as a binomial. 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 7-5. The specific datasets used to develop these estimates are identified in Table 7-6. As an example, for the ION Spot type detector within a naturally ventilated cabinet, the data indicates 145 alarms out of 162 trials. The mean effectiveness is calculated as a beta distribution, with:

$$\alpha = 145 + 0.5 = 145.5$$
$$\beta = 162 - 145 + 0.5 = 17.5$$
$$\tau_{mean} = 1 - (\alpha/(\alpha + \beta)) = 1 - (145.5/(145.5 + 17.5)) = 0.1$$

Table 7-5. ASD VEWFD System In-Effectiveness Estimates Based on Test Data

Application	Cabinet/Room Ventilation	Detector Type	Mean (τ) [5th/95th percentile]
In-Cabinet	Natural and Forced <100 cabinet ACH	ION Spot	**1.0×10^{-1}** [6.8×10^{-2} / 1.4×10^{-1}]
		PHOTO Spot	**7.7×10^{-1}** [7.1×10^{-1} / 8.3×10^{-1}]
		SS	**2.6×10^{-1}** [2.1×10^{-1} / 3.2×10^{-1}]
		ASD CC	**2.7×10^{-3}** [1.1×10^{-5} / 1.0×10^{-2}]
		ASD LS1	**5.3×10^{-1}** [4.5×10^{-1} / 6.5×10^{-1}]
		ASD LS2	**1.9×10^{-1}** [1.4×10^{-1} / 2.4×10^{-1}]
	Forced ≥100 cabinet ACH	ION Spot	**7.9×10^{-1}** [6.5×10^{-1} / 9.0×10^{-1}]
		PHOTO Spot	No Data
		SS	No Data
		ASD CC	**1.9×10^{-2}** [7.8×10^{-5} / 7.3×10^{-2}]
		ASD LS1	No Data
		ASD LS2	**3.7×10^{-1}** [2.2×10^{-1} / 5.2×10^{-1}]

Table 7-5. ASD VEWFD System In-Effectiveness Estimates Based on Test Data (Continued)

Application	Cabinet/Room Ventilation	Detector Type	**Mean (τ)** [5th/95th percentile]
Area-wide, Air Return Grill	HVAC in room	ASD CC	**3.0×10^{-1}** [1.7×10^{-1} / 4.5×10^{-1}]
		ASD LS2	**5.2×10^{-1}** [3.6×10^{-1} / 6.7×10^{-1}]
Area-wide, Ceiling	Any	ION Spot	**8.1×10^{-1}** [7.3×10^{-1} / 8.9×10^{-1}]
		PHOTO Spot	**8.7×10^{-1}** [8.0×10^{-1} / 9.3×10^{-1}]
		SS	**5.7×10^{-1}** [4.7×10^{-1} / 6.7×10^{-1}]
		ASD CC	**3.2×10^{-1}** [2.3×10^{-1} / 4.2×10^{-1}]
		ASD LS2	**1.1×10^{-1}** [4.6×10^{-2} / 1.8×10^{-1}]

Table 7-6. Identification of Datasets Used To Estimate the System In-Effectivness Estimates (See Table 7-3)

	In-Cabinet		**Area-wide**	
	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 7-6. Identification of Datasets Used To Estimate the System In-Effectivness Estimates (See Table 7-3)

	In-Cabinet		Area-wide	
	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

7.2.3.1 Estimating "in-effectiveness" when system sensitivity differs from that reported here

All of the detectors evaluated in this test program have the capability to be configured to a range of sensitivity settings. Most ASD VEWFD systems are capable of being configured with multiple alarm settings (three to five for the systems tested). The data analyzed above to develop the "in-effectiveness" estimates (Table 7-5) were based on either the 'alert' sensitivity of National Fire Protection Association (NPFA) 76 (i.e, 0.20 percent obscuration/ft. at the sampling port above background) or from a range of particle count per unit volume sensitivities for the cloud chamber technology.

In actual applications there may be a desire to configure the VEWFD system either more or less sensitive than reported here. If actual system sensitivity differs from those used here, the "in-effectiveness" parameter should be estimated using data applicable to that sensitivity. Since data for multiple sensitivity settings were recorded as part of this testing program, the data included here could potentially be used to support such an analysis. However, if the data collected as part of this research do not support the sensitivities used in actual plant application, then additional data may be required to support parameter estimation. In addition, because the focus of this research was to evaluate VEWFD systems that met the minimum sensitivity requirements of NFPA 76, less data is available at other sensitivities. As such, limited data will broaden the uncertainty of the parameter estimate. Good engineering practice would suggest conducting a sensitivity analysis with the development of any new parameter. Appendix B describes the process to follow to estimate a detector in-effectiveness (τ) parameter for VEWFD detection systems configured to "alert" sampling port sensitivities other those reported in Section 5.

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 within the electrical enclosure 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.

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

- Estimate of incipient stage duration for electrical enclosure equipment
  - Results are presented in Section 8.2

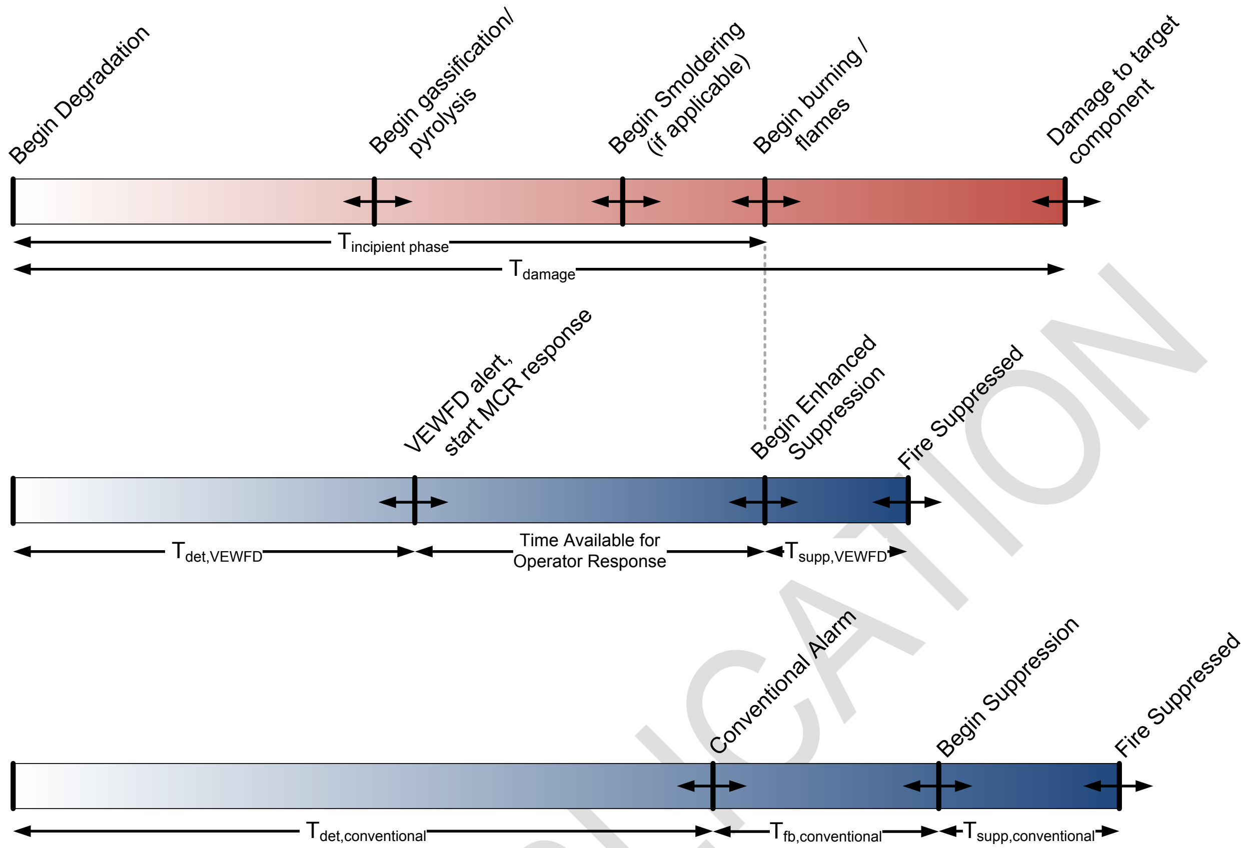


Figure 8-1. Generic fire scenario event timeline. Fire scenario progression (top), VEWFD/operator response (center), conventional smoke detection/operator response (bottom). Illustration only—event markers may not be indicative of actual system response

At some point following flaming combustion 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. For information on modeling electrical enclosure fire hazards can be found in NUREG-2178, “Refining and Characterizing Heat Release Rates from Electrical Enclosures During Fire (RACHELLE-FIRE).”

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 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 in the range of auto-ignition and 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 VEWFD system test results showing an example of the normalized time for in-cabinet VEWFD system response with an “alert.” Statistical *K-S* tests were run between the groups (test durations) 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. The results presented in Figure 8-2, provide a generalized representation of the response of ASD VEWFD systems used for in-cabinet applications. The mean for individual detectors are used to support development of an estimate of time availability for operator response as discussed in the next section. A similar approach is used for the conventional system evaluation. If detector sensitivities other than those discussed in Section 7.2.3.1 are used in actual plant applications, additional data and analysis will be required to develop a normalized mean time to detection, which is used to estimate the time available curves (Section 8.1.2). A description of the process to develop time available curves for systems using different sensitivities is presented in Appendix B and D. These curves (see Figure 8-4) are used in Section 10 to estimate a human error probability (HEP) for the field operator response. The process used here is summarized in Appendix D.

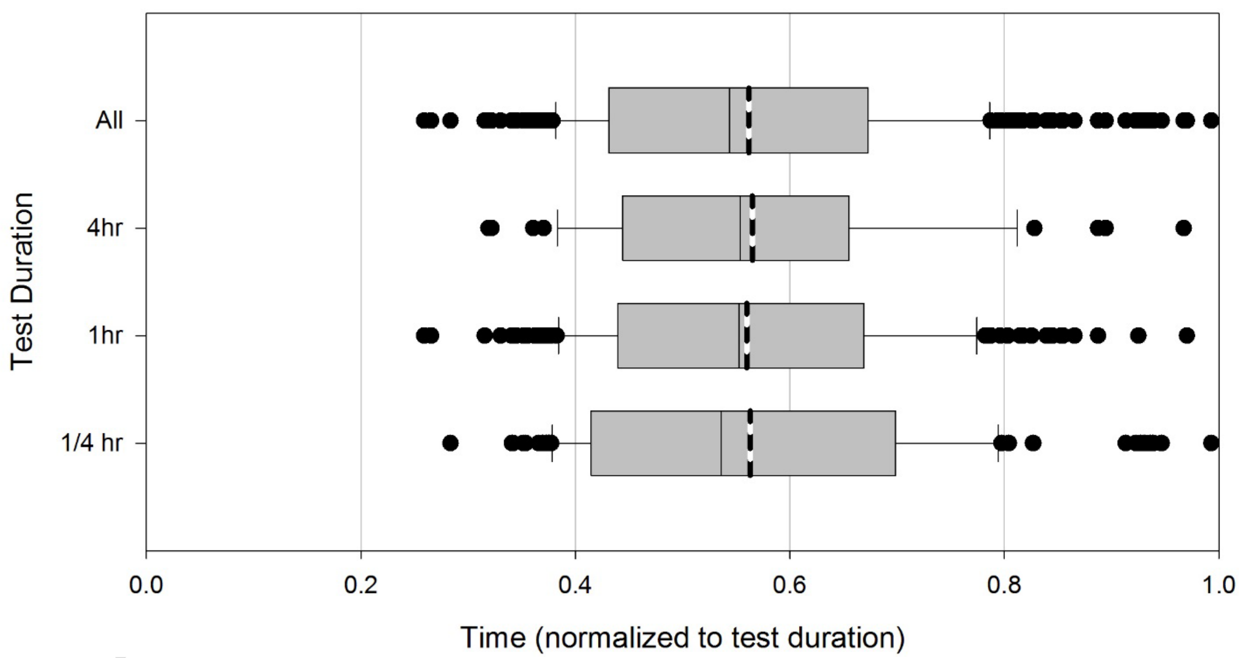


Figure 8-2. Summary of ASD VEWFD in-cabinet test results showing normalized time of alert (box and whisker plot shows 10th, 25th, 50th (median), 75th, and 90th percentiles with outliers shows as dots, mean shown as dashed line)

8.2 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 affect 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 anything 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 generates smoke, 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. It must allow plant personnel sufficient time to locate and suppress the fire before damage to external targets occur. 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 (or 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 or community 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. The events reviewed included those events contained in the recently updated fire events database (Ref. 45, 46), along with more recent operating experience obtained from LERs and presentations made at NEI fire protection information forums.

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, exponential, or other 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. It should be noted that the incipient stage duration and time available for operators response differ as shown in Figure 8-3. In using the operating experience to inform a time available curve, the mean time to detection for the systems tested is used. This information, along with the VEWFD system performance as presented above, allows for the development of distributions representing the time available for operators to respond as shown in Figure 8-4. This time available 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.

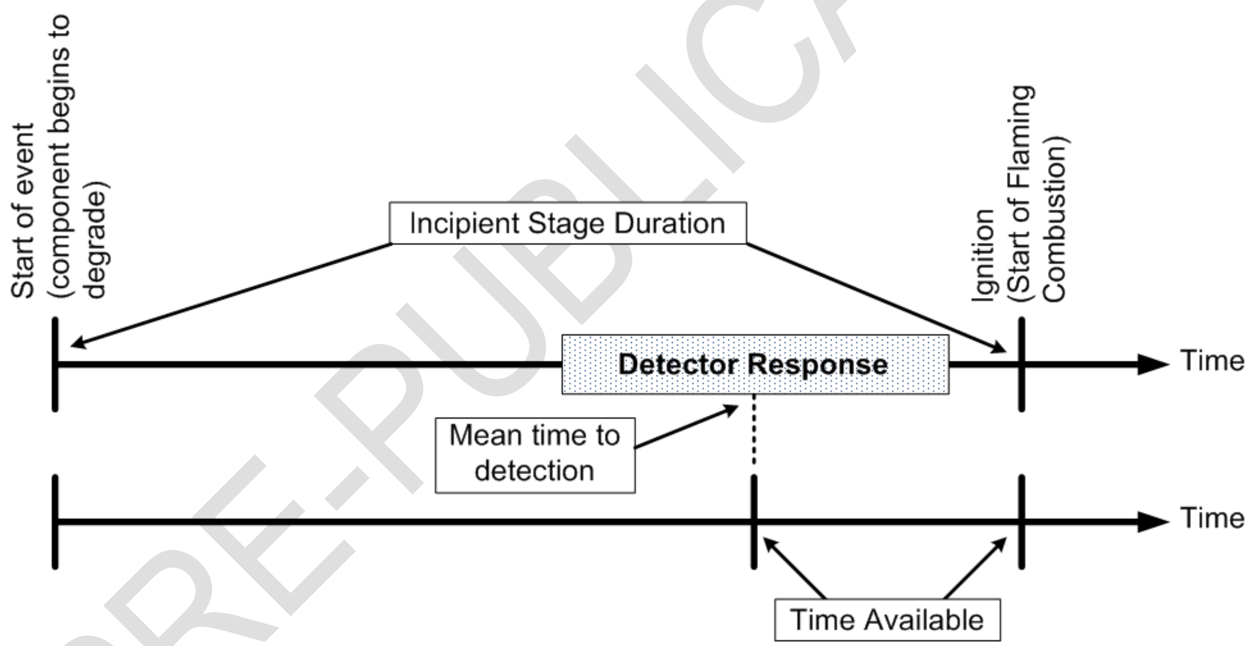


Figure 8-3. Illustration of difference between incipient stage and time available.

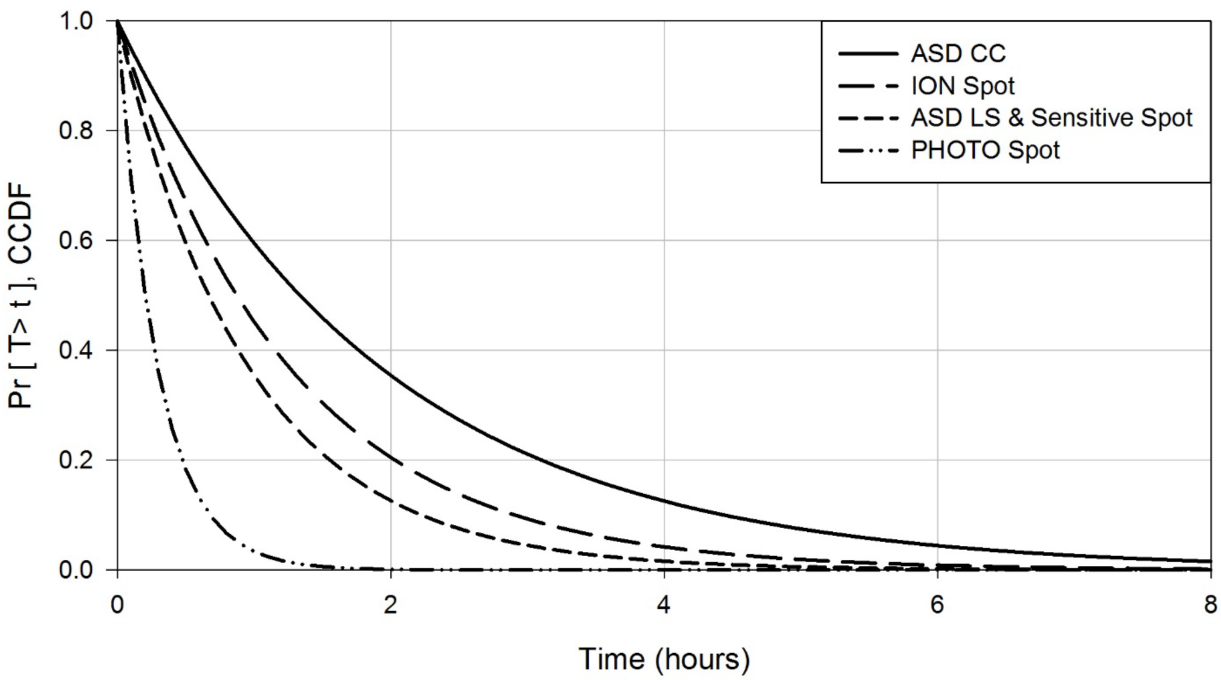


Figure 8-4. Distribution for duration of time available for plant personnel to respond to VEWFD system “alert” or conventional “alarm” notification of incipient fire conditions, for those fires, which exhibit an incipient stage for in-cabinet applications

Figure 8-4 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 modified based on system response test data. 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, the actual incipient duration could be shorter in duration than used here. 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. In the draft report, the interim staff position estimate of “at least one hour of warning” was used, since this value was presented in both industry and NRC documents, it could be viewed as somewhat of a consensus opinion.

Because of public comments, the authors reconsidered the applicability of using this estimate. 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 use of this estimate does not support a consistent treatment of smoke detector performance for low-energy fires. As such, the 1-hour estimate has been removed and the distributions recreated in this final report. With its removal, the lambda parameter for the exponential distributions changed less than 5 percent for all distributions. However, an additional event occurring at Shearon Harris in August of 2015 was also provided as part of the set of comment received on the draft report. The authors reviewed this event and ended up including it to update the time available distributions. This event is described in detail in Appendix D. Accordingly, the information in Appendix D and Section 10 have been updated in this final report to reflect this change.

These distributions are developed to support human error probability quantification (see Section 10.4) 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 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 provided. 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 <u>Information Gathering</u>

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[1] 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

[1] 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[2] and the other provided responses via teleconference. The following departments were represented on the teleconference:[3]

- 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
4. Site Visit
    - o trip to a licensee currently using ASD VEWFD system to follow-up on recent operational experience
        - discussions and tour focused on the event and the subsequent response

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 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.

[2] Positions and titles of the personnel that contributed to the written responses were not provided.

[3] 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[4] 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 location of the VEWFD in "alert" and positioned in close proximity to the specific affected cabinet, thus, ensuring 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) the fire brigade. MCR operators are responsible for detecting an alert, using the correct alarm response procedure (ARP), dispatching personnel to the alert location, monitoring the situation from the MCR during the field investigation and, on alarm, activating the fire brigade. The field operator is responsible for serving as the initial fire watch (with suppression capabilities) and maintaining communications with the control room. The technician is responsible for gathering necessary equipment, traveling to the fire location, unlocking and opening cabinets, 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.

[4] The scope of the analysis was determined by the information required to support the HRA (discussed in Section 10).

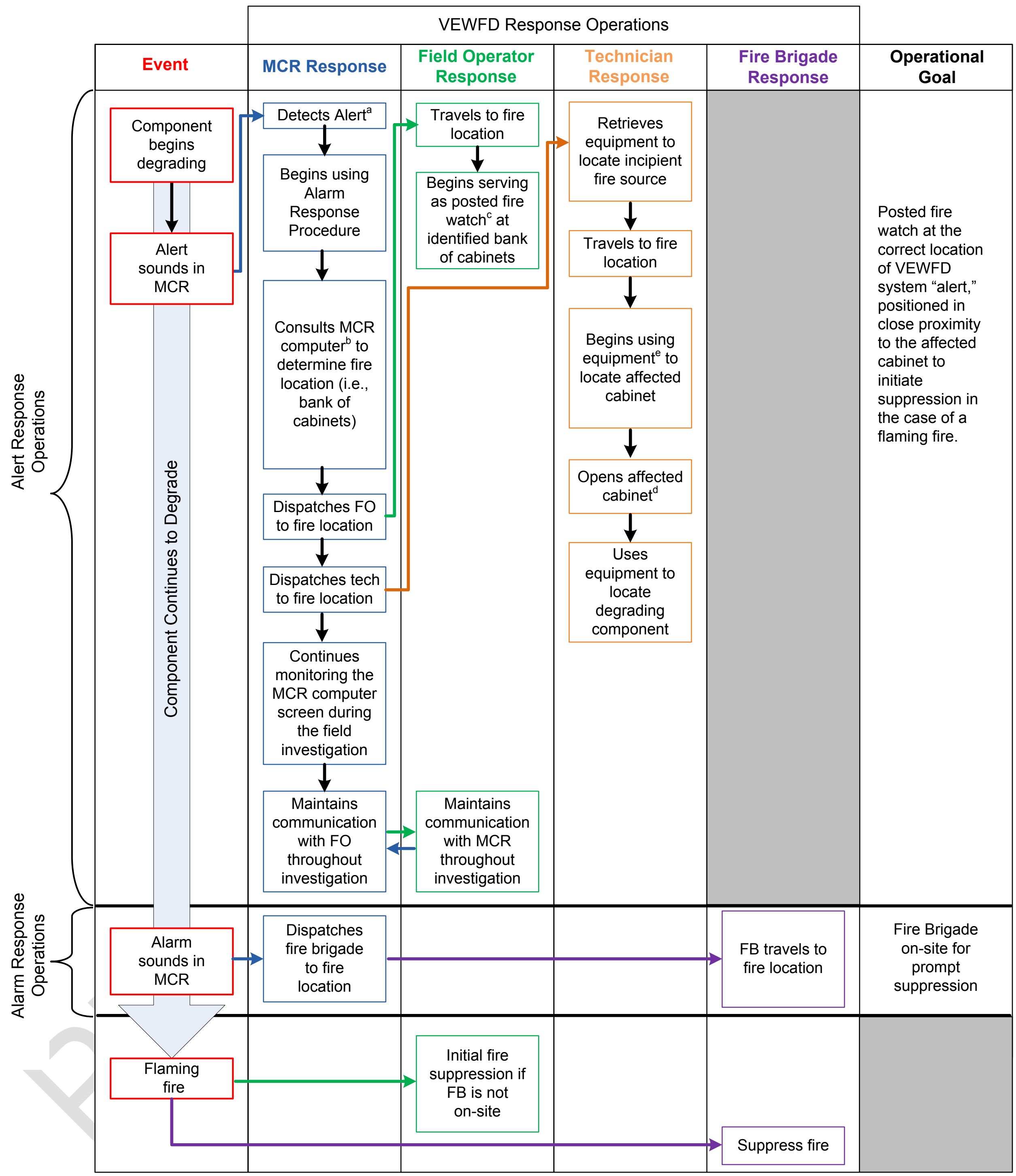


Figure 9-1. Generic depiction of operations in response to an in-cabinet ASD VEWFD alert followed by alarm where a suppression strategy is being used[5]

[5] If at any time during response operations flaming conditions are observed, the main control room would be alerted and the fire brigade dispatched.

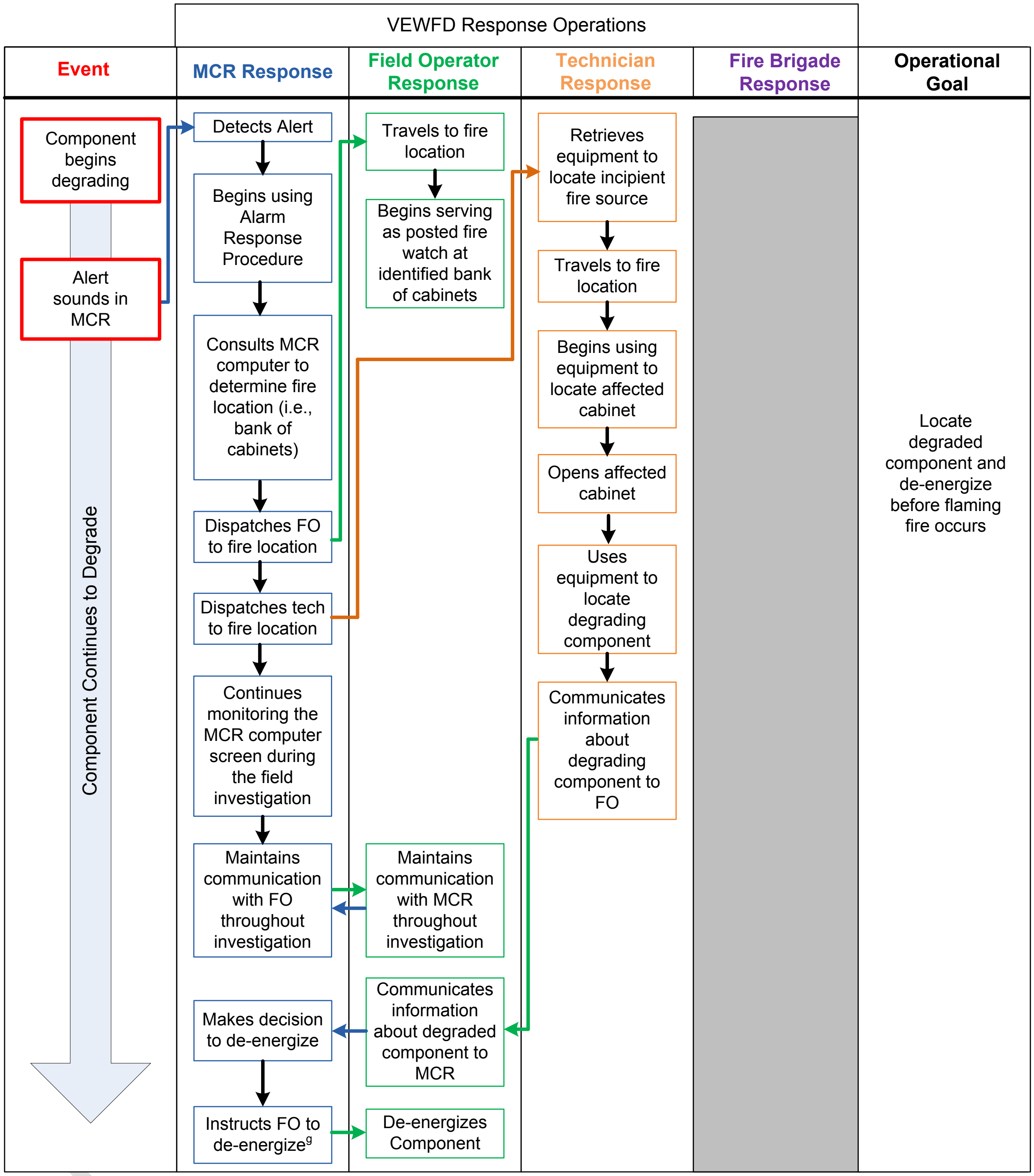


Figure 9-2. Generic depiction of operations in response to an in-cabinet ASD VEWFD alert followed by alarm where a de-energization strategy is being used

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:

a. 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 in the MCR. The implications of this variation are discussed in Section 9.2.2.2.

b. Licensees differ with regard to how personnel retrieve information regarding fire location. At one licensee site, this information is provided via a 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.

c. 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.

d. Cabinets at some sites require keys to be opened. The implications of this variation are discussed further in Section 9.2.2.1.1. In addition, the personnel responsible (i.e., FO or I&C tech) for retrieving cabinet keys and unlocking cabinets varies between sites. This variation can affect the response timeline, and thus, affect the probability of successful response operations.

e. 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.

f. 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 response personnel 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 personnel 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 objects 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."