

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

Draft Report for Comment

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

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

1. System availability, including system down time and surveillance test interval for the aspirated smoke detection systems used in nuclear and non-nuclear facilities.
2. Time duration between a very early warning fire detection system “alert” condition and the commencement of flaming conditions. Alternatively, the time duration of the incipient stage, from start of component degradation to flaming conditions.

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ABSTRACT

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

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

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

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

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EXECUTIVE SUMMARY

1
2
3 The purpose of this research is to evaluate the relative performance of smoke detection
4 systems when configured for very early warning fire detection (VEWFD) applications, to
5 conventional spot-type detection systems for use in nuclear power plant (NPP) applications.
6 There has been recent interest in quantifying potential risk enhancement associated with these
7 systems to support fire probabilistic risk assessments (PRAs) developed for NPPs transitioning
8 to performance-based fire protection programs per National Fire Protection Association (NFPA)
9 Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric
10 Generating Plants, 2001 Edition." The performance objective for using these systems is to
11 provide earlier warning to plant personnel that may allow for additional time for human
12 intervention before fire conditions that threaten the ability to achieve safe shutdown conditions.
13

14 The need for this research is a result of limited test data and understanding of the performance
15 of these systems in NPP applications to detect low energy pre-flaming (incipient) fire conditions
16 typically originating in electrical enclosures. The availability of applicable empirical data is
17 scarce and operating experience in NPP applications for detection of electrical enclosures fires
18 are limited. Specifically, data on the detection of slowly developing, incipient stage, pre-flaming
19 conditions is not available. The focus of the research presented in this report is to better
20 understand these systems performance, operating experience, and their potential risk benefits
21 via a risk scoping study. Specific needs included evaluation of the effectiveness of using
22 VEWFD systems for in-cabinet and areawide applications, response to representative products
23 of combustion, system design aspects, comparison to conventional spot-type smoke detection,
24 and operator response.
25

26 The focus of this research is related to the use of these systems as potential fire risk reduction
27 measures, associated with electrical enclosures fire hazards by providing enhanced warning of
28 pre-flaming (incipient) fire conditions to support fire probabilistic risk assessments. A common
29 failure mode of electrical enclosures occurs as a result of slow overheating followed by electrical
30 component thermal decomposition (pyrolysis) that may eventually lead to flaming fire conditions,
31 if sufficient heat and ignition conditions exist.
32

33 This research includes a literature review, a review of available operating experience, several
34 scales of testing, and an evaluation of human performance. All of these elements taken
35 together support the risk scoping study. A literature review was conducted early on in the
36 project to understand the availability of information to support the risk analysis and test plan
37 development. The literature review concluded that, in general, there has been substantial
38 research supporting the use of aspirating smoke detection (ASD) VEWFD systems in special
39 applications, such as telecommunication facilities, warehouses, atria, and as a reference tool to
40 support evaluation of model prediction of conventional spot-type detector activation. However,
41 most of the available information was developed to acquire specific data needed to support
42 specific applications. Where applicable to NPP scenarios, these data have been used to
43 support the risk scoping study documented in this report. In addition to test data, several
44 sources have provided valuable information on the characteristics of smoke, and the
45 parameters that affect smoke aging and detector response associated with electrical enclosure
46 fires.
47

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

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

8
9 Following the operating experience and literature review, actual VEWFD system testing was
10 conducted. The testing evaluated three single-port ASD and two multi-port ASDs from three
11 different vendors, all configured to VEWFD. One spot-type VEWFD detector and two types of
12 conventional spot-type detectors, and three scales of testing were completed. Laboratory scale
13 tests evaluated detector response to a variety of material in a small instrument cabinet and in
14 reactor protection system cabinets procured from an unfinished NPP. The next scale of testing
15 evaluated both in-cabinet and areawide detector response in a small room. This testing
16 included variations in both cabinet and room ventilation conditions. The final large-scale testing
17 again evaluated the in-cabinet and areawide detector response, but also included testing
18 VEWFD system performance in an air return grill application. The test results provide a wealth
19 of information regarding the performance of these systems to support a better understanding of
20 their risk benefit of detecting low energy pre-flaming fire conditions.

21 22 Objectives Supported by Testing

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

41
42 Contrasting the performance of conventional detection devices to VEWFD systems, the
43 following insights were identified. The amount of additional time will vary based on the failure
44 mechanism of the degrading component and the associated length of its incipient stage. In an
45 effort to capture an estimate on the range of additional warning time provided by ASD VEWFD
46 systems over conventional spot detectors a wide variety of materials, range of heating rates,
47 and space configurations were explored. For areawide applications, all ASD VEWFD systems
48 performed better, on average, than the conventional spot type detectors when responding to
49 low-energy smoke sources. In-cabinet application showed mixed results based upon detection
50 technology. The experimental tests show for in-cabinet applications, a conventional ionization
51 (ION) spot type detector performed better, on average, than three of the five ASD VEWFD

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

3
4 VEWFD system response to common products of combustion encountered in NPP electrical
5 enclosures was also evaluated. Laboratory scale tests evaluated the characteristics of the
6 products of combustion generated from the selected components expected to be found in NPP
7 electrical enclosures, and allowed for a reduction of the materials tested in large-scale testing.
8 The mean diameters of smoke particles were measured and shown to vary by a factor of three
9 for the materials tested. This particle characteristic information was used to down select the
10 number of materials used in subsequent testing to bound the range of particle characteristics.

11
12 Literature and testing supported an evaluation of several parameters that affect in-cabinet
13 VEWFD system layout and design characteristics with regard to system response. The
14 following findings were made with regard to this objective:

- 15
16 • Cabinet design, loading, and ventilation effects can have an influence on the
17 performance of ASD VEWFD systems, as well as conventional spot-type detectors
18 installed inside electrical cabinets. Mechanical (forced) cabinet ventilation is a primary
19 influence factor on detector response, especially with high rates of cabinet air exchange.
20 As cabinet ventilation rates increase, so does smoke dilution. High ventilation conditions
21 affect both time to detection and the effectiveness of the VEWFD systems to detect
22 low-energy incipient stage fires. However, in the empty ventilated cabinet tests in which
23 lower rates of cabinet ventilation were used, the ASD VEWFD response marginally
24 improved relative to the naturally ventilated cabinet case.
- 25
26 • For in-cabinet applications, the presence of openings, or lack of partitions between
27 adjacent cabinet sections having ASD sampling ports, enhances the time to detection.
28 This is because of the cumulative effect of drawing samples from multiple sampling
29 ports. The full-scale, small room, in-cabinet tests indicated that ASD response to a
30 single cabinet with no openings to adjacent cabinets, was slowest, compared to multi-
31 section cabinets without cabinet partitions.
- 32
33 • Source location inside the electrical cabinet also has an effect on VEWFD response. In
34 the full-scale small room tests where the source was elevated off the cabinet floor
35 approximately two-thirds of the height of the cabinet, the ASDs responded approximately
36 9 percent faster than when the sources were located on the floor.
- 37
38 • Other parameters not explicitly explored in this program, but covered in the literature,
39 relate to soot deposition and loss of aerosol thorough ventilation. Soot deposition
40 internal to the electrical cabinet will be influenced by the obstructions (impactation),
41 thermal gradients (thermophoresis), and electric fields (electrophoresis). Cabinets with a
42 large surface area of ventilation, such as louvered vents compounded by
43 thermophoresis, could result in a fraction of aerosol being lost through these vents.
44 These phenomena would cause less aerosol to transport to the ASD sampling ports or
45 spot-type detectors located at the ceiling of the electrical cabinet, resulting in a delay in
46 detection, as compared to the data in this report, and a decrease in effectiveness in the
47 detection of low-energy fire during the incipient stage.

1 Objective Supported by Human Performance

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

9
10 Information obtained from operating experience, literature review, and the tabletop analysis,
11 supported a human reliability analysis. Based on the expected operational response and timing
12 estimate developed from operating experience and test results, and the overall strategy that
13 parallels post-initiator operator actions, a human reliability analysis was conducted. The results
14 of this HRA analysis indicate that human error probabilities vary with the number of protected
15 electrical cabinets and range from 5×10^{-4} for main control room, to 5×10^{-1} for field
16 operator/technician response to a 10-cabinet bank, protected by a single zone of a light-
17 scattering ASD VEWFD system.

18
19 Risk Scoping Study Objectives

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

30
31 Evaluation of ASD VEWFD system reliability and availability confirmed the reliability estimate
32 from the Electric Power Research Institute (EPRI) in its EPRI 1016735 "Fire PRA Methods
33 Enhancements: Additions, Clarification, and Refinements to EPRI 1019189." Based on the
34 information collected during the site visits, a wide variance of system downtime was observed.
35 It was noted that system availability improved for facilities that had these systems installed and
36 operating for a substantial period of time. Facilities that were using ASD VEWFD systems for
37 the first time indicated longer system downtime likely because of the lack of understanding of
38 the system start-up and maintenance requirements to ensure proper operation. This early
39 downtime was not included in the unavailability estimates. For areawide air return grill
40 applications, the reliability and availability of the ventilation system need to be modeled into the
41 risk quantification as the air return grill application requires forced ventilation to perform as
42 intended.

43
44 The risk benefit for using these systems varies by application with in-cabinet detection being the
45 optimal approach for detecting low-energy incipient sources early enough to allow for enhanced
46 suppression capabilities and avoidance of damage to multiple components within the electrical
47 cabinet or to targets outside of the electrical cabinet. Areawide applications also provide some
48 risk benefit; however, they are usually slower to detect low-energy fires when compared to in-
49 cabinet applications because of a number of contributing factors, which are identified above.
50 Overall, the approach and information presented in this report provides the best available
51 information on VEWFD system performance and PRA application.

ACKNOWLEDGMENTS

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ACRONYMS AND ABBREVIATIONS

1		
2		
3		
4	ACH	air changes per hour
5	ADAMS	Agencywide Documents Access and Management System
6	AHJ	authority having jurisdiction
7	AHU	air handling unit
8	AMD	arithmetic mass diameter
9	APCSB	Auxiliary and Power Conversion Systems Branch
10	ARP	alarm response procedure
11	ASD	aspirating smoke detection (or detector)
12	ASD-CC	cloud chamber aspirating smoke detector
13	ASD-LS	light-scattering aspirating smoke detector
14	ASIC	application specific integrated circuit
15	ASME	American Society of Mechanical Engineers
16	AUO	auxiliary unit operator
17	AW	areawide
18	AWG	American wire gauge
19		
20	BS	British Standard
21	BSI	British Standard Institution
22	BTP	branch technical position
23		
24	CBDTM	cause based decision tree method
25	cd	candela
26	CDF	Core damage frequency
27	CFR	Code of Federal Regulations
28	CPT	control power transformer
29	CSA	Canadian Standards Association
30	CSPE	chlorosulfonated polyethylene
31	CVPC	chlorinated polyvinyl chloride
32		
33	DCRDR	detailed control room design review
34	DI&C	digital instrumentation and controls
35		
36	EDG	emergency diesel generator
37	ELPI	electrical low pressure impactor
38	EOP	emergency operating procedure
39	EOT	end of test
40	EPRI	Electric Power Research Institute
41	EWFD	early warning fire detection
42		
43	FACP	fire alarm control panel
44	FAQ	frequently asked question
45	FCC	Federal Communications Commission
46	FIA	Fire Institute Association
47	FM	Factory Mutual
48	FO	field operator
49		
50	GL	generic letter

1		
2	HCR/ORE	human cognitive reliability/operator reliability experiments
3	HEAF	high-energy arc fault
4	HEP	human error probability
5	HEPA	high efficiency particulate air
6	HF	human factors
7	HFE	human failure event
8	HRA	human reliability analysis
9	HRP	heating ramp period
10	HSI	human-system interface
11	HVAC	heating, ventilation, and air conditioning
12		
13	I&C	instrumentation and controls
14	ID	inside diameter
15	IEEE	Institute of Electrical and Electronic Engineers
16	IN	information notice
17	ION	ionization detector
18	IPEEE	individual plant evaluations of external events
19	IR	infrared radiation
20	IST	in-service testing
21	IT	information technology
22		
23	LCS	local control station
24	LED	light emitting diode
25	LER	licensee event report
26	LQ	lower quartile
27		
28	MCC	motor control center
29	MCR	main control room
30	MMD	mass mean diameter
31	MOU	memorandum of understanding
32		
33	NASA	National Aeronautics and Space Administration
34	NEI	Nuclear Energy Institute
35	NFPA	National Fire Protection Association
36	NIST	National Institute of Standards and Technology
37	NPP	nuclear power plant
38	NRC	U.S. Nuclear Regulatory Commission
39		
40	PCB	printed circuit board
41	PHOTO	photoelectric detector
42	PPE	personal protective equipment
43	PRA	probabilistic risk assessment
44	PVC	polyvinyl chloride
45		
46	QA	quality assurance
47		
48	RA	return air
49	RES	Office of Nuclear Regulatory Research
50	RoHS	restriction of hazardous substances
51	RTGB	reactor turbine generator board

1		
2	SDP	significance determination process
3	SIS	synthetic insulated switchboard
4	SPAR-H	standardized plant analysis risk human reliability analysis
5	SRO	senior reactor operator
6	SS	sensitive spot detector
7	SSC	systems, structures, and components
8	STA	shift technician advisor
9		
10	TB	terminal block
11	THERP	technique for human error rate prediction
12	THT	total heating time
13		
14	UL	Underwriters Laboratories
15	ULC	Underwriters Laboratories Canada
16	UQ	upper quartile
17		
18	VEWFD	very early warning fire detection
19		
20	XLPE	cross-linked polyethylene
21	XLPO	cross-linked polyolefin insulated

1. INTRODUCTION

1.1 Overview

This report describes an evaluation of the performance of smoke detection systems configured as either conventional or very early warning, including aspirating smoke detection (ASD)¹ systems, for use in nuclear power plant (NPP) applications. In addition to this evaluation, general information applicable to NPP installation is presented. This research is confirmatory in nature, such that its primary purpose is to evaluate the technical adequacy of a U.S. Nuclear Regulatory Commission (NRC) interim staff position documented in a National Fire Protection Association (NFPA) Standard 805 Frequently Asked Question (FAQ) 08-0046, "Incipient Fire Detection Systems." FAQ 08-0046 provides an interim staff position on the use of ASD systems configured as very early warning fire detection (VEWFD) to protect electrical enclosures² containing low voltage control components found in U.S. NPPs. This research was funded and managed by the NRC Office of Nuclear Regulatory Research (RES). Testing was performed by the National Institute of Standards and Technology (NIST). In addition to the testing, staff from the NRC supported this project by conducting site visits, reviewing literature, and evaluating human performance and smoke detection system performance for fire probabilistic risk assessment applications.

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

1.2 Need for Confirmatory Research

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

¹ Definitions are presented in Section 15.

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

1 guidance for fire PRA, including re-evaluation of fire ignition frequency, a framework for
2 quantifying incipient-fire detection systems in fire PRA, and treatment of large oil fires caused by
3 main feed water pumps. Chapter 3 and Appendix C contain information pertaining to incipient
4 detection systems. Although, EPRI was working with NRC-RES on many of these issues, the
5 methods presented in the interim report were never endorsed by NRC.
6

7 To improve accuracy and realism, and in an effort to close out FAQ 08-0046, the NRC staff took
8 the EPRI approach and modified it to address several issues and conditions, and to develop an
9 acceptable approach to evaluate the performance of ASD VEWFD systems in fire PRA
10 applications. On June 24, 2009, the NRC released a draft interim position on FAQ 08-0046,
11 regarding the use of VEWFD systems for use in NFPA 805 applications, on which the staff
12 requested comments. The NRC staff reviewed all comments received on the draft interim
13 position, and on November 30, 2009, closed out the FAQ as the final interim staff position,
14 which was later incorporated into NUREG/CR-6850, Supplement 1, "Fire Probabilistic Risk
15 Assessment Methods Enhancements," dated September 2010.
16

17 Given the number of comments received on the draft interim position and the authors'
18 discussions with knowledgeable individuals from both the industry and the regulatory
19 arenas/sides, vastly differing views regarding these systems' performance, and suitable
20 application in fire PRA, were apparent. Notably, both empirical data and operating experience
21 in NPP applications are scarce; additionally, terminology is commonly used inconsistently.
22 Because of these difficulties, the NRC identified a need to obtain a better understanding of
23 these systems' performance and their operating experience(s). Thus, the NRC began a
24 confirmatory research program to address the objectives identified below.
25

26 **1.3 Purpose and Objectives**

27

28 The research completed by NRC and NIST staff as documented in this report provides an
29 assessment on the use of smoke detection systems in NPP applications. This research focuses
30 on the use of these systems in risk-informed performance-based applications.
31

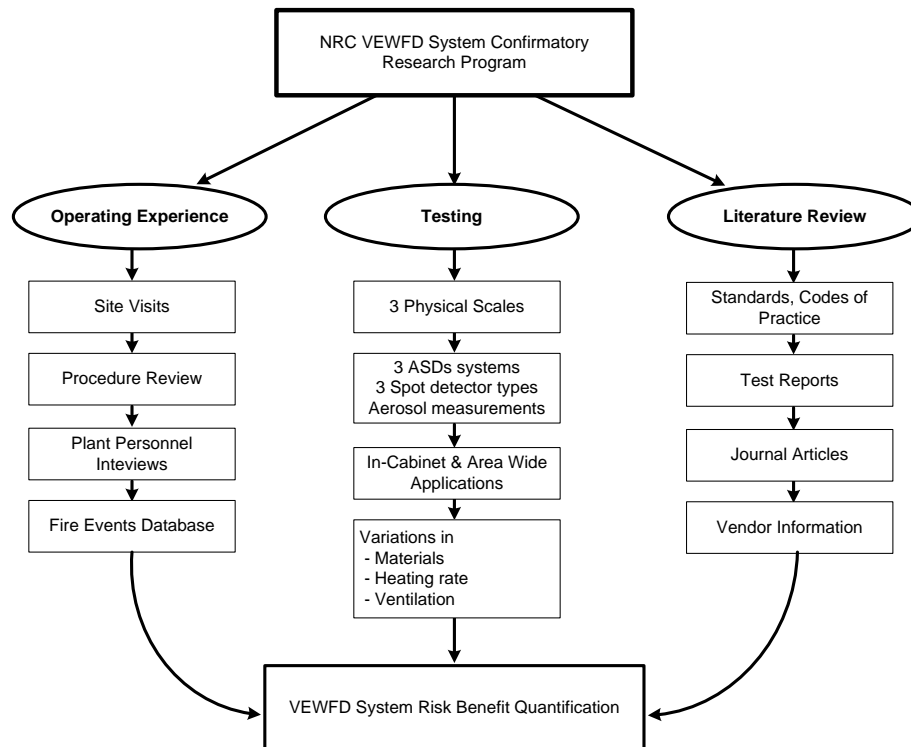
32 The objectives of this report are as follows:

- 34 A. To evaluate the effectiveness of smoke detection systems
 - 36 o This evaluation includes an evaluation of in-cabinet and areawide applications.
- 38 B. To compare the performance of common smoke detection systems currently used in
39 NPPs to VEWFD systems
- 41 C. To evaluate the response and effectiveness of equipment used to locate a pre-fire
42 source(s) through the use of human reliability analysis (HRA)
- 44 D. To evaluate smoke detection system availability and reliability
- 46 E. To evaluate smoke detection system response to common products of combustion
47 applicable to NPPs
- 49 F. To evaluate electrical cabinet layout and design effect on smoke detection system
50 response

- 1
2 G. To evaluate the performance of smoke detection technologies in various applications,
3 including in-cabinet and areawide
4
5 ○ The evaluation should support fire PRA applications and provide a technical
6 basis and approach for updating the interim approach described in FAQ 08-0046,
7 “Incipient Fire Detection Systems.”
8

9 **1.4 Project Planning and General Approach**

10 This confirmatory research is broken down into three distinct tasks: operating experience,
11 review of literature, and testing. Each area has its own sub-tasks, as shown in Figure 1-1.
12 In addition to these tasks supporting the risk scoping study, the tasks also supported the human
13 performance evaluation. Early in the project, staff from NIST reviewed available literature on
14 ASD VEWFD systems to support development of a test plan. Following the literature review,
15 staff from NIST and the NRC performed several site visits to operating NPPs in the United
16 States and Canada, as well as visits to non-nuclear facilities. These site visits provided two
17 benefits. First, it was realized early during the literature review that testing alone would not be
18 able to provide answers to all of the project objectives. Second, the site visits provided
19 information on system layout and designs being used in plants, such that a test plan could be
20 developed that adequately represented the design and use of these systems in NPP
21 applications.
22
23



24
25
26 **Figure 1-1. Illustration of VEWFD System Confirmatory Research Project**

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

8
9 During the course of this project, two non-public meetings were held with external parties.
10 The first meeting occurred on May 16, 2013 between the NRC staff and vendors of ASD
11 VEWFD systems equipment being tested. The second meeting occurred on July 24, 2013,
12 between the NRC and EPRI. Both meetings were considered information exchanges, and were
13 used to receive additional feedback on the project approach, specifically testing. The NRC
14 presentations are available electronically from the NRC's Agencywide Documents Access and
15 Management System (ADAMS), Accession No ML14356A581.

16
17 Once the literature review, test data, operator response characteristics, and operating
18 experience were understood, that information was used to evaluate how the effect of these
19 systems performance in fire PRA applications.
20

21 **1.5 Scope of this Report**

22
23 This report provides information on ASD and spot-type systems configured for VEWFD and
24 conventional spot-type smoke detector performance in various NPP applications, with a focus
25 on their response to low-energy fires during the early stages (pre-flaming). The potential risk
26 benefits from using these systems and associated operator response characteristics are also
27 provided. The focus on these two types of systems was directed by the regulatory need and
28 doesn't represent any determination that these are the only fire detection methods suitable for
29 NPP applications. Additionally, this report doesn't explore negative impact from using
30 ASD systems such as whether single failure potential is increased, configurations where other
31 detections systems perform better, or any significant risks associated with inappropriate
32 equipment de-energization.

33
34 This report specifically focuses on evaluating ASD VEWFD systems' ability to detect electrical
35 enclosure fires during low-energy fire conditions. Electrical enclosures are defined as items
36 such as switchgears; motor control centers; direct current (dc) distribution panels; relay
37 cabinets; control and switch panels, (excluding panels that are part of machinery); fire protection
38 panels, etc. Voltages in electrical enclosures vary from low voltage to 6.9kV switchgear.
39 Although other types of equipment found in NPPs are likely to have equipment failure modes
40 which exhibit an incipient stage of sufficient duration to allow for enhanced operator response,
41 this report does not provide an evaluation of ASD VEWFD performance to protect those other
42 types of equipment.
43

44 **1.6 Report Organization and How to Use This Report**

45
46 This report is broken into three parts. Part I contains a collection of supporting information
47 associated with smoke characteristics, detection technologies, operating experience and
48 presentation of the experimental program approach and results. Part II presents a refined
49 method for quantifying the performance of smoke detection in fire PRA applications. Part III

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

3
4 PART I

- 5
- 6 • **Section 2** provides general background information on fire dynamics; smoke detection
7 principles; system performance measures; and the importance of quality assurance and
8 inspection and testing; and maintenance programs.
- 9
- 10 • **Section 3** presents a review of operating experience associated with VEWFD systems,
11 NPP use of these systems, and information obtained during site visits. An overview of
12 national consensus standards, listing and approval standards and information found in
13 codes of practice is also provided. A literature review summary is also presented.
- 14
- 15 • **Section 4** describes the experimental approach taken to address the objectives of this
16 project. Included in this section are descriptions of the detectors, incipient fire source,
17 instrumentation, test facilities, test protocols and experimental design.
- 18
- 19 • **Section 5** documents the test results obtained and presents them graphically.
20 Characteristics of the incipient fire source with regard to heat conduction and ignition
21 potential are also presented. The last subsection presents the results in a format to
22 support the scoping risk study documented in Part II.
- 23

24
25 PART II

- 26
- 27 • **Section 6** presents a summary of previous efforts used to quantify the performance of
28 ASD VEWFD systems in fire PRA. An overview of the model used in this project is also
29 presented.
- 30
- 31 • **Sections 7–11** provides a basis for estimating the parameters of the model presented in
32 Section 6.
- 33
- 34 • **Section 12** presents illustrative examples using the model and parameters developed in
35 this project to quantify the performance of various smoke detection technologies.
- 36

37 PART III

- 38
- 39 • **Section 13** presents a summary from the findings of this project and conclusions.
- 40
- 41 • **Section 14** identifies recommendations for future research
- 42
- 43 • **Appendices A–E** contain supporting information including; view graphs from meetings
44 with vendors, experimental data, human performance, operating experience, and
45 literature reviewed.
- 46

PART I

Knowledge Base

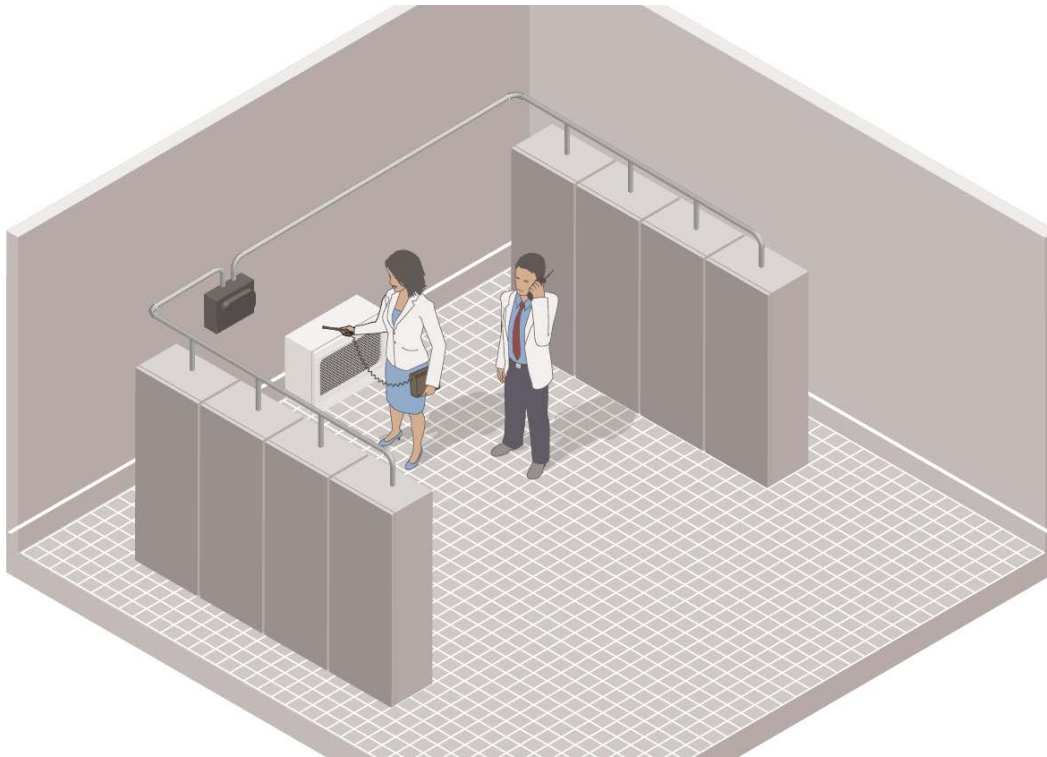
1 **2. FUNDAMENTALS OF SMOKE GENERATION AND FIRE**
2 **DETECTION TECHNOLOGIES**
3

4 Success in limiting or even preventing fire damage is dependent on the rate of fire development.
5 The earlier a fire is detected the sooner fire suppression activities can be initiated to reduce the
6 likelihood of damage to equipment. This section provides an overview of the fundamental fire
7 science underlying the performance of fire detection systems and key definitions of the fire
8 stages used throughout this report. Included in this discussion are a generalized representation
9 of fire growth and fire classification, fire byproduct generation and the principles of smoke
10 detection. The fundamental information presented here supports assessing smoke detection
11 system performance and quantifying the use of these systems in fire probabilistic risk
12 assessments.
13

14 **2.1 Background**
15

16 Very early warning fire detection (VEWFD) is defined in National Fire Protection Association
17 (NFPA) Standard 76, "Fire Protection of Telecommunication Facilities," as *systems that detect*
18 *low-energy fires before the fire conditions threaten telecommunications service.* VEWFD
19 systems are used extensively in the telecommunications industry in areawide applications to
20 meet the intent of NFPA 76, protect high value or mission critical contents and limit interruption
21 of services. Their extensive use in mission critical and telecommunications industries is a result
22 of smoke damage being the biggest risk to electrical equipment, not fire. Telecommunications
23 facilities also find VEWFD systems useful because of the high air exchange rates needed to
24 cool electronic equipment, whereas conventional spot-type smoke detector performance is
25 degraded because of smoke dilution. Most Canadian and some U.S. nuclear power plants
26 (NPPs) also use some form of air aspirated VEWFD systems to reduce risk and provide
27 advanced warning of fire conditions. In general, VEWFD systems are finding wide applications
28 in a variety of other industries, especially in performance-based design.
29

30 Air aspirated (sampling-type) smoke detectors are commonly used to meet the NFPA 76
31 requirements for VEWFD systems. These ASD VEWFD systems actively sample air from the
32 protected space and transport the air samples through a smooth bore piping network back to a
33 centralized detector unit where the air samples are monitored for combustion-based products
34 (in accordance with either light-scattering or cloud chamber smoke detection principles). An
35 illustration of such a system is shown in Figure 2-1. These systems have the potential to
36 provide numerous advantages over conventional systems. However, their difference from
37 conventional spot-type detectors presents several challenges to successful implementation and
38 proper quantification of any risk improvements in fire PRA.
39



1

2

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

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

16

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

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

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

3
4 Following the issuance of FAQ 08-0046, “Incipient Fire Detection Systems,” the U.S. Nuclear
5 Regulatory Commission (NRC) initiated a research program along with confirmatory testing at
6 NIST to ensure the interim position is technically adequate. This report documents that
7 research.

8 9 **2.1.1 Fire protection defense-in-depth**

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

- 21
22
23 a. Preventing fires from starting.
- 24
25 b. Detecting fires quickly, suppressing those fires that occur, putting them out quickly and
26 limiting their damage.
- 27
28 c. Designing plant safety systems such that if a fire does get started in spite of the fire
29 prevention program, and burns for a considerable time, in spite of fire protection
30 activities, it will not prevent essential plant safety functions from being performed.

31
32 VEWFD systems partially support the second echelon by providing a means of quickly detecting
33 fires. Because VEWFD systems support defense-in-depth, there have been differing views on
34 the role of VEWFD systems in performance-based fire protection programs, leading to
35 complexity in the evaluation of these systems’ performance in a fire PRA.

36 37 **2.2 Dynamics of Fire Stages**

38
39 A fire development profile is typically discussed in terms of “fire stages.” These are commonly
40 referred to as the “incipient,” “growth,” “steady-state,” and “decay” stages as illustrated in
41 Figure 2-1 (Ref. 5). This idealized representation provides a foundation for understanding the
42 various fire stages; however, the shape and, more importantly, the duration and transition point
43 of each stage are scenario dependent. Having a clear definition and understanding of the
44 incipient stage and transition point as it relates to performance-based methods, is paramount to
45 the research performed under this project.

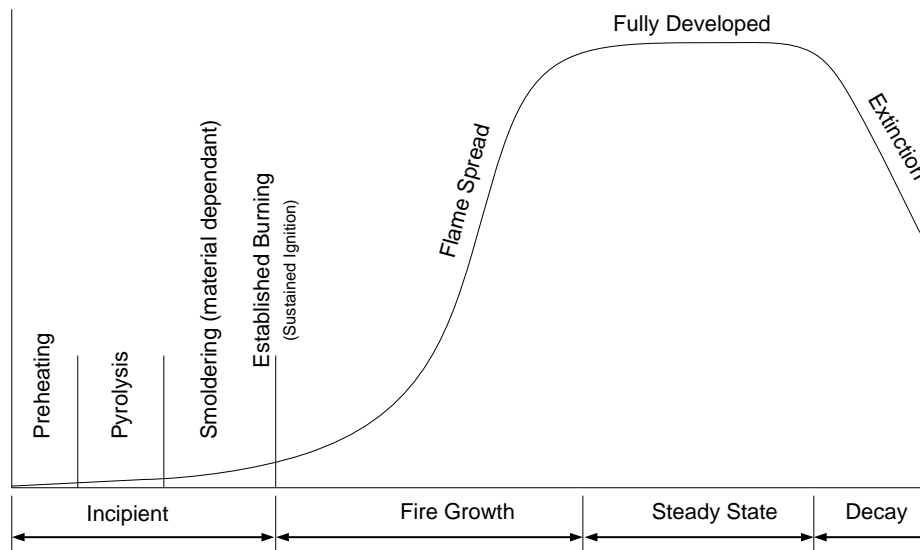


Figure 2-2. Fire stages

1
2
3
4 The incipient stage includes the preheating, gasification and smoldering phases, which are all
5 stages before flaming combustion. The preheating phase is the process of heating combustible
6 materials to a point where gasification begins. As combustible material continues to heat up, it
7 is decomposed, or broken down into more simple molecular compounds; this stage is known as
8 pyrolysis. Smoldering is a slow, low-temperature, flameless form of combustion, sustained by
9 the heat evolved when oxygen directly attacks the surface of a condensed-phase fuel (Ref. 6).
10 True self-sustaining smoldering conditions will not occur for many of the materials of interest in
11 electrical enclosures (Ref. 7).

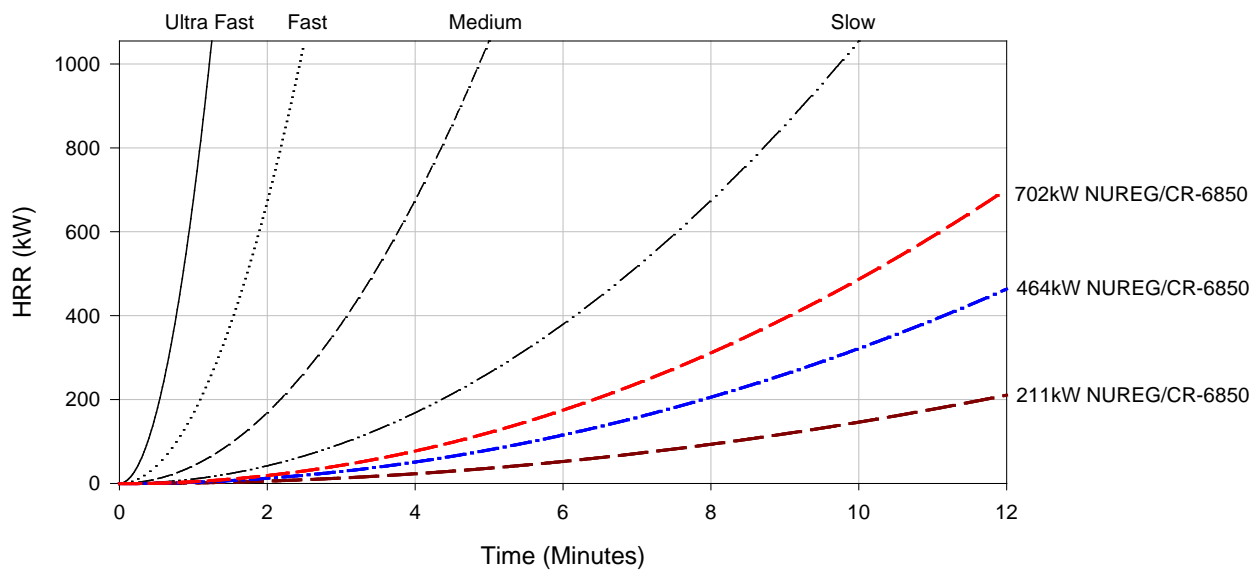
12
13 A common fire scenario includes an initial pre-heat phase, typically followed by a pyrolysis
14 phase, then followed by a transition to either smoldering or flaming conditions. In electrical
15 enclosures, the preheating phase could start as a result of circuit, component, or
16 inter-connecting electrical conductor failure, or by some other mode. Regardless of how the
17 initial degradation begins, a source of energy to cause the preheating is needed to initiate the
18 potential fire scenario. Once sufficient concentrations of combustible material are present
19 during the gasification phase, electrical energy within the electrical enclosures provides the
20 potential ignition source to end the incipient stage.

21
22 There are also variations on this prototypical fire scenario. The degradation mechanism may
23 not continue to progress in severity. For example, the pyrolysis phase may be reached, but
24 sufficient vapor may not be evolved to support combustion, or an ignition source may not be
25 present at a physical location where flammable concentrations are present. Another example
26 would be an instance in which the component degradation begins to decrease in severity before
27 the ignition and fire growth stage. Although these cases may produce considerable combustion
28 products, the heat output could be relatively low, and thus, not all situations involving an
29 incipient stage actually result in a fire.

30
31 For the purposes of this report, "ignition" will be defined as the point where "self-sustained
32 flaming combustion is initiated." This definition of ignition corresponds to the start of the growth
33 phase as depicted in NUREG/CR-6850. The logic for using this definition will become apparent
34 later on when the risk scoping study structure is presented, showing the dependency between

1 fire-initiating events that are risk-significant and are counted in the fire initiating frequency, and
2 the fraction of those fires which exhibit an incipient stage of sufficient duration to support
3 enhanced suppression capabilities.
4

5 In addition to underscoring/highlighting the stages of a fire, it should also be emphasized that
6 different fire growth profiles have been defined. Figure 2-3 illustrates common fire growth
7 profiles across various electrical enclosure heat release rate categories, as found in
8 performance-based designs, such as the slow, medium, fast and ultrafast growth profiles as
9 presented in fire protection literature (Ref. 5 and 8) and NUREG/CR-6850 Appendix G. Notably,
10 the growth profiles of actual fires that occur in NPPs will vary, and are functions of the
11 component failure mode and configuration of combustibles; simply, just as the fire growth
12 profiles are variable, the incipient stage duration can vary dramatically as well (Ref. 9).
13



14

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

16

17 Alternative definitions

18

19 For completeness, it should also be mentioned that there are alternative definitions of an
20 incipient stage. For instance, Heskestad and Yao define three fire stages for solid materials
21 with an input heat source of relatively low energy (Ref. 10). The three phases included
22 “incipient,” “smoldering,” and “flaming” stages of a fire. Here, Heskestad and Yao identified
23 ignition as the point where smoldering combustion starts. Therefore, they did not consider
24 smoldering combustion to be included in the incipient stage.
25

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

1 connection to the observed fire phenomena, and is not based solely on the success of human
2 intervention to suppress fires.
3

4 **2.3 Aerosol Generation**

5 Fire signature response

6
7
8 From its inception, fire produces a variety of changes to the ambient conditions within the fire
9 environment. These changes are referred to as “fire signatures” and have the potential to be
10 measured by detection systems. Examples of the fire signatures include aerosol (commonly
11 referred to as smoke), energy release, gas, and transport fire signatures. For a specific fire
12 signature to be of value, a measurable change in ambient condition is required, and that
13 magnitude change (“the signal”) must be greater than the normal background variations (“the
14 noise”). Thus, the preferred fire signature for a specific application will be that which generates
15 the highest signal-to-noise ratio in the earliest period of fire development (Ref. 11). Proper
16 application of fire detection technologies requires an understanding of the fire conditions for
17 which detection system response is required.
18

19 Aerosols are the type of fire signatures that can be detectable by smoke detectors, and will be
20 studied exclusively for the purpose of this research. Smoke is defined as, “*the airborne solid*
21 *and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion,*
22 *together with the quantity of air that is entrained or otherwise mixed into the mass*” (Ref. 6).
23 Some ASD vendors do sell components for their systems that have the capability of detecting
24 gas signatures; the performance of ASDs used in the latter application will not be evaluated in
25 this report.
26

27 Aerosols are classified as solid and liquid particles ranging in size from 5×10^{-4} to 10
28 micrometers (μm) and suspended in air. The characteristics of the aerosol are a function of the
29 source material (source composition), combustion stage (incipient, smoldering or flaming), and
30 amount of dilution with air, coagulation from Brownian motion, and surface deposition. These
31 factors play an important role in determining the chemical composition, refractive index, particle
32 size distribution, and concentration. The characteristics of the aerosol play an important role in
33 the response of the detector because specific characteristics will affect sensing technologies
34 differently. For instance, flaming fires tend to produce smokes that have a large fraction of
35 sub-micron particles that tend to absorb a greater fraction of incident light than the fraction
36 scattered, while smokes from smoldering fires tend to have a larger fraction of particles
37 micrometer sized or greater, and they tend to scatter more incident light than the fraction
38 absorbed. Based primarily on these factors, an ionization type detector is better suited for
39 detecting flaming fires and a photoelectric type detector is better suited for detecting smoldering
40 fires. Because of these differences, combination detectors have been developed and are
41 available on the commercial market (Ref. 12).
42

43 **2.4 Smoke Detection Principles**

44
45 Reliable fire detection is an essential part of the fire protection program in NPPs. The use of
46 smoke detectors is common because they typically detect fires before heat detectors and
47 sprinkler activation. The NFPA Glossary of Terms defines the following types of smoke
48 detectors (Ref. 13):
49

1 Cloud Chamber Smoke Detection:

2 The principle of using an air sample drawn from the protected area into a high-humidity
3 chamber combined with a lowering of chamber pressure to create an environment in which
4 the resultant moisture in the air condenses on any smoke particles present, forming a cloud.
5 The cloud density is then measured by a photoelectric principle. The density signal is
6 processed and used to convey an alarm condition when it meets preset criteria.
7

8 Ionization Smoke Detection:

9 The principle of using a small amount of radioactive material to ionize the air between two
10 differentially charged electrodes to sense the presence of smoke particles. Smoke particles
11 entering the ionization volume decrease the conductance of the air by reducing ion mobility.
12 The reduced conductance signal is processed and used to convey an alarm condition when
13 it meets preset criteria.
14

15 Photoelectric Light Obscuration Smoke Detection:

16 The principle of using a light source and a photosensitive sensor onto which the principal
17 portion of the source emissions is focused. When smoke particles enter the light path, some
18 of the light is scattered and some is absorbed, thereby reducing the light reaching the
19 receiving sensor. The light reduction signal is processed and used to convey an alarm
20 condition when it meets preset criteria.
21

22 Photoelectric Light-Scattering Smoke Detection:

23 The principle of using a light source and a photosensitive sensor arranged so that the rays
24 from the light source do not fall (as normal) onto the photosensitive sensor. When smoke
25 particles enter the light path, some of the light is scattered by reflection and refraction onto
26 the sensor. The light signal is processed and used to convey an alarm condition when it
27 meets preset criteria.
28

29 Video Image Smoke Detection:

30 The principle of using automatic analysis of real-time video images to detect the presence of
31 smoke.
32

33 In NPP applications, smoke detectors have traditionally been considered best-suited for fire
34 detection in spaces with physical barriers where rapid heat generation and smoke confinement
35 can be expected in the event of a fire. The purpose of these systems is to provide early warning
36 to building occupants, and rapid notification of the fire brigade. Some detection devices will also
37 perform the function of automatically actuating suppression systems, and interfacing with other
38 building systems such as HVAC. Advancements in electronics have aided in the improvement
39 of the smoke detector signal processing, allowing for algorithms to be developed to reduce
40 nuisance alarms from non-fire combustion products.
41

42 For room fire detection, smoke detectors have typically been placed in the uppermost space of
43 the protected area. This placement assumes a growing or high-energy (steady-state) fire in
44 which the energy released causes a strong buoyant plume to force the products of combustion
45 upward and outward along the horizontal ceiling where the detectors are located. For
46 low-energy fires, characterized by low temperatures and relatively small amounts of combustion
47 products, the plume strength may not be sufficient to transport the products of combustion to the
48 uppermost level where the detectors are located. In addition, if the room has a vertical
49 temperature gradient (on the order of a few degrees Celsius) such a weak plume could result in
50 stratification of the smoke (Ref. 14).
51

1 **2.4.1 Smoke characteristics**

2
3 Smoke production of a given fuel will vary with the type of fuel; mode of combustion; size of fuel
4 package; arrangement; physical configuration; material moisture content; and ignition input
5 energy. The earliest indication of a fire occurrence usually involves the heating of materials
6 during the pre-ignition (incipient) stages, which produces submicron particles ranging in size
7 from 5×10^{-4} to 1×10^{-3} micrometers. Under ambient conditions, particles of this size are normally
8 found in concentrations from several thousand per cubic centimeter to several hundred
9 thousand per cubic centimeter. Incipient stage conditions can raise the sub-micrometer particle
10 concentration sufficiently above the background levels (noise) to be used as a fire detection
11 signal. As a reference point, a match flame can produce ten million particles per cubic
12 centimeter (Ref. 15).

13
14 The size of the particle produced by diffusion flame⁴ combustion also varies with the heating of
15 the air and the development of the fire progressing to flaming combustion. Large particles are
16 formed by coagulation, with the particle size distribution varying between 0.1 micrometer and
17 4.0 micrometers. The smaller particles below 0.1 micrometer tend to disappear as a result of
18 the formation of larger particles by coagulation, while the larger particles tend to settle out
19 through the process of sedimentation (Ref. 15). Both of these properties contribute to smoke
20 aging.

21
22 The performance of ASD systems exposed to smoke is dependent on the particular ASD
23 technology (i.e., light-scattering vs. cloud chamber), because the ASD technologies respond
24 differently to varying particle sizes and particle concentrations. For instance, cloud chamber
25 technology is more sensitive to particle concentration and less sensitive to particle size. This is
26 because the particles act as a condensation nucleus when the cloud is formed, and the
27 response of the system is similar whether 100 large particles or 100 small particles are present.
28 Light-scattering ASD technology requires the particles to be of sufficient size to scatter light. In
29 this sense, the system response would differ between 100 large particles (more light-scattering
30 occurs) and 100 small particles (less light-scattering occurs). Smoke detector response
31 depends on detector type and accumulation of smoke particulate within the sensing chamber.
32 In addition to the differences among detector technology, the performance within a technology
33 may differ because of the design and characteristics of the detector. For instance,
34 light-scattering based technologies may use forward scattering, back scattering or a
35 combination, along with employing different wavelengths of light sources. These design
36 variations result in variable performance levels. Consequently, the motivation for choosing one
37 ASD technology over another for use in NPP applications is not clear. The test results
38 documented in this report confirm this statement (see Section 5).

39
40 **2.4.2 Smoke properties**

41
42 The Lambert-Beer Law (also known as Bouguer's law) provides an expression for the light
43 intensity reduction caused by smoke. The Lambert-Beer Law is shown mathematically as:

44
45
$$I = I_0 \exp(-\kappa CL)$$

46
47 where: I = intensity of transmitted monochromatic light (cd)
48 I_0 = initial intensity of monochromatic light (cd)

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

1 κ = extinction coefficient, (m²/g)
2 C = mass concentration of smoke particles, (g/m³) and
3 L = pathlength of the optical beam passing through smoke (m).
4

5 The use of this law allows for the development of a parameter known as optical density,
6

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

8
9 Obscuration is the effect that smoke has on reducing visibility. Higher smoke concentrations
10 result in higher obscuration, which results in lower visibility. Light obscuration is defined as:
11

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

12
13
14 Obscuration is the standard definition of smoke detector sensitivity in the fire protection industry
15 today. Detector sensitivity is reported in units of percent obscuration per unit length (e.g., %/ft
16 obscuration or %/m obscuration). Percent obscuration per unit of length (meter or foot) is
17 shown mathematically as:
18

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

20 21 **2.4.3 Spot-type detectors** 22

23 Most of the devices associated with conventional fire detection are typically located near the
24 ceiling surfaces of NPP compartments. In the event of a fire, hot gases in the buoyancy-driven
25 fire plume rise directly above the burning fuel, and impinge upon the ceiling. The ceiling surface
26 causes the flow to turn and move horizontally beneath the ceiling, to other areas of the room,
27 located some distance from the fire. The response of detection devices installed below the
28 ceiling, submerged in this hot flow of combustible products, provides the basis for the
29 construction of active fire detection features.
30

31 The response of conventional spot-type (also referred to as “point type”) detectors like those
32 shown in Figure 2-4, are influenced by several parameters. Smoke characteristics, smoke
33 transport and detector characteristics are the predominant factors that influence detector
34 response. The performance of spot-type smoke detectors is also dependent on fire-induced
35 flow velocities near the detector. Typically, spot-type smoke detectors operate on two types of
36 detection principle: ionization or photoelectric.
37



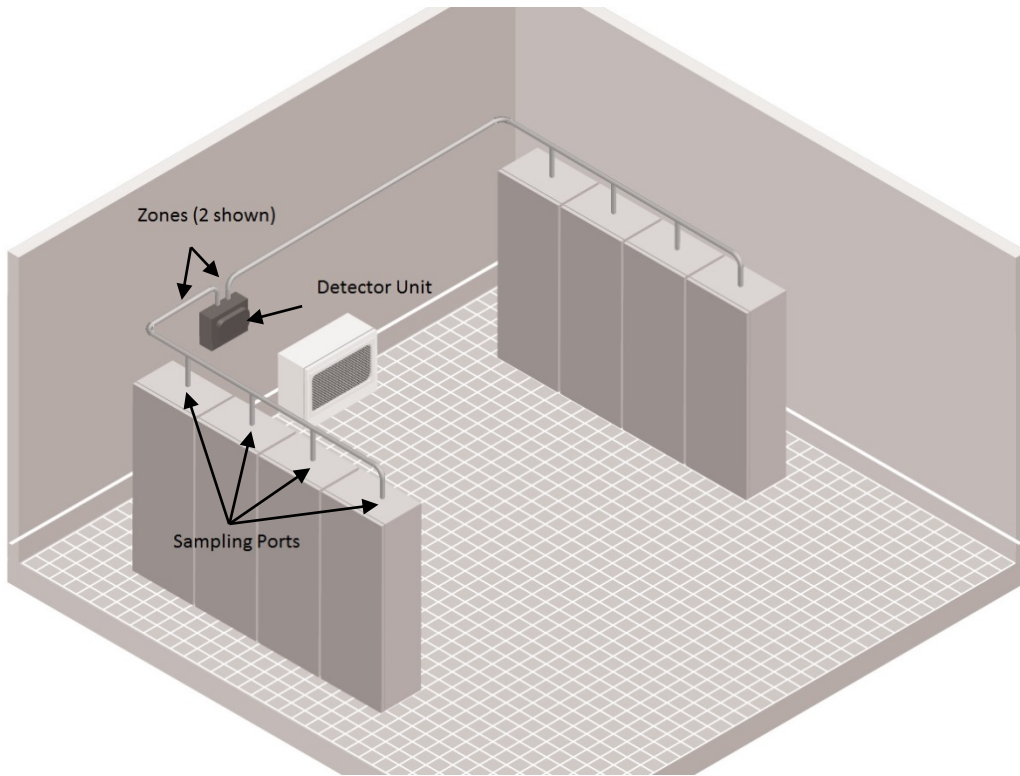
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Figure 2-4. Image of conventional spot-type detectors

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

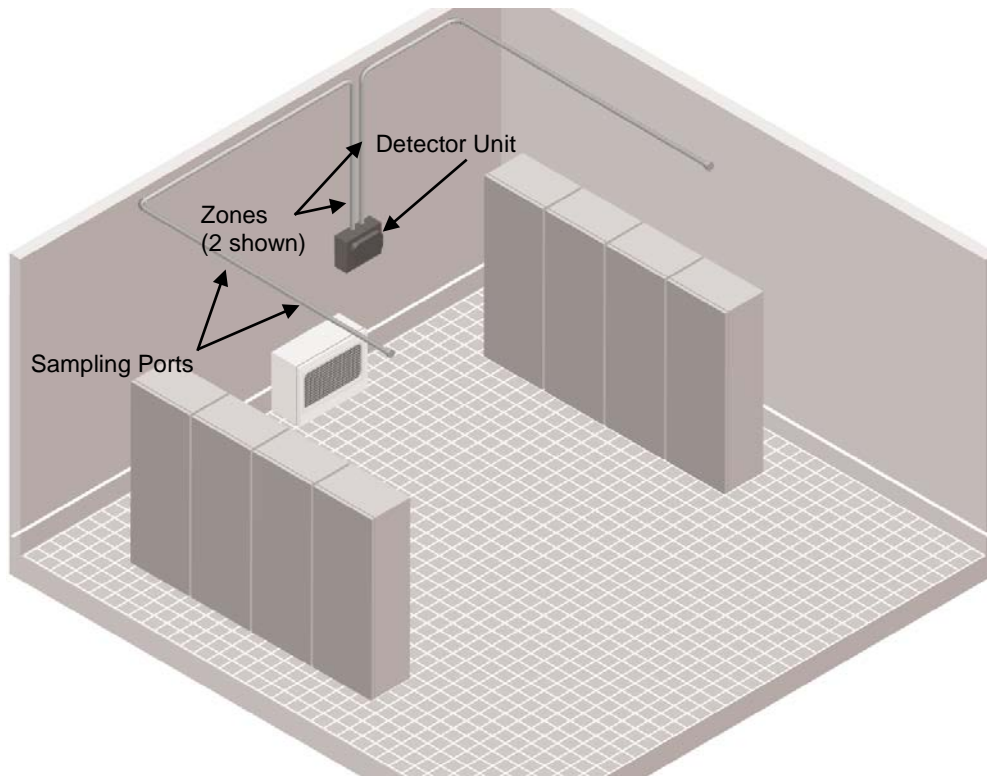
2.4.4 Aspirating smoke detectors

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



1
2
3

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



4
5

Figure 2-6. Illustration of an ASD areawide application

1
2 Two types of detector unit technology are commonly used; one is based on the light-scattering
3 principle, while the other uses cloud chamber technology. The light scattering-type ASDs detect
4 smoke particles using the same principles as photoelectric spot detectors, but typically have an
5 improved detection unit that is more immune to external light sources that can affect
6 conventional photoelectric spot detectors. The cloud chamber detector places the air sample in
7 a humidifier where distilled water is used to bring the relative humidity to nearly 100 percent.
8 Then, a vacuum pump reduces the chamber pressure to cause supersaturated conditions
9 (i.e., relative humidity above 100 percent). When this occurs, any smoke particles present will
10 act as condensation nuclei for water droplets to form on, resulting in the formation of a cloud in
11 the sensing chamber. The particle concentration (cloud density) is measured by light-scattering
12 detector principles, which provide an output that is proportional to the number of droplets.
13 Either of the detector technologies will respond when a pre-programmed threshold is exceeded
14 (Ref. 5).

15
16 The ability to mechanically transport air to the detector allows for the use of filters to remove
17 dust. Physical filters remove large dust particles from the air sample, before it being analyzed.
18 The filters can minimize unwanted alarms and contamination of the detector. Filter placement
19 and designs vary by manufacturer, but typically are built or fused into the ASD detector unit or
20 installed in the pipe network.

21
22 ASD systems typically have multiple alarm thresholds that are determined by the performance
23 objectives of the application and the pipe network design. Per NFPA 76, for an ASD to be
24 classified as a VEWFD system, the following minimum sensitivity setting above ambient air
25 borne levels must be achieved:

26
27 Alert condition: 0.2 percent obscuration per foot (effective sensitivity at each sampling
28 port)

29
30 Alarm condition: 1.0 percent obscuration per foot (effective sensitivity at each sampling
31 port)

32
33 Alert and alarm threshold settings more sensitive than these may be achievable in an
34 application and will provide for an enhancement over these minimum requirements. However,
35 the ability to use more sensitive settings will be dependent on a number of variables, including
36 operational transients on background aerosol noise levels. Thus, most vendors recommend at
37 least a two week burn-in period, (sometimes referred to an auto learn cycle), during which the
38 detector monitors background noise variations, such that an optimum alert and alarm threshold
39 can be chosen, which enables a sensitive system with few unwanted nuisance alarms.
40 Additionally, per NFPA 76 to be classified as VEWFD a maximum transport time from the most
41 remote port to the detection unit of an air-sampling system shall not exceed 60 seconds.

42
43 It is important to point out that the sensitivity of a detector unit is not equivalent to the sensitivity
44 at the sampling port. The sensitivity of each sampling port is a function of “detector unit”
45 sensitivity and the number of sampling holes in a sampling zone. Most ASD VEWFD systems
46 require multiple sampling ports per zone. The smoke entering the air sampling port network will
47 be diluted by air entering the network from other ports that does not contain smoke. Thus, for
48 an ASD system to be able to detect a specific smoke concentration, the detector must have
49 greater sensitivity than at the air sampling port for which the system is designed. For example,
50 assume a 2,000 square feet (ft²) room is protected by an areawide ASD system consisting of a
51 single zone piping network located at the ceiling, having 10 sampling ports, spaced per NFPA

1 76 requirements, and all sampling ports have been calculated to have an equivalent sensitivity
2 (i.e., balanced). If the design requires each sampling port to have a sensitivity of 1.0 percent
3 per foot obscuration, the detector sensitivity would be required to be set at 0.1 %/ft obscuration.
4 This estimation method is applicable to a balanced system; however, it is typically not sufficient
5 to ensure the performance of the ASD VEWFDF system. Such assurance can only be given
6 through product testing and approvals. Vendors of ASD systems have software tools to assist
7 in designing an ASD system pipe network and calculating detector unit sensitivity threshold
8 setting to achieve the required sampling port sensitivities. As discussed in the literature and
9 confirmed in this project's test results (Section 5), ASD VEWFDF systems may have varying
10 response times if they are from different vendors; use identical piping networks; are set to the
11 same sampling port sensitivities; and are exposed to the same smoke sources. Given the
12 different technologies and processing algorithms, it is reasonable to expect differences in
13 response.

14
15 It is important to understand the difference because much of the literature reports the detector
16 unit sensitivity, and not the various sensitivities at the sampling ports, which are not equivalent,
17 and will differ by design. The use of a single piping zone sampling from multiple ports also has
18 an effect on the performance of the system. For instance, in areawide applications, the
19 phenomenon known as cumulative air sampling may improve the performance of ASD systems,
20 and allow for earlier detection by permitting smoke sampled from multiple ports to contribute to
21 the total smoke particulate being sampled at the detector from a protected space. Sample port
22 spacing has a direct correlation to the cumulative air sampling effect. As the spacing of
23 sampling ports is reduced, there is a greater possibility for smoke particles from a single source
24 to enter into more than one sampling port, thus improving detector response. Theoretically, the
25 concept of cumulative air sampling can be understood; however, there are many variables that
26 influence the effect of this phenomenon, and unless specific validation testing is performed for
27 the scenario under evaluation, it is a difficult phenomenon to quantify. Thus, standards such as
28 NFPA 76 specify minimum port sensitivity (above background) for each sampling port.

29
30 Spot-type air sampling detectors are also available on the market. These detectors combine the
31 spot-type light-scattering smoke detector with filtered aspirating features. Typical applications
32 are heated stables, paper plants, cotton and textile mills, commercial laundries, food processing
33 areas, and other applications where very dusty conditions exist. Performance of these types of
34 detectors is not evaluated in this research.

35 36 **2.4.5 Ambient conditions affecting detector response**

37
38 Ambient environmental conditions influence the performance of smoke detection technologies.
39 The improper selection of detector type and location can lead to problems ranging from false or
40 delayed alarms, to, in some cases, no alarms when fire conditions exist. Issues to consider
41 when selecting and locating detectors/sampling ports include, but are not limited to:

- 42
43 • Background noise
 - 44 – Detectors responding to invisible aerosol fire signatures are prone to detecting
 - 45 signals from cigarette smoke and automobile exhaust fumes. Thus, placement of
 - 46 a smoke detection system which responds to invisible aerosol fire signatures in
 - 47 proximity to an emergency diesel generator (EDG) should be evaluated to ensure
 - 48 that the frequent operation of the EDG does not result in numerous nuisance
 - 49 alarms.

- 1 – Routine maintenance of plant structures, systems and components may increase
2 the background noise level above the alarm threshold for detection systems set
3 up to signal very early warnings.
4
- 5 • HVAC effects
 - 6 – Ventilation conditions within rooms and electrical enclosures are important to
7 understand, because detecting/sampling port location without considering the air
8 movement and thermal effects within the room, especially for low-energy
9 incipient fires, may slow the detection systems' response(s), and could result in
10 the detection system missing the fire signal completely. Areas of low air flow or
11 stagnation should be considered and avoided when designing the detection
12 system layout.
 - 13 – ASD systems may be prone to pressure change within a room because of
14 periodic changes in HVAC operational state.
- 15 • Humidity
 - 16 – High relative humidity of the air space affects the smoke transport to detectors or
17 sampling ports located at the ceiling such that a high relative humidity will
18 enhance the agglomeration of smoke particles. Depending on room conditions,
19 the moist smoke laden air may not be transported to the elevations where
20 detectors and sampling ports are located.
- 21 • Radiation
 - 22 – Ion type detectors are not suitable for use in applications in which high
23 radioactivity levels are to be expected; the radiation causes a reduced sensitivity
24 of ion type detectors.

25 **2.5 Quality Assurance Program**

26
27 Each licensed NPP is required to have a quality assurance (QA) program that provides
28 reasonable assurance that the requirements for design, procurement, installation, testing and
29 administrative controls for the fire protection program are satisfied. Licensees typically meet the
30 fire protection QA program criteria by (1) implementing those fire protection QA criteria as part
31 of their QA program under 10 CFR Part 50 Appendix B, or by (2) providing for NRC review a
32 description of the fire protection QA program and the measures for implementing the program.
33 Commitments made by licensees regarding fire protection quality assurance are applicable to
34 both deterministic [10 CFR 50.48 (b)], and performance-based [10 CFR 50.48(c)] fire protection
35 plans.
36

37 In 1977, a letter sent to each licensee titled, "Nuclear Power Fire Protection Functional
38 Responsibilities, Administrative Controls, and Quality Assurance," provided NRC supplemental
39 guidance on the quality assurance necessary to assure an effective fire protection program,
40 which was reiterated in Generic Letter (GL) 82-21, "Technical Specifications for Fire Protection
41 Audits." These documents provided supplemental guidance on the 10 fire protection
42 QA program criteria, which included:
43

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

- 1 8. corrective action
- 2 9. records
- 3 10. audits

4
5 All 10 of these criteria have application to the QA of VEWFD systems. However, because of the
6 fact that ASD VEWFD systems are engineered systems, several of these QA criteria can have a
7 high impact on assuring the adequate performance of VEWFD systems. Some of these criteria
8 are discussed in detail below.

9
10 Design Control and Procurement Document Control

- 11
- 12 a. Control of design and procurement documents changes—including field changes and
- 13 design deviations are subject to the same level of controls, reviews, and approvals that
- 14 were acceptable to the original document—is controlled.

15
16 The sensitivity of the ASD at the sampling port is dependent on the size and number of
17 sampling port holes on an individual zone. Any deviations or field changes (sometimes referred
18 to as “as-built”) from the original engineered design of the system (as-designed) will have a
19 direct impact on the performance of the system. Depending on the differences between the
20 as-built and the as-designed system this may improve or degrade the performance of the
21 system.

- 22
- 23 b. Quality standards are specified in the design documents such as appropriate fire
- 24 protection codes and standards, and deviations and changes from these quality
- 25 standards are controlled.
- 26
- 27 c. New designs and plant modifications, including fire protection systems, are reviewed by
- 28 qualified personnel to assure inclusion of appropriate fire protection requirements.
- 29

30 Installations, Procedures, and Drawings

- 31
- 32 a. Configuration control activities such as design, installation, inspection, test,
- 33 maintenance, and modification of fire protection systems are prescribed and
- 34 accomplished in accordance with documented instructions, procedures, and drawings.
- 35
- 36 b. Instructions and procedures for design, installation, inspection, test, maintenance,
- 37 modification and administrative controls are reviewed to assure that proper inclusion of
- 38 fire protection requirements.
- 39

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

44
45 Inspection

46
47 A program for independent inspection of activities affecting fire protection should be established
48 and executed by, or for the organization performing the activity to verify conformance to
49 documented installation drawings and test procedures for accomplishing activities. The
50 independent inspectors should be knowledgeable in the design and installation requirements of
51 the structures, systems and components (SSCs) being inspected and follow appropriate

1 procedures, instructions and checklists to perform a comprehensive inspection. For ASD
2 VEWFD systems, these inspections and, the applicable code requirements should be followed
3 and could include, but are not limited to, the following:
4

- 5 • Verify that sampling ports or points are not obstructed.
6
 - 7 – If drop-down flexible capillary tubing is used, this should include a verification that
8 no blockage has occurred at the sampling end of the capillary or at the junction of
9 where the capillary connects to the rigid smooth bore piping.
- 10 • Verify that filters are clean and have been changed per manufacturer's
11 recommendations, plant procedure, or code requirements.
- 12 • Visually verify that sampling piping has been permanently installed per design
13 requirements, or as-built if calculations based on as-built configurations, fittings appear
14 air tight, and piping is clearly identified.
- 15 • Verify that the system sensitivity settings are consistent with any code requirements or
16 regulatory commitments.
- 17 • Verify that the system sensitivity calculations are adequate and correct.
- 18 • Verify that system testing has been completed per code, plant, or regulatory
19 requirements.
- 20
- 21
- 22
- 23
- 24
- 25

26 Test and Test Control

27
28 A test program should be established and implemented to ensure that testing is performed and
29 verified by inspection and audit to demonstrate conformance with design and system
30 requirements. Following construction, modification, repair or replacement, sufficient testing
31 (referred to as "installation testing" or "start-up testing") is performed to demonstrate that the
32 detection system will perform satisfactorily when it is placed in service and that all design criteria
33 are met. Written test procedures for installation tests incorporate the requirements and
34 acceptance limits contained in applicable design documents. Periodic testing (referred to as
35 "in-service testing" or IST) should be conducted on a pre-defined schedule to assure that the
36 system will properly function and continue to meet the design criteria. For example, testing
37 should be conducted with smoke or other acceptable product per manufacturers'
38 recommendations and instructions. Testing should be conducted at the farthest end sampling
39 port or test port in each piping run (zone). Airflow through all ports on each piping run should
40 also be verified. Additionally, sensitivity testing should be conducted to ensure detector
41 operability per design requirements.
42

43 Records

44
45 Records should be prepared and maintained to furnish evidence that the criteria enumerated
46 above are being met for activities affecting fire protection systems. Records should include
47 results of inspections, tests, reviews, and audits; non-conformance and corrective action
48 reports; and construction, maintenance and modification records and certified manufacturers'
49 data. Records can also be an important part of documenting the trending system performance

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

3 4 Audits

5
6 Audits should be conducted and demonstrated to verify compliance with design and
7 procurement documents, instructions, procedures, and drawings and inspection and test
8 activities. Audits should follow written procedures, and be conducted by knowledgeable
9 personnel not directly responsible for the area being audited. Audit results should be
10 documented, and follow-up actions should be taken by responsible management to correct any
11 deficiencies identified.
12

13 **2.6 System Performance Measures**

14
15 As with any system, there are attributes that affect the systems performance. Performance of a
16 specific detector will be dependent on the as-built system configuration⁵, manufacturing
17 procedures, quality and reliability control procedures, and the training and supervision of the
18 persons who install, use, and maintain the system. Quality assurance programs for fire
19 protection are maintained at each U.S. NPP and provide a level of assurance that fire protection
20 systems are designed, fabricated, erected, tested, maintained, and operated so that they will
21 function as intended (Ref. 16). Although no QA program will be able to identify all deficiencies,
22 the application of the fire protection defense-in-depth concepts provide added assurance that if
23 system deficiencies are not identified other echelons of protection are available to ensure
24 safety. Additionally, NFPA 805 requires procedures be established for inspection, testing, and
25 maintenance for fire protection features credited by the fire protection program.
26

27 This subsection provides a high-level overview of some of the system performance measure
28 associated with smoke detection systems. Several of these system performance measures will
29 be used to quantify the performance of smoke detection systems in Section 7.2. In addition, the
30 NFPA 805 standard requires monitoring programs to be established with methods to monitor
31 system effectiveness measures such as availability, reliability, and performance⁶.
32

33 **2.6.1 Reliability**

34
35 Reliability is an important aspect to consider when quantifying the usefulness of a detection
36 system. Reliability relates to the ability of the system and each individual component to be in
37 proper working condition at all times ready to perform its intended function (Ref. 17). The
38 complement to reliability is unreliability, which is commonly used in PRA and is defined in the
39 ASME/ANS PRA Standard as the *probability that a system or component will not perform its*
40 *specified function under given conditions upon demand or for a prescribed time.*
41

42 **2.6.2 Availability**

43
44 Availability is defined by NFPA Std. 805 as *the probability that a system, structure or component*
45 *of interest is functional at a given point in time* (Ref. 18). In PRA terms, the complement to

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

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

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

5 6 **2.6.3 Effectiveness**

7
8 System effectiveness is a measure of how well a design solution will perform or operate given
9 anticipated operational scenarios (Ref. 19). Effectiveness estimates for smoke detection
10 systems are influenced by the several parameters including detector technology; fire
11 combustion type; smoke generation material; smoke characteristics (particle size, concentration,
12 and transport length); ventilation configurations; and stratification effects. For ASD systems, the
13 as-built system configuration with regard to the application, layout, and sensitivities is also
14 important with regard to system effectiveness. Thus, the design of the smoke detection system
15 should be suited for the systems and components being protected. Effectiveness provides a
16 measure of how well a particular design solution will perform in meeting its design objectives.

17 18 **2.6.4 Maintainability**

19
20 The maintainability of detection units varies directly according to the complexity of the design
21 (Ref. 17). Detection systems should be maintained to ensure that performance deficiencies as
22 a result of outside influences such as dust, insects, requiring periodic maintenance include the
23 detector, filters and piping.

24
25 Smoke detectors are typically designed for a life expectancy of 10 years or more. Extended use
26 beyond 10 years should be evaluated, and, for systems expected to perform in excess of
27 10 years, detectors should be replaced or sent out for re-calibration to ensure proper
28 functionality. In addition, in-field calibrations such as re-baselining the alert and alarm
29 thresholds, drift compensation, or any other methods that could reduce the sensitivity of the
30 system to slowly developing fires, should provide evidence that such calibrations do not
31 compromise the early detection function of the system. Any reductions in sensitivity will affect
32 system performance, and the fire PRA quantification should be modified as a reduction in the
33 system's effectiveness (Ref. 20). Vendor recommendations should be followed regarding
34 calibration requirements.

35
36 Filters can be used for different purposes depending on the design of the system, but are
37 commonly used to remove dust particles from the air sample. High-efficiency particulate air
38 (HEPA) filters may be used on some ASDs as part of a dual air filtering design where the HEPA
39 filtered air is used to protect and isolate the detector optics from the actual air sample (non-
40 HEPA filtered) being analyzed. Protecting the detector optics can extend the life of the detector
41 and reduce the likelihood of detector soiling. Soiling of detector optics over time will reduce the
42 sensitivity of the system. The non-HEPA type filters are used to remove dust particles from the
43 sampled source but allow smaller particles of combustion to pass through into the sampling
44 chamber of the detector unit. These filters may be found inside the detector unit or in the
45 sampling manifold external to the detector unit. Depending on the environment where air
46 samples are taken, the rate of filter loading will vary, and periodic maintenance based on vendor
47 recommendations or field operating experience should be factored into determining the filter
48 replacement period.

49
50 The ASD smooth bore piping network must be maintained to ensure sampling points are not
51 blocked because of accumulation of dust or other foreign materials. Although the detector units

1 are capable of annunciating a trouble alarm because of low- or high-flow conditions, they are
2 not sensitive enough to alert when only one air sampling point is blocked. Gottuk and McKenna
3 reported that ASD system supervisory trouble alarms did not provide a low air flow warning until
4 76 percent of the total air flow was blocked on one sampling line for the system they use in
5 testing (Ref. 21). Operating experience has identified at least one instance in which systems
6 were commissioned, but not all sampling points were verified to be open and able to sample
7 from the protected space. Thus, for an extended period of time, the system was partially
8 nonfunctional. Operating experience from Canadian NPPs has also identified that collection of
9 dust balls within the ASD piping having degraded system performance. This has resulted in the
10 development of internal cleaning methods using compressed air and condenser balls to pass
11 through the ASD piping network to push out and clear any obstructions.

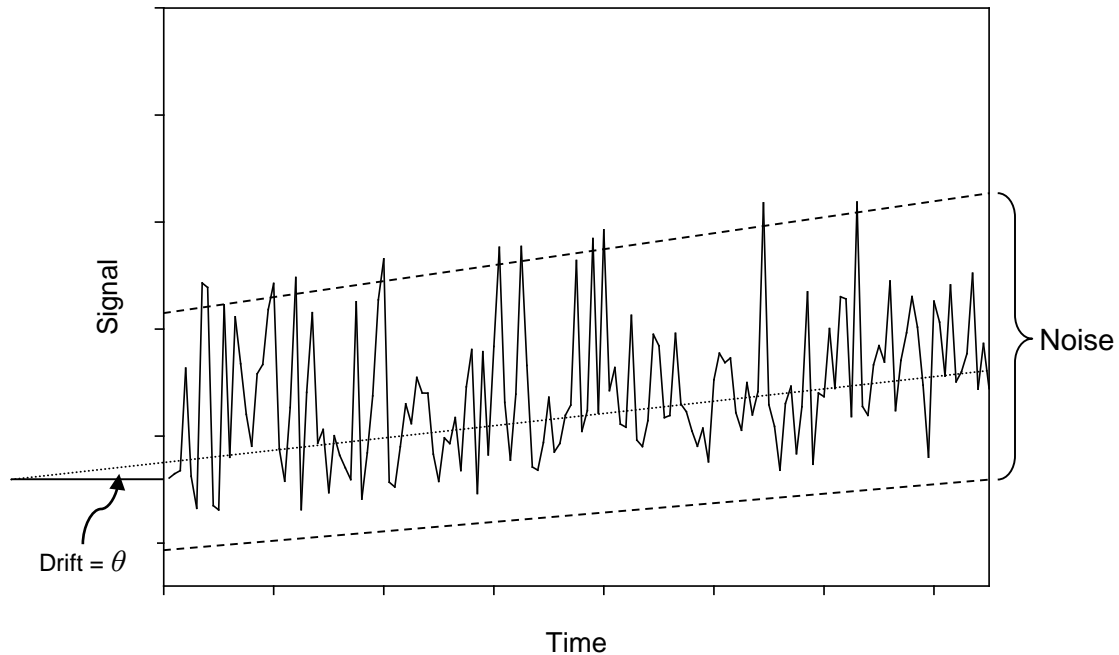
12
13 Ensuring sampling point functionality (ability to sample at each sampling point within a zone) is
14 important when the ASD VEWFD systems are installed for in-cabinet applications. Because
15 cleanliness of the air being sampled will vary among applications and plants, an increased
16 surveillance beyond the vendors' recommended surveillance period may be warranted to
17 ensure proper system function. In addition to using compressed air or vacuum cleaning
18 methods (depending upon vendor recommendations), a verification of openness of ASD
19 sampling points should be conducted, especially for in-cabinet applications. Although a blocked
20 sampling point in an areawide ceiling-mounted ASD type application will degrade the systems
21 performance, the blockage in the zone will result in increased flow in the other sampling points.
22 In addition to ensuring the ASD piping is clear and clean of any foreign materials and
23 accumulation of dust particles, the ASD piping network must also be periodically inspected to
24 ensure that no portions of the pipe have become dislodged or broken from other plant activities.
25 Any openings in the pipe will reduce the VEWFD system effectiveness, because the system is
26 no longer balanced as designed and the volume of air from the sampling points is both reduced
27 and diluted by the air flowing through the pipe opening.

28 29 **2.6.5 Stability**

30
31 The stability of a detector relates to its ability to sense fires over extended periods of time with
32 no change of sensitivity (Ref. 17). Stability is sometimes also referred to as detector sensitivity
33 drift. For ionization spot-type detectors, the accumulation of dust within the sensing chamber
34 over time can interfere with the detectors' sensitivity rendering them more sensitive, and hence
35 more prone to spurious nuisance alarms. The same effect occurs in photoelectric detectors
36 where by the accumulation of dust in the sensing chamber results in increased internal
37 reflectance and detector sensitivity, and makes the detector more prone to spurious nuisance
38 alarms (Ref. 5). However, light-scattering detectors become less sensitive as light intensity is
39 decreased because of the accumulation of dust and film (Ref. 15).

40
41 Detector sensitivity drift is a uni-directional gradual shift in the range of combustion products that
42 will activate the smoke detector. Background noise is the short time variation of the detector
43 signal. Most smoke detector use some form of drift compensation to counter this effect.

44
45 Figure 2-7 provides an illustration of noise and drift. Noise is considered to be the high
46 frequency peak-to-peak fluctuations. Background noise levels may fluctuate throughout the
47 day, or as a result of changing environmental conditions (e.g., HVAC changes, maintenance,
48 housekeeping, etc.). During commissioning of ASD VEWFD systems, background noise levels
49 are typically monitored for an extended period of time (up to 90 days) before making the system
50 operational, such that the relative sensitivities for the alert and alarm set points have a
51 background reference point that will minimize nuisance alarms.



1
2 **Figure 2-7. Illustration of detector signal background noise and drift**

3
4 **2.6.6 Serviceability**

5
6 The ease of which a system can be repaired is referred to as serviceability, and can be a
7 desirable aspect from a cost perspective (Ref. 21). Serviceability is a characteristic of the
8 system's design and is usually evaluated in the design stage. It is difficult to measure on a
9 numerical scale, and typically is evaluated by comparing various alternatives and assigning, a
10 ranking to each system in terms of its ease of serviceability.

11
12 For smoke detection systems in NPPs, numerous system design aspects should be considered
13 when evaluating serviceability. For instance, detection systems require periodic inspection,
14 testing and maintenance. The purpose of periodic inspection, testing and maintenance is to
15 ensure operational integrity of the system. Equipment performance can be affected by building
16 modifications; environmental changes; physical obstructions; physical damage; configuration
17 issues related to as-built and as-designed differences; improper installation; improper system
18 startup testing; degree of cleanliness; and other problems that may not be readily apparent.
19 The accessibility of the detection systems to support visual inspections and functionality and
20 sensitivity testing should be evaluated. In many areas of an NPP, obstructions in the upper
21 volume of the compartment can negatively impact the ease of performing periodic inspections
22 and testing. In some instances, the amount of obstructions (cable trays in particular), can make
23 it difficult or impossible to view the detector from floor level. On some occasions, scaffolding
24 would need to be constructed to support inspection and testing of detection systems.
25 Depending on the number of detectors or sampling ports in a room requiring scaffolding to be
26 erected, there could be a negative impact on the cost of performing such inspections and
27 testing, along with potentially increasing the risks to plant worker safety and NPP operational
28 continuity.
29

1 **2.6.7 Nuisance alarms**

2
3 Nuisance alarms (also known as *unwanted alarms*) are associated with non-fire conditions that
4 produce ambient conditions which mimic fire signatures and can cause a smoke detector to go
5 into an alarm condition. The detector sensitivity is frequently tailored to the particular
6 application to achieve the performance capability desired without being susceptible to nuisance
7 alarms.
8

9 **2.7 Inspection, Testing and Maintenance of Smoke Detection**
10 **Systems**

11
12 The use of performance-based approaches places greater dependence on fire detection system
13 success as a foundation of the fire protection strategy. The use of ASD VEWFD systems in fire
14 PRA as a risk reduction method requires the ASD systems to achieve a high level of
15 performance. With the increased reliance on ASD VEWFD systems to improve plant fire safety,
16 an increased importance on maintaining the predictability of these types of systems is required.
17 The required high level of performance necessitates the use and implementation of an effective
18 inspection, testing and maintenance program. The use of an ASD VEWFD system results in the
19 use of a single detector unit to cover a large area (up to 20,000 square feet) where traditionally
20 a large number of single spot-type detectors would have been needed. Simply, an ASD
21 VEWFD system detector unit failure (loss of protection in an entire area), causes further
22 consequences than spot-type detector failures in which the additional number of detectors
23 provides redundancy. Thus, use of ASD systems necessitates a high level of performance be
24 maintained to achieve the performance-based objectives and assumptions used in the
25 quantification of these systems. This section provides an overview of the types of inspections,
26 testing, and maintenance that support ensuring a high level of performance for ASD VEWFD
27 systems.
28

29 The performance of any fire detection system is dependent on system elements such as design,
30 installation, equipment, and maintenance (Ref. 5). An adequate inspection, testing, and
31 maintenance program allows for a method to reduce deficiencies in these elements.
32 For instance, room ventilation conditions may not allow for smoke to be transported to the
33 location where smoke detector sampling points are located. Initial inspection and testing of the
34 system should identify any problems that are designed into the system so that they can be fixed
35 before the system being accepted and placed into operation. Unlike spot-type detectors,
36 ASD systems are engineered systems. That is, these systems can be designed to meet a wide
37 variety of performance goals and objectives. As such, any deviations in the system from
38 as-designed to as-built, will affect the ASD's performance. Depending on the deviation, the
39 "as-built" system could be performing better or worse than expected. Thus, a thorough initial
40 inspection and testing of the system should be conducted to identify any deviations and then it
41 should be evaluated to ensure adequate system performance. Periodic maintenance and
42 inspection programs also provide assurance that statistical failures of the electronic components
43 and mechanical blockage or breakages of the smooth bore piping network are promptly
44 identified and properly corrected.
45

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

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

5
6 The telecommunications industry consensus standard NFPA 76 on the use of these systems in
7 performance-based applications requires installation, testing and maintenance in accordance
8 with NFPA 72 (Ref. 22). NFPA 72 provides methods and schedules for inspection, testing, and
9 maintenance of fire detection systems. With regard to air sampling-type initiating devices, the
10 NFPA 72 standard recommends following vendor guidance for testing detector alarm response
11 (functionality) and verifying air flow through all sampling ports (Ref. 8). It also provides the
12 frequency for conducting the recommended inspections, testing and maintenance.

13
14 Based on the available information and the need to ensure a highly reliable system through
15 proper inspection, testing and maintenance, it is recommended that, for NPP applications, the
16 requirements of NFPA 72 and vendor-recommended practices be followed. The fire risk
17 scoping study described in Part II is based on the assumption that these practices are followed
18 at a minimum.

1 **3. OPERATING EXPERIENCE, STANDARDS, AND LITERATURE**
2 **REVIEW OF VEWF D SYSTEMS**
3

4 **3.1 Review of VEWF D System Operating Experience**
5

6 Early on, the project team determined that testing alone would not provide all of the information
7 needed to quantify the performance of very early warning fire detection (VEWF D) systems in fire
8 probabilistic risk assessment (PRA) applications. Project objective Item C, “human reliability
9 analysis”; Item D “system availability and reliability”; and in part, Item E “system response to
10 common products of combustion applicable to NPP,” could not be adequately addressed by
11 testing alone. Consequently, the project team coordinated several site visits and expanded the
12 team with human reliability and human factor experts. The human factors and HRA aspects of
13 this project are presented in Section 9 and 10, respectively. This section describes how the site
14 visits and actual operating experience were used to gain a better understanding of these
15 systems applications, and their reliability, availability, and general operating experience.
16

17 **3.1.1 Site visits**
18

19 The National Institute of Standards and Technology (NIST) and U.S. Nuclear Regulatory
20 Commission’s (NRC’s) Office of Nuclear Regulatory Research (RES) staff conducted several
21 site visits to nuclear and non-nuclear facilities to gather information and operating experience for
22 aspirating smoke detection (ASD) applications. These site visits provided two benefits. First,
23 observing how the systems were used in the field allowed the planning of the testing to be
24 conducted in a manner that reflected actual use. Second, the team gathered information on the
25 operating experience (e.g., reliability and availability) of these systems to address project
26 objectives. Site visits were conducted at the following facilities;
27

- 28 • NASA Goddard Space Flight Center (Maryland)
- 29 • Shearon Harris Nuclear Power Plant (North Carolina)
- 30 • H.B. Robinson Nuclear Generating Station (South Carolina)
- 31 • Bruce Nuclear Generating Station (Ontario, Canada)
- 32 • Darlington Nuclear Generating Station (Ontario, Canada)
- 33 • Pickering Nuclear Generating Station (Ontario, Canada)
- 34 • Three Mile Island Nuclear Station (Pennsylvania)
- 35 • Operator response questionnaire (through the Electric Power Research Institute)
- 36

37 To facilitate a structured, consistent, and thorough exchange of information during these site
38 visits, a checklist of questions was developed and used. Topics included system performance
39 objectives, system design, installation and maintenance, operator interface, and actual system
40 performance. A summary of the insights obtained during these visits is provided herein.
41

42 **3.1.1.1 U.S. nuclear facilities**
43

44 For the U.S. nuclear facilities visited, licensees indicated that VEWF D systems were installed as
45 risk reduction measures to support risk quantification studies, or to support an exemption from
46 deterministic fire protection requirements. The VEWF D systems used were of the ASD type.
47

1 Deterministic Applications

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

15
16 Operating experience obtained during interviews (with fire protection staff regarding the
17 successes from these systems), included a case in which a potential fire from an air-handling
18 unit (AHU) fan motor failure was detected by this ASD system and operators responding to the
19 alarm were able to identify the failing component and isolate it before any fire conditions. It was
20 indicated that the early detection and response to this event possibly prevented a plant trip.
21 Other events detected by these systems, but not directly related to reactor safety, include
22 detecting hot work in a battery room and burned popcorn from a microwave oven.
23 Documentation of success cases can play an important role in understanding and quantifying
24 the reliability of operator response to ASD system notifications. Unfortunately, these cases
25 were not documented.

26
27 Risk Applications

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

32
33 In an IPEEE case, the licensee postulated a fire scenario in a control room reactor turbine
34 generator board (RTGB) contributing to a core damage frequency (CDF) of 4.47×10^{-5} per year.
35 Installing the in-cabinet ASD VEWFD system resulted in an increased time period between fire
36 detection and mitigation, which the IPEEE states a drop in the overall CDF for the postulated
37 fire scenario to 6.86 E-6 per reactor year (Ref. 23).

38
39 The use of ASD VEWFD systems in fire PRA for plants transitioning to NFPA 805 typically
40 followed the interim staff position method described in Supplement 1 to NUREG/CR-6850,
41 Frequently Asked Question (FAQ) 08-0046 titled, "Incipient Fire Detection Systems." In one
42 scenario, several installations of the VEWFD systems were used as defense-in-depth measures
43 only and were not quantified in fire PRA.

44
45 For the risk analysis applications, ASD VEWFD systems were exclusively used for in-cabinet
46 (within electrical enclosures) applications in non-continuously occupied areas and in most
47 cases, are complemented by conventional NFPA 72 standard areawide spot detectors within
48 the same room. The installation of ASD VEWFD in-cabinet detection either replaced
49 conventional in-cabinet spot detectors, or provided new detection within the electrical enclosure.
50 The electrical enclosures protected by ASD VEWFD systems contain safe shutdown system
51 function and components. Within these enclosures vital electronic circuitry, instrumentation and

1 control devices are found along with electrical cable and wiring used by these systems.
2 Ventilation flow rates were not known, but all electrical enclosures that used VEWFD systems
3 were of a vented design. There were no applications identified at the sites visited where
4 VEWFD systems were used to detect smoke entering the return air ducts of the compartment
5 ventilation system.
6

7 NFPA 72, "National Fire Alarm and Signaling Code," was used⁷ as the code of record for these
8 systems and in one case the response time of 60 seconds found in NFPA 76, "Standard for the
9 Fire Protection of Telecommunications Facilities" was adopted over the 120-second maximum
10 response time specified in NFPA 72. Section 8.5 of NFPA 76 states several requirements for
11 VEWFD and early warning fire detection (EWFD) systems, such as the maximum coverage
12 area per port; minimum sensitivity settings for alert and alarm conditions; and the maximum
13 transport time from the most remote sensing port to the detector (Ref. 22). Section 3.2 of this
14 report provides more detail on smoke detection standards.
15

16 Two types of ASD technologies were found to be in use at the sites visited. One site used a
17 laser-based detection technology that had been in use for over 14 years. The other site used a
18 cloud chamber detector technology that had been in service since 2010 (about 20 months of
19 operation at the time of the site visit). Both systems were ASD VEWFD, Underwriters
20 Laboratories (UL) listed, and installed by certified installers. In all cases, the detector unit was
21 located within the same room as the electrical enclosures that were being protected. The
22 distance the detector is located away from the cabinets was dependent on meeting the NFPA
23 response time criteria. One unit consisted of a single zone with five sampling ports, whereas
24 the other system was capable of sequentially sampling multiple zones (up to four) connected to
25 the detector. In the latter case, the cycle time to complete sampling of all four zones was one
26 minute.
27

28 The systems were installed by plant craft (instrumentation and control, electrical maintenance,
29 or electrical craft personnel). Once installed, plant operations, engineering, system certifying
30 officials, and the VEWFD system vendor technical representative performed the initial system
31 configuration and testing. The VEWFD systems were initially configured with sensitivity settings
32 consistent with the vendors experience in similar monitoring locations and environments. For
33 one site using a cloud chamber detector, the sensitivity settings were set to a gain of 7 or 8 out
34 of 10, with 10 being the most sensitive range. The specific sensitivity settings within this gain
35 setting were set to vendor predetermined values (30 percent, 50 percent, 70 percent, and
36 90 percent). Acceptance testing followed, which, depending on the VEWFD systems included
37 the following:
38

- 39 • validation of detector response to smoke source
 - 40 – (small element heat gun) provided by the vendor for generation of particles of
 - 41 combustion
 - 42 – British Standard (BS) 6266 annex tests
 - 43 – test gas/aerosol
 - 44
- 45 • validation of transport times (detector response times)
- 46
- 47 • placing the detector in fault by restricting air flow
- 48

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

- 1 • placing the backup batteries in fault condition
- 2
- 3 • placing the air separator in a fault condition
- 4
- 5 • putting the alternating current (ac) power in a fault condition
- 6
- 7 • confirming proper alarms on detector panel, local interface panel, and fire alarm console
- 8 in control room.
- 9

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

21
22 Availability of these systems varied among the two sites visited. In one instance, the systems
23 were down for semi-annual and annual testing, trouble alarms and for any cases in which the
24 systems were intentionally turned off because of hot work, or other activities that would cause
25 unwanted alarms. Any time the system is off, fire watches are in place. Testing alone could
26 account for up to 8 hours per device per year of downtime. Trouble alerts/alarms received
27 included lower water level; vacuum fault (cloud chamber failure); airflow exceed set point (out of
28 set point tolerance, but within system range); and transport time faults. Most of these
29 troubleshooting alerts/alarms required vendor input to resolve. The other site experienced
30 roughly the same down time for testing, but also experienced several weeks of outage time
31 because of hardware failure. At this site, the system was out for 27 days in 2002 for a panel
32 replacement. The lengthy interruption resulted from not having a replacement panel on site, nor
33 the lead time to acquire a replacement from non-domestic sources. The second outage
34 occurred in 2007 and lasted for 20 days. In this instance, staff initially thought that another
35 panel failure had occurred. This time there was a replacement panel on site, but upon
36 installation, it was determined that the replacement panel experienced an infant mortality failure.
37 The site ultimately determined that the root cause of the initial panel failure was the need for a
38 battery replacement. Upon battery replacement in the initial panel, the system was returned to
39 operation. In all cases, trouble alarms were received from the system and the site
40 instrumentation and controls technicians promptly began their investigation. The sites
41 corrective measure to avoid future excessive downtime was to have spare parts available
42 on site.

43
44 No fire, even in its earliest pre-flaming phase, occurred in the areas where the VEWFD systems
45 were installed at either site. In other words, there were no opportunities for these systems to
46 respond to actual incipient fire conditions. However, there were several cases in which the
47 systems generated nuisance alarms because of hot work, grinding and operation of a floor
48 buffer. None of these instances resulted in fires, but this information does provide some
49 quantitative information on the sensitivity of these systems. In response to future unwanted
50 alarms, the utility intends to turn off the VEWFD systems and station fire watches while the

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

5
6 As identified by the users, a drawback to these systems was that the required quarterly and
7 annual surveillances were time-consuming and expensive. The sites identified that the systems
8 were complicated and required significant vender interface to ensure proper operation. Lastly,
9 one of the sites ran into an issue with receiving replacement parts in a timely manner, which
10 resulted in an extended outage of the system. Their recommendation was for end users to
11 determine the timeliness of acquiring replacement parts, and to, wherever possible, have spare
12 units on site to reduce extended outage times.

13
14 Operator actions in response to system alert/alarm conditions are important to understand in
15 characterizing the failure probability of operators trying to complete specific actions. During the
16 site visits, several questions were asked focusing on how operators would respond to
17 notification from the installed VEWFD systems. The operator responses were slightly different
18 between the facility that used the ASD for fire PRA applications and the one that used it for
19 IPEEE risk reduction.

20
21 For the fire PRA case, when an "alert" (pre-alarm) notification is received in the main control
22 room (MCR), an auxiliary unit operator (AUO) and technician are dispatched to the detector
23 zone electrical enclosure(s) to look for source of the notification. The technician is responsible
24 for bringing along a portable ASD, that he/she is trained and qualified to operate. The AUO
25 uses his/her human senses (sight and smell) to try to identify the source of the notification, while
26 the technician uses the portable device. Meanwhile, in the control room, the VEWFD systems
27 software is monitored from the shift technical advisor (STA) desk. If the ASD goes into an alarm
28 state, the fire brigade is activated and sent to the area where the detector is located with
29 necessary equipment for fighting any potential fires.

30
31 In the non-fire PRA case, it is important to note that the ASD VEWFD system is installed in the
32 RTGB located in the MCR. The RTBG is located in the front of the MCR, visible to the
33 operators. Both the VEWFD system detector and fire alarm panel are located within the MCR.
34 Upon detector alarm, the response procedure prescribes than an operator is to investigate the
35 five sections of the RTGB for smoke, charring, or overheating components. In addition to a
36 visual inspection, thermography equipment can be used to further investigate the source of the
37 alarm. Upon identification of the component causing the detector alarm condition, shutdown
38 and repair of the affected component are initiated. If necessary, the fire brigade is to be
39 activated. If no source component can be located, then the operator is to attempt to reset the
40 detector. If detector resetting doesn't clear the alarm, a fire watch is to be started, and
41 preparations should be made to activate the fire brigade. If an additional alarm on an opposite
42 zone is received, then the fire brigade is to be activated and the ventilation fans are to be
43 secured.

44
45 In all U.S. sites visited, any changes to the ASD VEWFD system sensitivity set points would
46 require an engineering change evaluation. If such changes were deemed appropriate,
47 personnel trained and qualified in the use of VEWFD system software for the installed detectors
48 were to make the approved changes. At the site with the longest operating experience (more
49 than 14 years), the sensitivity has never been changed.

1 **3.1.1.2 Non-U.S. nuclear facilities**
2

3 The non-U.S. facilities visited use ASD VEWFD systems because at the time of installation
4 (mid-1990s to mid-2000s), they were thought to be the best available detection technology to
5 protect critical areas of the plant that house critical control equipment. In addition, these
6 systems were installed in areas where spot detectors were difficult to install, inspect, test and
7 maintain. Currently, a regulatory design basis standard CSA N293-07, "Fire Protection for
8 Nuclear Power Plants" requires the installation of ASD VEWFD systems that meet the
9 requirements of NFPA 76 where redundant safe shutdown systems are located within the same
10 fire compartment. This standard also has a "control room complex" requirement to detect fires
11 at their incipient stages. In addition, some sites identified the use of standard Underwriters
12 Laboratories Canada (ULC) 536, "Fire Alarm Verification." Some respondents identified using a
13 0.1 factor in their fire PRAs for detection using ASD VEWFD system in non-continuously
14 occupied cases. No basis for this estimate was provided.
15

16 The VEWFD systems were installed in areawide configurations protecting critical electrical
17 control and instrumentation equipment. VEWFD systems were used to protect control
18 equipment and instrumentation rooms that contained critical reactor control and shutdown
19 equipment. These rooms included the main control room (four unit), control equipment rooms,
20 digital control computer rooms, and cable spreading rooms. The ASD VEWFD systems were
21 typically employed in areas where highly congested overhead components existed, making
22 routine maintenance and testing difficult for conventional spot detection heads, or multi-sensor
23 spot detectors. The ASD VEWFD systems complemented, replaced, or provided new detection
24 to the areas being protected.
25

26 Laser-based ASD VEWFD systems, which were used exclusively, operate on a light-scattering
27 principle and use dual photoelectric sensors. The multi-zone detector was the most commonly
28 used design, but there were a few instances in which single-zone detectors were used to protect
29 small rooms. As a pre-requisite for procurement, all detectors had to be ULC listed.
30 Additionally, the systems used also contained listings from UL and Factory Mutual (FM).
31

32 The detector units are typically located within the protected zone to minimize any pressure
33 differential effects. The ASD air sample is exhausted into the protected space to ensure that
34 smoke or airborne radioactive particles are not inadvertently propagated to other areas. The
35 detector sampling port coverage is typically 50-75 ft², which is less than that required by NFPA
36 76 (200 ft²). However, there are several areas near but still below the 200 ft² coverage area
37 required by NFPA 76. Ventilation conditions in rooms using ASD ranged from 2.5 to 4.5 air
38 changes per hour⁸. A third party installed the piping network and detectors, while an
39 independent certified engineering firm verified the installation. Commissioning of the system
40 was completed by a trained and qualified entity. Acceptance testing included verifying
41 parameter setup; determining alarm set points; verifying relay/wiring configurations; taking flow;
42 pressure and transport time measurements from each sample hole, conducting heated wire
43 testing, and third party verification.
44

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

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

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

9 10 Operator Interface

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

19
20 When pre-alarm conditions are detected, operators attempt to clear the pre-alarm. If
21 unsuccessful, an operator initiates an alert and requests emergency response technician
22 support. When detector alarm conditions are met, operators consult the fireworks computer and
23 data gathering panels for fire alarm message information. In an alarm condition, Operations
24 staff sound the emergency response tones for fire alarm response, which results in the
25 response of the fire brigade. Upon entry into the protected area, staff uses thermal imaging
26 cameras to detect incipient fires.

27 28 System Performance

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

36
37 Early on during the use of these systems, several nuisance alarms were received. Over the
38 years of use, some of these systems’ set points have been offset to account for the
39 environmental conditions, which as a result, have reduced the number of nuisance alarms. The
40 causes of these nuisance alarms include airborne charcoal dust from charcoal filters, fumes
41 from floor stripping, nitrogen purging, dust accumulation within the air sampling ports, but, in
42 some cases, are unknown. The most common cause of nuisance alarms was related to work
43 activities in the protected area when the system was not bypassed for such activities. Also,
44 during the summer immediately following the installation, heavy smog and wildfires in the
45 adjacent province resulted in higher than normal background conditions and resulted in
46 nuisance alarms.

47
48 Some final qualitative insights from the non-U.S. nuclear facilities visited included issues with
49 maintenance and sensitivity settings. For maintaining the systems, the users found that it is
50 very difficult to perform any maintenance outside of what is identified by the manufacturer. For
51 instance, if issues with flow, pressure, or transport time measurements are observed at the test

1 point, it may be required to test the individual sample holes. This can be difficult, time
2 consuming, and may potentially have a negative impact on safety because of the complexity of
3 accessing the sampling pipes and ports in very sensitive areas. In addition, foreign particles or
4 dust may accumulate in the air piping, and in several cases it has been found that the
5 manufacturer's recommended practice of using compressed air is not effective. Alternative
6 actions were required to restore system operations. This specific problem occurred in a 3/4-inch
7 diameter piping network. Regarding sensitivity, both operations and control maintenance have
8 indicated that the system is overly sensitive to dust and smog. It was also emphasized that
9 plant personnel are pleased with the ASD VEWFD systems and they work well for small rooms,
10 but in several cases in-duct, non-ASD type detectors were preferred for protecting larger rooms.

11 **3.1.1.3 Other U.S. facilities (non-nuclear)**

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

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

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

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

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

38 The NASA experience with VEWFD systems includes the following observations:

- 39 1. Fewer nuisance alarms were installed than spot detectors.
- 40 2. Issues arose from flow imbalances tripping airflow trouble alerts. The fix usually involves
41 piping the exhaust back to the protected space.

- 1 3. One system sensitivity adjustment was made (lowered) because of picking up a circuit
2 board “fry,” which is not unusual in areas with instrumentation assembly.
3
- 4 4. Nuisance alarms occurred because of vacuum dust.
5
- 6 5. Fire was recently picked up in a lab space.
7

8 The technicians check all pre-alert and trouble signals; (response is not time sensitive) Fire I
9 level does not evacuate the building; however, Fire II results in fire department response.
10 Sensitivity set to an equivalent 3 %/ft obscuration at sampling locations.
11

12 **3.1.2 Other sources of operating experience information**

13 Conference Proceedings

14 Forell and Einarsson identified one weakness in the fire detection systems evaluated in German
15 NPP units associated with the battery system (Ref. 25). Fire detection systems are connected
16 to the emergency power supply and equipped with an additional battery, making the fire
17 detection systems’ power supply both reliable and redundant. However, in one reportable case
18 it was identified that the emergency power supply failed, the fire detection system properly
19 functioned on the backup battery supply until its energy was depleted. It wasn’t until sometime
20 later (not reported) that operators identified the failure, leaving portions of the plant unprotected
21 for an extended period of time. Although the fire detection system backup power supply
22 performed as designed, human error, in not recognizing that the primary power supply had
23 failed, resulted in unavailability of the system.
24

25
26 Forell and Einarsson also reported that the primary cause of failures in ASD systems can be
27 attributed to flow changes caused by clogging of inlets and leaks in the pipework. The use of
28 ASD systems in German NPP units is a result of changes to Insurance Europe (formally the
29 Comite European des Assurances) and the European Standard EN 54 Part 20. Because of the
30 clogging and pipe leakage issue, the new specifications require an increased tolerance of
31 changes in ASD air volume flow from ± 50 percent to ± 20 percent (Ref. 25).
32

33 **3.1.3 Experience within other industries**

34 Telecommunications

35
36
37 The Network Reliability Council of the Federal Communications Commission (FCC) identified
38 fire protection challenges related to the network reliability of public telecommunications. Their
39 focus on a need to improve reliability in protecting the network from fire effects was largely a
40 result of a main switching room fire that occurred in the Hinsdale Central Office of the Illinois
41 Bell Telephone Company on May 8, 1988.
42

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

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

10
11 As a result of the recurrence of severe fire events in telecommunication facilities, and the need
12 to maintain high reliability and business continuity for these types of installations, the
13 telecommunications industry developed NFPA 76, "Standard for Fire Protection of
14 Telecommunications Facilities." This standard provides the minimum level of fire protection in
15 telecommunications facilities to protect equipment and service continuity where services such
16 as telephone (landline, wireless), data, internet, voice-over internet protocol and video
17 transmission are rendered to the public. Details on this standard are provided in Section 3.2.

18
19 As a result of this standard, the telecommunications industry has extensively used ASD
20 technology in certain applications to provide advanced warning. Part of the reasoning for using
21 ASD technologies are employed in telecommunication facilities, in part, as a result of difficulties
22 in implementing conventional spot-type smoke detection in environments with high air
23 ventilation rates and numerous complex physical configurations. Common telecommunication
24 challenges to detecting fires in information technology (IT) server room environments include
25 the following (Ref. 27):

- 26
27 1) varying fuel loads and ignition sources
28 - large number and concentration of electronic devices generate excessive
29 amounts of heat
30
31 2) obstructions that interfere with movements of smoke toward detection points
32 - server enclosures
33
34 3) high airflow
35 - smoke dilution
36

37 U.S. Navy

38
39 Engineers at the Naval Sea Systems Command indicated that they were unaware of any U.S.
40 Navy ships that employ these types of systems. Spot-type smoke, heat and flame detectors are
41 commonly used on surface ships. Because of the large size and number of compartments
42 aboard, the increased cost and installation difficulties make using ASD systems challenging.
43 However, future ship designs are expected to use ASD systems (not configured as VEWFD) in
44 a limited number of special applications, because of unique overhead structures (Ref. 28).
45

46 **3.2 Standards, Listings, Approvals and Codes of Practice**

47
48 Standards, listings, and approvals provide a means to demonstrate that a product meets a
49 minimum level of performance. Applicable standards for air sampling smoke detection systems
50 include NFPA 72, "National Fire Alarm and Signaling Code," and NFPA 76, "Standard for the

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

7
8 The remainder of this subsection provides a brief overview of the associated standards and
9 listings. For specifics on these standards, the reader may reference the applicable standard(s).

10 11 NFPA Standards

12
13 NFPA 72 establishes the minimum required level of performance for the application, installation,
14 location, performance, inspection, testing and maintenance of fire alarm systems. It provides
15 installation guidance for air sampling-type smoke detectors, but doesn’t identify any
16 requirements for VEWFD or EWFD systems. The guidance provided includes maximum
17 transport time, each sampling port to be treated as a spot-type detector, air flow trouble signal,
18 pipe labeling and a requirement the sampling pipe networks be designed and supported by fluid
19 dynamic principles.

20
21 NFPA 76 provides installation requirements for VEWFD systems used in telecommunication
22 facilities. The requirements of NFPA 76 detail the maximum coverage area; requirements for
23 monitoring air return ventilation from protected space; minimum sensitivity settings for alert and
24 alarm conditions; and the maximum transport time of the system. Although NFPA 76 provides
25 requirements for protection of telecommunications facilities, there is no other U.S. consensus
26 standard that is available for these systems, and as such, most U.S. NPP utilities reference
27 NFPA 76 as the standard applicable to their VEWFD system.

28
29 In addition to specifying the performance requirements of VEWFD systems, Annex B of
30 NFPA 76 also provides performance test procedures. Two types of tests are presented in the
31 annex. One uses a heated wire, while the other uses chemicals. Both tests are designed to
32 simulate small amounts of visible smoke that would be present in the early stages of a fire in a
33 telecommunications equipment area. The intent of the tests is to provide a quick, easy, and
34 repeatable functionality test (quantity, temperature, and color of smoke), while minimizing the
35 potential hazard to the facility and health of personnel in the test area. These test methods are
36 not intended to serve as a calibration of the ASD detection unit.

37 38 Listings and Approvals

39
40 UL provides a URXG product category listing that covers smoke-automatic fire detectors,
41 including air sampling types, employing a special construction different from conventional
42 detectors and designed to detect products of combustion in a specific location. Detectors with
43 this listing are installed in accordance with manufacturer installation instructions, in a manner
44 acceptable to the AHJ, and in accordance with NFPA 72. The basic standard used to
45 investigate products in this category is UL 268, “Smoke Detectors for Fire Alarm Signaling
46 System.”

47
48 UL 268 covers smoke detectors defined as “*an assembly of electrical components arranged to*
49 *detect one or more products of combustion.*” It provides a standard set of requirements for
50 smoke detectors employed in ordinary indoor locations, in accordance with NFPA 72. These
51 include assembly and component requirements, evaluation of detector performance under

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

13
14 FM provides independent testing and approval of smoke actuated detectors, including any
15 aspirating-type detectors for indoor locations, per its Class Number 3230 “Approval Standard for
16 Smoke Actuated Detectors for Automatic Alarm Signaling.” FM approval criteria include
17 performance and marking requirements, manufacturing facility examinations, quality assurance
18 procedure audits, and a followup program. Performance requirements include air flow, transport
19 time, sensitivity, and fire tests, per UL 268 Section 39 guidance.

20 21 Codes of Practice

22
23 British Standards Institution (BSI) publication BS 6266, “Fire Protection of Electronic Equipment
24 Installations—Code of Practice,” provides recommendations for the protection of electronic
25 equipment from fire. It identifies electronic equipment such as computer servers,
26 communications systems, design, manufacturing and distribution equipment. Because the
27 scope of this standard is for the protection of electronic equipment, it covers a variety of fire
28 protection topics, including separation, construction, building services, detection, suppression,
29 smoke control, and management. BSI 6266 indicates that all ASD systems should conform to
30 BS EN 54-20, “Fire Detection and Fire Alarm Systems. Aspirating Smoke Detectors,” and be
31 used in accordance with the Fire Industry Association (FIA) Code of Practice. For the interests
32 of this report, the information on detection, along with the material presented in Annex A on
33 spacing and location, are useful.

34
35 Annex A of BSI 6266 provides recommendations for the spacing and location of aspirating
36 sampling holes. For return air vent applications, it is recommended that each sampling port
37 have a maximum 0.4 square meter (m²) area of coverage, be a Class A system per EN 54-20,
38 and that manufacturers’ recommendations should be followed. For ceiling applications
39 (including floor or ceiling voids), a nominal effective sampling hole coverage area of 25 m² is
40 specified. The Annex then identifies that the coverage area can be increased or reduced
41 depending on various room attributes (e.g., air flow velocity, air conditioning state, detector
42 class, or layered detection configuration). For in-cabinet applications, the Annex recommends
43 that the sampling hole be placed where the ventilation exits the electrical enclosure, or within
44 the top 10 percent of a cabinet with no ventilation (sealed). There are also provisions for using
45 multiple sampling points within the same cabinet that has large vents. Annexes B through H
46 describe the various performance tests, including smoke pellet; paper; overheated enamel wire;
47 polyvinyl chloride/low smoke and fume (PVC/LSF) wire; PVC coated wire; resistor; polyurethane
48 mat; and potassium chlorate/lactose chemical test.

49
50 The FIA (England) has also developed a code of practice document titled, “Design, Installation,
51 Commissioning and Maintenance of Aspirating Smoke Detector (ASD) Systems” (Ref. 29).

1 This document defines three sensitivity classes (Class A, B, C), with Class A being described as
2 “Very High Sensitivity” applicable for in-cabinet application with high risk, as well as five ASD
3 sampling methods, including in-cabinet applications. It also explains that when operating as a
4 Class A or Class B system, the source of the alarm may not be readily visible and special
5 training should be provided to acquaint responders with the performance of these systems.
6 With regard to in-cabinet detection, the code of practice recommends that a sample point in
7 each cabinet be installed, and specifies preferred locations of sampling within the cabinet for
8 cabinet ventilation configuration (sealed, natural or forced). The in-cabinet application section
9 also provides recommended limits on the number of cabinets protected by various classes of
10 systems. In general, the FIA document provides fundamental design guidance of ASD systems
11 for various applications and supports the use of vendor experts to ensure that the design will
12 meet the intended design goals.
13

14 **3.3 Literature Review**

15
16 A literature review was conducted to better understand the information available on the use of
17 ASD VEWFD systems. Literature was collected from publically available sources, academia,
18 Internet, vendor Web sites, and journal articles. The collected literature was reviewed and
19 evaluated for its applicability in developing the test plan and to better advice regarding the
20 capabilities of this technology. Appendix E provides a summary of relevant literature reviewed.
21

22 In general, there has been substantial work in supporting the use of ASD VEWFD systems in
23 special applications, such as telecommunications facilities, warehouse, atria, and as a reference
24 tool to support evaluation of model prediction of conventional spot-type detector activation.
25 Unfortunately, most of the available test programs were developed to acquire data needed to
26 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 m² floor area, 90 m³ volume fire test room (small room) located at the Montgomery County Public Service Training Academy in Rockville, MD; and a 93 m² floor area, 283 m³ fire test room (large room) at Hughes Associates Inc., located in Arbutus, MD.

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

4.1 Detectors

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

Table 4-1. Smoke Detection Technologies Generic Identification System

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

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

1 The aspirated detector systems ASD1-ASD5 are stand alone, while the spot detectors are
2 interfaced to a fire alarm control panel (FACP). Because the spot detectors interfaced to the
3 FACP were addressable, the individual detector response times were identifiable.
4

5 The intent of this research was to examine the gross differences between VEWFD systems and
6 conventional detectors, and the expected performance from a range of VEWFD system
7 implementations. Because National Fire Protection Association (NFPA) 76 specifies the
8 minimum sensitivity settings above ambient background levels for VEWFD systems as an **Alert**
9 level of 0.2 %/ft obscuration at each port (or sensitive spot detector), and an **Alarm** level of 1.0
10 %/ft obscuration, these were the target sensitivities for ASDs and the sensitive spot detector. In
11 addition to **Alert** and **Alarm** settings, ASDs typically have additional adjustable settings. Thus,
12 a **Pre-alert** setting, more sensitive than the **Alert** setting, may be considered to instigate a non-
13 emergency investigation. Conventional photoelectric and ionization detector sensitivities were
14 set to the factory default settings. The specific photoelectric and ionization detectors were
15 individually addressable and had the feature of two sensitivity settings, a **Pre-alarm** and an
16 **Alarm** threshold. Per NFPA 72, 13th Ed., an alarm condition poses immediate threat to life,
17 property or mission, while a pre-alarm condition poses a potential threat but time is available for
18 investigation. For the testing completed, the pre-alarm setting is more sensitive than an alarm
19 setting, but still within the listing of the detectors used.
20

21 There was an issue identified concerning sensitivity settings for the procured cloud chamber
22 ASDs, which was not fully resolved. These ASDs do not report detector sensitivity in terms of
23 ANSI/UL 268 standard engineering units of percentage of obscuration per foot, but, in terms of
24 numeric (dimensionless) settings. That being said, for the testing performed to support this
25 research, the dimensionless units were converted to a nominal particle number concentration
26 obtained from the cloud chamber ASD software. An assumption was made that the number
27 concentration is a linear function of the obscuration, as would be the case with low
28 concentrations of the same smoke particles. The cloud chamber ASD sensitivity settings were
29 selected to represent **Alert** and **Alarm** settings that covered a range. These settings were not
30 fixed, but may have changed for different experimental configurations. The exception was the
31 last series of experiments with the multi-zone cloud chamber ASD, in which the vendor
32 commissioned the system, and provided the sensitivity settings.
33

34 The terms **Alert** and **Pre-alarm** are synonymous. Both intended to present a condition where a
35 potential threat is posed and sometime of unknown duration is available for investigation.
36 However, this report will use the terms consistent with the associated NFPA standards. That is,
37 **Alert** will be used exclusively for VEWFD systems per NFPA 76 and **Pre-alarm** will be used
38 exclusively for the conventional spot-type detectors per NFPA 72.
39

40 **4.2 Incipient Fire Sources**

41

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

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

3
4 It is assumed that the most probable, slowly developing incipient fire sources of the type that a
5 VEWFD system would be used to detect, would be electrically initiated. That is, electrical power
6 is the energy source used to produce the heat needed for the incipient source. Electrically
7 initiated fires are often preceded by some form of arcing or joule heating of electrical
8 components. The literature lists various ways electrical fires may be initiated including arcing,
9 overloads, poor connections and corrosion (Ref. 30, 31, 32). Regardless of the failure
10 mechanism, heat is typically conducted from a metallic electrical conductor to an insulating
11 polymeric material. Upon heating, insulating polymeric materials degrade, and pyrolysis
12 products can condense into smoke particles, which in sufficient concentration, can be detected.
13 Therefore, to assess the performance of VEWFD systems, smoke sources were developed that
14 mimic slow overheat conditions which degrade polymeric insulating materials and produce
15 smoke before flaming combustion.

16
17 The smoke sources were designed to mimic smoke evolution from a particular scenario likely to
18 be experienced in various electrical fires. A current overload, a high-resistance connection, or
19 combination of both produces joule heating that conducts heat to polymeric insulating material,
20 here, wire insulation, a printed circuit board, or terminal block insulation. As the material heats
21 up, it starts to thermally degrade, gases are released, and a fraction forms pyrolysis smoke
22 particles. The temperature at which particles are formed, the amount, and particle size depends
23 in part on the specific material, including the base polymer and additives.

24
25 The goal was to produce sufficient smoke to initiate alert and alarm conditions in some or all
26 detectors during a test. No attempt was made to achieve a flaming combustion transition as a
27 test end point. It is not necessary to have flaming ignition to provide a relative comparison
28 between detector technologies. It is, however, useful to specify a condition indicative of
29 imminent hazard for performance analysis purposes. In the data analysis, the end of test is
30 specified as an imminent hazard based on the heating source end temperature, and the extent
31 of thermal damage to the materials being heated. The rationale for choosing the final heat
32 source temperature achieved at the end of the test as an imminent hazard given the ignition
33 potential of the materials studied is detailed below

34
35 Transition to flaming requires an ignition event which would be scenario specific and frequently
36 a stochastic event. The ignition event could be piloted or non-piloted. A piloted ignition would
37 occur when a flammable mixture of the pyrolysis gases and air encounter an electrical arc or
38 spark whereas it ignites and a flame is established. A non-piloted ignition would occur when the
39 temperature of the degrading material is such that the reaction of the pyrolysis gases and air
40 spontaneously ignites and establishes a flame. For solids, piloted ignition is often characterized
41 by a piloted ignition temperature specific to a material, while non-piloted ignition is characterized
42 by a non-piloted ignition or auto-ignition temperature specific to a material. Piloted ignition
43 temperatures are lower than auto-ignition temperatures. Babrauskas tabulated a range of
44 ignition temperatures of plastics obtained by various literature sources based on broad polymer
45 property classes for both piloted ignition and auto-ignition experiments (Ref. 33). The classes in
46 the table represent a range of electrical insulation materials. The tabulated values are shown in
47 **Error! Reference source not found.** below.

1 **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

2
3 One can imagine three scenarios influencing the probability of ignition. In the first scenario, an
4 ignition source of sufficient strength is available at the onset of material heating. The material
5 must be heated to a point where the necessary gaseous pyrolysis fuel and air form a flammable
6 mixture. At that time, the gases ignite and establish a flame. This would be piloted ignition at
7 the lowest possible material temperature. An example would be continuous arcing that provides
8 sufficient heating to form a flammable mixture, with the arc itself acting as the ignition source.
9

10 In the second scenario, no piloted ignition source is available, and the material must be heated
11 to its auto-ignition temperature, whereas the material ignites. Whereas the auto-ignition
12 temperature is higher than piloted ignition temperature, these two temperatures bound the
13 minimum temperatures for ignition, below the minimum piloted ignition temperature the
14 necessary conditions do not exist for ignition, and at or above the auto-ignition temperature both
15 necessary and sufficient conditions exist and ignition will occur.
16

17 The third scenario involves an intermediate temperature range above the minimum piloted
18 ignition temperature and below the auto-ignition temperature. This scenario would involve the
19 introduction of an ignition source at some time when the material is in the intermediate
20 temperature range. The introduction of an ignition source would be a stochastic ignition event
21 involving a shorting spark, a wire breaking spark, a tracking arc, or a glowing hot surface either
22 of which at the right location and of sufficient energy to ignite the material. For a current
23 overload condition, or a high resistance connection, it is plausible to assume that the probability
24 of any stochastic ignition event described above would increase as the heating time increased
25 because of the level of local damage to the insulating material.
26

27 Given the smoke sources developed for the VEWFD experiments, the ignition scenario above is
28 an appropriate assumption to make, where some stochastic ignition event occurs before auto-
29 ignition of the material being heated. The end of test heating source temperature was initially
30 selected as 450 degrees C, for scoping experiments conducted in the laboratory at NIST, and
31 subsequently raised to 485 degrees C to produce more smoke at the end of the test for full-
32 scale experiments. Given the tabulated values of the piloted and auto-ignition temperature
33 ranges above, the end of test was specified as a condition of imminent hazard because the end
34 of test heat source temperature is in the range of auto-ignition temperatures and the materials
35 being heated appear to be above piloted ignition temperatures based on temperature
36 measurements detailed in Section 5.8. Also, ignitability experiments in Section 5.8 show that
37 piloted ignition is achievable at heating source temperatures well below the end of test value for
38 three down-selected materials. A more detailed analysis of ignition scenarios or ignition
39 probability is not within the scope of this research.
40
41

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

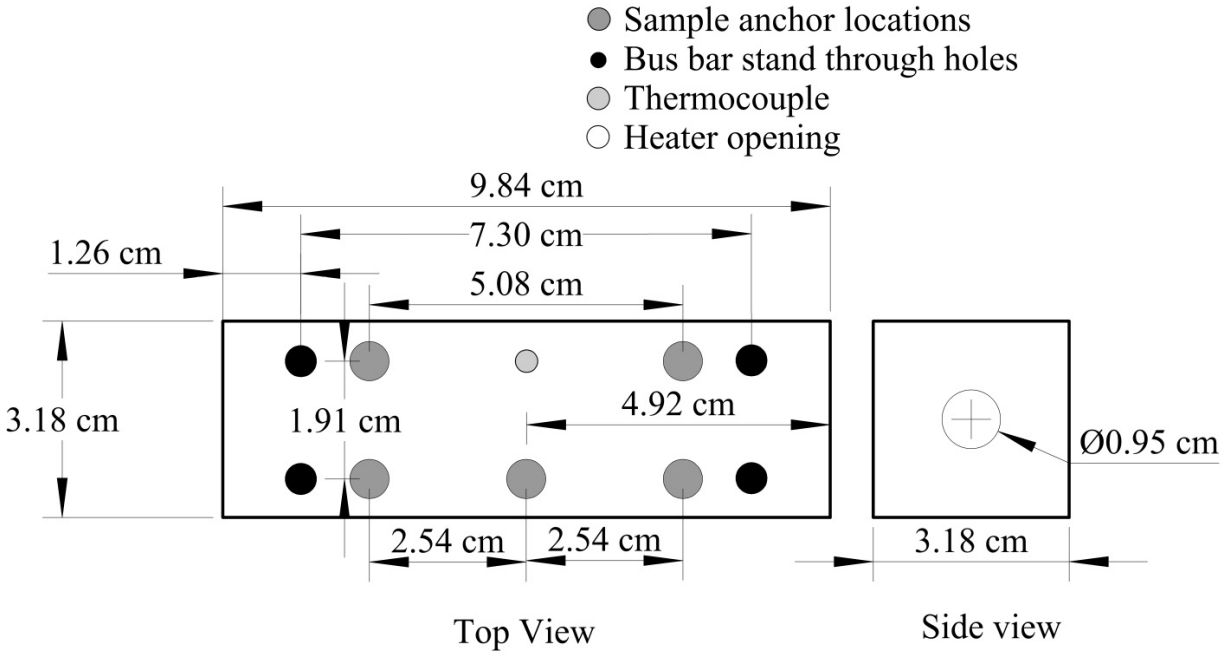
17 * Wires 4, 6, 7, and 11 were classified as qualified per IEEE 383, "IEEE Standard for Type Test of Class 1E
 18 Electric Cables, Field Splices and Connections for Nuclear Power Generating Stations."
 19

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

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

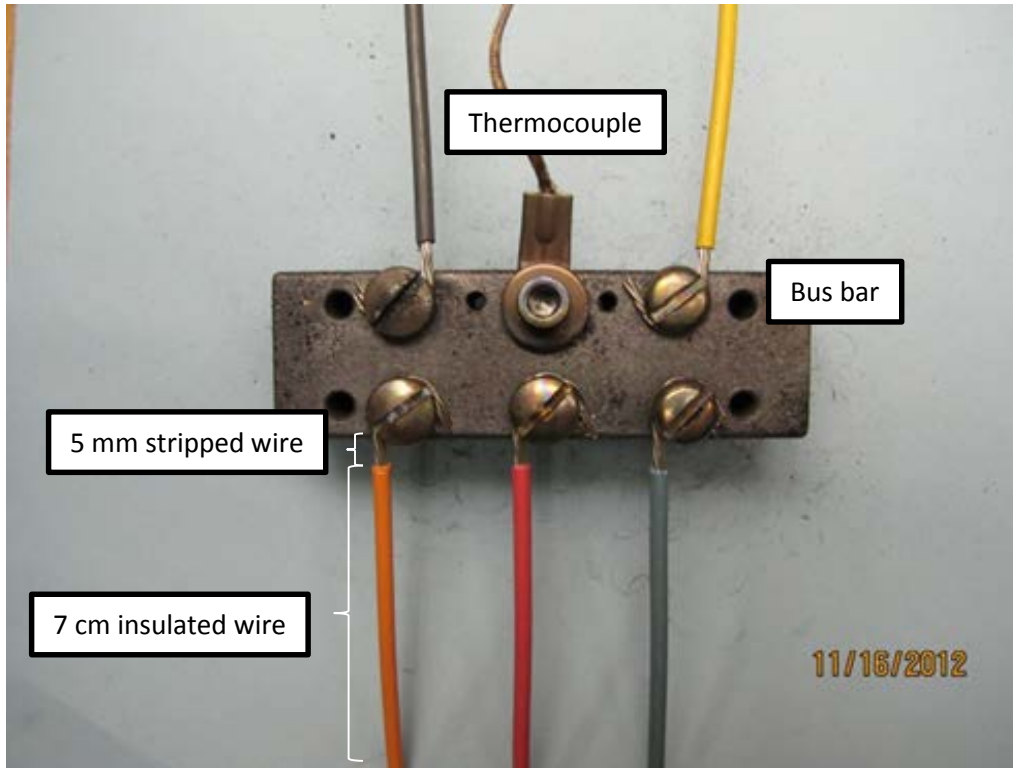
4
 5 **4.2.1 Bus bar heat source (insulated conductors, terminal block and printed**
 6 **circuit board)**

7
 8 The first 10 materials were degraded by conduction of heat from a copper block bus bar whose
 9 temperature was ramped from ambient to 450 °C or 485 °C. The bus bar was 9.84 cm long and
 10 3.2 cm square with a 9.5 mm hole drilled out along the long axis to accommodate a 500 watt
 11 electric cartridge heater. Figure 4-1 is a schematic of the bus bar.
 12



13
 14 **Figure 4-1. Schematic of the bus bar**

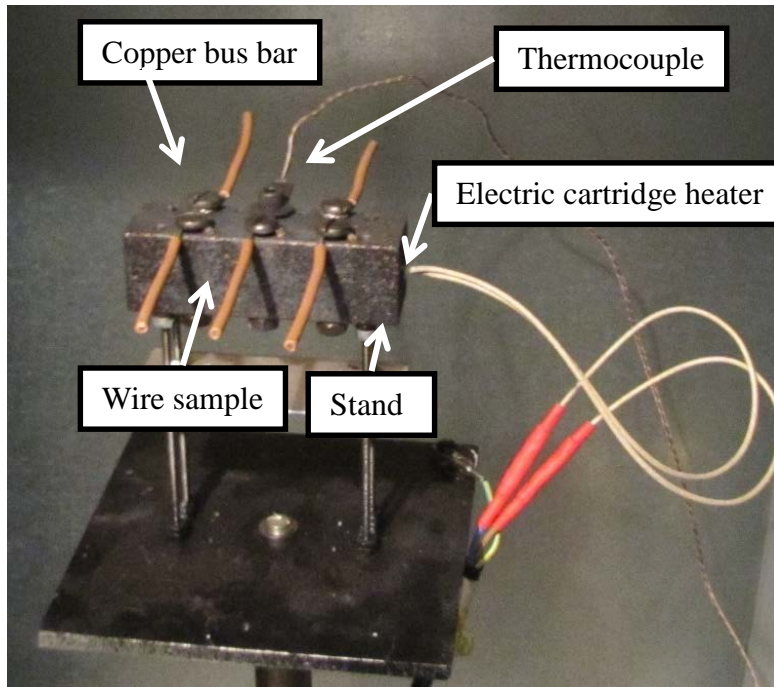
15 Wire samples were cut to 10.0 cm lengths, with 3.0 cm of insulation stripped from one end.
 16 Up to five samples of the same wire type were attached to the bus bar by wrapping the stripped
 17 wire end around a machine-head screw that passed through the bus bar and was held in place
 18 with a nut.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



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

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



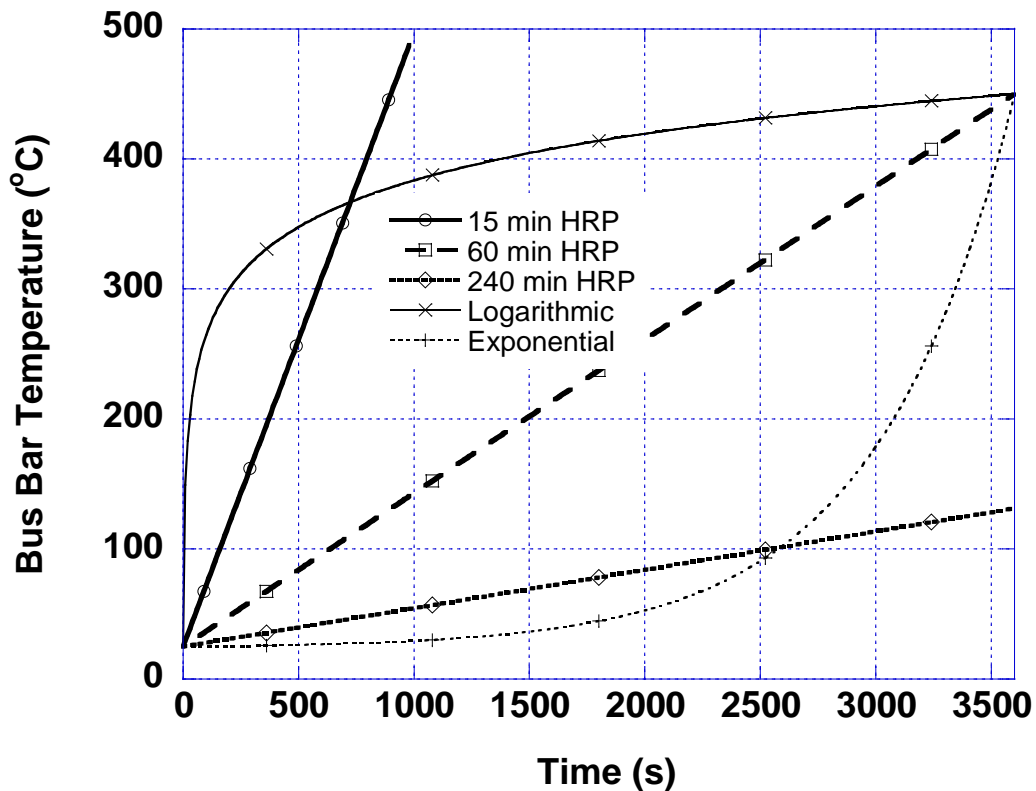
1
2 **Figure 4-3. The bus bar mounted on the stand inside a cabinet**

3
4 Six heating profiles were specified using three set point heating ramp periods (HRPs) and two
5 final set point ending temperatures. The first set of preliminary experiments were conducted
6 with three heating profiles: a 15 minute set point ramp from ambient to 450°C with a 5 minute
7 soak period where the set point remained at 450°C, a 60 minute ramp to 450°C with a 5 minute
8 soak, and a 240 minute ramp to 450°C with a 5 minute soak. Subsequent experiments were
9 conducted using three set point ramps to 485°C, keeping the same slope as the first set, which
10 extended the HRP to 16.3, 65, and 260 minutes, and maintaining the 5 minute soak period for
11 total heating times (THTs) of 21.3, 70, and 265 minutes, respectively. Set points read back from
12 the controller and bus bar temperatures were recorded in a heater log file for all experiments.

13
14 The three heating profiles of nominally 15-, 60-, and 240 minute heating duration represent a
15 factor of four increase from the first to the second, and the second to the third heating duration,
16 and heating rates of 28.33°C/min, 7.08°C/min, and 1.77°C/min, respectively.

17
18 Actual failure mechanisms that cause heating of polymeric insulating materials could present
19 other than linear heating profiles in the incipient phase that could be increasingly faster or
20 slower than a linear heating ramp. Linear heating ramps were chosen since actual heating
21 profiles are unknown, and the three linear heating ramps cover a wide range of heating rates.
22

23 Figure 4-4 shows set point ramps for 15-, 60-, and 240 minute HRP along with two bounding
24 heating profiles, a logarithmic and exponential increase in the heating profiles ending at
25 485 degrees Celsius (C) after 1 hour. The three linear ramp slopes are bound by the
26 logarithmic profile from 265 degrees C to 412 degrees C, and the exponential profile from
27 41 degrees C to 446 degrees C which covers a temperature range where degradation is
28 detectable by the ASDs.



1
 2 **Figure 4-4. Heating ramp profiles for 15, 60, and 240 minute HRP, with logarithmic**
 3 **and exponential bounding profiles that reach 485 °C in 60 minutes**

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

7
 8 In addition to the wire samples, printed circuit board (PCB, 10.1 cm by 10.2 cm by 0.1 cm thick)
 9 and phenolic resin terminal block (TB, 5.5 cm by 1.8 cm by 0.6 cm thick) samples were also
 10 used in experiments. The PCB was clamped between two 25 mm by 10 mm by 6 mm thick
 11 copper plates, with the bolts tightened using a torque screwdriver to 110 ± 5 N-m. Because the
 12 degradation was localized to the side being heated, a PCB could be reused for an additional
 13 experiment. The terminal block was mounted to a copper plate (2.5 cm by 10 cm by 0.3 cm
 14 thick) with two screws, with the plate then bolted to the bus bar. A mounted PCB and terminal
 15 block can be seen in Figure 4-5 and Figure 4-6, respectively.

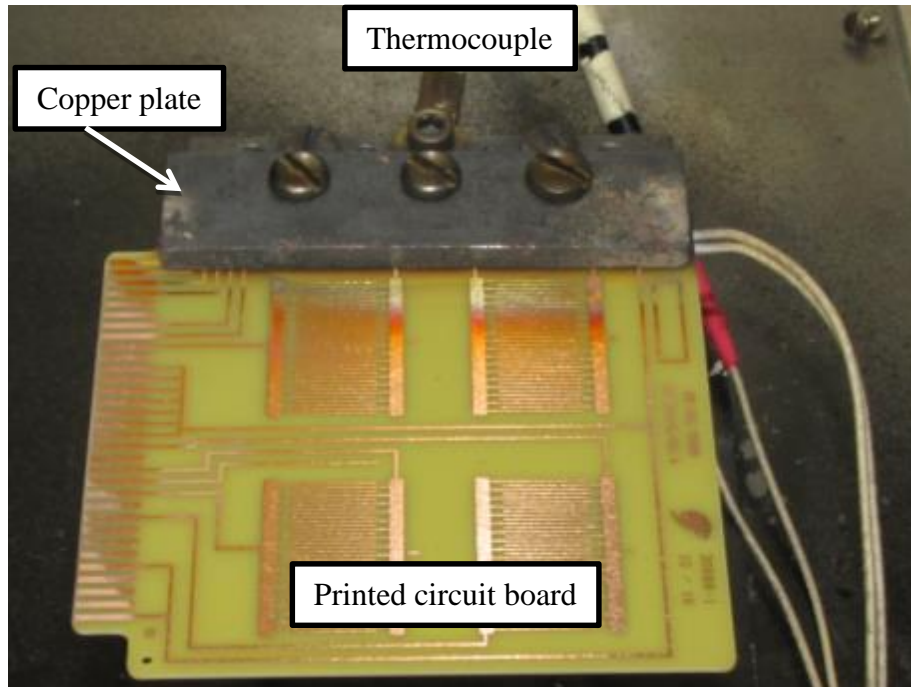


Figure 4-5. Printed circuit board (PCB) mounted to the bus bar

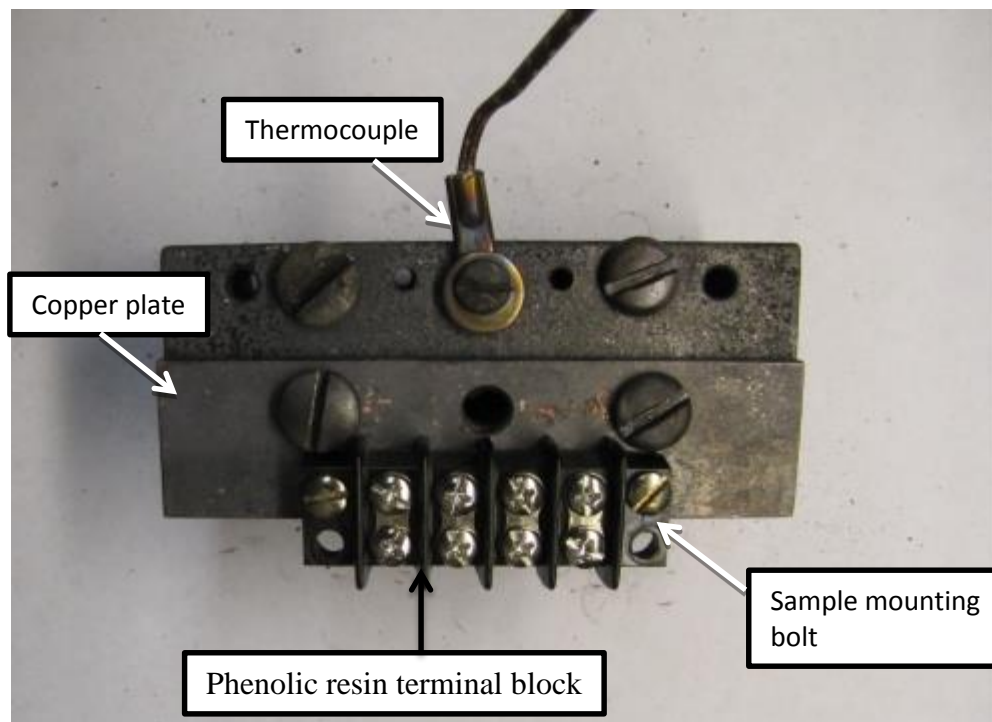


Figure 4-6. Terminal block (TB) mounted to the bus bar

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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 cm 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 copper tube as seen in Figure 4-7. The 400W heater replaced the 500W heater because the extra power was not needed to elevate the surface of the cable material to the 485 degrees C and the 400W heater was longer, allowing for more contact with the cable samples. Three HRP's were specified for these experiments: 16.3, 65.0, and 260.0 minutes, and THT's 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 copper 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.

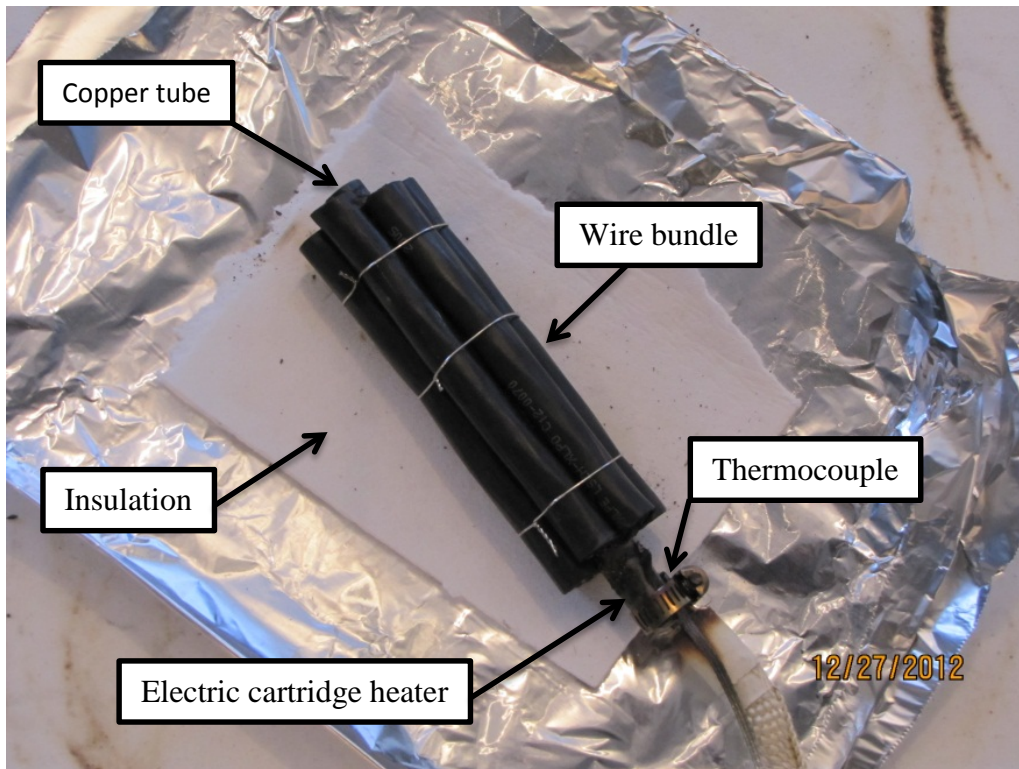
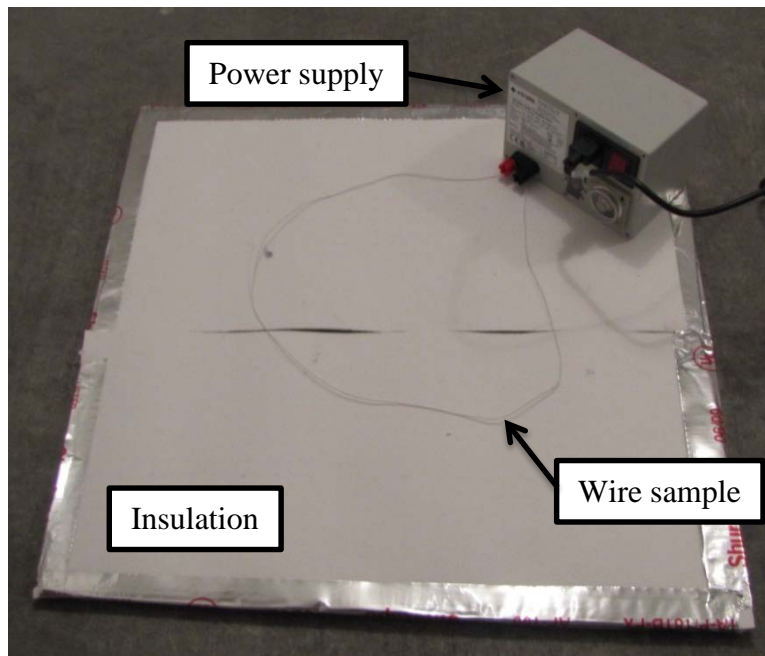


Figure 4-7. The cable bundle sample

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

1 chloride (PVC) insulated wire was heated for 60 seconds by passing a current through it from a
2 power supply capable of generating current up to 30 amps at 6 VAC. Additional tests were
3 based on a modified BS 6266 test which involves replacing the single wire with two 1 m wires in
4 parallel. Wire samples were placed on electrically and thermally insulated ceramic paper on top
5 of gypsum wallboard. An example of a single wire configuration can be seen in Figure 4-8. The
6 current causes significant resistive heating that subsequently cooks off the PVC insulation.
7 A pass/fail criterion of detection system response (any sensitivity) was used within 120 seconds
8 after the end of the electrical power application for the single wire source or **Alert** for two
9 parallel wire tests for VEWFD systems.
10



11
12 **Figure 4-8. A single wire test was setup following the British Standard 6266**

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

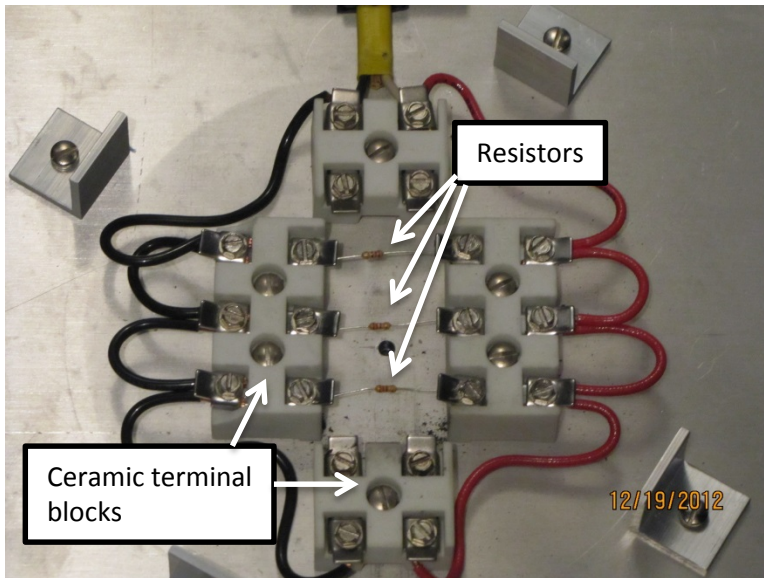


Figure 4-9. A set of three resistors wired in parallel.

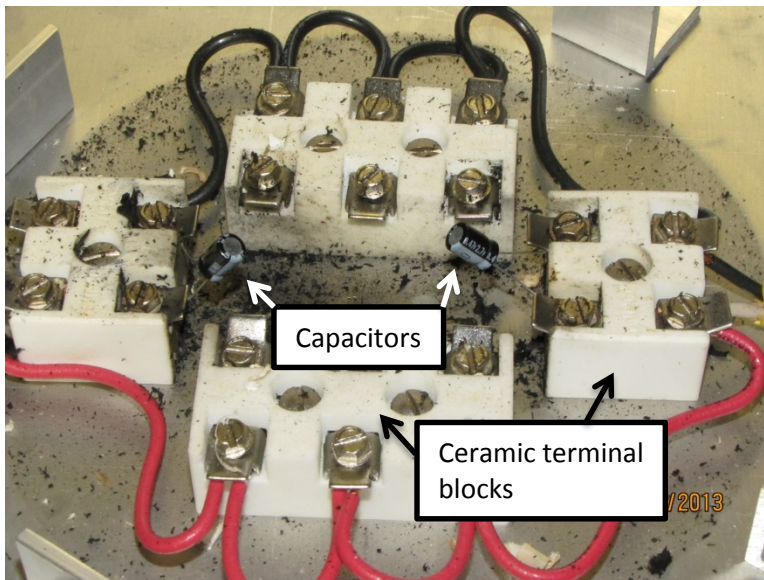
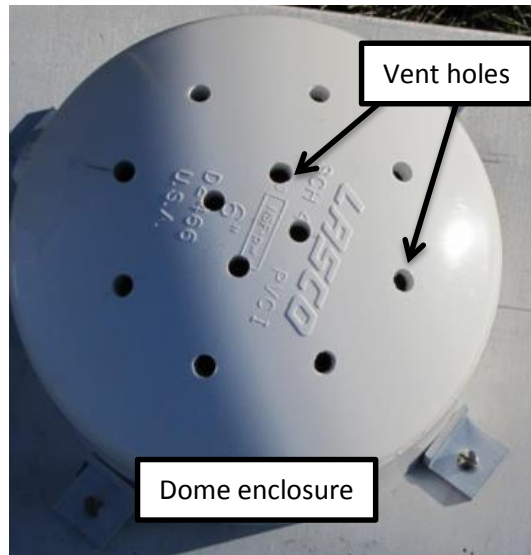


Figure 4-10. A pair of capacitors wired in parallel

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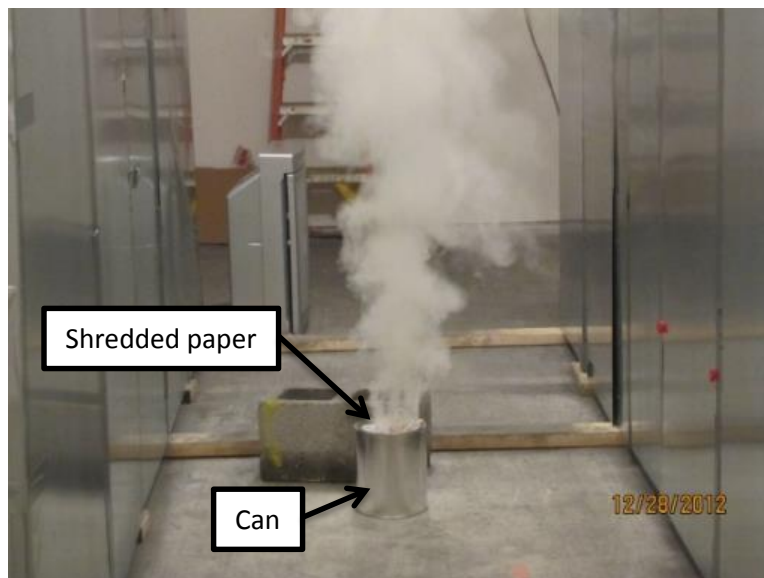
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1
2 **Figure 4-11. Dome enclosure for the resistor and capacitor tests**

3 **4.2.4 Shredded paper smoldering source**

4
5 Two experiments were conducted with a smoldering paper source. The purpose of introducing
6 this source was to evaluate detector response to smoldering conditions. Two cotton wicks
7 (same used in UL smoke box) were inserted into a clean one gallon can, filled with shredded
8 paper. Approximately two handfuls of shredded copy paper were used. The wicks were ignited
9 before they were placed inside the can. The test began when the sample was placed in the
10 center of the test room, and concluded when the fire transitioned to flaming combustion. The
11 test generated a substantial amount of visible smoke during the smoldering process before it
12 transitioned to flaming combustion. An example of the smoldering paper can be seen in Figure
13 4-12.
14



15
16 **Figure 4-12. Shredded paper test**

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4.3 Measurement and Control Instrumentation

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

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

4.3.1 Temperature controls

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

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

4.3.2 Smoke detector monitoring

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

4.3.3 Aerosol instrumentation

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

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

4 4.3.4 Ambient environment measurements

5
6 Measurements were taken at all locations to monitor the ambient environment before, during
7 and after each test. For small-scale tests, ambient temperature was monitored near the top and
8 bottom of the cabinet. In most laboratory experiments, the particle concentration was also being
9 recorded. The large-scale tests in the 38 m² room had its room temperature monitored at
10 various heights in the center of the room. A portable particle counter was used to monitor the
11 ambient particle concentrations. Humidity was monitored at all the test locations for the duration
12 of all tests. Background information was taken for up to 120 seconds.

14 4.3.5 Thermal imaging

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

22
23 The emissivity of the bus bar was taken to be 0.78, that of oxidized copper, and was kept
24 constant for all the tests. The transmissivity of the IR window was taken to be 0.5. The camera
25 was controlled remotely from the computer via a USB cable. The settings on the camera, such
26 as emissivity and transmissivity, could be changed after the test by using the accompanying
27 software. The camera was limited to measuring temperatures up to 370°C. An example of a
28 temperature profile measured using the thermal camera can be seen in Figure 4-13. All images
29 for the monitored experiments are given in the Appendix.



31
32 **Figure 4-13. Thermal image of XLPE wires following a 60.0 minute heating ramp and a**
33 **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.

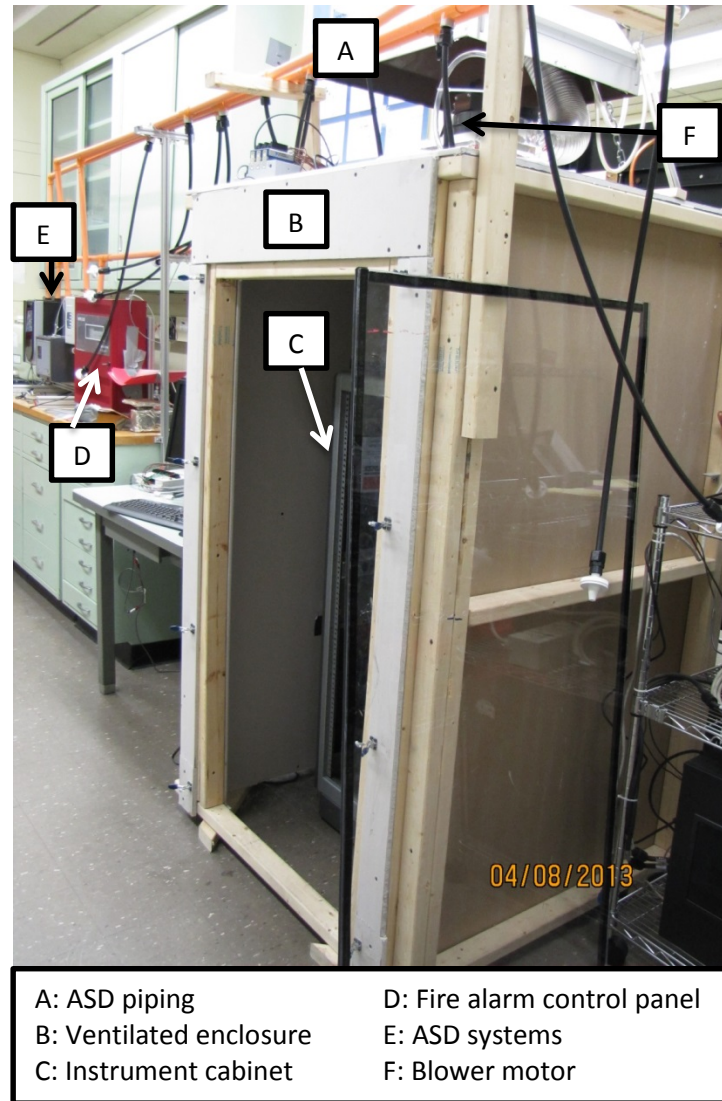
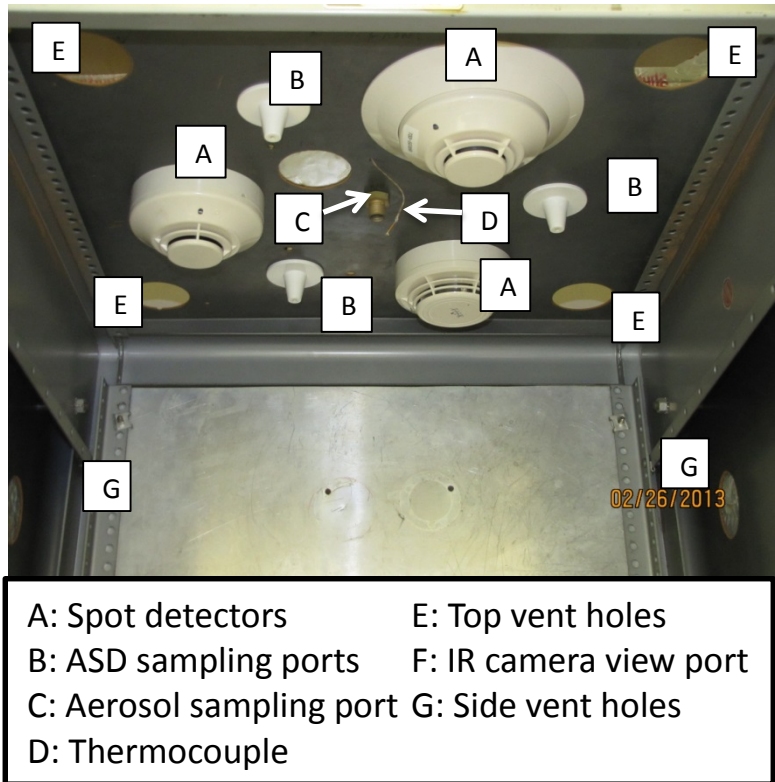


Figure 4-14. Laboratory instrument cabinet experimental configuration

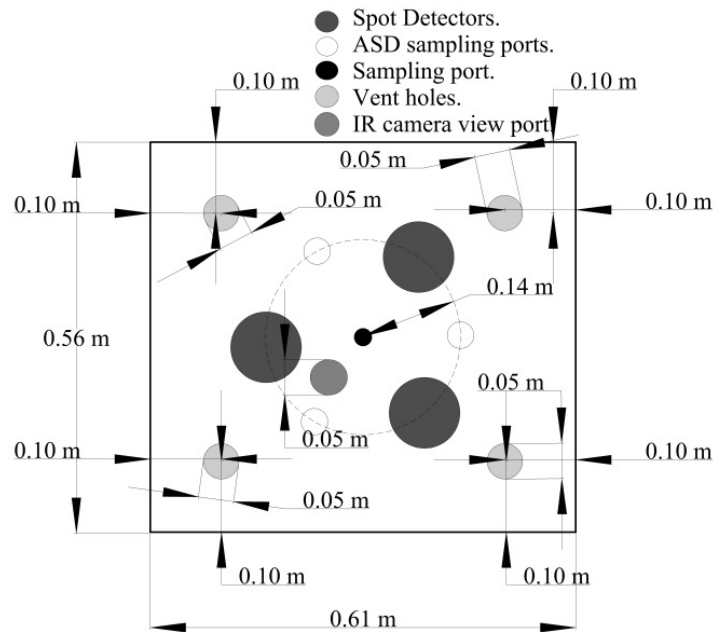
The instrument cabinet had spot detectors and air-sampling detector ports installed on its ceiling. Figure 4-15 shows how they were mounted inside the cabinet, and a schematic of the top plate hole pattern is shown in Figure 4-16. The ASD detector units were located outside the

1 cabinet and individual but identical piping networks were used to transport air samples from
2 within the cabinet to the detector units. The pipe used was a 1.91 cm inside diameter (ID)
3 chlorinated polyvinyl chloride pipe (CPVC). Flexible tubing, 1.24 cm ID, was used to connect
4 the sampling port to the CPVC piping. The ASD piping layout can be seen in Figure 4-17. Each
5 detector had four sampling ports, one routed to the inside of the cabinet and three sampling
6 laboratory-space ambient air. The sampling port diameters were 3.2 mm.
7

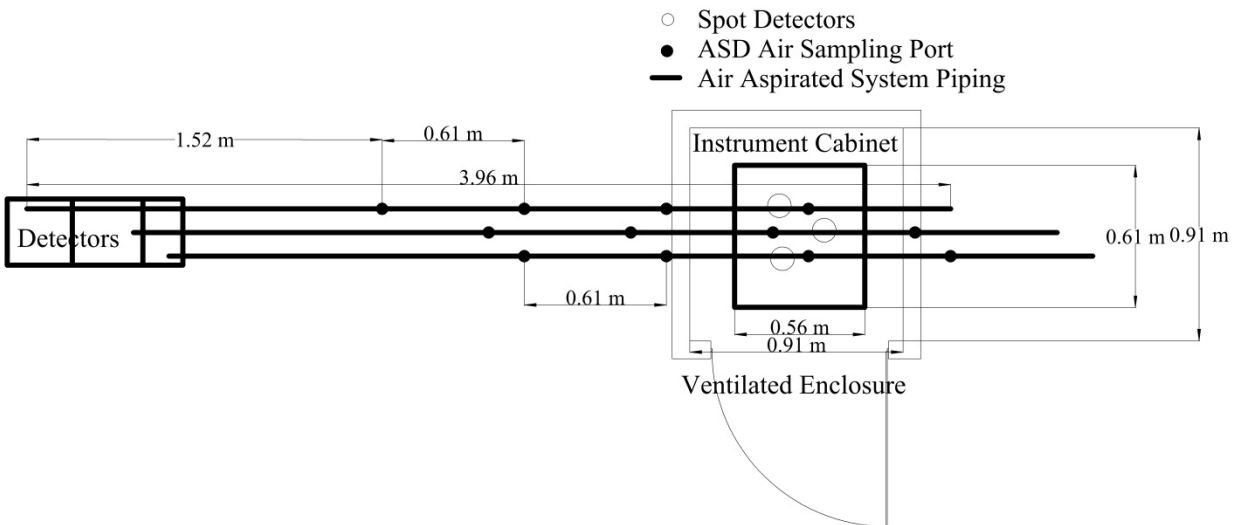


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Figure 4-15. Instrument cabinet ceiling view



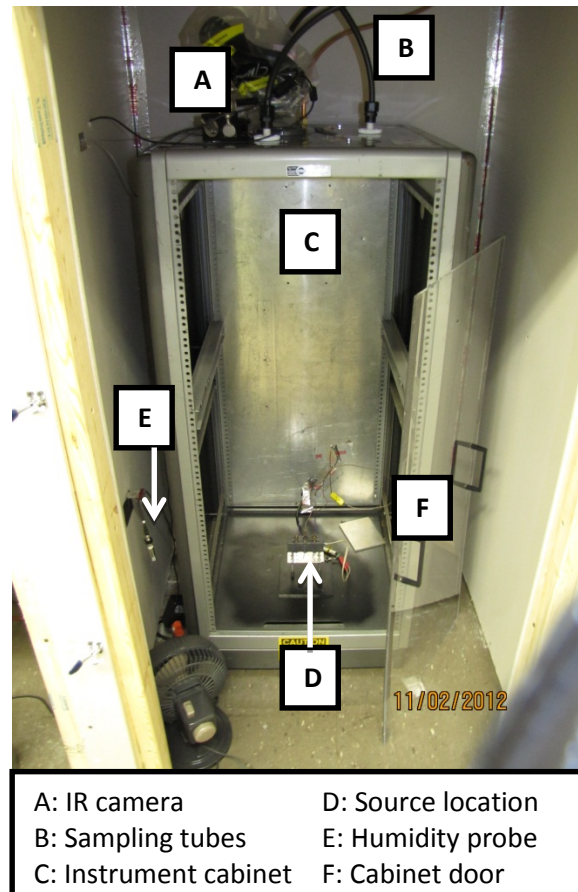
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2 **Figure 4-16. Instrument cabinet top plate hole pattern**



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

6
7 The cabinet had two sets of vent holes, four through the ceiling and three each on the left and
8 right sides. The locations of the top vent holes and some of the side vent holes can be seen in
9 Figure 4-16. The top vent hole configuration consisted of four 5.08 cm holes, while the side
10 vent configuration had six. The side vent holes, consisting of three holes separated by 0.18 m,
11 were placed on left and the right sides 0.2 m from the top of the cabinet. Each test had either
12 the top or side vents opened, but in no test were both open.

1
2 The cabinet was located inside a ventilated enclosure to contain and evacuate the smoke. The
3 ventilated enclosure was 0.91 m by 0.91 m and 1.75 m tall. A blower motor installed on top of
4 the enclosure provided the ventilation to exhaust smoke fumes through the top of the cabinet,
5 and into the laboratory fume hood. A 3.8 cm gap between the bottom of the enclosure and the
6 floor, allowed fresh air to enter the enclosure. Inside the test cabinet the air was quiescent,
7 except for the thermal plume generated by the heat source. A close-up of the cabinet inside the
8 ventilated enclosure can be seen in Figure 4-18.
9



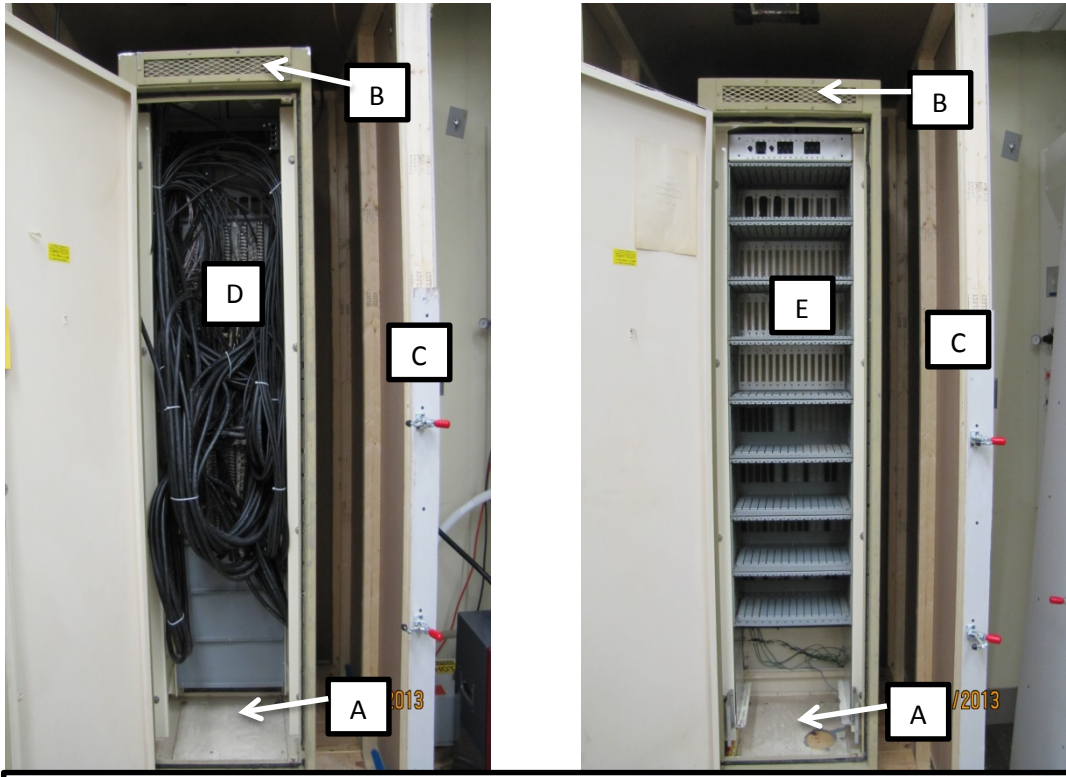
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11 **Figure 4-18. Instrument cabinet inside NIST laboratory**

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13 **4.4.2 Laboratory, large NPP cabinet configurations**

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

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

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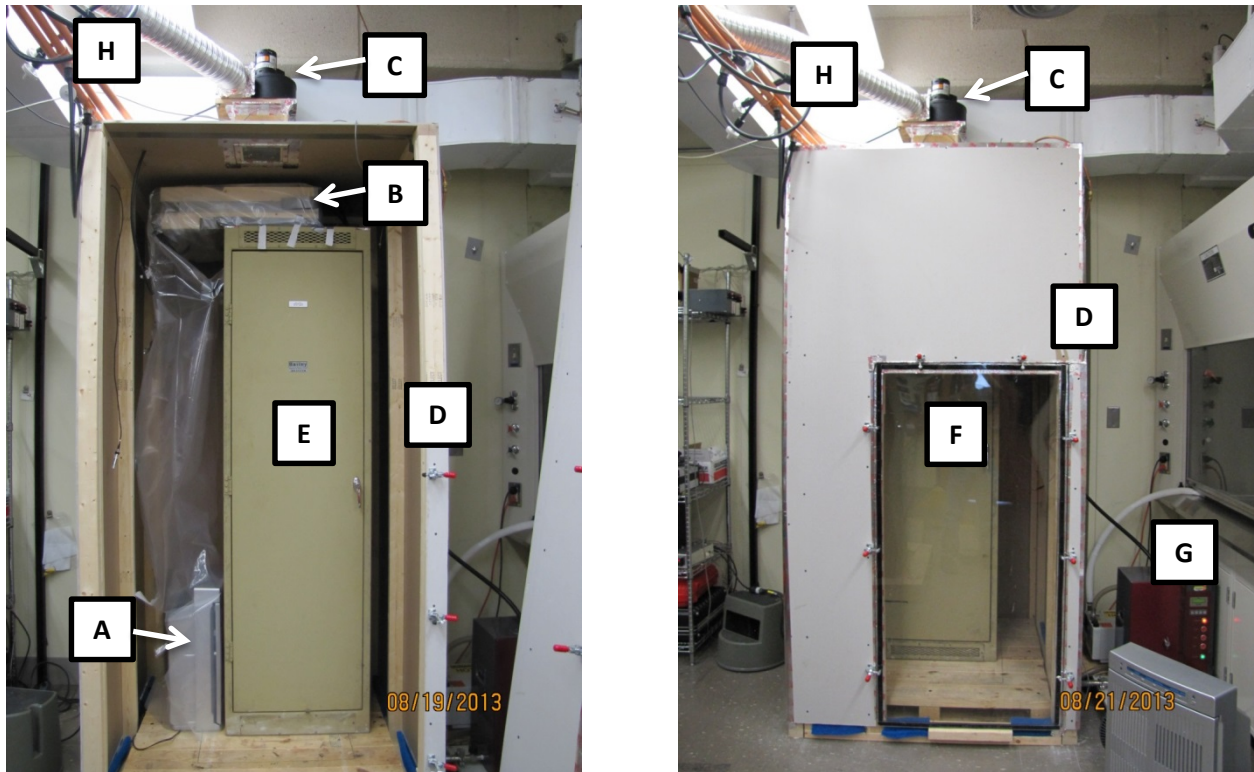
8

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

9

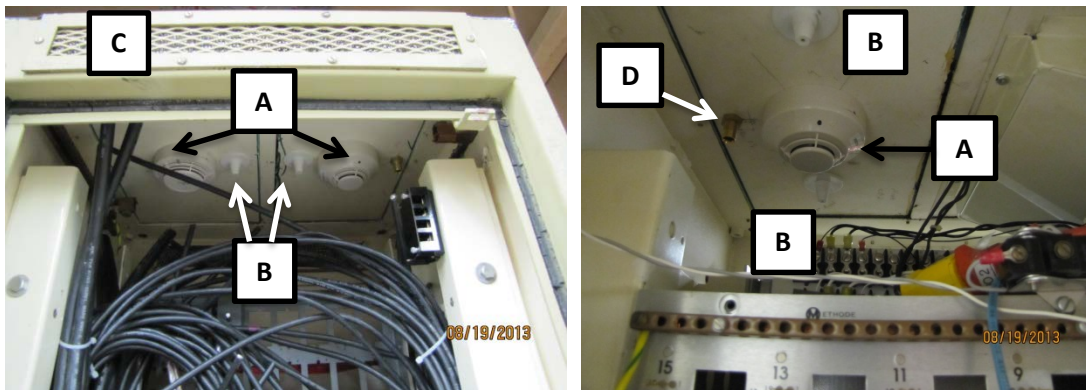
Figure 4-19. NPP cabinets used in large cabinet experiments

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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

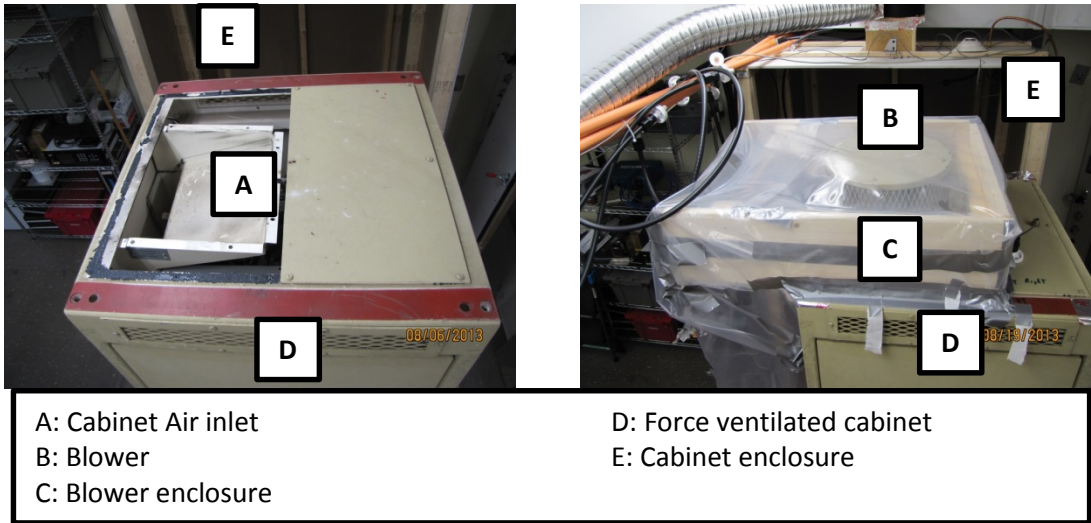
Figure 4-20. Large cabinet installation and enclosure detail



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

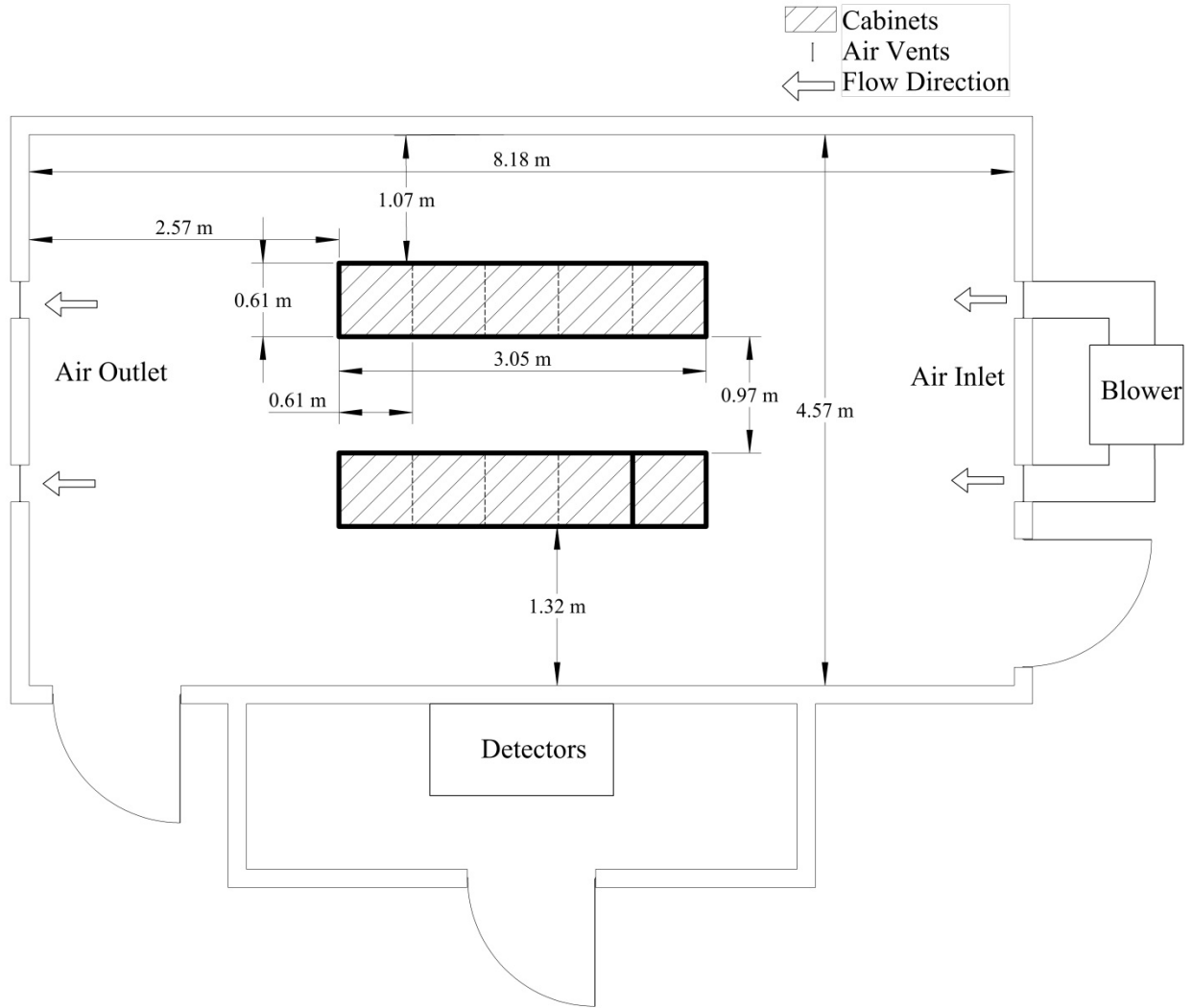
1 Cabinet 2 had a blower installed on top that was used for cooling of the circuit cards. The
 2 blower forced air down through a series of vents and across the circuit card slots, then back up
 3 to the top of the cabinet. To limit the effects of air recirculation in the cabinet enclosure, air to
 4 the blower was sampled from the bottom of the enclosure into a plastic shroud containing a
 5 heap-filter air cleaner. A close-up of the top of the cabinet with and without the blower can be
 6 seen in Figure 4-22. This configuration was meant to simulate a large compartment with
 7 abundance of clean air, such that the air being sucked into the cabinet would be clean air.
 8 ASD1 was used to monitor the air entering the cabinet.
 9



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

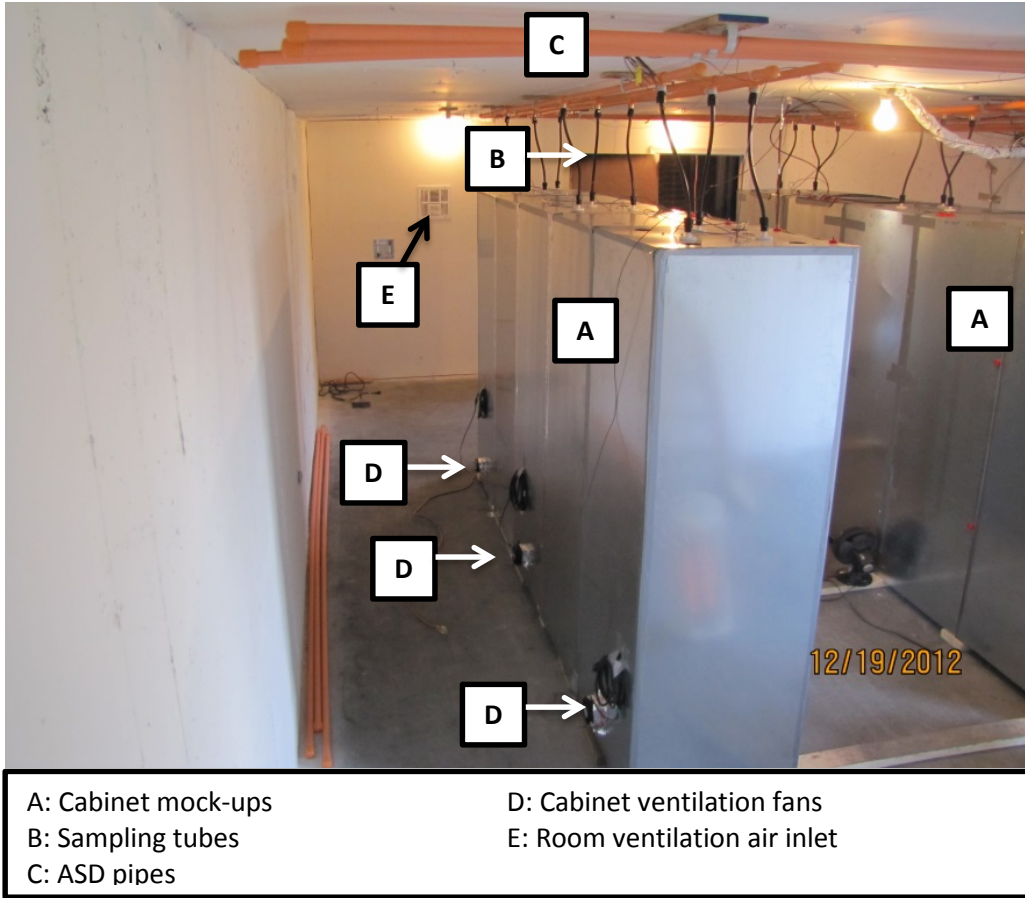
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 17 **4.4.3 In-cabinet, small room, cabinet mock-up configurations**

18
 19 The single-zone experiments were conducted at the Montgomery County Public Safety Training
 20 Academy, in the Burn Prop building. A space on the lower floor was used to configure an 8.2 m
 21 x 4.6 m room containing electrical cabinet mock-ups. The ceiling height was 2.4 m. A forced-air
 22 ventilation scheme could be implemented in the room using a variable-speed blower and
 23 ducting to direct air flow to wall registers, which exhaust air grills vented to the outside of the
 24 building. The cabinet mock-ups were constructed to simulate naturally ventilated, or forced-air
 25 ventilated electrical equipment cabinets. Individual cabinets were 0.61 m wide by 0.61 m deep
 26 and 1.78 m tall. Figure 4-23 shows the small room experimental space layout. Photographs of
 27 the setup can be seen in Figure 4-24 and Figure 4-25.
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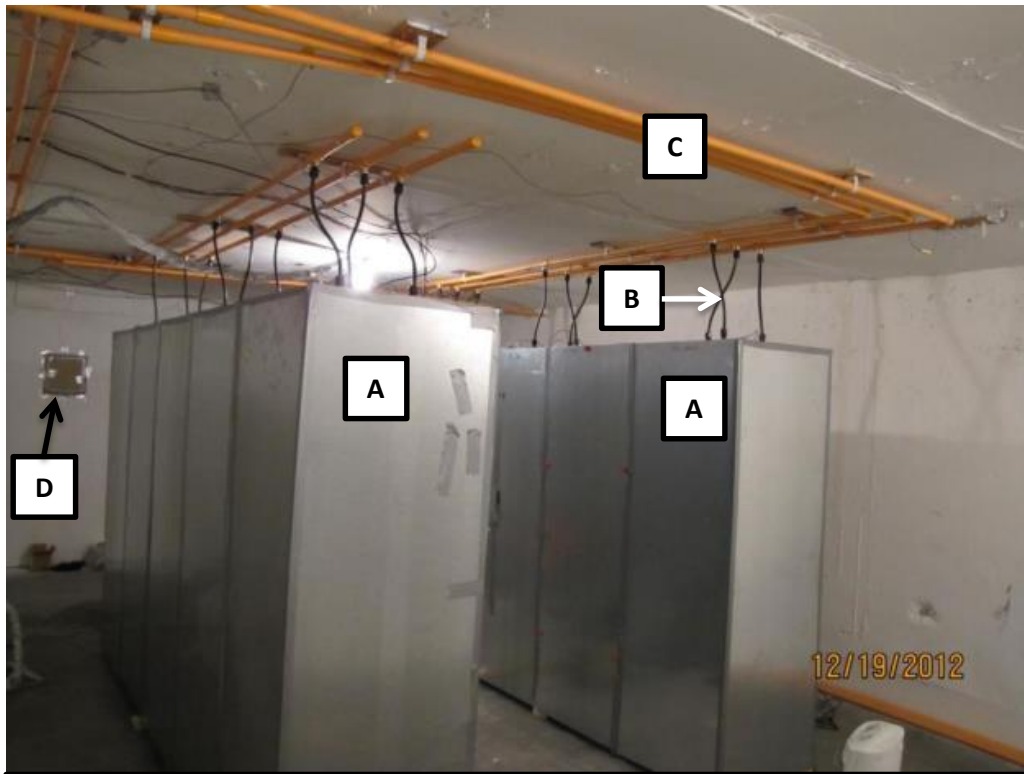
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Figure 4-23. Small room full-scale experiment space layout



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

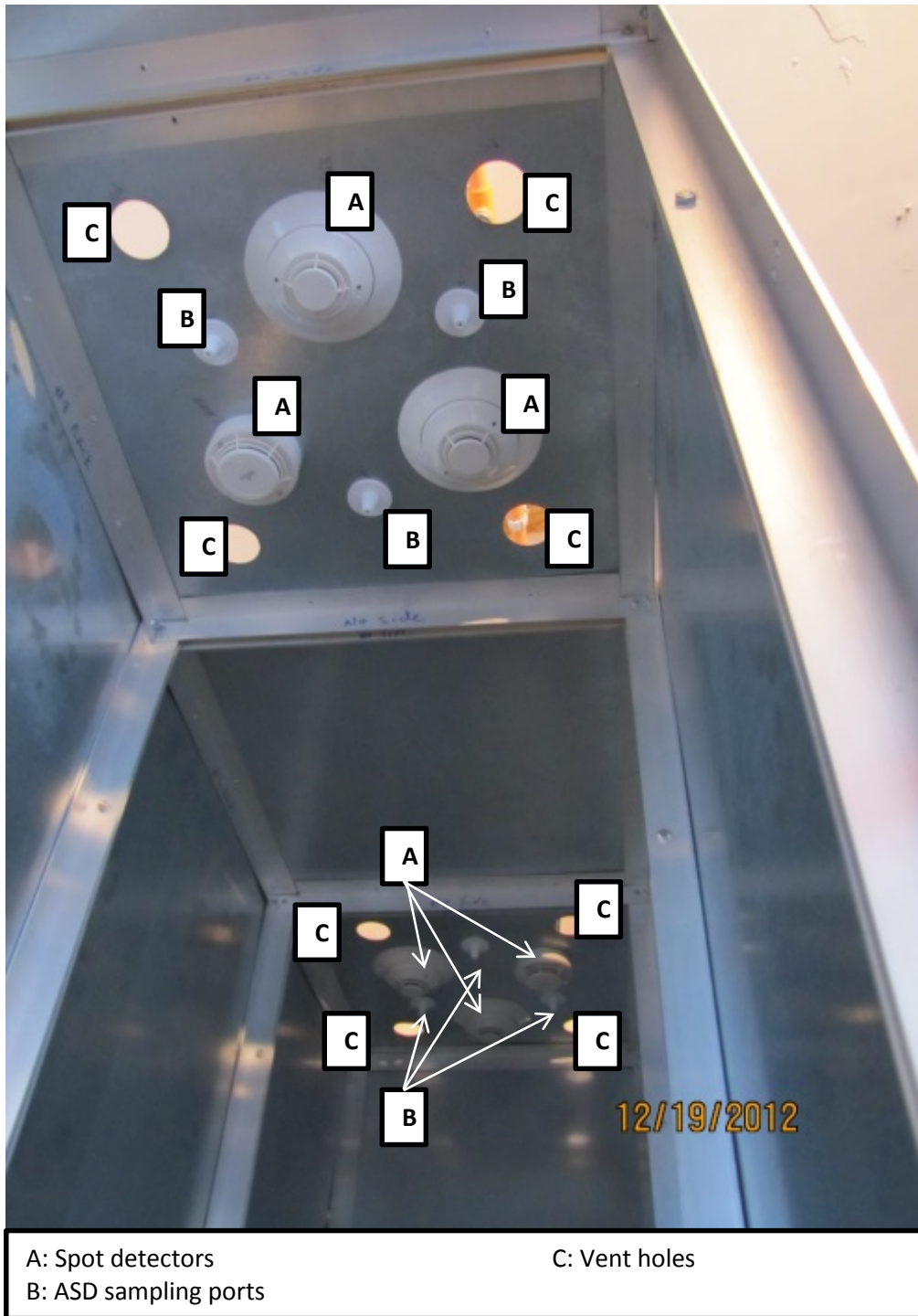


A: Cabinet mock-ups	C: ASD pipes
B: Sampling tubes	D: Room ventilation air inlet

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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.



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

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

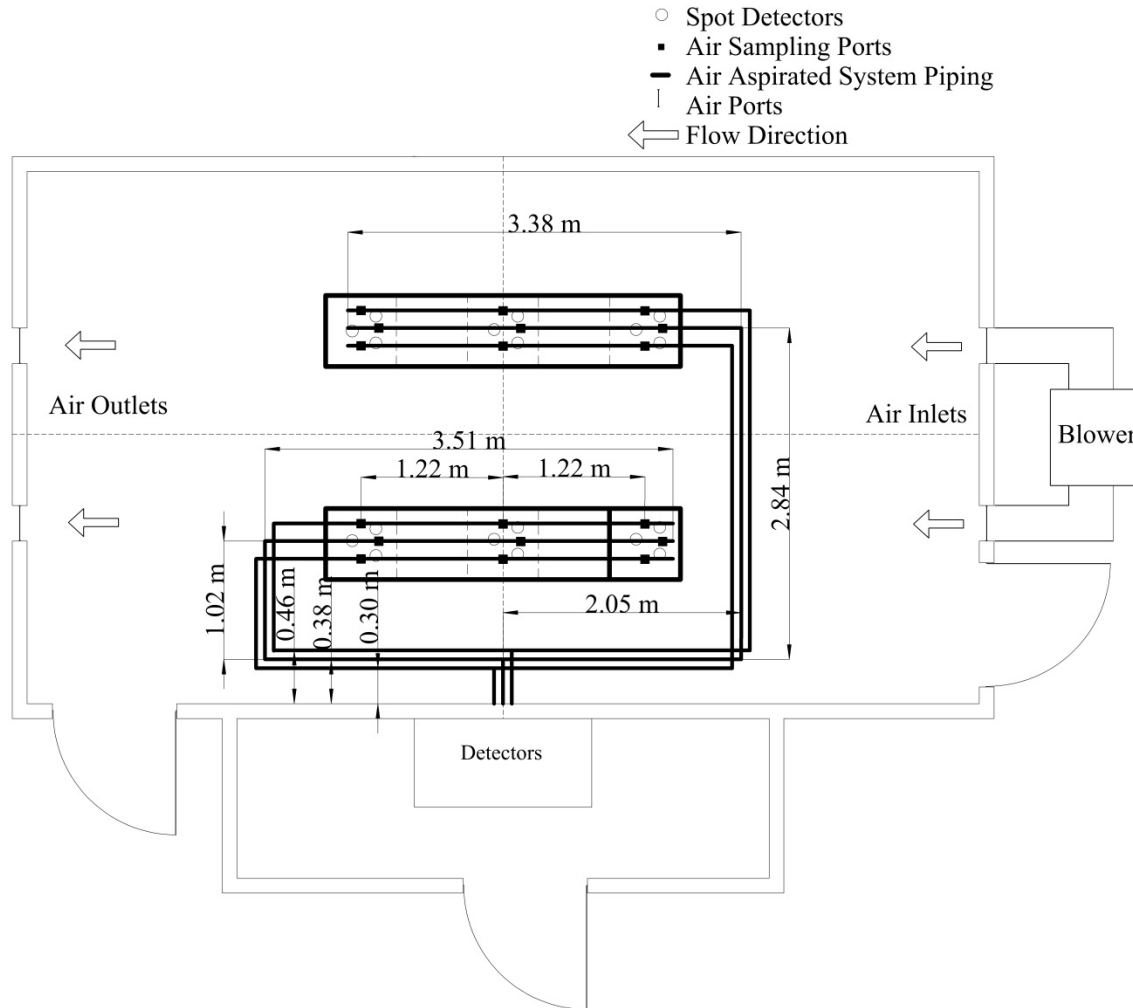


Figure 4-27. In-cabinet ASD pipe layout

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

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

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

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

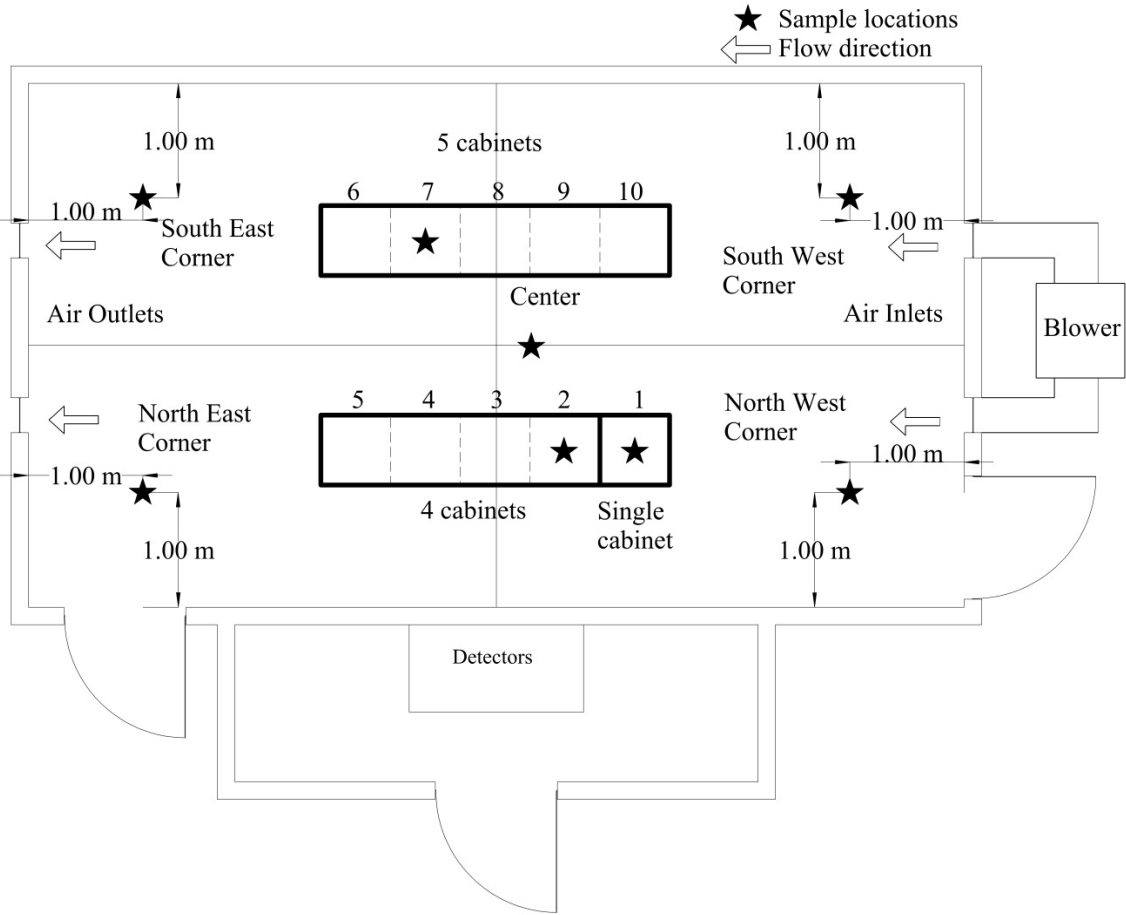


Figure 4-28. Smoke source sample locations

4.4.4 Areawide, small room configuration

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

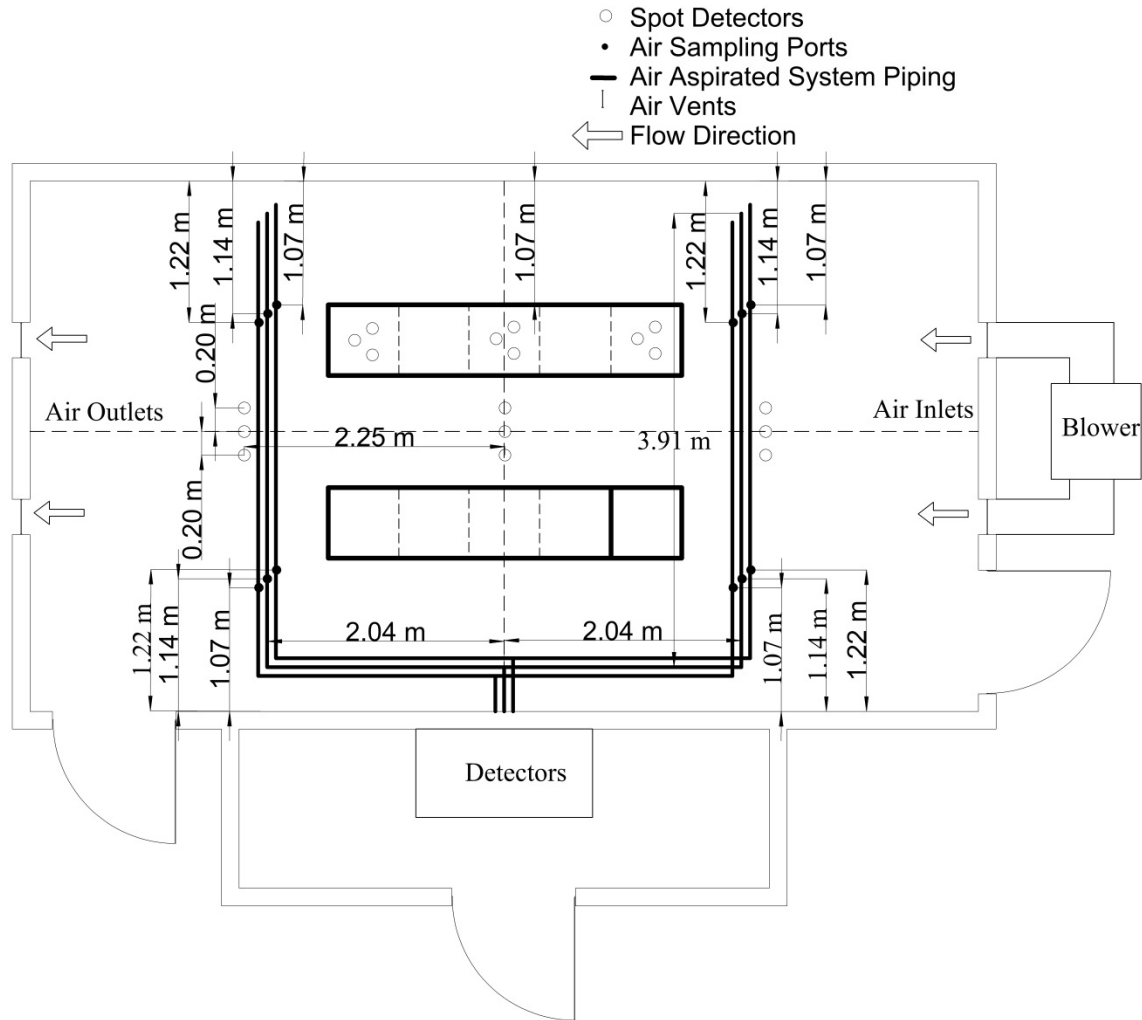
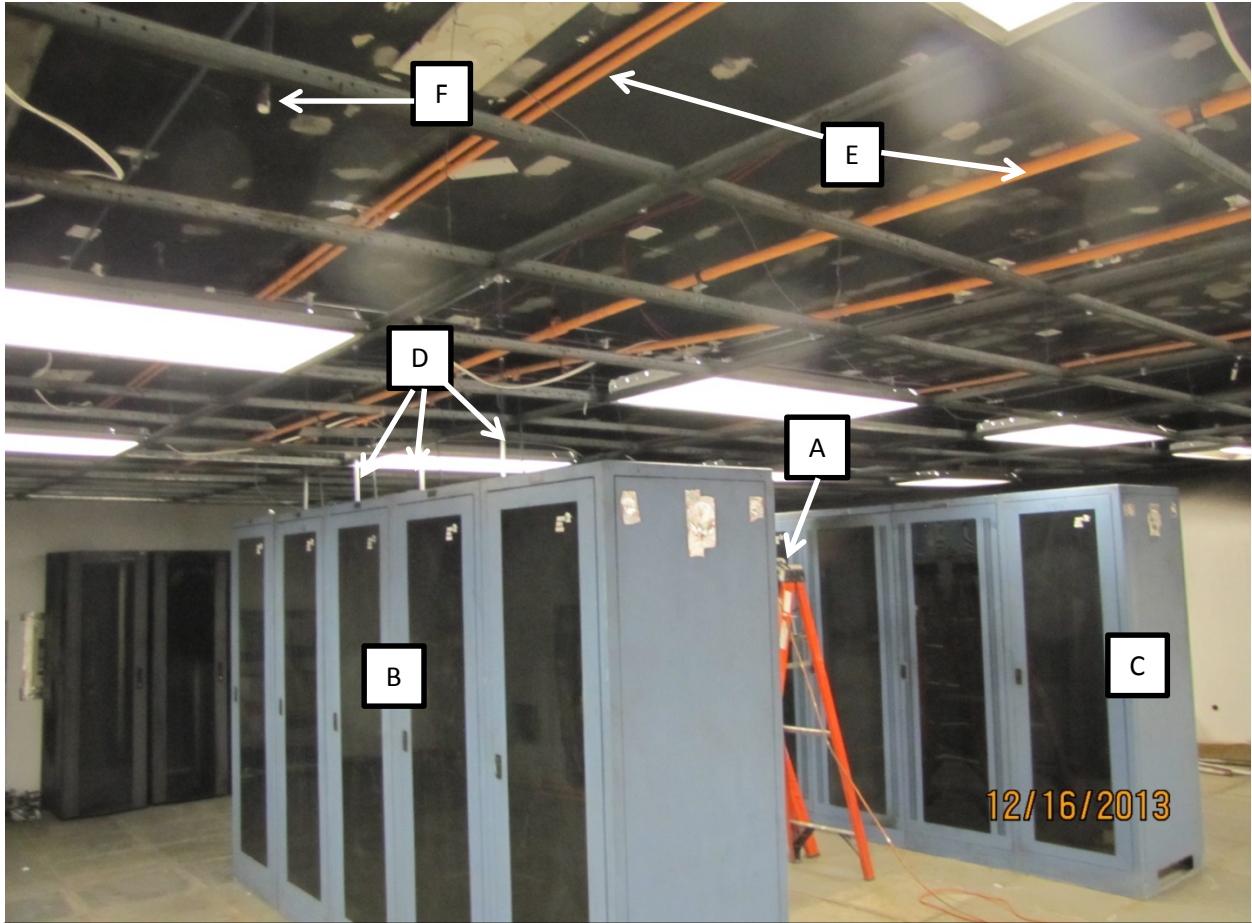


Figure 4-29. Areawide ASD pipe layout

4.4.5 In-cabinet, large room, electrical cabinet configurations

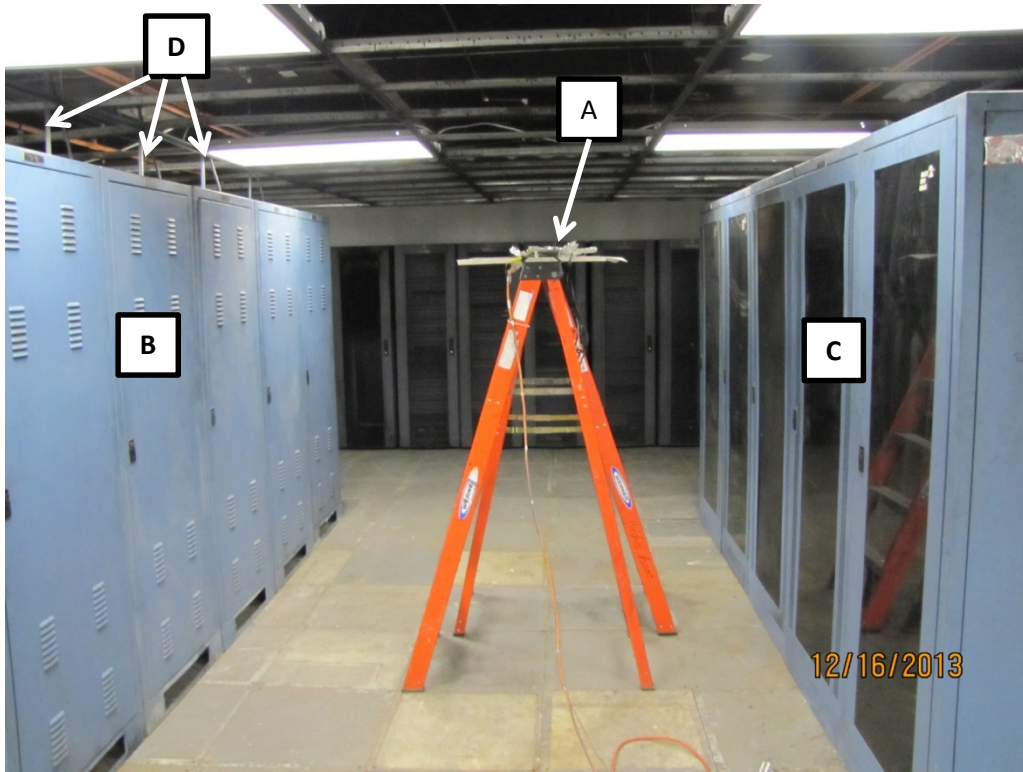
The experimental space for the large-room, full-scale experiments was 10 m x 10 m x 3 m high ceiling with a variable speed ventilation fan. The facility can be seen in Figure 4-30 and Figure 4-31, and the complete layout can be seen in Figure 4-32. With access doors closed, air was pulled through two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



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

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Figure 4-30. Off angle view of 100 m² facility



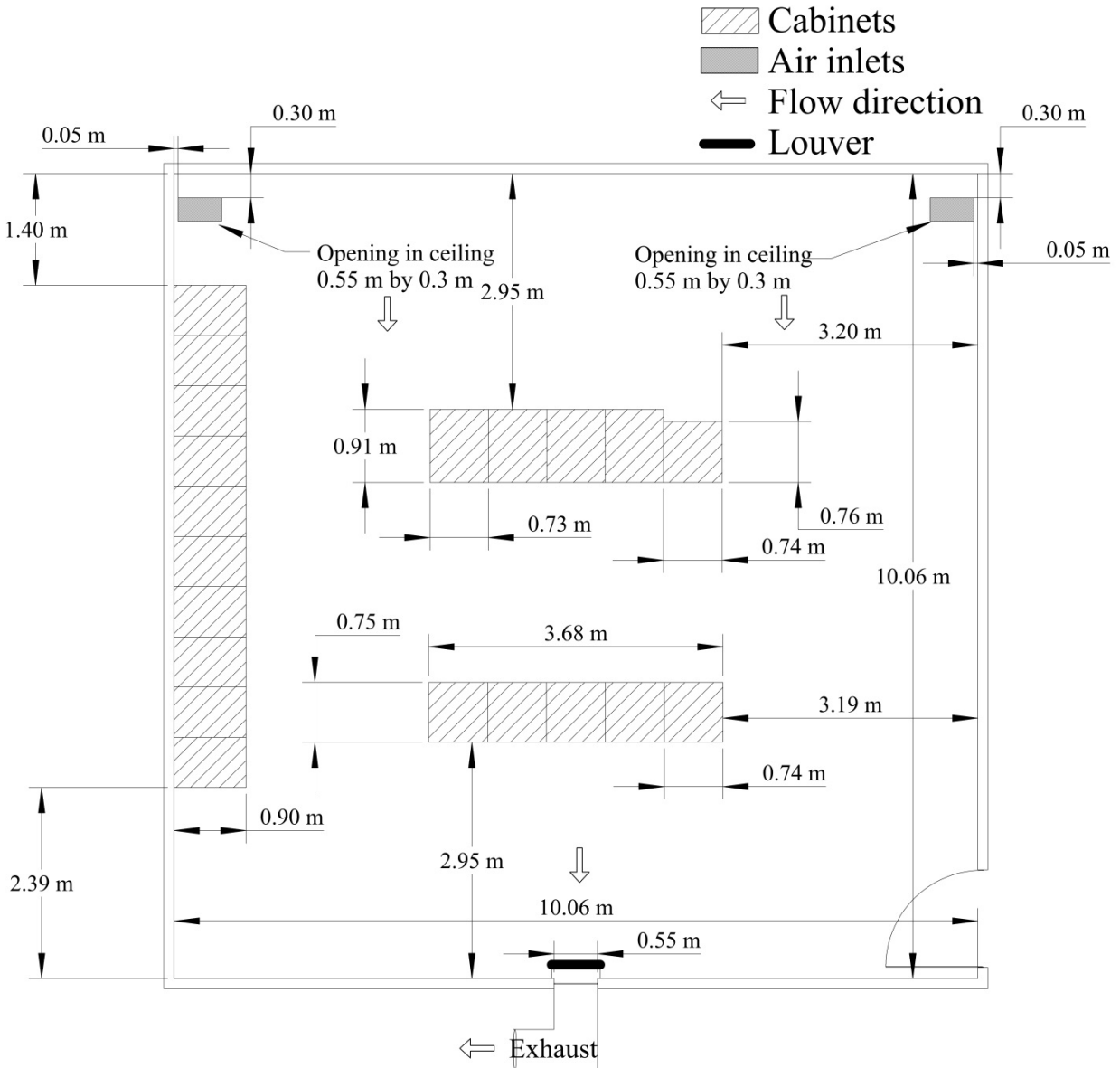
A: Source location, Wire bundle
B: Test Cabinets, Instrumented

C: Test Cabinets, Not Instrumented
D: In-Cabinet ASD Sampling Lines

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



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Figure 4-32. Large room testing facility layout

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

9

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

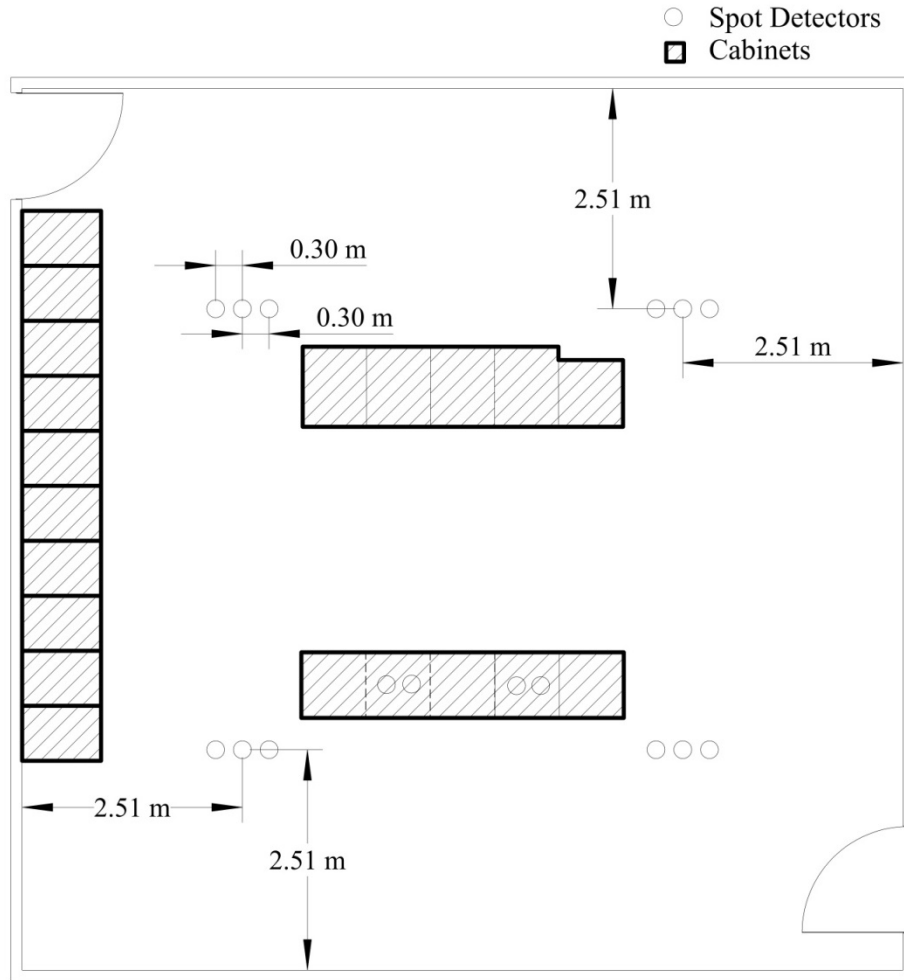
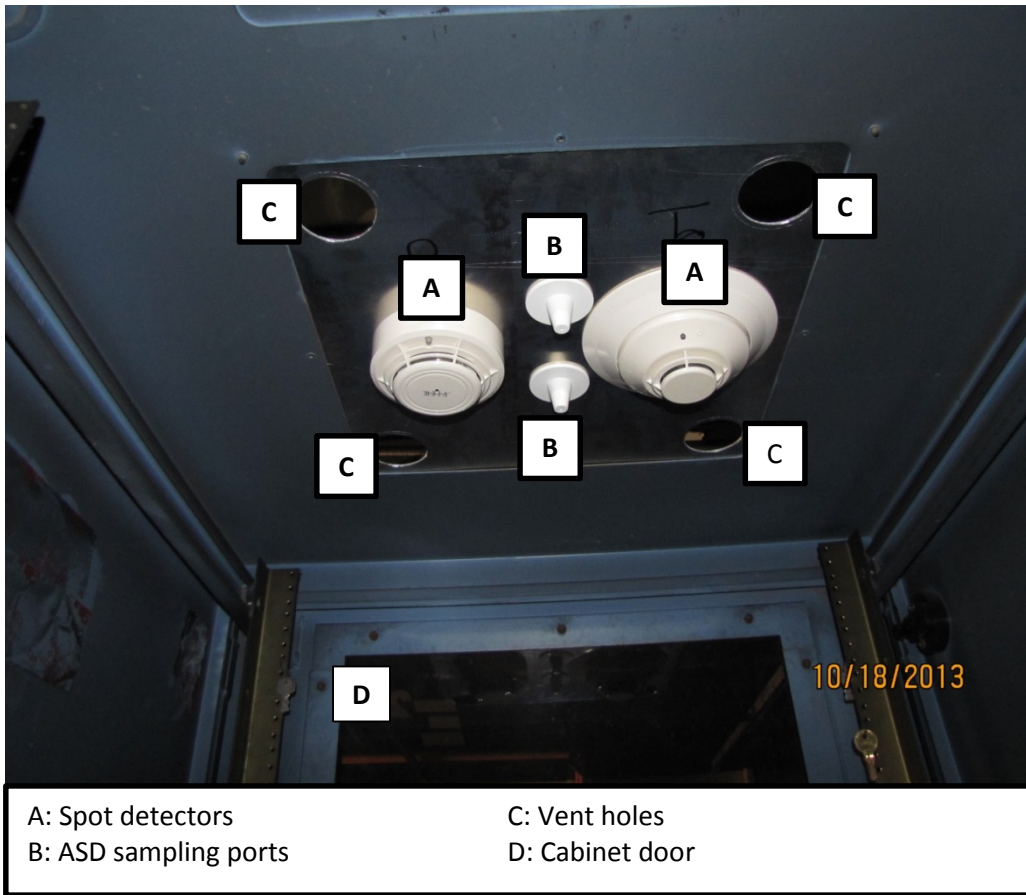


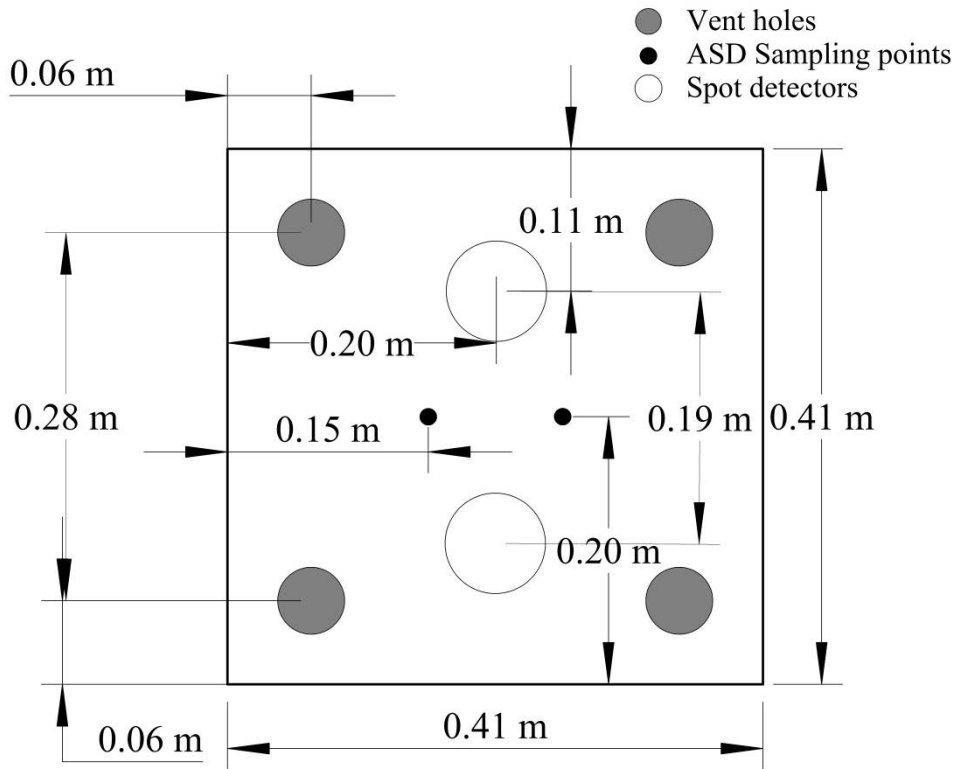
Figure 4-33. Spot detectors layout inside 100 m² facility

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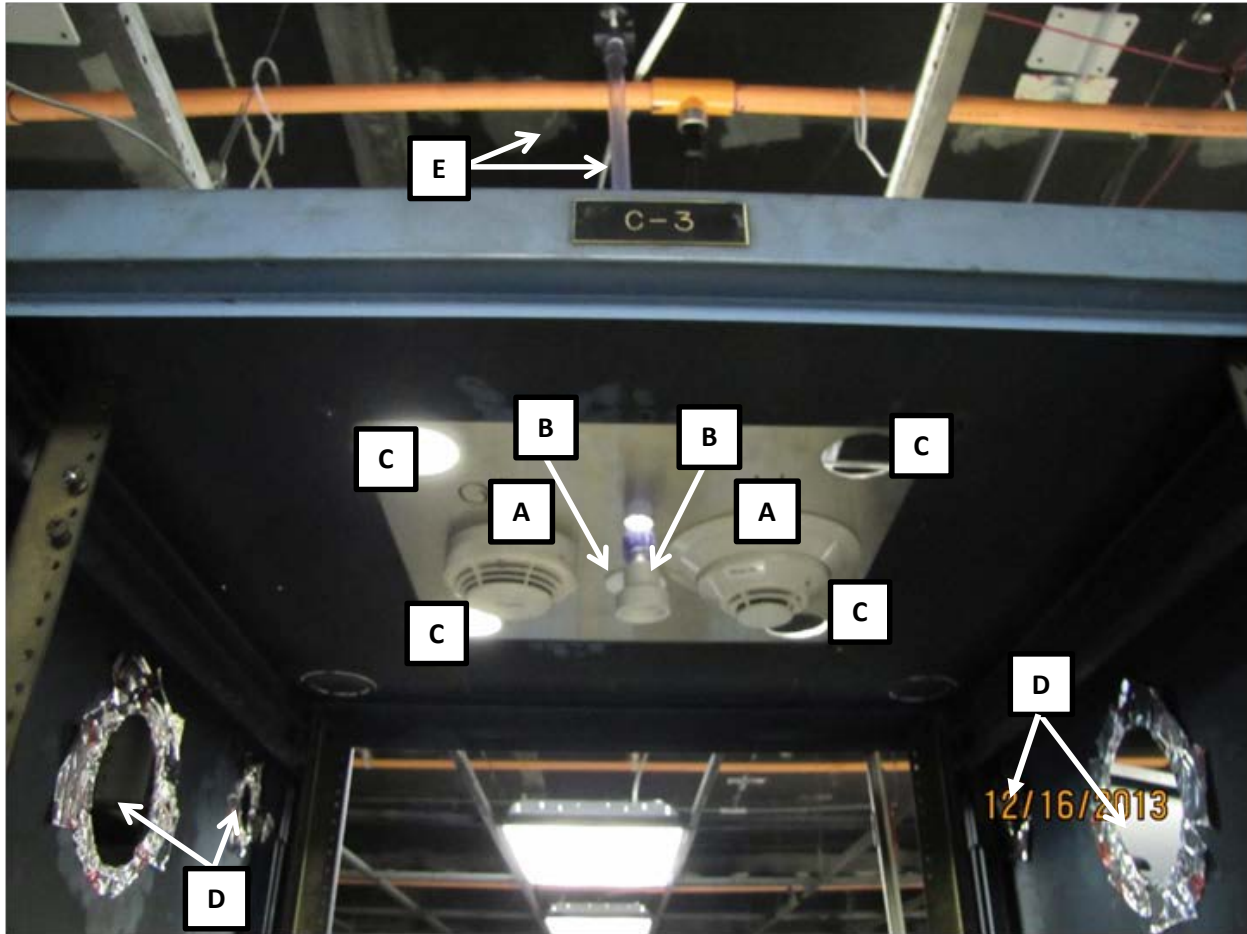
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Figure 4-34. Detector and sampling port locations for single-zone experiments



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



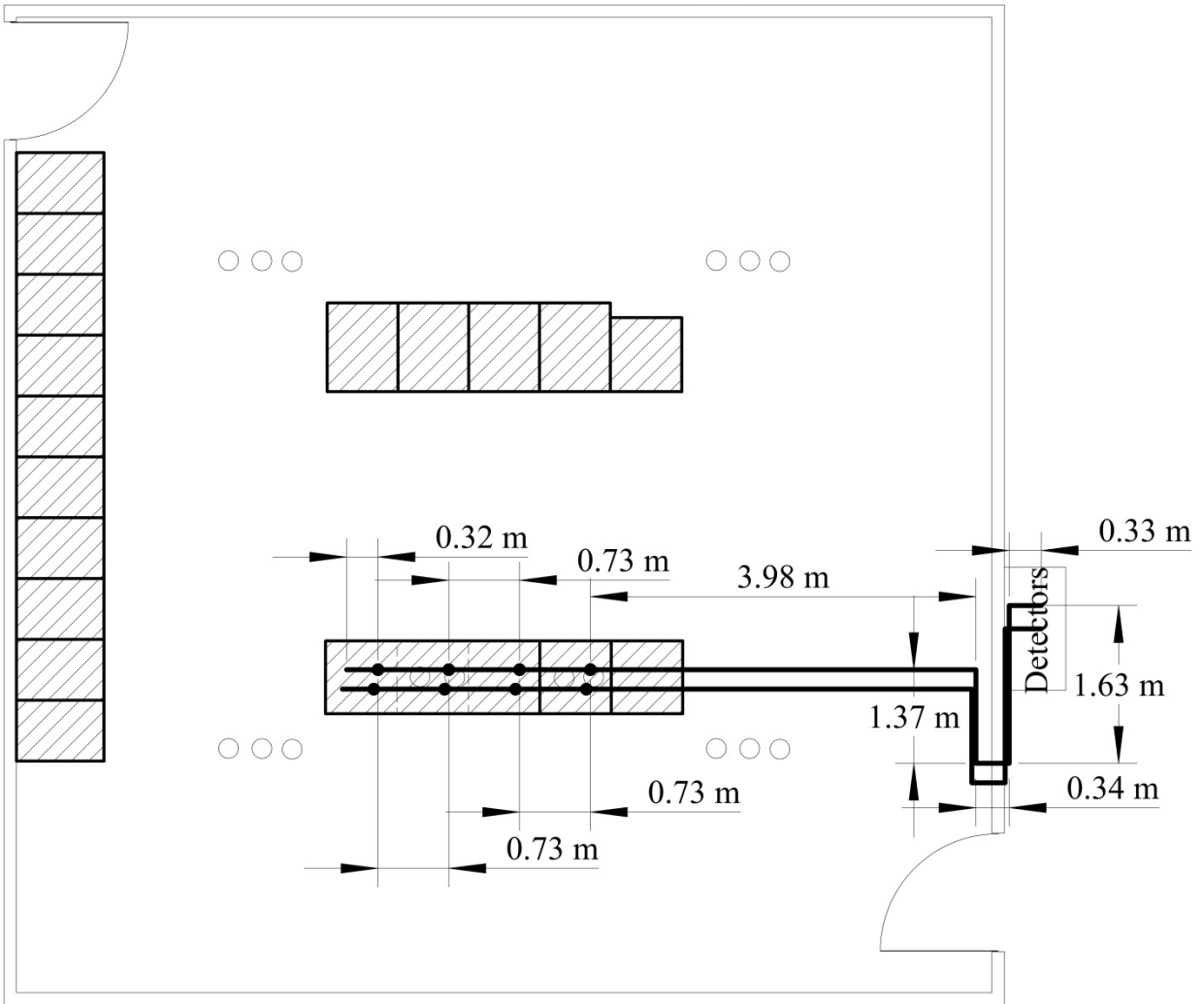
A: Spot detectors	D: Side vents
B: ASD sampling ports	E: ASD piping
C: Top vents	

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.

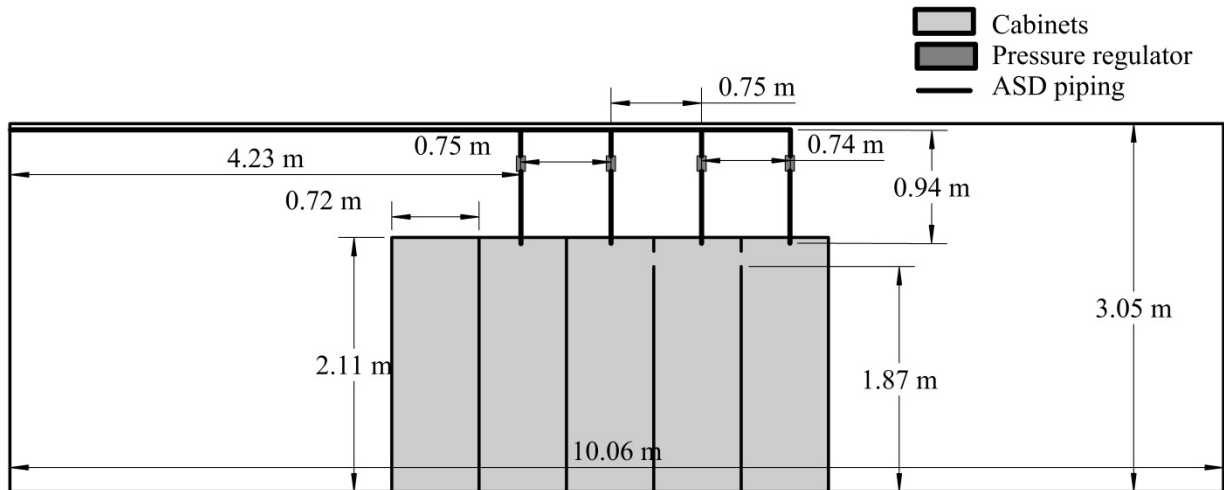
Figure 4-40 and Figure 4-41 show the details of the openings between the three-cabinet configurations. Figure 4-42 shows the source locations.

- ASD piping
- Sampling points
- Spot Detectors
- ▣ Cabinets



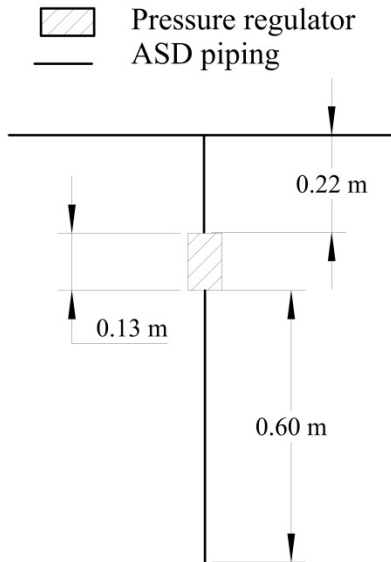
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Figure 4-37. Single zone piping configuration for ASD2 and ASD3



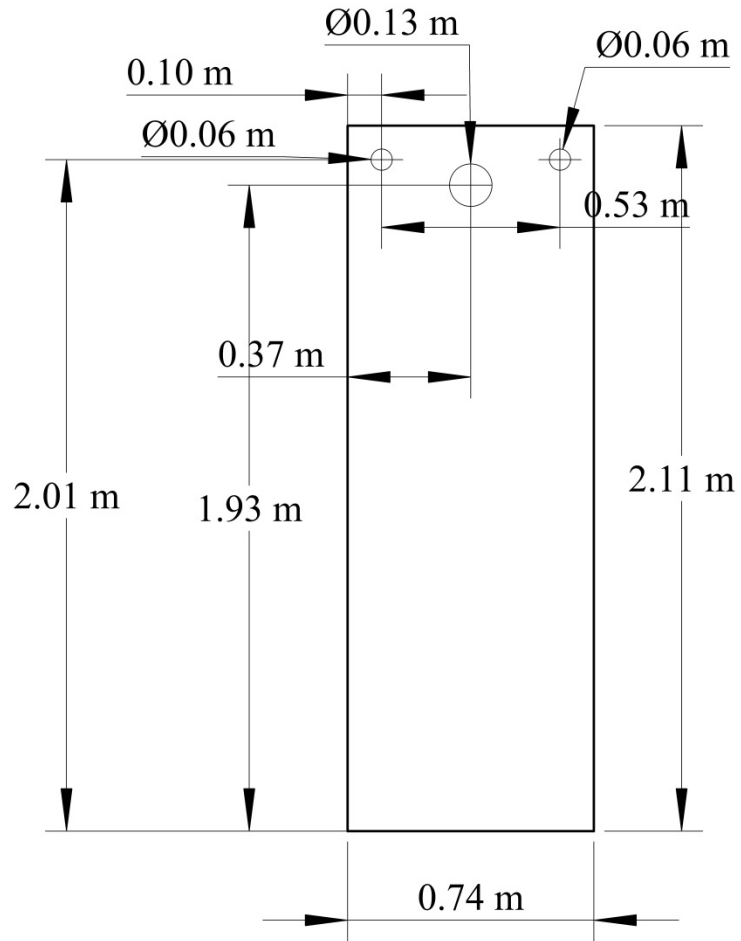
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Figure 4-38. Front view of the ASD4 piping setup for the in-cabinet sampling



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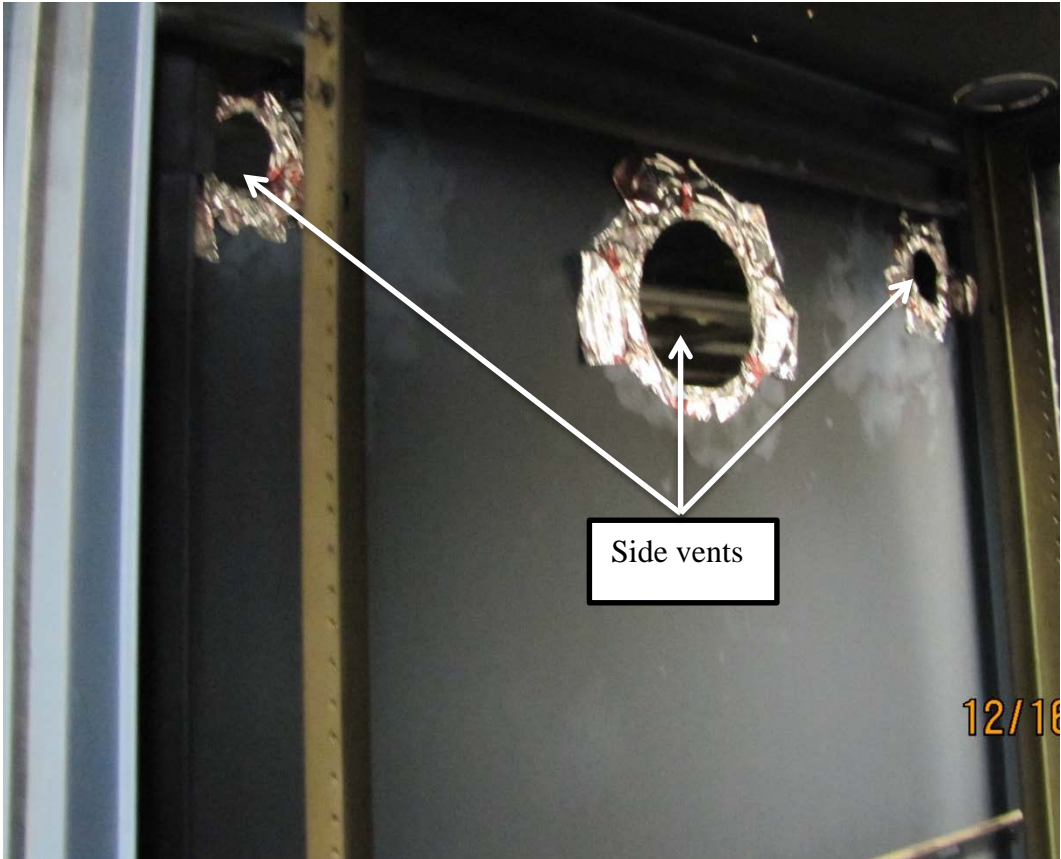
Figure 4-39. Pressure regulator located above each sampling port for ASD4



1

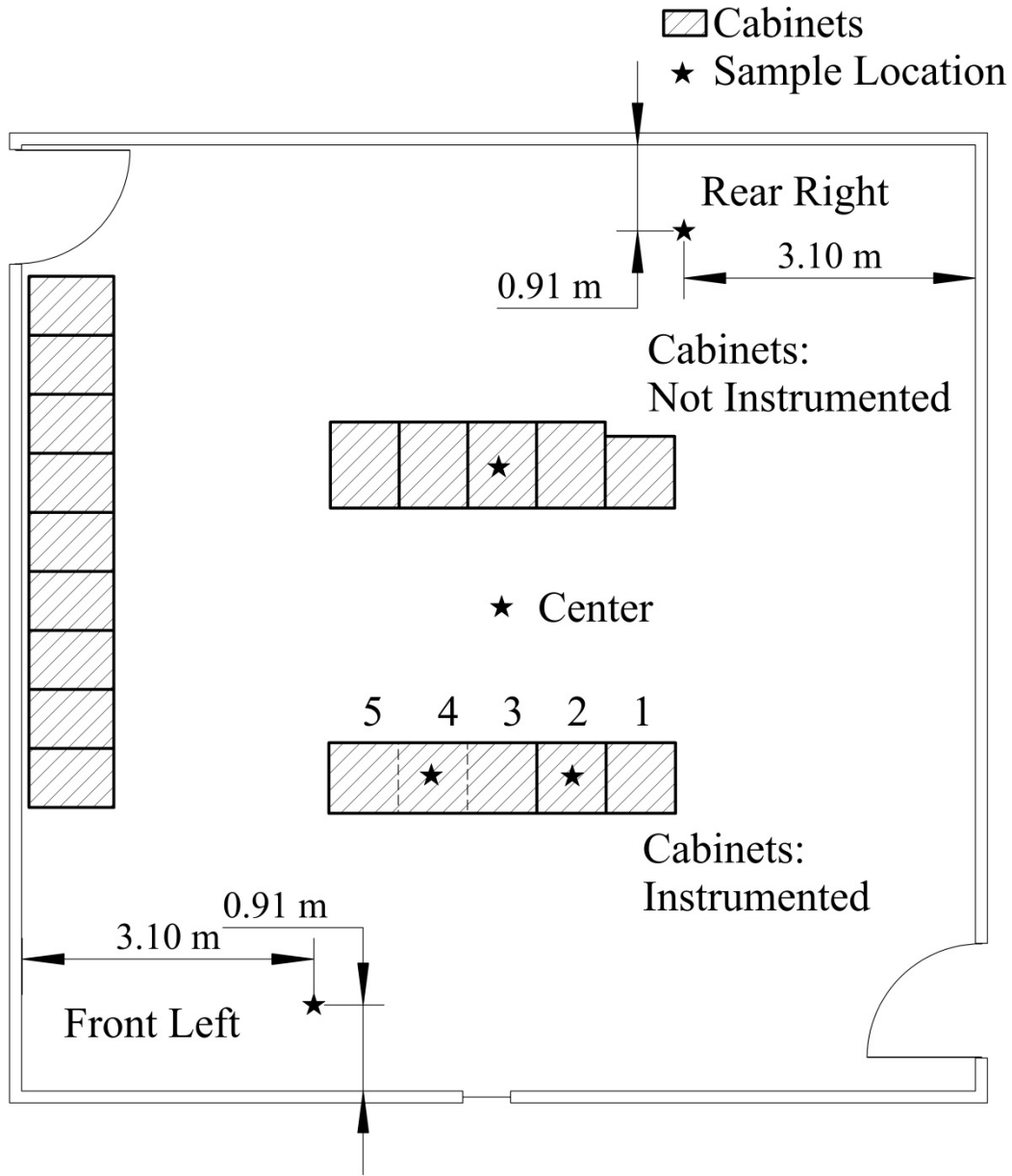
2

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



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



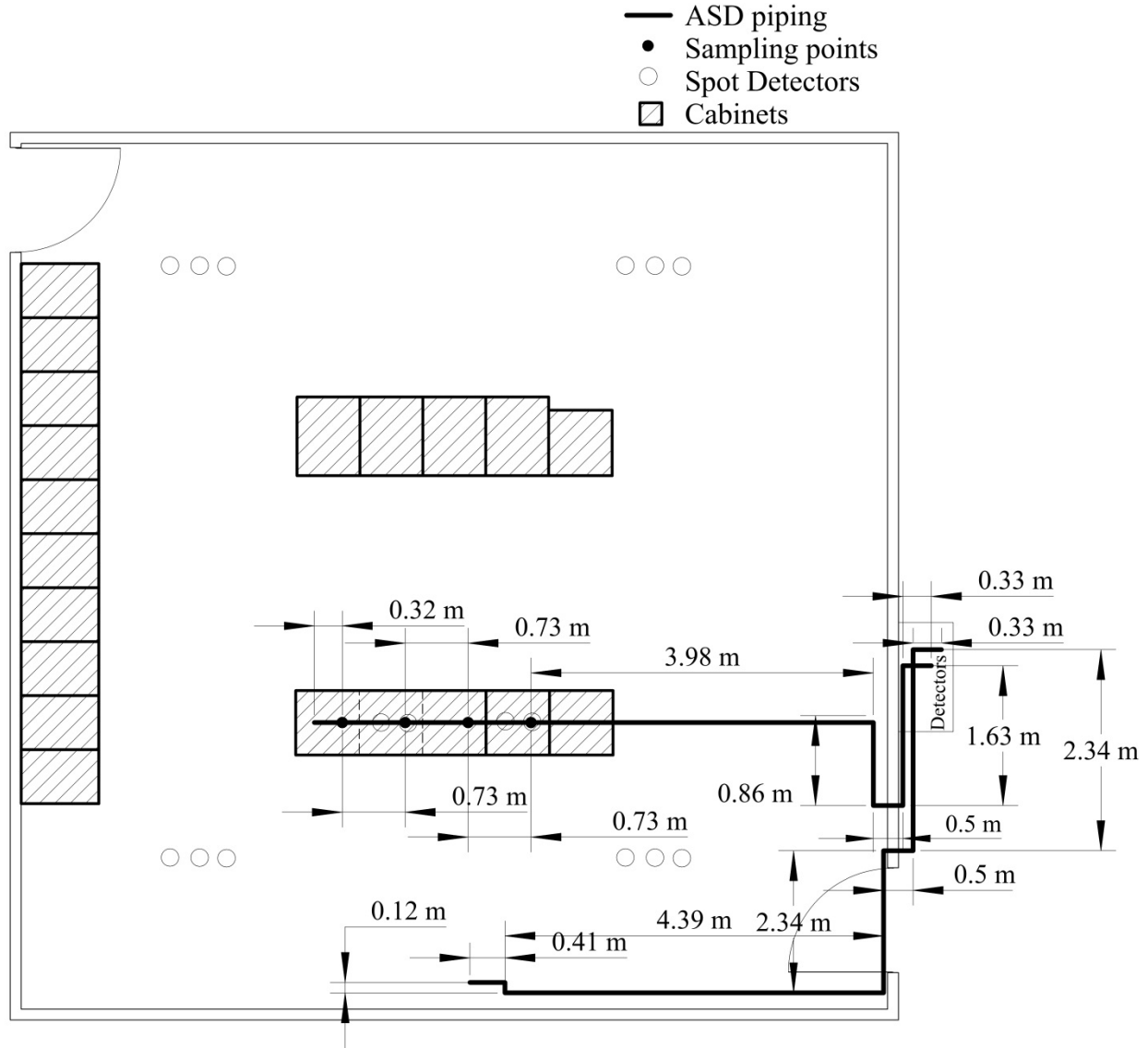
1
2 **Figure 4-42. Sample locations in the experiments performed**

3
4 **4.4.6 Areawide, large room configurations**

5
6 In the multi-zone ASD VEWFD experiments, two areawide smoke detection zones were
7 covered, (i.e., the return air grill, and the ceiling). A separate zone monitored the four-cabinet
8 that were monitored during the single-zone experiments. Figure 4-43 and Figure 4-44 show a
9 plan view of the piping network layout for the return air grill, and the cabinets for ASD4 and
10 ASD5. Figure 4-45 and Figure 4-46 show elevation views of the return air grill piping network
11 layouts. Figure 4-47 shows a picture of the return air grill and the piping for the two ASDs.
12 Figure 4-48 and Figure 4-49 show the plan view of the areawide ceiling ASD piping networks.

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

3

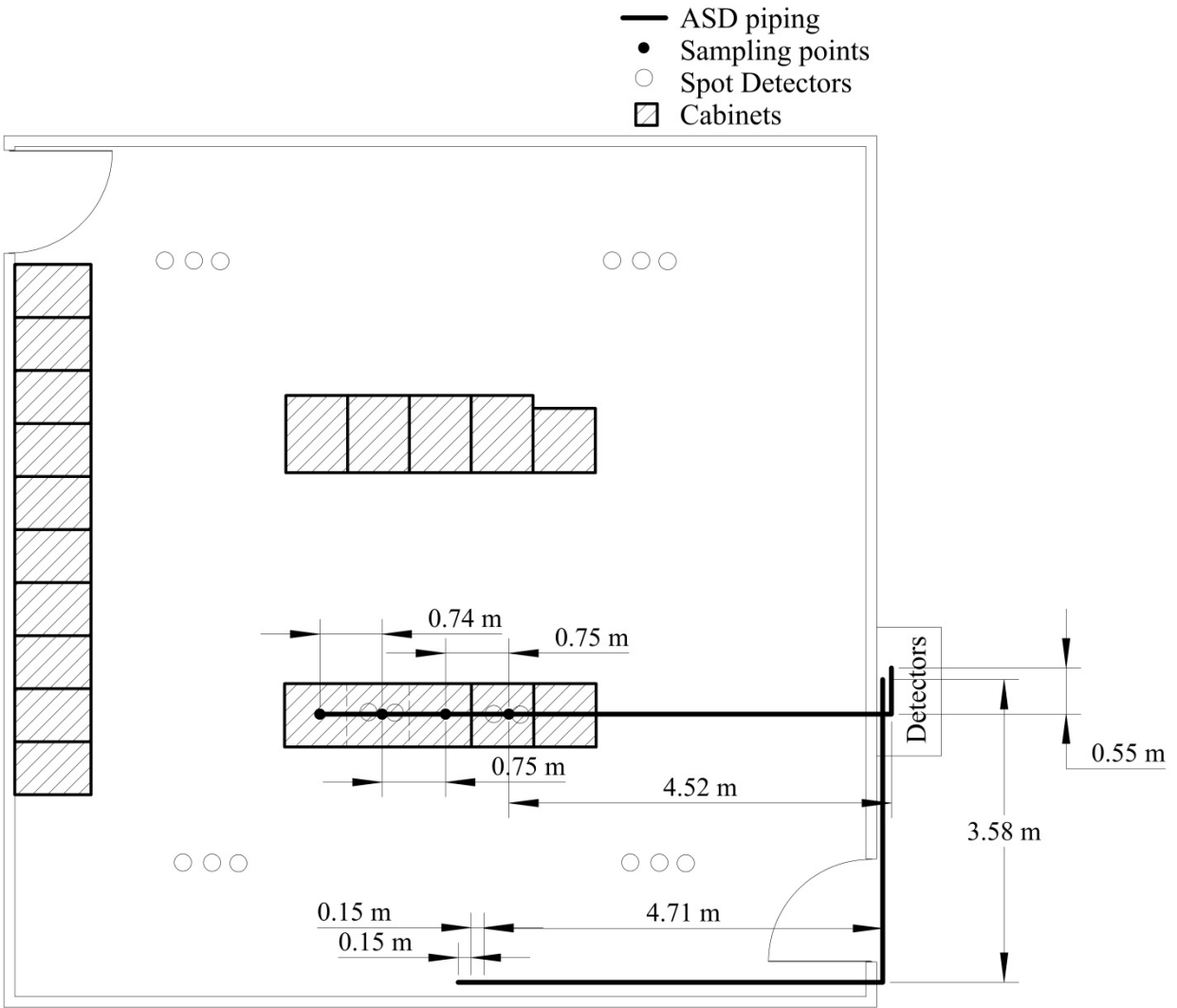


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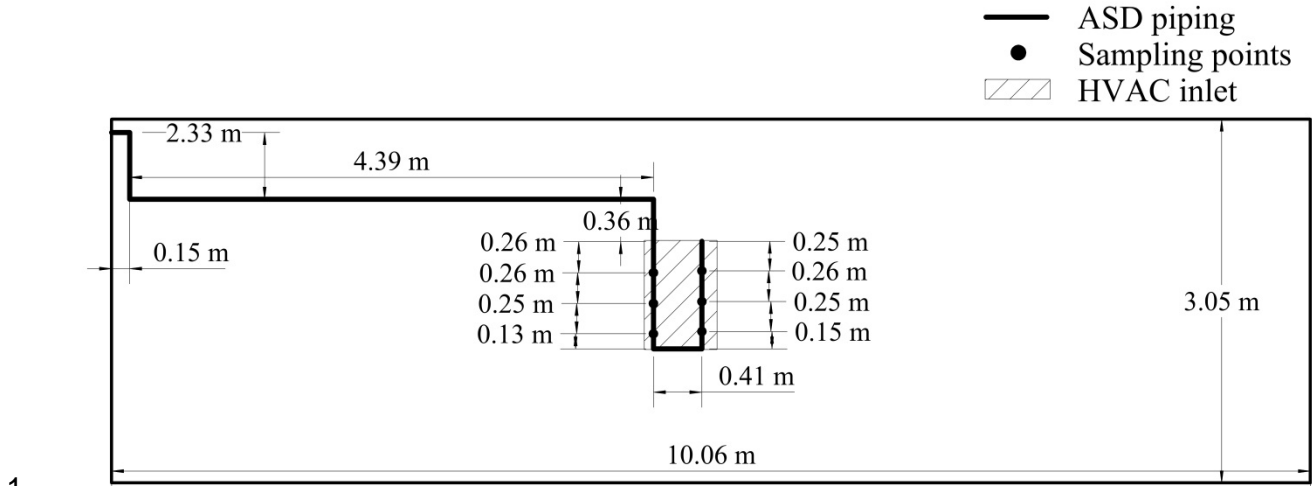
Figure 4-43. ASD4 piping layout for the in-cabinet and HVAC inlet sampling

6

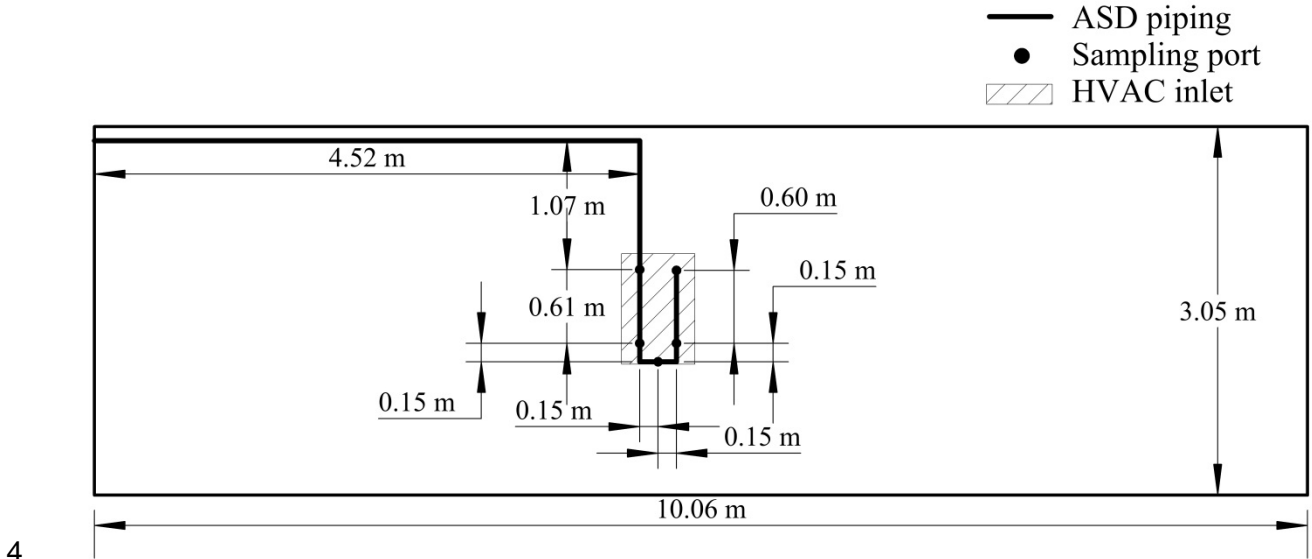


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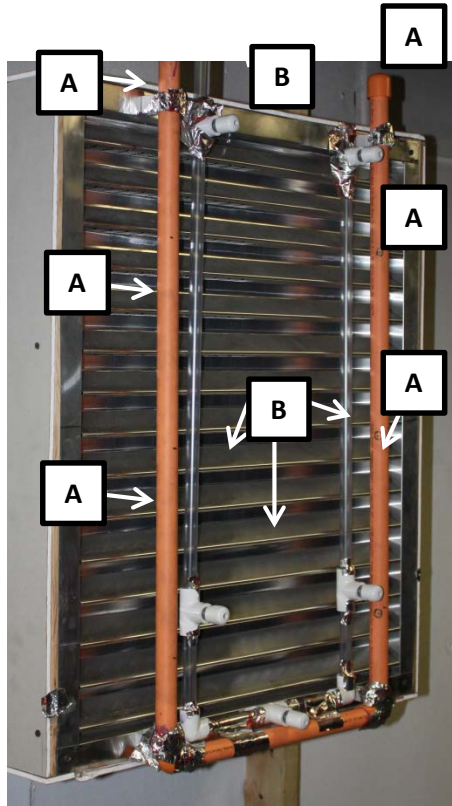
Figure 4-44. ASD5 piping layout for the in-cabinet and HVAC inlet sampling



1
2 **Figure 4-45. ASD5 piping layout, with sampling locations located at the HVAC exhaust**
3



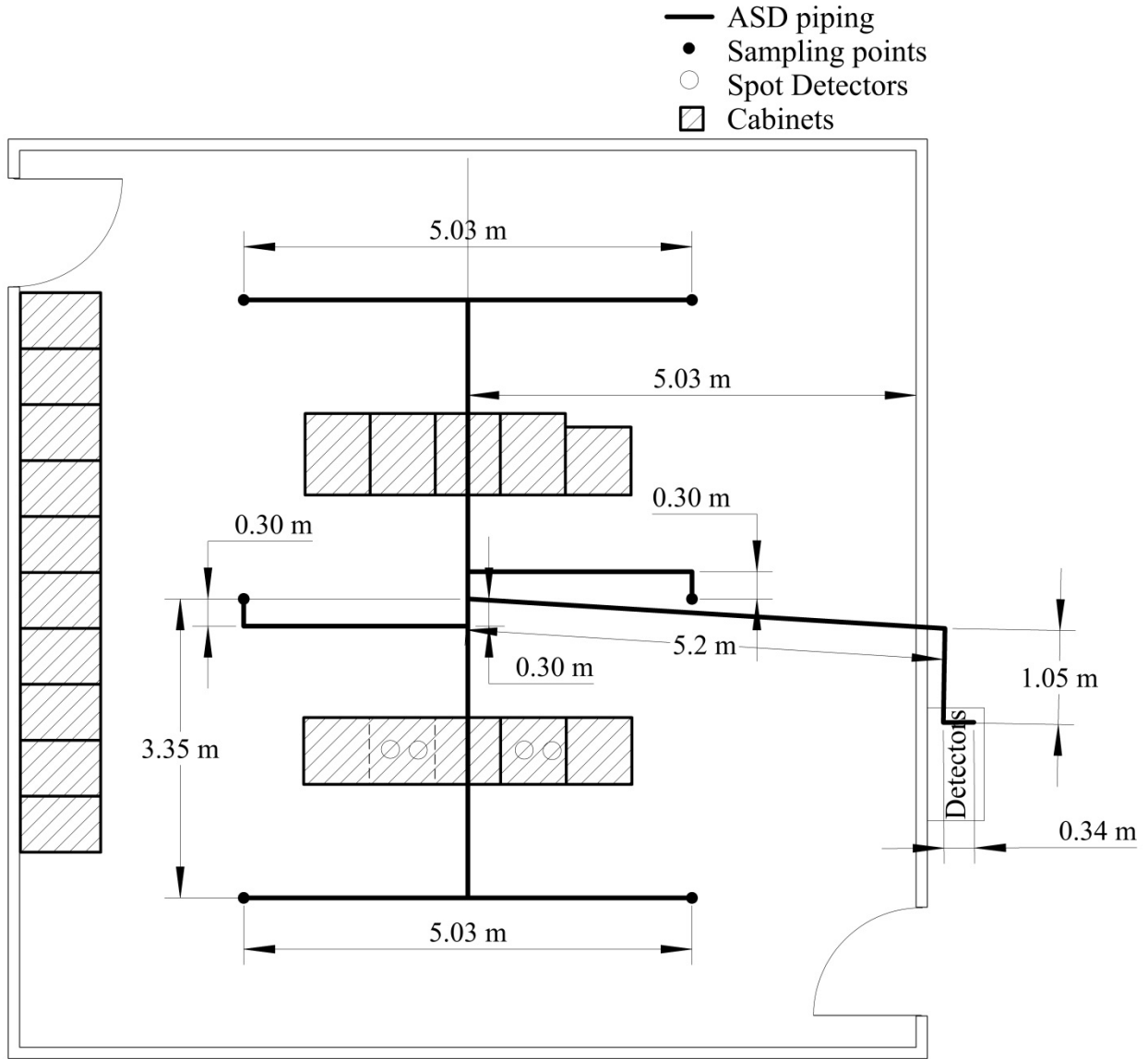
4
5 **Figure 4-46. ASD4 piping layout, with sampling location located at the HVAC exhaust**
6



A: ASD 5 B: ASD 4

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

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Figure 4-48. Areawide ASD4, piping layout

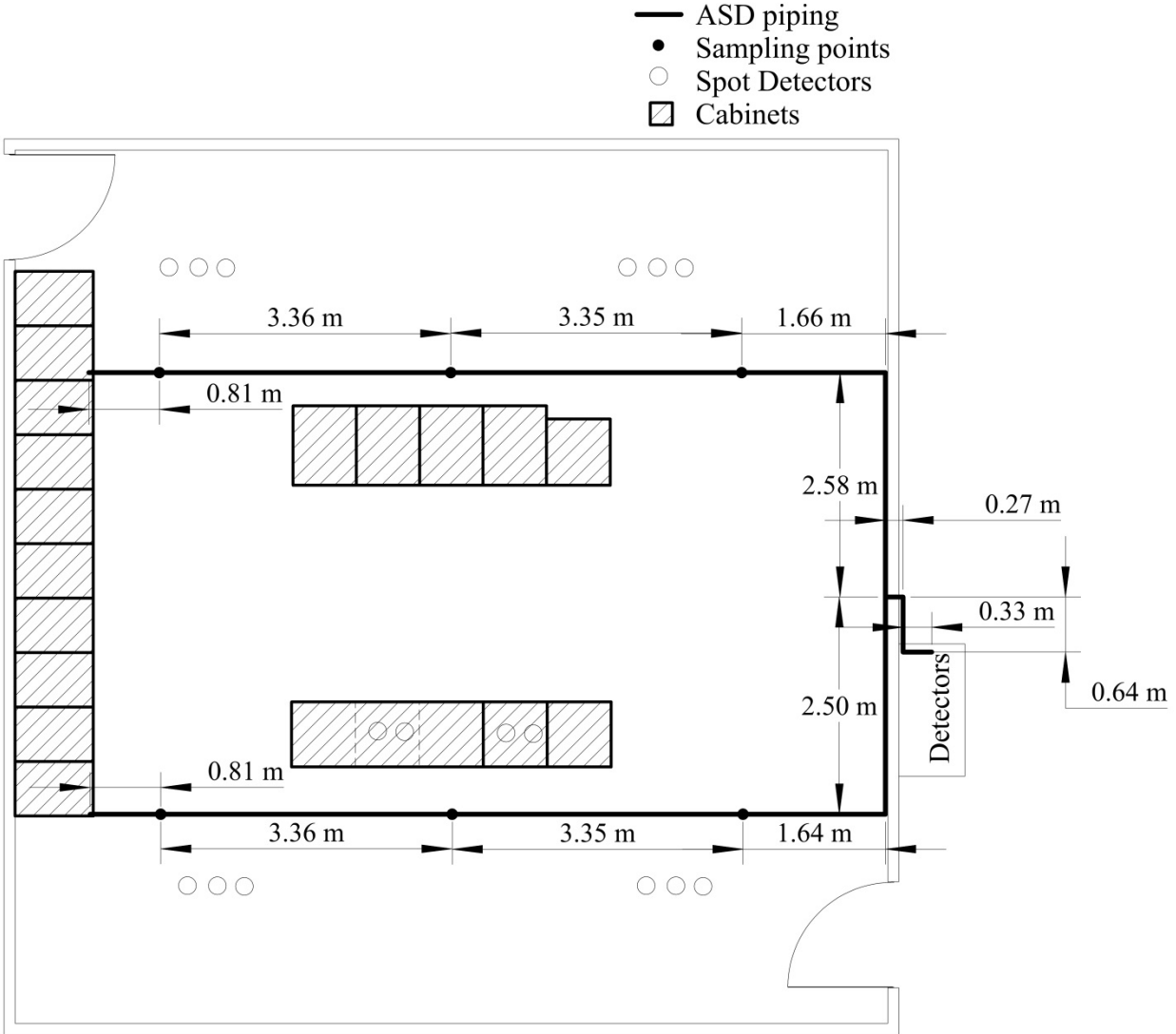


Figure 4-49. Areawide ASD5, piping layout

4.5 Experimental Procedure

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

4.5.1 Laboratory instrument cabinet experiments

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

1 ASD port. The port pressures were 0.20 kPa, 0.14 kPa and 0.15 kPa for ASD1, ASD2 and
2 ASD3, respectively. Smoke from a smoldering punk was used to verify the smoke transport
3 times. Each ASD responded to smoke presented at the furthest sampling port within 10 s.
4

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

11 **4.5.2 Laboratory large-cabinet experiments**

12 The initial setup of the large-cabinet experiments followed the instrument cabinet setup. Only
13 two ASDs were used to monitor the cabinets, ASD2 and ASD3. The measured port suction
14 pressures were the same for each ASD piping arrangement, 0.11 kPa for ASD2, and 0.12 kPa
15 for ASD3.
16
17

18 One large cabinet, used for ventilated cabinet experiments, had a cooling fan mounted on top.
19 Experiments were conducted to estimate the fan flow given the specific internal arrangement of
20 the cabinet as tested. Carbon dioxide was injected at a fixed rate into the fan inlet. The carbon
21 dioxide mixed with the incoming air, and was diluted to a lesser value based on the ventilation
22 air. Injection of ~ 10 l/min of carbon dioxide yielded 0.20 percent (by volume), once mixed with
23 the ventilation air. The mean of four measurements was 4,800 l/min \pm 100 l/min. Assuming a
24 cabinet volume of 0.8 m³, an air exchange rate of about 360 air changes per hour (ACH) would
25 be expected.
26

27 **4.5.3 Small room in-cabinet experiments**

28 The small-room experiments posed some challenges, since the offsite test location had no
29 central heating, and the experiments were conducted in the month of December. Electric space
30 heaters were used to heat the small room and the attached data acquisition room. The heaters
31 were turned on in the morning and allowed to heat the test room to a temperature above 12°C.
32 A vertical array of thermocouples stretching from 30 cm above the floor to the ceiling, was
33 monitored to determine the temperature gradient. The maximum temperature difference was
34 typically about 1°C.
35

36 The suction pressures for the six in-cabinet sampling ports for the three ASDs were 0.123 kPa,
37 0.074 kPa, and 0.083 kPa for ASD1, AD2 and AD3, respectively.
38

39 The smoke transport time was measured at cabinets 1 and 6. Those cabinets represented the
40 closest and furthest points in the setup. The average smoke response times for three
41 measurements at the first cabinet were 19.4 \pm 2.4, 33.2 \pm 6.7 and 13.7 \pm 0.2 seconds for ASD1,
42 ASD2 and ASD3, respectively. The measurements at the last cabinet were 20.3 \pm 1.8, 32.0 \pm
43 1.7 and 15.3 \pm 1.2 seconds for ASD1, ASD2 and ASD3, respectively.
44

45 Experiments were conducted with forced ventilation of the row of five interconnected cabinets.
46 The air exchange rate between the cabinet and the room air was estimated by monitoring
47 carbon dioxide concentration inside the cabinets, following a discharge of a carbon dioxide fire
48 extinguisher. The decay in the concentration was fitted to an exponential equation to yield a
49 time constant for the decay, giving the air changes per hour (ACH). A detailed description for
50
51

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

5
6 Additional experiments were conducted with room ventilation air flow. The air exchange rate of
7 the room with air ventilation was estimated by monitoring carbon dioxide concentration in the
8 center of the room, following a discharge of a carbon dioxide fire extinguisher, and fitting the
9 decay curve as described above. For the room with mechanical ventilation running, three
10 measurements were made yielding a mean value of $9.2 \text{ ACH} \pm 1.4 \text{ ACH}$.

11 12 **4.5.4 Small room areawide experiments**

13
14 The small-room, areawide experiments were conducted with three ASD VEWFD systems
15 monitoring ceiling-mounted pipe network. Four sampling holes were drilled into each piping
16 network to cover each quadrant of the room. The suction pressures for the four sampling holes
17 for the three ASDs were 0.14 kPa, 0.15 kPa, and 0.20 kPa for ASD1, AD2 and AD3,
18 respectively. Smoke response times were less than 30 seconds for all ASDs and sampling
19 holes.

20
21 Experiments were conducted with and without room ventilation air flow. The fan setting was the
22 same one used during the in-cabinet room ventilation experiments (i.e. $9.2 \text{ ACH} \pm 1.4 \text{ ACH}$).

23
24 The room was heated with electric space heaters before the start of an experiment. For no
25 room ventilation experiments, the heaters were turned off just before the start of an experiment.
26 With no ventilation, the room temperature was nominally constant for the duration of an
27 experiment. For experiments with room ventilation, after heating the room before the start of an
28 experiment, the heaters were moved to the room where the blower was located, so the
29 incoming air during an experiment was heated to maintain the room air temperature throughout
30 an experiment.

31 32 **4.5.5 Large room single-zone in-cabinet experiments**

33
34 ASD2 (cloud chamber type) and ASD3 (light-scattering type) were used for the large-room,
35 single-zone in-cabinet experiments, where a single cabinet (second in line) isolated from
36 adjacent cabinets was one sample location configuration, and the fourth cabinet in line that had
37 vent holes to the third and fifth cabinets was the other sample location. Sample port openings
38 were 4.75 mm in diameter for both piping networks. The sample port suction pressures for
39 ASD2 were 0.069 kPa for the first two sampling ports (closest to the detector), and 0.64 kPa for
40 the last two sampling ports. For ASD3, the suction pressures were 0.088 kPa for the first two
41 sampling ports, and 0.083 kPa for the last two sampling ports.

42
43 The air exchange rate of the room with the air exhaust fan fixed at a speed of 32 Hz was
44 estimated by monitoring carbon dioxide concentration in the center of the room following a
45 discharge of a carbon dioxide fire extinguisher, and fitting the decay curve to an exponential
46 function. Three measurements were made yielding a mean value of $7.4 \text{ ACH} \pm 0.6 \text{ ACH}$.

1 **4.5.6 Large room multi-zone in-cabinet experiments**

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

16
17 The air exchange rates of the room with the room air exhaust fan fixed at speeds of 32 Hz and
18 60 Hz were estimated by monitoring carbon dioxide concentrations in the center of the room
19 following a discharge of a carbon dioxide fire extinguisher, and fitting the decay curve to an
20 exponential function. Repeated measurements were made yielding mean values of $6.5 \text{ ACH} \pm$
21 0.6 ACH , and $14.0 \text{ ACH} \pm 1.0 \text{ ACH}$ for 32 Hz and 60 Hz fan settings respectively. Note, there
22 was a difference between single-zone and multi-zone the 32 Hz fan setting ACHs, which was
23 because of a ducting configuration change between the two test series.

24 **4.5.7 Large room multi-zone areawide experiments**

25
26 ASD4 (cloud chamber type) and ASD5 (light-scattering type) were used for the large room multi-
27 zone areawide experiments. The smoke transport times for ASD4 areawide and return air grill
28 sampling ports furthest from the detector were 33 and 26 seconds, respectively. The smoke
29 transport times for ASD5 areawide and return air grill sampling ports furthest from the detector
30 were 45 ± 1 seconds and 25 ± 0.5 seconds, respectively.
31
32

33 **4.6 Experimental Design**

34
35 The following tables detail the experimental conditions for each experiment conducted. The
36 experimental design evolved throughout the project schedule. Information gained from
37 experiments, and feedback from observers was used to tailor successive experimental designs.
38 As part of the experimental design, select experimental conditions were replicated to allow an
39 assessment of repeatability of the experimental results.
40

41 **4.6.1 Laboratory, instrument cabinet experiments**

42
43 The laboratory instrument cabinet experiments were conducted at 15-, 60- and 240 minute
44 HRP's each with a 5 minute fixed ending set point soak period. Samples were located with the
45 bus bar block centered on the floor of the cabinet. The cabinet was naturally ventilated with
46 vents located on the top of the cabinet or on the cabinet sides, 0.2 m below the top of the
47 cabinet.
48
49

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

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4.6.2 Laboratory, large-cabinet experiments

Table 4-5. Laboratory Large-Cabinet Experiments

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

4

Table 4-6. Large Cabinet Experiments with Reduced HRP

Configuration Number	Experimental Configuration			
	Material	Maximum Set point (°C)	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

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4.6.3 Full-scale, small room tests

A series of mock cabinets was built in a 37.7 m² 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.

15

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

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

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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

2

3

4

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

5

6

7

8

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

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

2

3

4

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

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

5

6

1 **4.6.4 Full-scale, large room tests**

2

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

5

6 **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

7

8

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

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

Table 4-14. Full-Scale, Multi-Zone Experiments (Continued)

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

Table 4-14. Full-Scale, Multi-Zone Experiments (Continued)

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

1

5. EXPERIMENTAL RESULTS

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

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

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

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

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

1 **5.1 Laboratory, Small-Cabinet Experiments**

2
3 These experiments were the first set conducted and were designed to gain an understanding of
4 the heated wire/component source, typical ASD and conventional detector response to the
5 various materials selected. In addition, it was a goal of these experiments to find a rational
6 basis for down-selecting the number of materials to be used in subsequent experiments; the
7 materials tested in this series are identified in Table 5-1.
8

9 **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

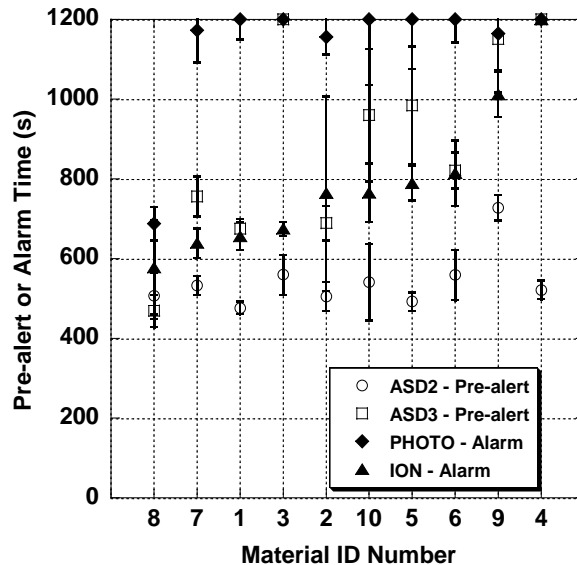
10
11 Two sets of experiments were conducted with different heating rate and experimental time
12 conditions. One condition was a heating ramp period (HRP) of 15.0 minutes to a final set point
13 of 450 degrees C, followed by a 5.0 minute period heating period at the final set point, for a total
14 heating time (THT) of 20.0 minutes. The other condition was a heating ramp period (HRP) of
15 60.0 minutes to a final set point of 450 degrees C, followed by a 5.0 minute period heating
16 period at the final set point, for a total heating time (THT) of 65.0 minutes. The results
17 aggregate those experiments with top and side ventilation conditions, because there was no
18 apparent response time difference between these configurations.
19

20 The ASD and spot detector sensitivities are listed in Table 5-2. ASD piping configuration was
21 nominally 3.7 m long with four equally spaced tee'd sampling ports, three drawing ambient
22 laboratory room air and one drawing cabinet air. In the case of the ASD3, the pre-alarm and
23 alarm sensitivities represent the port sensitivities equal to 0.2 %/ft obscuration and
24 1.0 %/ft obscuration. The sensitivities for ASD2, the cloud chamber device, were factory default
25 settings, and not necessarily what would be used for in-cabinet VEWFD system applications,
26 but most likely less sensitive settings.
27
28

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

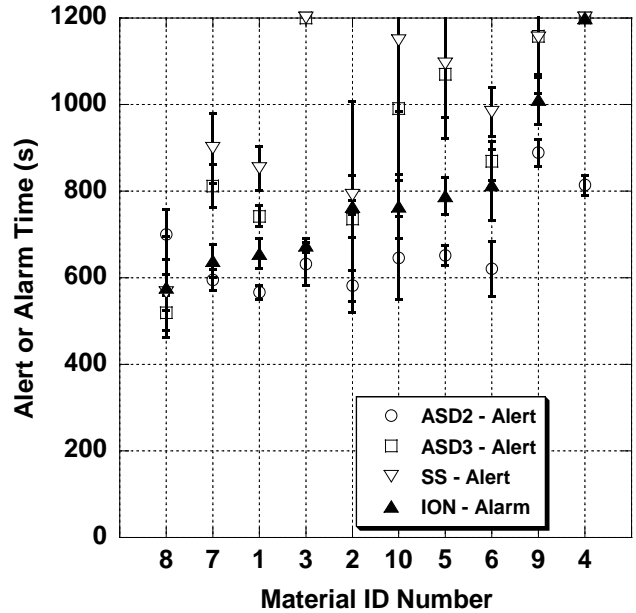
Sensitivity Setting	ASD1 Detector / Port %/ft Obsc	ASD2 Detector / Port Particles/cm ³	ASD3 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc	PHOTO %/ft Obsc
VEWFDS Pre-alert	0.013 / 0.05	5.1x10 ⁵ / 2.4x10 ⁶	0.025 / 0.10	-	-	-
VEWFDS Alert	0.05 / 0.20	1.2x10 ⁶ / 4.8x10 ⁶	0.05 / 0.20	0.20	-	-
VEWFDS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

2
 3 Figure 5-1 shows the pre-alert or alarm times for experiments conducted in the small cabinet
 4 with the 15.0 minute HRP. The materials are ordered in terms of increasing average ION spot
 5 alarm times. In most cases, ASD2 pre-alerted first, typically before 600 seconds of heating.
 6 With silicone and PTFE, ASD3 did not reach a pre-alert threshold before the end of
 7 experiments. The ION did not alarm with PTFE wire, while the PHOTO did not alarm with 6 out
 8 of 10 materials.



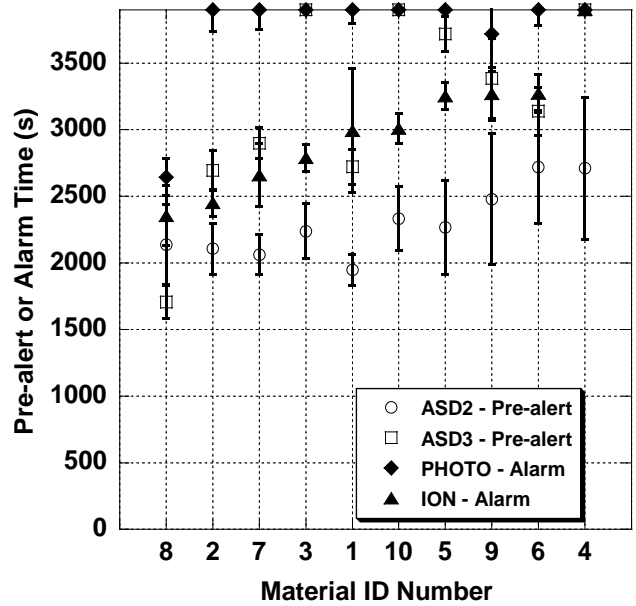
9
 10 **Figure 5-1. VEWFD pre-alert and conventional alarm times for the 15 minute HRP**
 11 **instrument cabinet experiments. (Error bars represent ± one standard**
 12 **deviation for repeated tests)**

1
 2 Figure 5-2 shows VEWFD system alert and ION alarm times for experiments conducted in the
 3 small instrument cabinet with the 15.0 minute HRP. Again, the materials are ordered in terms of
 4 increasing average ION spot alarm times. ASD2 alerted first for all materials except CSPE
 5 (chlorosulfonated polyethylene). ASD3 alerted before ION alarm with two materials.
 6 ASD3 typically alerted before SS, while neither alerted with two materials.

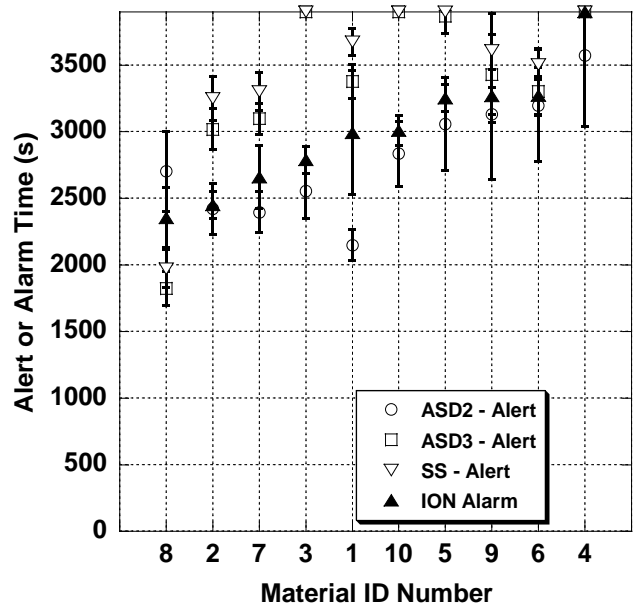


7
 8 **Figure 5-2. VEWFD alert and ION alarm times for the 15 minute HRP instrument cabinet**
 9 **experiments. (Error bars represent ± one standard deviation for repeated**
 10 **tests)**

11
 12 Figure 5-3 shows the pre-alert or alarm times for experiments conducted in the small cabinet
 13 with the 60.0 minute HRP, and Figure 5-4 shows alert and ION alarm times. In both figures, the
 14 materials are ordered in terms of increasing average ION spot alarm times. The trends are
 15 similar to the 15.0 minute HRP results. ASD3 pre-alerted and alerted before other detectors
 16 with CSPE, like the 15.0 minute HRP experiments. Neither ASD3 nor SS alerted before the end
 17 of test with four materials.
 18
 19



1
 2 **Figure 5-3. VEWFD pre-alert and conventional alarm times for the 60 minute HRP**
 3 **instrument cabinet experiments. (Error bars represent ± one standard**
 4 **deviation for repeated tests)**

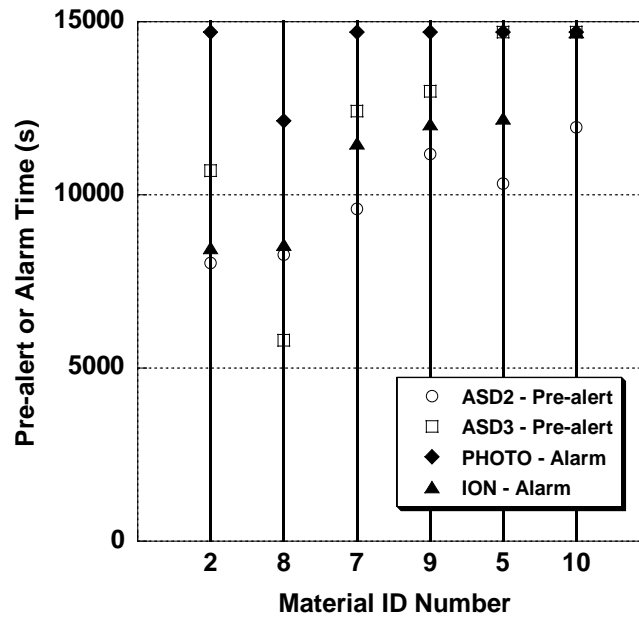


5
 6 **Figure 5-4. VEWFD alert and ION alarm times for the 60 minute HRP instrument cabinet**
 7 **experiments. (Error bars represent ± one standard deviation for repeated**
 8 **tests)**

9

1 Figure 5-5 shows the pre-alert or alarm times for experiments conducted in the small cabinet
2 with 240.0 minute HRP, while Figure 5-6 shows the alert and ION alarm times. The materials
3 are ordered in terms of increasing average ION spot alarm times.
4

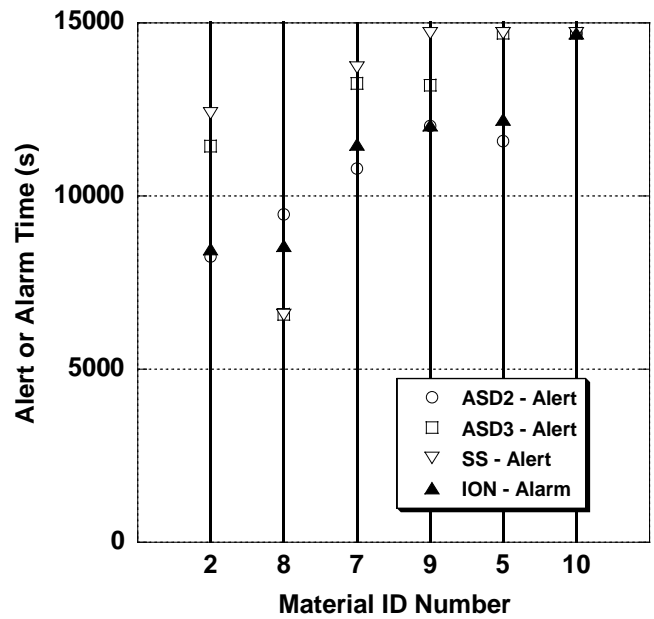
5 The overall trend between the three heating rates was the same. Essentially the order and
6 relative time that the detectors alarmed did not depend on the heating rate. Therefore, the
7 concept of "end of test" (EOT), is used later in this report to merge test results from similar tests
8 that only varied in heating rate and test length. ASD2 typically pre-alerted or alerted before
9 ASD3 and the ION detector. The ION typically alarmed before ASD3 alerted, and ASD3
10 typically alerted before the SS detector alert.
11



12

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

15



1
 2 **Figure 5-6. VEWFD alert and ION alarm times for the 240 minute HRP instrument**
 3 **cabinet experiments**

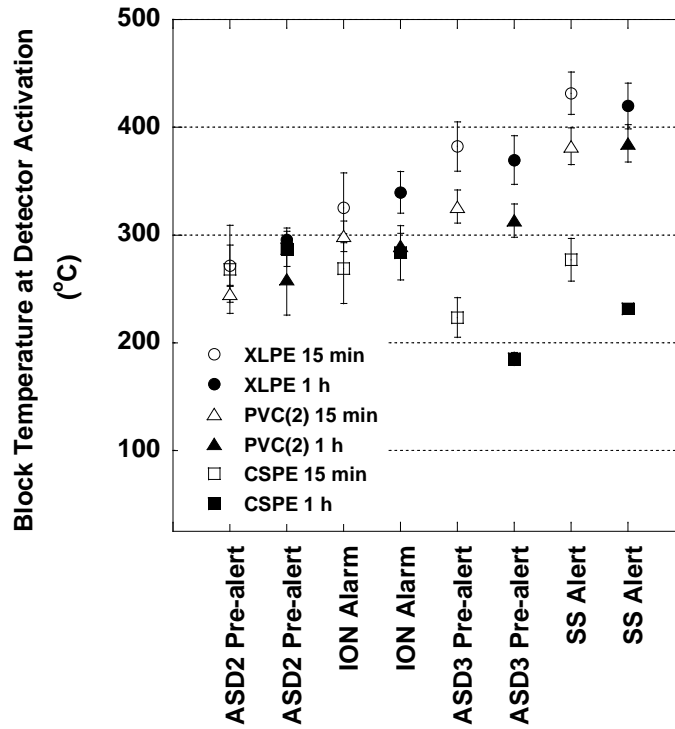
4
 5 Table 5-3 shows typical smoke particle arithmetic mean diameter (AMD) and mass mean
 6 diameter (MMD) results averaged over the 5 minute soak period for the 15.0 minute HRP
 7 experiments for each wire sample. Both the AMD and MMD vary by a factor of three from PFTE
 8 to CSPE insulation. These results, plus the alert and alarm activation results, were used to
 9 down-select the wire samples for full-scale experiments. PVC wire (2), XLPE wire, and CSPE
 10 wire materials were selected to (1) cover the observed (relatively) small, medium and large
 11 mean particle sizes, and (2) to have the ability to produce sufficient smoke to activate the
 12 detectors being studied in the various experimental configurations. Therefore, these selected
 13 materials (PVC, XLPE, and CSPE) are intended to represent the aerosol characteristics
 14 generated from a large variety of materials commonly found in NPP electrical enclosures.
 15 The selection is not intended to bound all materials and these materials (PVC, XLPE, and
 16 CSPE) likely do not represent the most difficult aerosols to detect.

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

ID #	Name	AMD (μm) ($\pm 20\%$)	MMD (μm) ($\pm 20\%$)
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

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

1
2 To examine trends by extending the HRP from 15.0 to 60.0 minutes, the block temperature⁹ at
3 alarm was plotted for the various detector activations in Figure 5-7. The trend between the
4 15.0- and 60.0 minute HRP for ASD2 and ASD3 was consistent for all three materials, but in
5 opposite directions. ASD2 responded at higher block temperatures when the HRP was
6 increased, while ASD3 responded at lower block temperatures. The magnitude of the
7 temperature difference was not large, thus the practical implications may be minor.
8



9
10 **Figure 5-7. Block temperature at pre-alert, alert or alarm time for various detectors.**
11 **(Error bars represent +/- one standard deviation for repeated tests)**

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

- 13
14 1. ASD2 pre-alerted and alerted before ASD3 and SS for all materials with the exception of
15 CSPE.

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

- 1 2. At both HRP, ASD2 was the only detector to respond to PTFE samples before the end
2 of test.
- 3 3. The overall trend between the three heating rates was the same, ASD2 typically
4 pre-alert or alerted before ASD3 and the ION detector. The ION typically alarmed before
5 ASD3 alerted, and ASD3 typically alerted before the SS detector.
- 6 4. By the end of the test, both the arithmetic mean diameter and the mass mean diameter
7 of the smoke varied by a factor of three from PTFE wire (smallest particles) to CSPE
8 wire (largest particles), but this made no difference except with ASD3 and SS's better
9 performance in detection CSPE.
- 10 5. The heating ramp period affected the observed block temperature when ASDs
11 responded. ASD2 responded at higher block temperatures when the HRP was
12 increased, while ASD3 responded at lower block temperatures.

13 5.2 Laboratory, Large-Cabinet Experiments

14 Experiments were conducted in two surplus NPP cabinets, one with natural ventilation, and one
15 with forced ventilation provided by a fan and ducting. The cabinet sizes were dimensionally the
16 same, but the internal configurations were different. These tests primarily show the effects of
17 natural ventilation versus high-flow forced ventilation cabinet conditions. These experiments
18 were conducted in the laboratory with an ASD2, an ASD3, an ionization spot detector (ION) and
19 a sensitive spot detector (SS). The detector sensitivities are listed in Table 5-4. The ION spot
20 was installed in both cabinets and the sensitive spot was only installed in the naturally ventilated
21 cabinet, as there wasn't sufficient room in the forced ventilation cabinet to install both. The ASD
22 piping configuration was four equally spaced ports, three sampling laboratory room air and one
23 sampling cabinet air. The materials used in these experiments were polyvinyl chloride insulated
24 (PVC2), XLPE, CSPE, and PCB.
25

26 For these experiments, the heating ramp period and final set point were extended. Based on
27 the results of the small-cabinet experiments, it was decided to increase the final block
28 temperature set point to 485 degrees C. The slope of the set point ramp remained the same as
29 the 450 degrees C final set point experiments, but the duration of the ramp period was
30 increased to 16.3, 65, and 460 minutes for the new heating ramp periods. The total heating
31 times (THTs) were 1,278, 4,200 and 15,900 seconds for the three HRP, respectively.
32

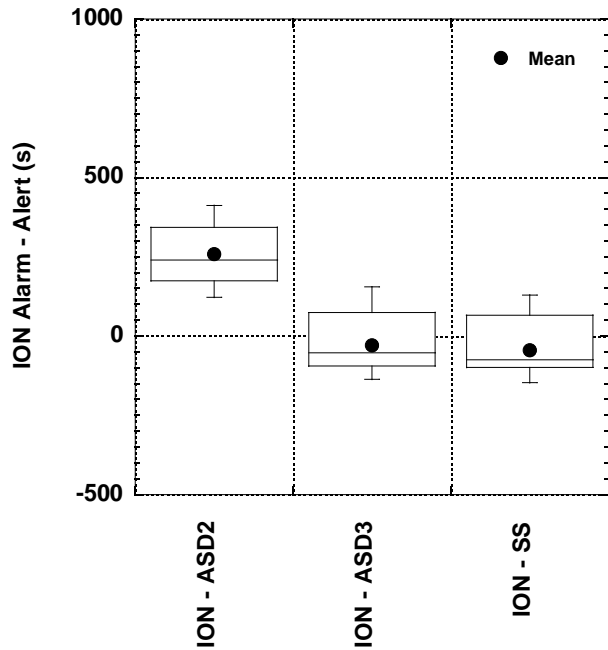
33 **Table 5-4. Nominal Detector Sensitivities for Laboratory—NPP Large-Cabinet**
34 **Experiments**

Sensitivity Setting	ASD2 Detector/Port Particles/cm ³	ASD3 Detector/Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc
VEWFD Pre-alert	5.1x10 ⁵ /2.4x10 ⁶	0.0063/0.025	-	-
VEWFD Alert	1.2x10 ⁶ /4.8x10 ⁶	0.05/0.20	0.20	-
VEWFD Alarm	1.5x10 ⁶ /6.0x10 ⁶	0.25/1.00	1.00	-
Conventional Pre-Alarm	-	-	-	0.5
Conventional Alarm	-	-	-	1.0

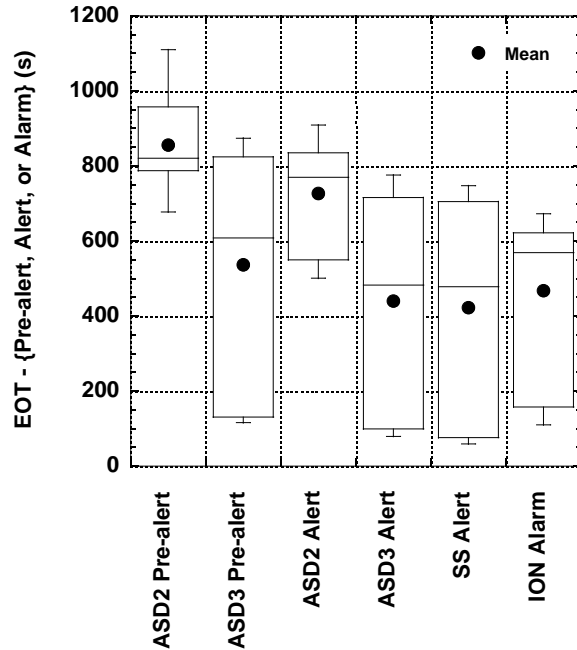
1
 2 Results are presented in box plots where the box's vertical limits represent the range in which
 3 the middle 50 percent of the data lay, the vertical line inside the box indicates the median, and
 4 bars above and below the box represent the upper quartile (UQ) and lower quartile (LQ), with
 5 individual outlier values represented by an open circle symbol. Outliers are defined as values
 6 greater than $(UQ+1.5*(UQ-LQ))$ or less than $(LQ-1.5(UQ-LQ))$, in other words, 1.5 times the
 7 inter-quartile range above the upper quartile or below the lower quartile. A filled circle symbol
 8 represents the mean of all values including outliers.
 9

10 The first data set examined consists of the naturally ventilated cabinet, 16.3 minute HRP
 11 experiments. Three experiments with each of the four materials were conducted for a total of
 12 12 experiments. Figure 5-8 shows the difference between the ION alarm and the ASD and SS
 13 alert times. Only ASD2 had mean and median values greater than 0, and in all cases, ASD2
 14 alerted before the ION alarmed. ASD3 and SS have about the same average response.
 15

16 Figure 5-9 shows the differences between the end of the test (1,278 s) and the ASD pre-alerts,
 17 ASD and SS alerts, and ION alarm times. All detectors alerted or alarmed before the end of
 18 test.
 19



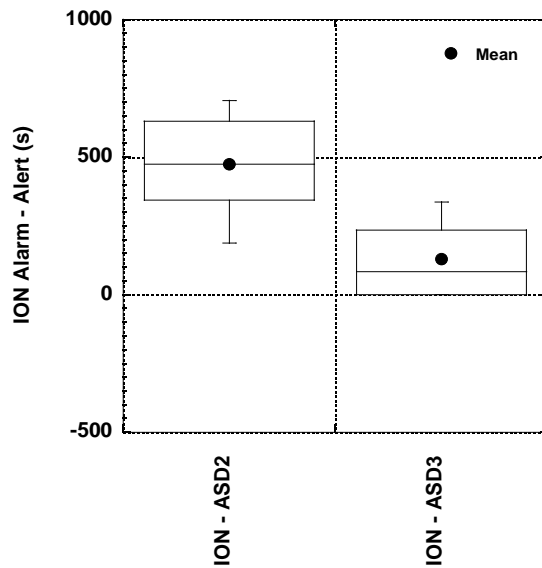
20
 21 **Figure 5-8. Time difference between ION alarm time and the ASD alerts and SS alert**
 22 **time for large cabinet, natural ventilation, 16.3 minute HRP experiments**
 23



1
 2 **Figure 5-9. Time difference between the end of test (EOT) time (1278 s) and ASD pre-**
 3 **alerts, ASD and SS alerts or ION alarm time for large cabinet, natural**
 4 **ventilation, 16.3 minute HRP experiments**

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

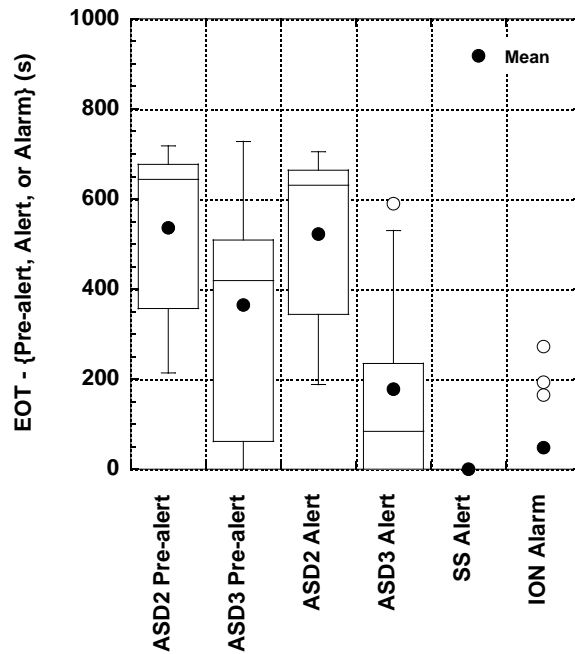
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11
 12 **Figure 5-10. Time difference between ION alarm time and the ASD alert time for large**
 13 **cabinet, forced ventilation, 16.3 minute HRP experiments**

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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.



5

6 **Figure 5-11. Time difference between the end of test (EOT) time (1278 s) and ASD pre-**
7 **alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation,**
8 **16.3 minute HRP experiments**

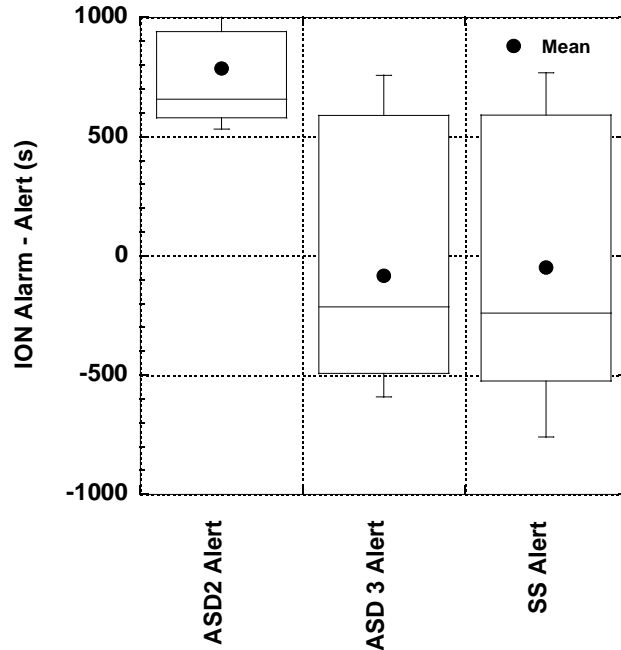
9

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

15

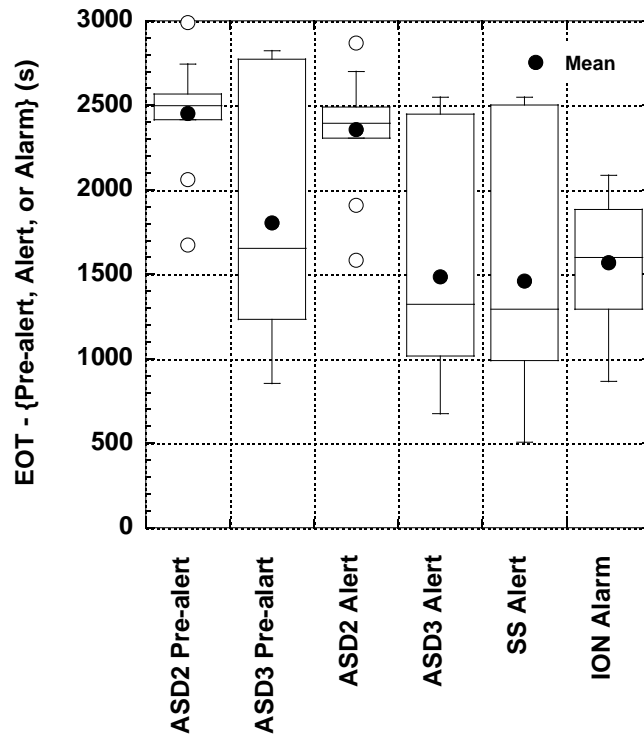
16 Figure 5-13 shows the difference between the end of the test (4,200 s) and the ASD pre-alerts,
17 ASD and SS alerts, and ION alarm times. The average detector response was about
18 1,500 seconds or greater before the end of test.

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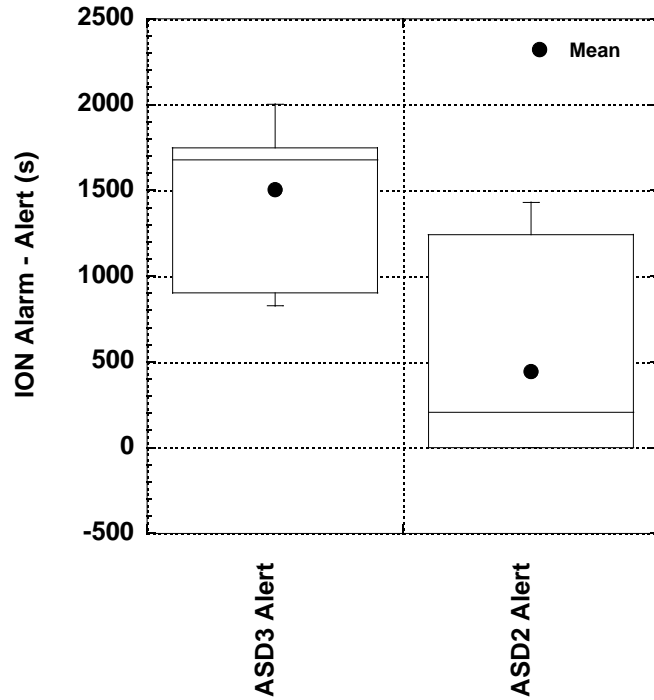
Figure 5-12. Time difference between ION alarm time and the ASD alerts and SS alert time for large cabinet, natural ventilation, 65.0 minute HRP experiments



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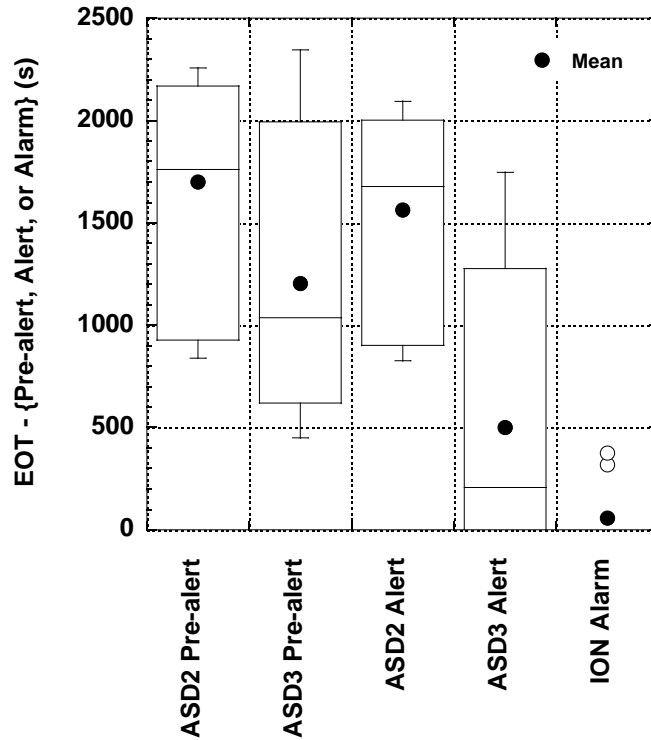
Figure 5-13. Time difference between the end of test (EOT) time (4200 s) and ASD pre-alerts, ASD and SS alerts or ION alarm time for large cabinet, natural ventilation, 65.0 minute HRP experiments

1 The fourth data set examined consists of the forced ventilation cabinet, 65.0 minute HRP
2 experiments. Three experiments with each of the four materials were conducted for a total of
3 12 experiments. Figure 5-14 shows the difference between the ION alarm and the ASD alert
4 times. Both ASDs alerted before the ION alarm on average.
5
6



7
8 **Figure 5-14. Time difference between ION alarm time and the ASD alerts times for large**
9 **cabinet, forced ventilation, 65.0 minute HRP experiments**

10 Figure 5-15 shows difference between the end of the test (4,200 s) and the ASD pre-alerts, ASD
11 alerts, and ION alarm times.
12



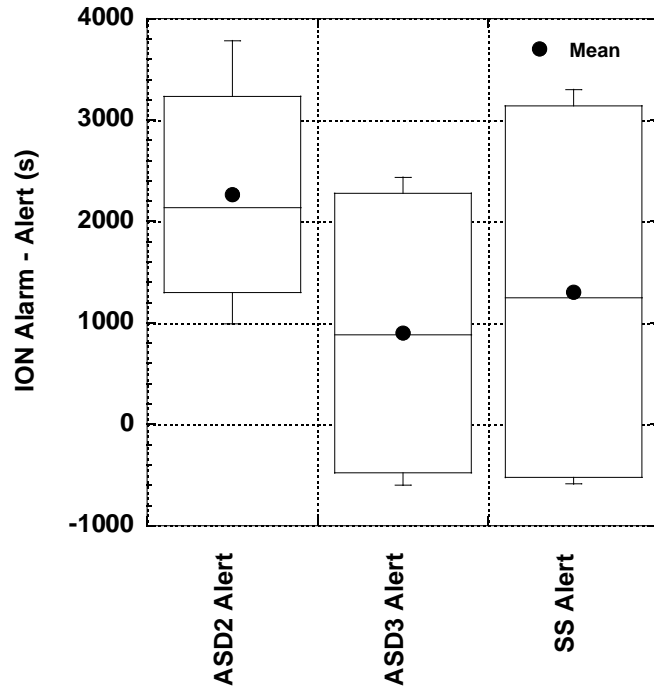
1

2 **Figure 5-15. Time difference between the end of test (EOT) time (4200 s) and ASD pre-**
 3 **alerts, ASD alerts or ION alarm time for large cabinet, forced ventilation,**
 4 **65.0 minute HRP experiments**

5

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

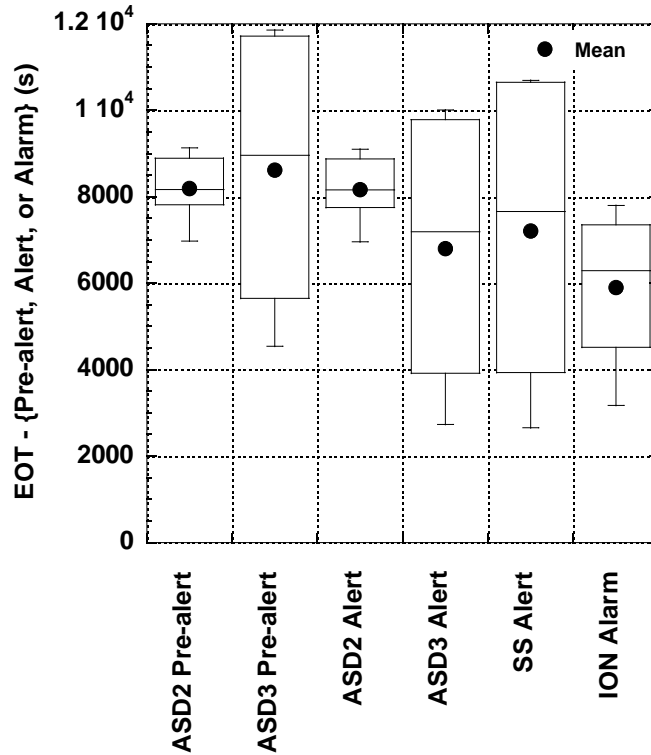
11



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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.



1

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

5

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

7

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

10 2. For the forced ventilation cabinet experiments, the ASD VEWFD systems significantly
 11 outperformed the ionization detector, which in many cases did not alarm during both
 12 16.3 and 65.0 minute heating period experiments.

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

16

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.

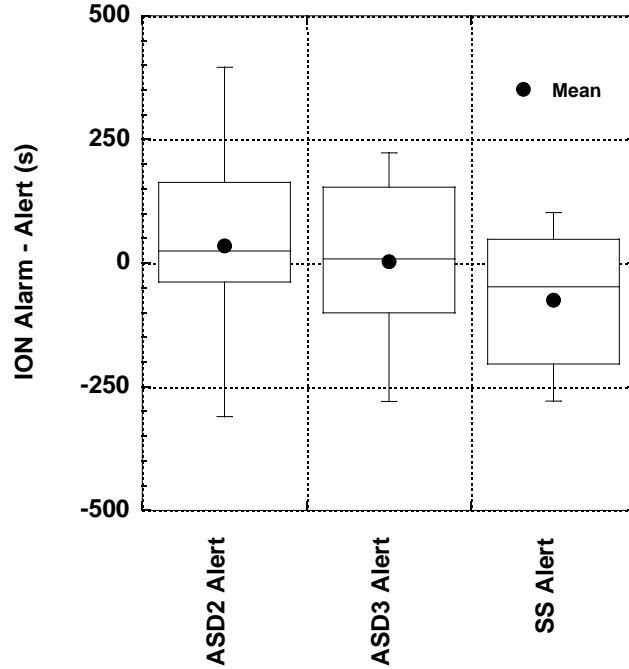
Table 5-5. Nominal Detector Sensitivities for Small Room, Cabinet Mock-Up Tests

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	5.1x10 ⁵ / 3.1x10 ⁶	0.0083 / 0.05	-	-	-
VEWFD Alert	0.05 / 0.30	8.2x10 ⁵ / 4.9x10 ⁶	0.033 / 0.20	0.20	-	-
VEWFD Alarm	0.25 / 1.50	1.5x10 ⁶ / 9.0x10 ⁶	0.167 / 1.00	1.00	-	-
Conventional Pre-alarm	-	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	-	1.0	2.1

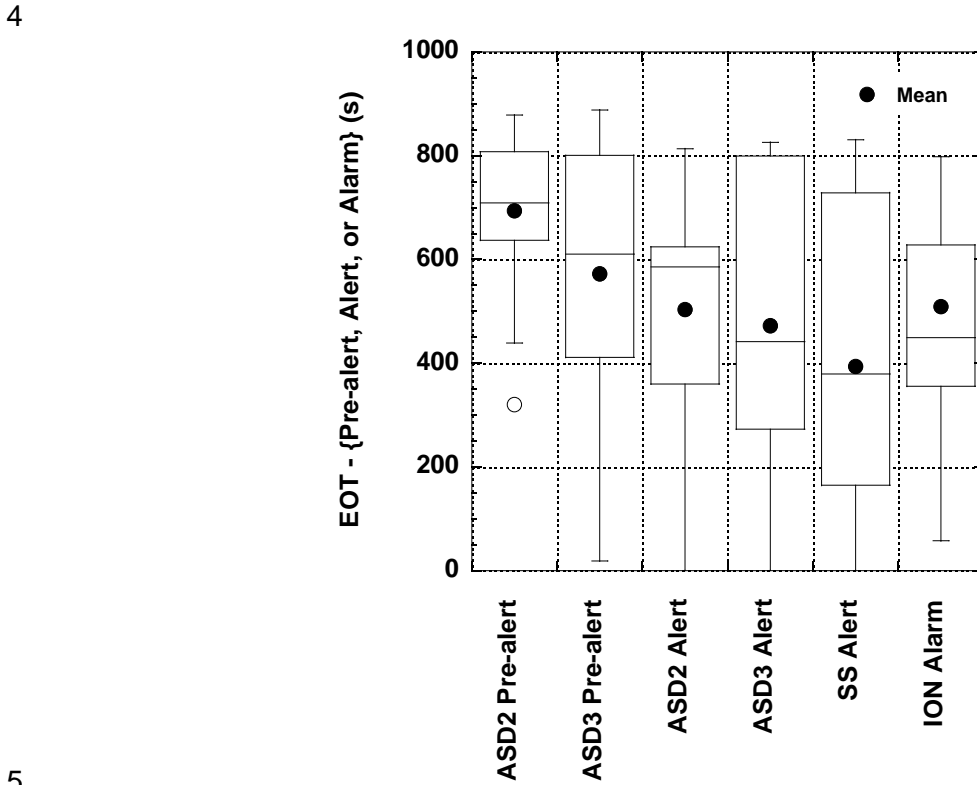
The first data set examined consists of 16.3 minute HRP experiments in the three cabinet configurations: single cabinet with XLPE, CSPE, PVC and PCB materials, the set of four cabinets with XLPE, CSPE and PVC materials, the set of five cabinets with XLPE, CSPE, PVC and PCB materials, and the set of five 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.



1
 2 **Figure 5-18. Time difference between ION alarm time and the ASD alerts and SS alert for**
 3 **small room, cabinet mock-up, 16.3 minute HRP experiments**



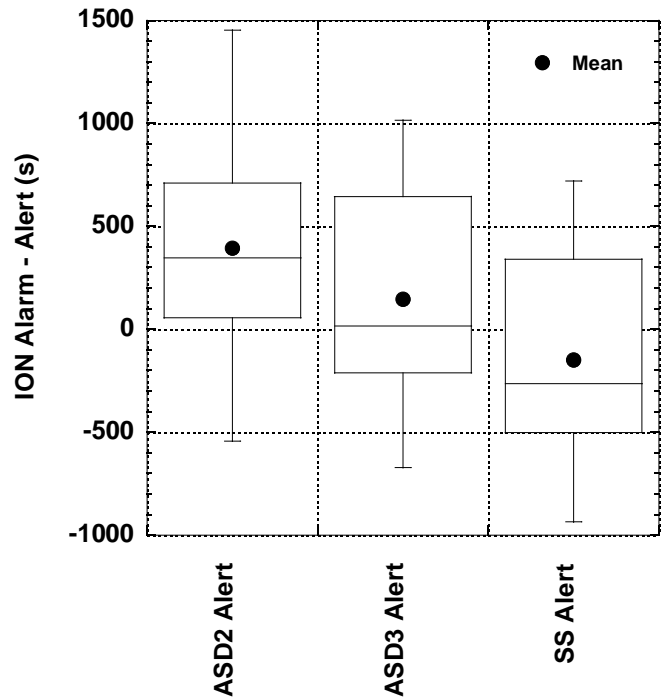
5
 6 **Figure 5-19. Time difference between the end of test (EOT) time (1278 s) and ASD**
 7 **pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet**
 8 **mock-up, 16.3 minute HRP experiments**

1
2 The second data set examined consists of 65.0 minute heating period experiments in the three
3 cabinet configurations: single cabinet with XLPE, CSPE, and PVC materials, the set of four
4 cabinets with XLPE, CSPE and PVC materials, the set of five cabinets with XLPE, CSPE, PVC
5 and PCB materials with no ventilation flows, cabinet ventilation and room ventilation, and the set
6 of five cabinets with XLPE, CSPE and PVC sources elevated to 2/3 of the cabinet height. The
7 single, four, and five cabinet configurations are presented in Section 4.4.3.

8
9 Figure 5-20 shows the difference between the ION alarm and the ASD and SS alert times. The
10 ASD mean time differences were greater than 0 and less than 0 for the SS.

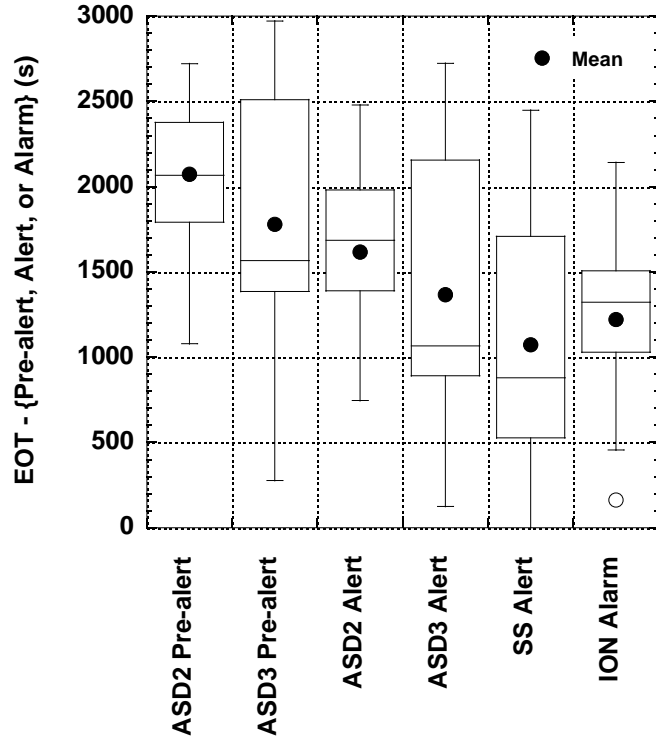
11
12 Figure 5-21 shows the difference between the end of the test (4,200 seconds) and the ASD pre-
13 alerts, ASD and SS alerts, and ION alarm times. Most detectors responded before 500 seconds
14 to the end of test.

15



16
17 **Figure 5-20. Time difference between ION alarm time and the ASD alerts and SS alert for**
18 **small room, cabinet mock-up, 65.0 minute HRP experiments**

19

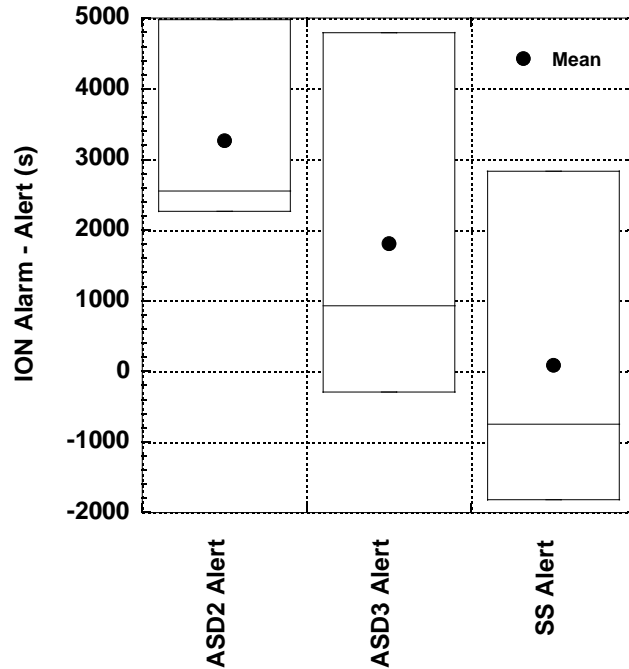


1
 2 **Figure 5-21. Time difference between the end of test (EOT) time (4200 s) and ASD pre-**
 3 **alerts, ASD and SS alerts or ION alarm time for small room, cabinet mock-**
 4 **up, 65.0 minute HRP experiments**

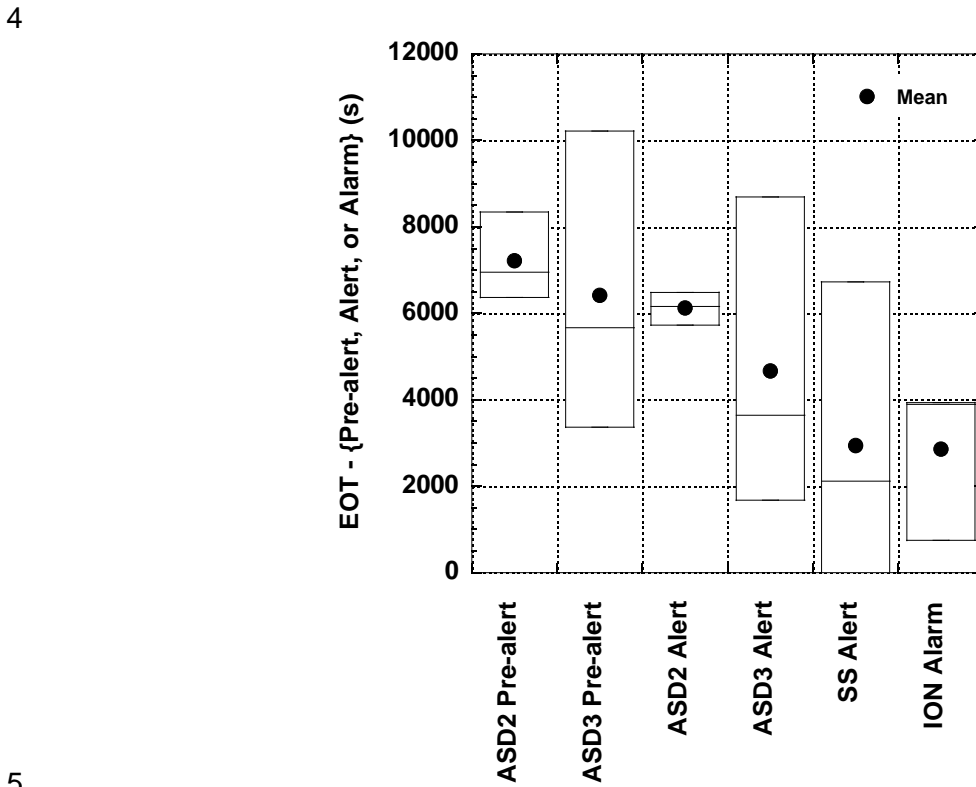
5
 6 The third data set examined consists of 260.0 minute HRP experiments in the set of five
 7 cabinets. Three experiments with XLPE, CSPE or PVC wire sources were conducted. Because
 8 only three data points are plotted, the box limits represent the minimum and maximum values.
 9

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

11
 12 Figure 5-23 shows difference between the end of the test (15,900 s) and the ASD pre-alerts,
 13 ASD and SS alerts, and ION alarm times.
 14



1
 2 **Figure 5-22. Time difference between ION alarm time and the ASD alerts and SS alert for**
 3 **small room, cabinet mock-up, 260.0 minute HRP experiments**



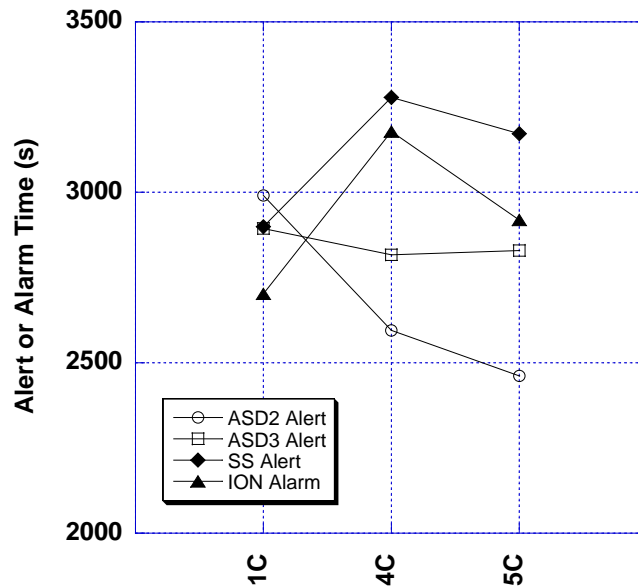
5
 6 **Figure 5-23. Time difference between the end of test (EOT) time (15900 s) and ASD**
 7 **pre-alerts, ASD and SS alerts or ION alarm time for small room, cabinet**
 8 **mock-up, 260.0 minute HRP experiments**

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

10
 11 Figure 5-24 shows ASD alert, SS alert and ION alarm time averaged over the three materials
 12 experiments for the isolated cabinet (1C), group of four cabinets (4C), and group of five cabinets
 13 (5C). Pre-alarm or alarm times for XLPE, PVC2 and CSPE wire samples subject to 65.0 minute
 14 heating periods.

15
 16 Figure 5-25 shows ASD alert, SS alert and ION alarm time averaged over the three materials
 17 experiments for the four group of five cabinets (5C) experimental configurations. Increasing and
 18 decreasing alert or alarm time trends were observed, moving from 1C to 4C to 5C
 19 configurations. Elevated-sample experiments tended to yield shorter alarm times than the base
 20 case (sample at bottom, no ventilation).

21



22

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

25

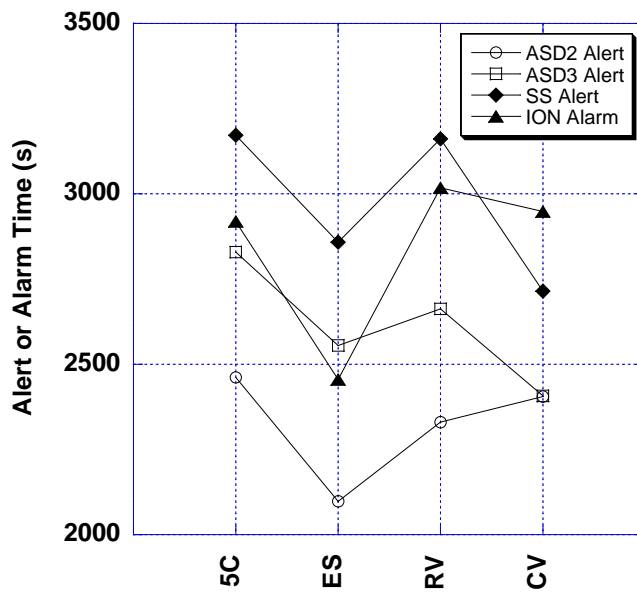


Figure 5-25. Mean alert or alarm times for small room, 5-cabinet mock-up configurations, 65.0 minute HRP experiments

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

1. The ASDs tended to pre-alert before the ION alarm for both heating period experiments.
2. All ASDs alerted before the end of test time,
3. On average, the SS detector pre-alarmed after the ION alarm for both heating period experiments
4. Cabinet-ventilated experiments and elevated-sample experiments tended to yield shorter alarm times than the base case (sample at bottom, no ventilation).

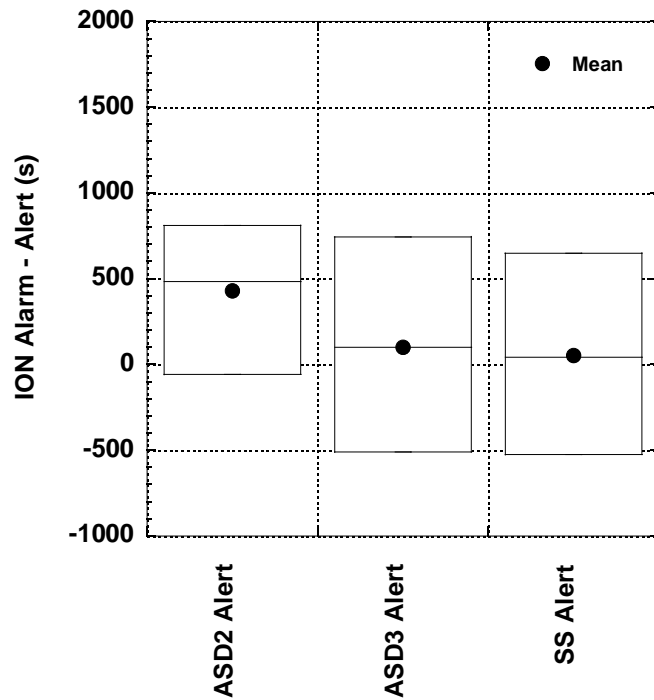
5.4 Full Scale, Large Room, Single-Zone, In-Cabinet Experiments

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

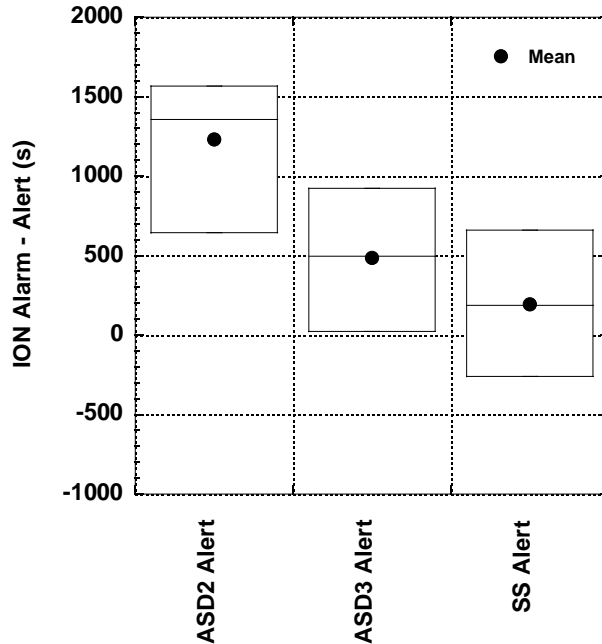
1 **Table 5-6. Nominal Detector Sensitivities for Large Room, Single-Zone Cabinet Tests**

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

2
 3 Results for the single cabinet and the three-cabinet arrangement are shown in Figure 5-26 and
 4 Figure 5-27. On average, the ASDs responded sooner than the ionization alarm for the
 5 three-cabinet arrangement suggesting some cooperative ASD sampling from adjacent cabinets.
 6



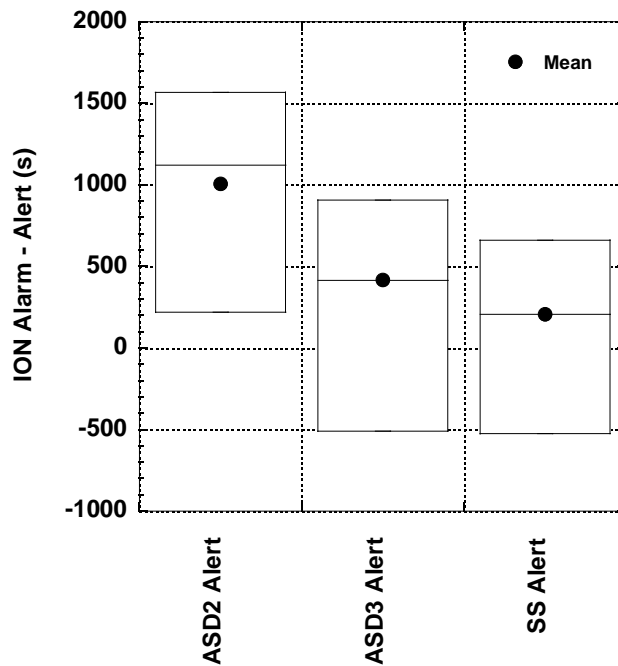
7
 8 **Figure 5-26. Time difference between ION alarm time and the ASD alerts and SS alert for**
 9 **large room, single-zone single-cabinet, 65.0 minute HRP experiments**



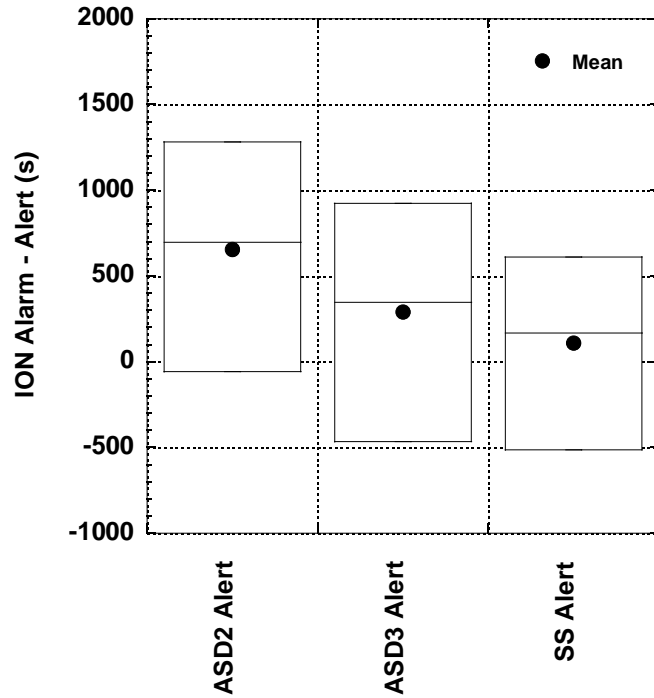
1
 2 **Figure 5-27.** Time difference between ION alarm time and the ASD alerts and SS alert for
 3 large room, single-zone, three-cabinet configuration, 65.0 minute HRP
 4 experiments

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

7



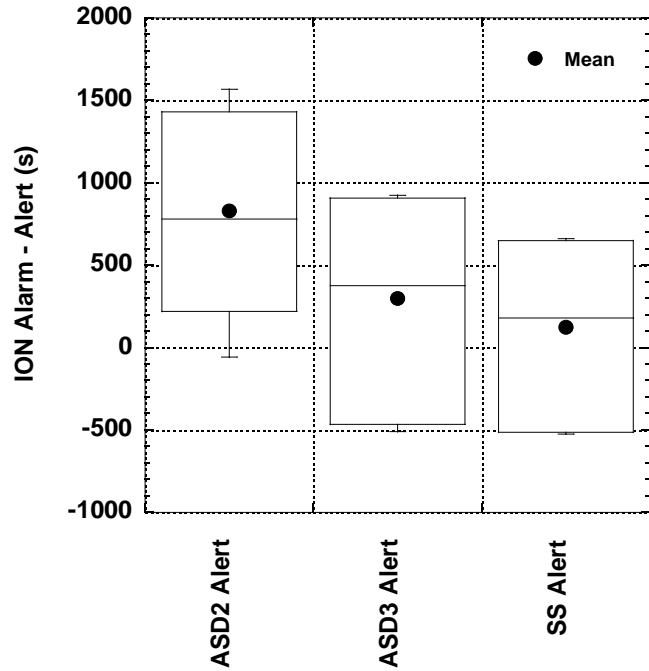
8
 9 **Figure 5-28.** Time difference between ION alarm time and the ASD alerts and SS alert for
 10 large room, single-zone, no ventilation, in-cabinet, 65.0 minute HRP
 11 experiments



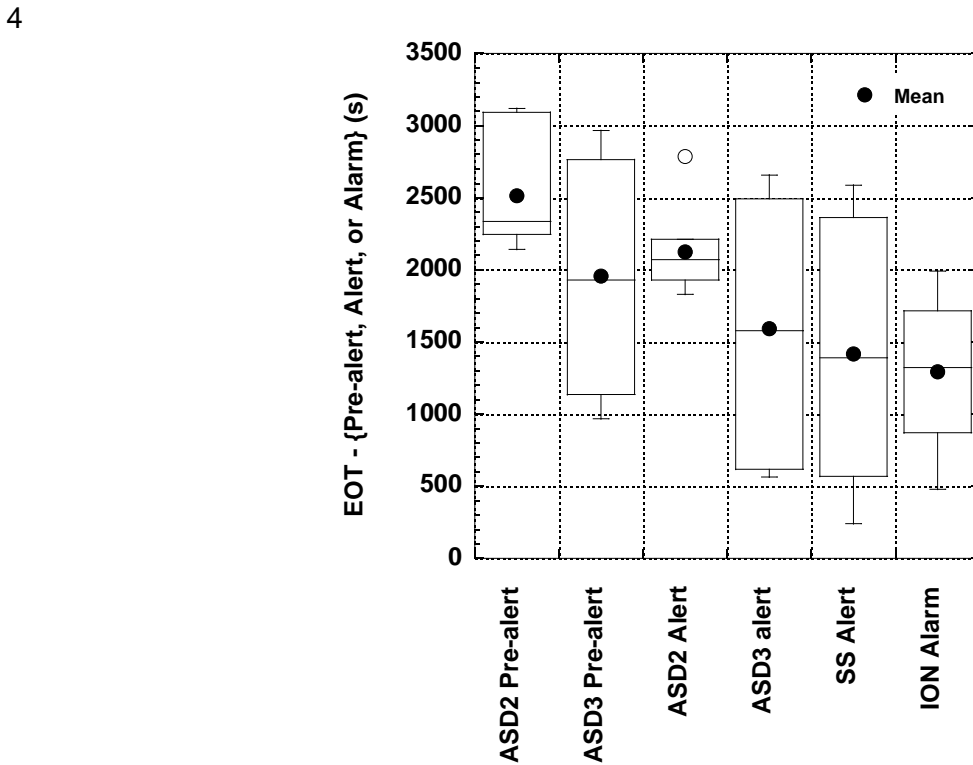
1
 2 **Figure 5-29. Time difference between ION alarm time and the ASD alerts and SS alert for**
 3 **Large room, single-zone, 7.4 ACH room ventilation, in-cabinet, 65.0 minute**
 4 **HRP experiments**

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

7
 8 Figure 5-31 shows the results of the time difference between the end of the test (4,200 s) and
 9 the ION alarm, the ASD alerts, SS pre-alarm time and the PHOTO alarm time. Both ASD
 10 pre-alert mean and median time differences were greater than 1,900 seconds. The decreasing
 11 mean time difference trend was ASD2 alert, ASD3 alert, SS alert and ION alarm.
 12



1
 2 **Figure 5-30.** Time difference between ION alarm time and the ASD alerts and SS alert for
 3 large room, single-zone, in-cabinet, 65.0 minute HRP experiments

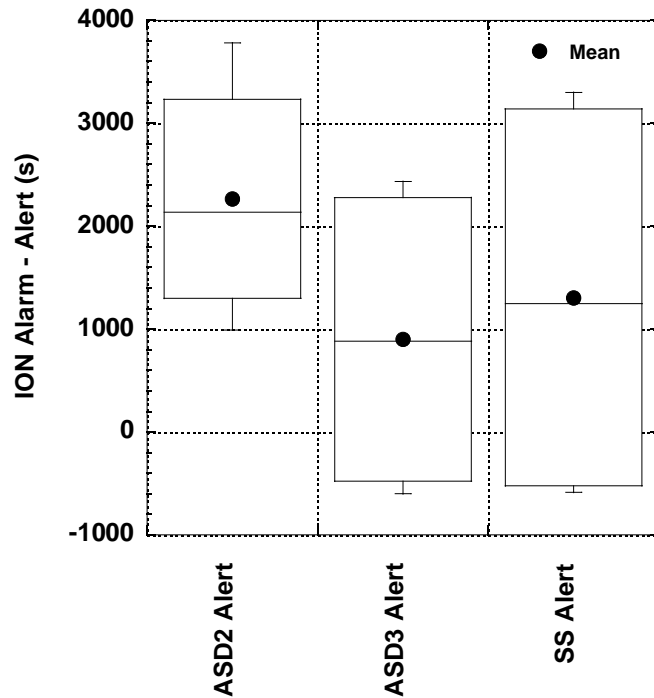


5
 6 **Figure 5-31.** Time difference between the end of test (EOT) time (4200 s) and ASD
 7 Pre-alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet,
 8 65.0 minute HRP experiments

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

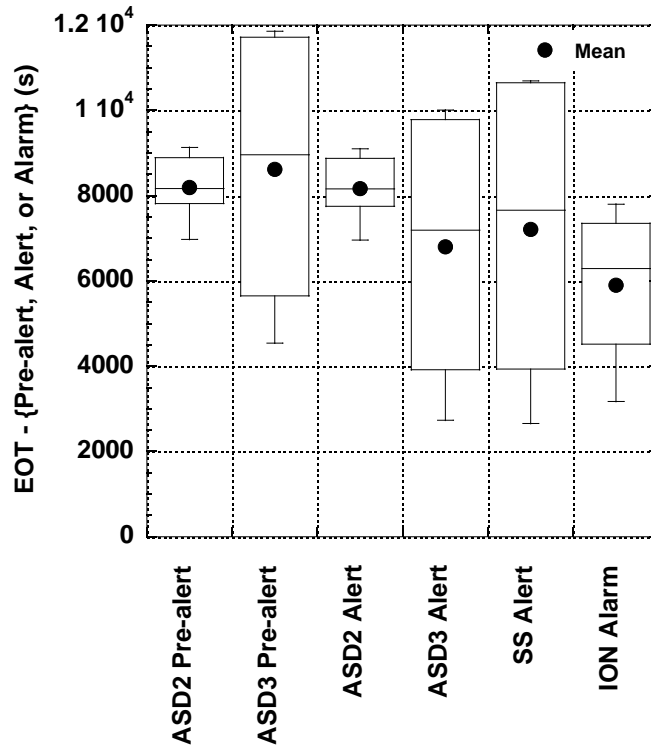
5
6 Figure 5-32 shows the results of the difference between the ION alarm, and the ASD alerts or
7 SS pre-alarm time for all eight experiments.

8
9 Figure 5-33 shows the results of the time difference between the end of the test (15,900 s) and
10 the ION alarm, the ASD alerts, SS pre-alarm time and the photo alarm time. The decreasing
11 mean time difference trend was ASD2 alert, SS alert, ASD3 alert and ION alarm.
12



13
14 **Figure 5-32. Time difference between ION alarm time and the ASD alerts and SS alert for**
15 **large room, single-zone, in-cabinet, 260.0 minute HRP experiments**

16



1
2 **Figure 5-33. Time difference between the end of test (EOT) time (15900 s) and ASD pre-**
3 **alerts, ASD and SS alerts or ION alarm time for large room, in-cabinet, 260.0**
4 **minute HRP experiments**

5
6 The large room single-zone cabinet results gave rise to the following observations:

- 7
8 1. The time difference between the ionization alarm and the ASD alerts was greater for the
9 three-cabinet arrangement than the single cabinet arrangement.
- 10 2. Room ventilation tended to reduce the time difference between the ionization alarm and
11 the ASD alerts.
- 12 3. All detectors alerted before the end of test time for both heating periods.

13
14 **5.5 Full-Scale, Large-Room, Multi-Zone, In-Cabinet Experiments**

15
16 Ten in-cabinet 65 minute heating period experiments were conducted in the large room, five
17 with XLPE wire sources and five with CSPE wire sources. For each wire source, experiments
18 were conducted in the isolated cabinet with and without room air ventilation flow (7.5 ACH), and
19 in a three cabinet arrangement (where the cabinet with the source had openings to its two
20 neighbors), with and without room air ventilation flow (7.5 ACH and 15 ACH). Table 5-7
21 presents the detector sensitivity settings used in these tests.
22

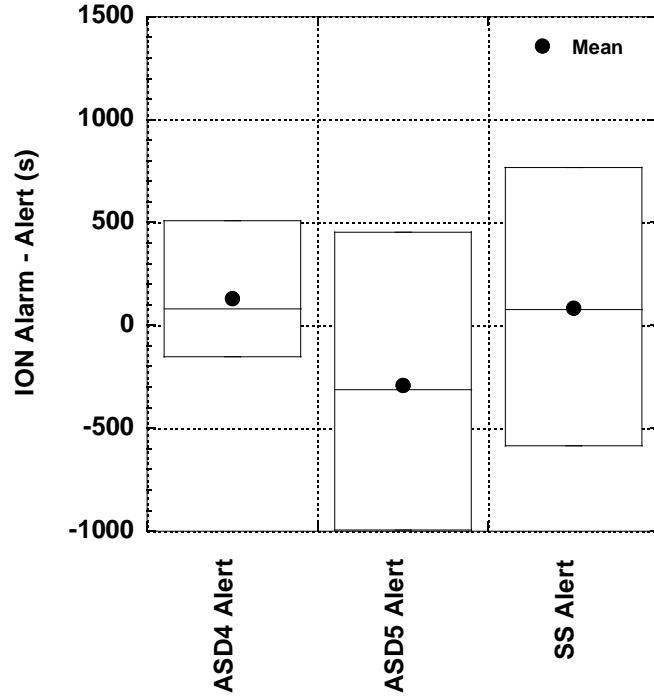
1 **Table 5-7. Nominal Detector Sensitivities for Large Room, Multi-Zone Cabinet Tests**

Sensitivity Setting	ASD4 Detector / Port Particles/cm ³	ASD5 Detector / Port %/ft Obsc	SS %/ft Obsc	ION %/ft Obsc
VEWFD Pre-Alert	1.5x10 ⁵ / 6.0x10 ⁵	0.0159 / 0.064	-	-
VEWFD Alert	2.5x10 ⁵ / 1.0x10 ⁶	0.0334 / 0.13	0.20	-
VEWFD Alarm	4.5x10 ⁵ / 1.8x10 ⁶	0.1665 / 0.67	1.00	-
Conventional Pre-alarm	-	-	-	0.5
Conventional Alarm	-	-	-	1.0

2
 3 Results for the single cabinet are shown in Figure 5-34. ASD4 (cloud chamber) responded
 4 before the ION alarm in all experiments, while ASD5 (light-scattering) responded after the ION
 5 alarm on average. Results for the three-cabinet arrangement are shown in Figure 5-35.
 6 Results for the non-ventilated and ventilated room experiments are shown in Figure 5-36 and
 7 Figure 5-37. The results are mixed: however, ASD4 responded before the ION alarm in all
 8 experiments.

9
 10 Results for all 10 experiments are shown in Figure 5-38. ASD4 responded 750 seconds sooner
 11 than the ION alarm on average, while ASD5 and SS responded about 150 seconds sooner than
 12 the ionization alarm, on average. The decreasing mean time difference trend was ASD4 alert,
 13 ASD5 alert and SS alert (tie), ION alarm and PHOTO alarm.

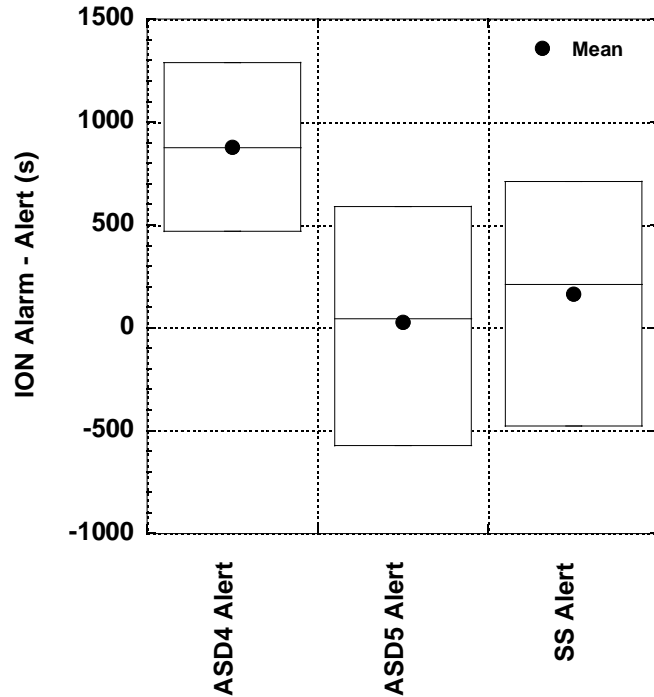
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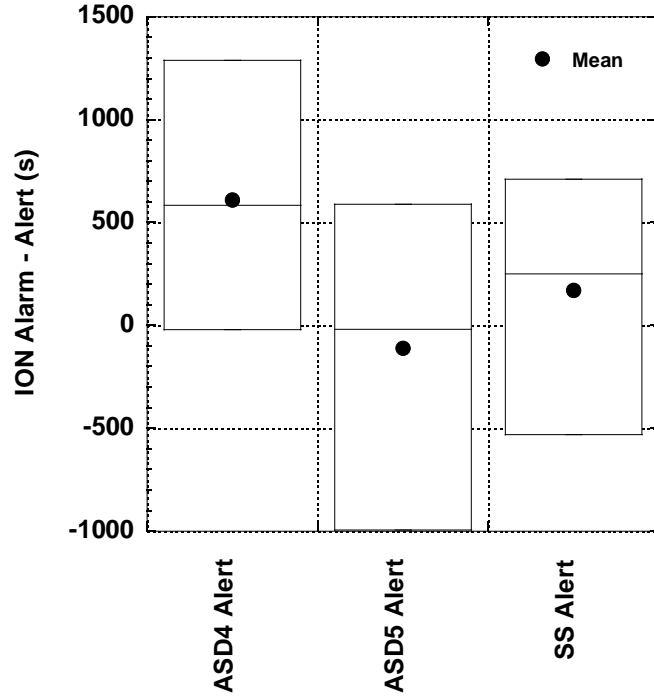
2 **Figure 5-34. Time difference between ION alarm time and the ASD alerts and SS alert for**
 3 **large room, multi-zone, single-cabinet, 65.0 minute HRP experiments.**

4



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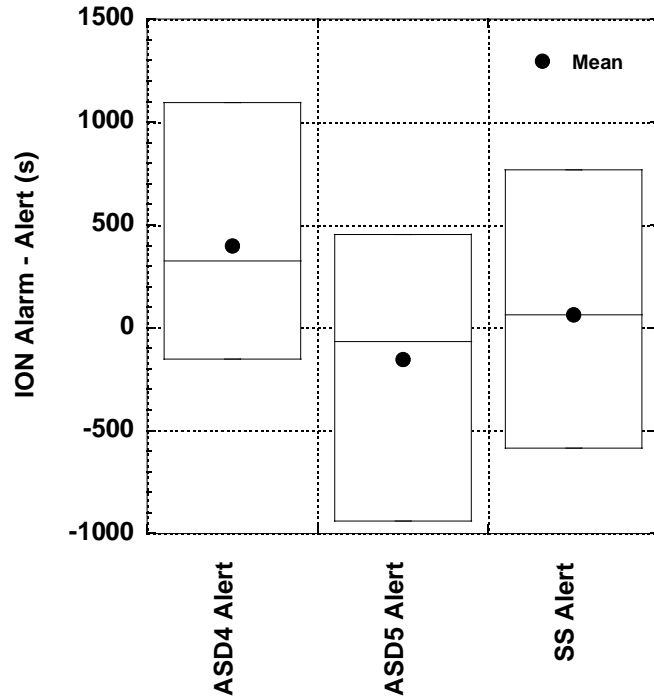
6 **Figure 5-35. Time difference between ION alarm time and the ASD alerts and SS alert for**
 7 **large room, multi-zone, three cabinet configuration, 65.0 minute HRP**
 8 **experiments**



1

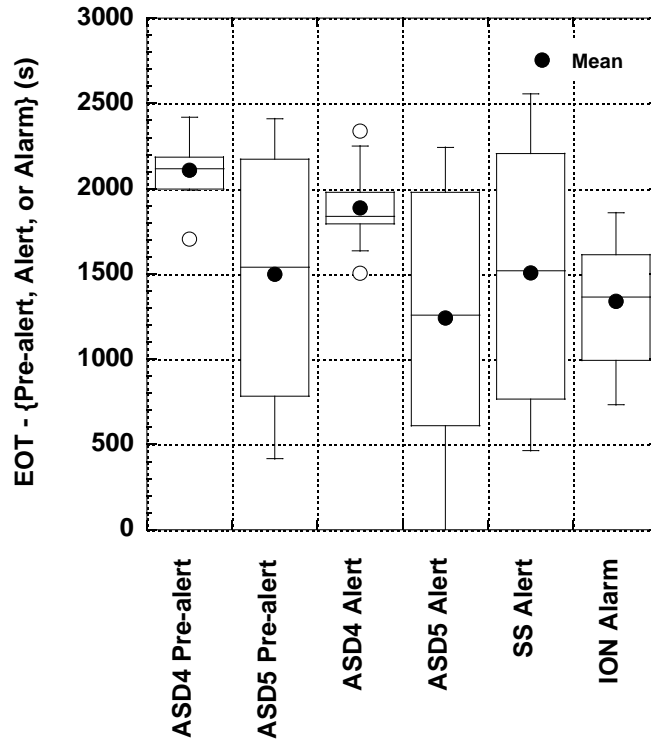
2 **Figure 5-36. Time difference between ION alarm time and the ASD alerts and SS alert for**
 3 **large room, multi-zone, no ventilation, 65.0 minute HRP experiments**

4



5

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



1

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

5

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

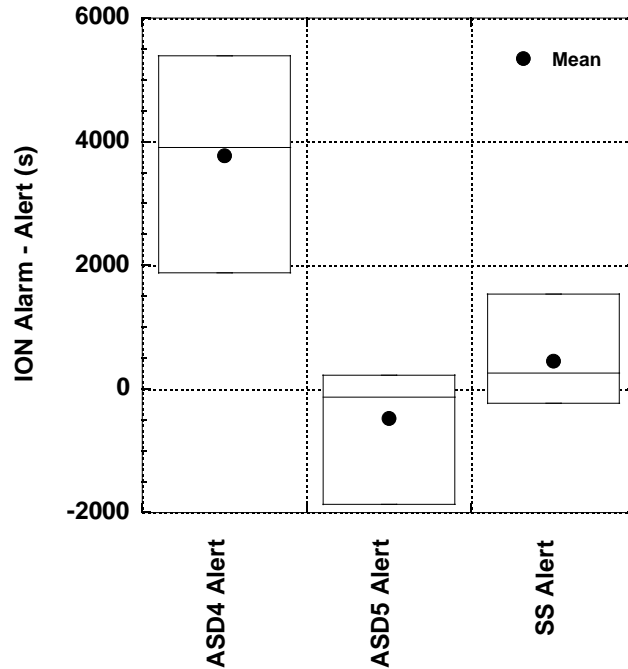
10

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

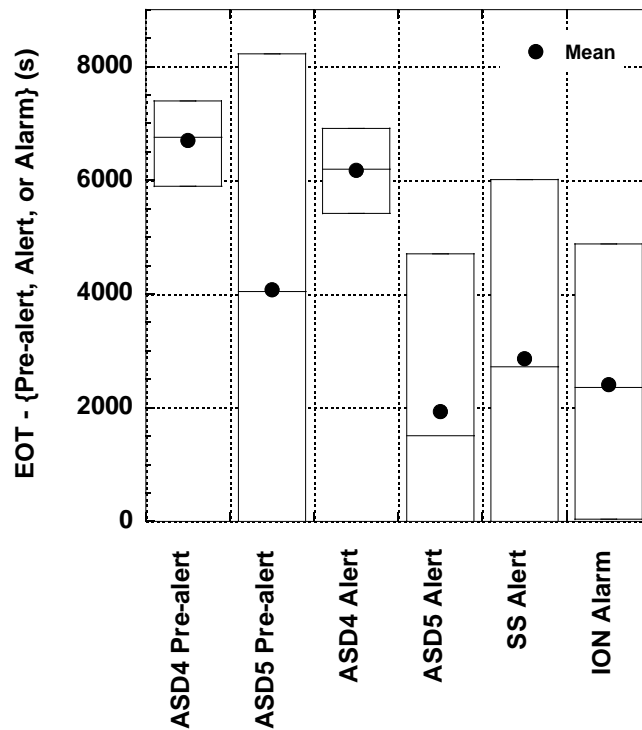
12

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

15



1
 2 **Figure 5-39. Time difference between ION alarm time and the ASD alerts and SS alert for large room, multi-zone, in-cabinet, 260.0 minute HRP experiments**
 3
 4



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

- 1 The large-room multi-zone in-cabinet results gave rise to the following observations:
- 2 1. ASD4 responded before the conventional ionization alarm for both heating period
 - 3 experiments.
 - 4 2. The time difference between the ION alarm and the ASD alerts was greater for the
 - 5 three-cabinet arrangement than the single-cabinet arrangement.
 - 6 3. Room ventilation tended to reduce the time difference between the ionization alarm and
 - 7 the ASD alerts.
 - 8 4. All detectors responded before end of test for all 60 minute HRP experiments.
 - 9 5. ASD5 and SS did not alarm with XLPE samples before end of test for 260 minute HRP
 - 10 experiments.

11

12 5.6 Full-Scale, Small-Room, Areawide Experiments

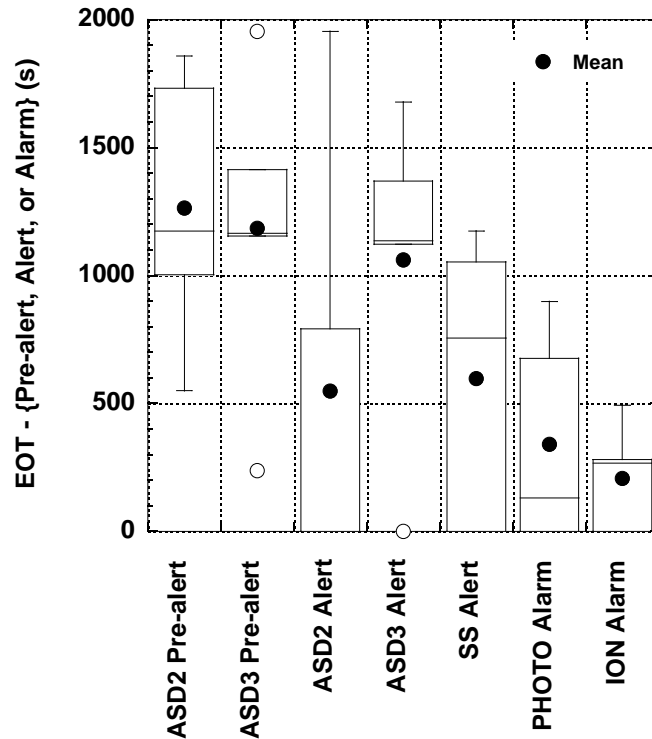
13
14 The data set examined consists of 65.0 minute heating period experiments for XLPE, CSPE and
15 three cable bundle sources located on the floor. There was room air ventilation during one of
16 the cable bundle experiments. The detector sensitivity settings used in these tests are shown in
17 Table 5-8.
18

19 **Table 5-8. Nominal Detector Sensitivities for Small Room, Single-Zone, Areawide**
20 **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	5.1x10 ⁵ / 2.0x10 ⁶	0.025 / 0.10	-	-	-
VEWFD Alert	0.05 / 0.20	8.2x10 ⁵ / 3.3x10 ⁶	0.05 / 0.20	0.20	-	-
VEWFD Alarm	0.25 / 1.50	1.5x10 ⁶ / 6.0x10 ⁶	0.25 / 1.00	1.00	-	-
Conventional Pre-alarm	-	-	-	-	0.5	1.3
Conventional Alarm	-	-	-	-	1.0	2.1

21

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



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

9 From these experimental results the following observations are made:

- 10 1. The trend in mean alert/conventional alarm time from earlier to later was ASD3, SS,
 11 ASD2, PHOTO, and lastly ION.
- 12 2. Each detector failed to alert or alarm before the end of test in at least one experiment.

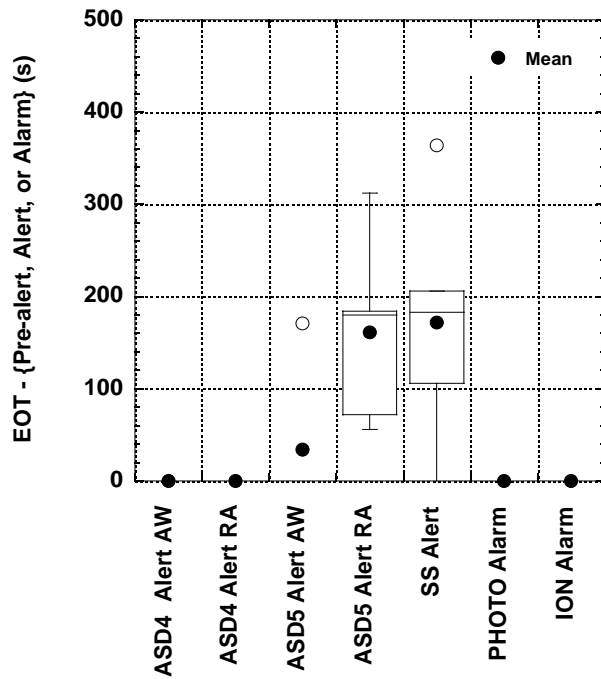
13
 14 **5.7 Large-Room, Multi-Zone Areawide Experiments**

15 The large-room, multi-zone, areawide experiments included in-cabinet, return air grill, and
 16 areawide ceiling ASD coverage and conventional alarm coverage on the ceiling and inside
 17 cabinets. Table 5-9 documents the detector sensitivity settings used for these tests. ASD4
 18 (cloud chamber) sensitivity settings were vendor-specified. Areawide and return air grill
 19 locations are referred to as AW and RA, respectively.
 20
 21

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

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

3
 4 Figure 5-42 and Figure 5-43 show the results for 16.3 and 65.0 minute HRP areawide
 5 experiments with ventilation air flow.
 6



7
 8 **Figure 5-42. Time difference between the end of test (EOT) time (1278 s) and ASD alerts,**
 9 **SS alerts, PHOTO and ION alarm time for large room, areawide, 16.3 minute**
 10 **HRP experiments**

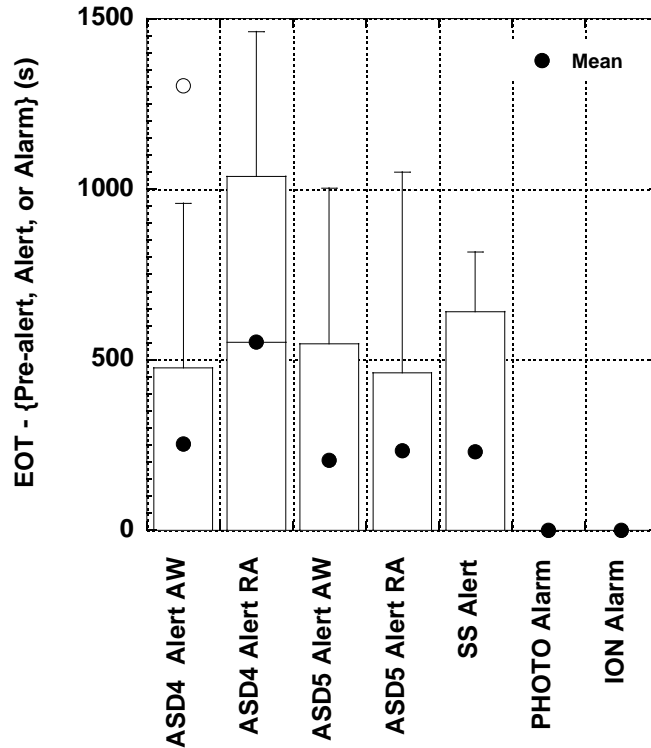


Figure 5-43. Time difference between the end of test (EOT) time (4200 s) and ASD alerts, SS alerts, PHOTO and ION alarm time for large room, areawide, 65.0 minute HRP experiments

From these experimental results the observations are made:

1. For the 16.3 minute HRP experiments ASD5 and SS detectors were the only systems that alerted before the end of test
2. For the 16.3 minute HRP experiments SS areawide outperformed the ASD5 return air zone and the ASD5 areawide.
3. For the 65.0 minute HRP experiments the ASD and SS detectors were the only systems that on average alerted before the end of test.
4. For the 65.0 minute HRP experiments the ASD5 areawide and return air zone provided about the same average alert times, while ASD4 return air zone outperformed all detectors on average.

5.8 Insulated Electrical Conductor Heat Conduction and Ignition Potential

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

1 flame. The ease of ignition from such a pilot flame is an indication of the potential hazard of the
2 heated wire insulation.
3
4 Heat conduction from the block to the wire, down its length and through the insulation is a
5 transient heat transfer process. The controlled variable is the block temperature via the
6 temperature controller's power-cycling of the cartridge heater. The wire insulation closest to the
7 block heats up first and produces the smoke particles sensed by detectors. Subsequently, more
8 wire insulation is heated to produce more smoke. The IR camera recorded images at different
9 times during HRP. A series of images is shown in Figure 5-44. The temperature profile
10 measured at the end of the nominal 60 minute test can be seen in Figure 5-45. The locations of
11 the thermocouples were represented by the cross symbol, with the corresponding IR camera
12 temperature measurements. The emissivity on the IR camera in was set for plastic (0.93).
13

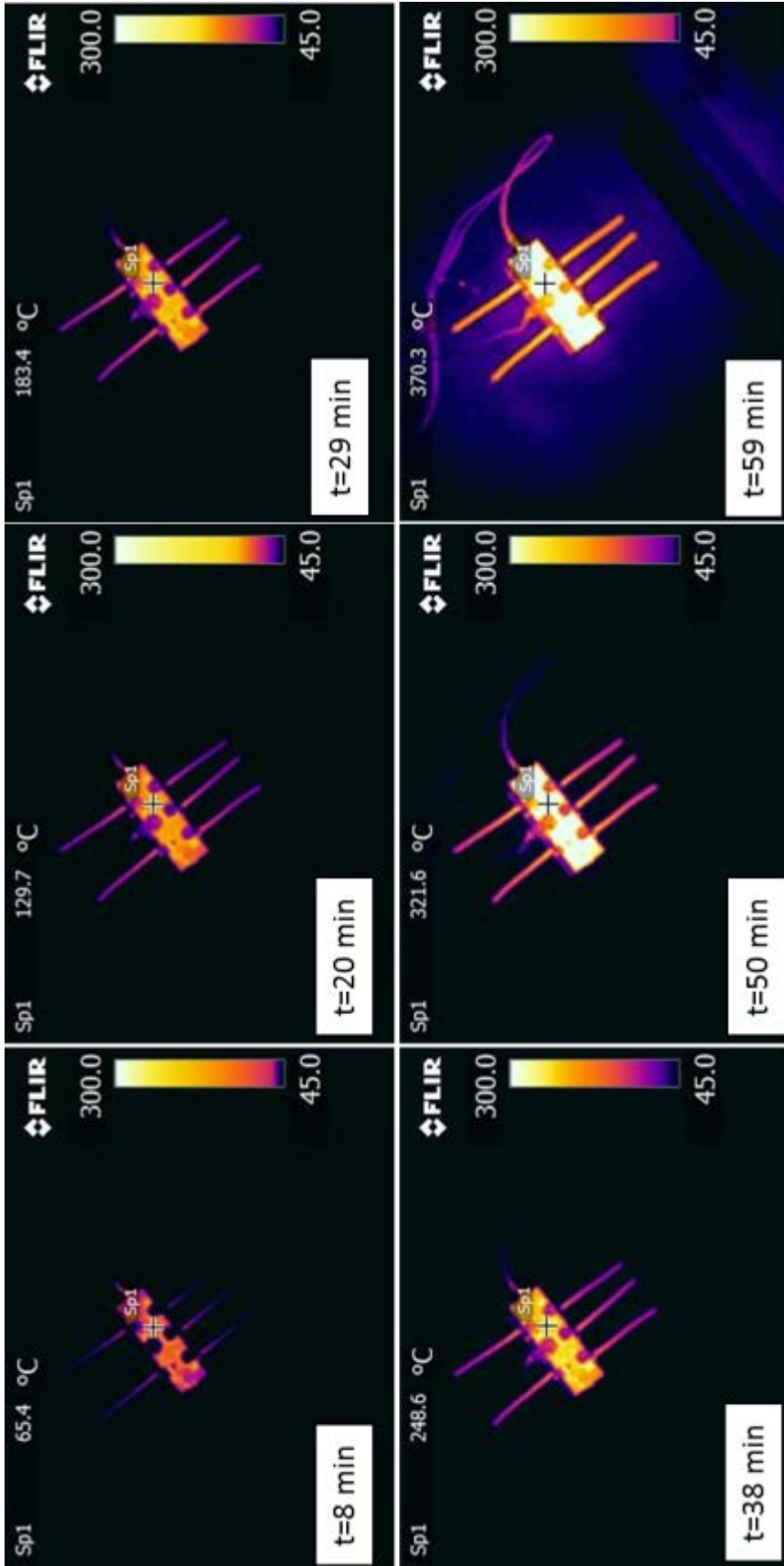
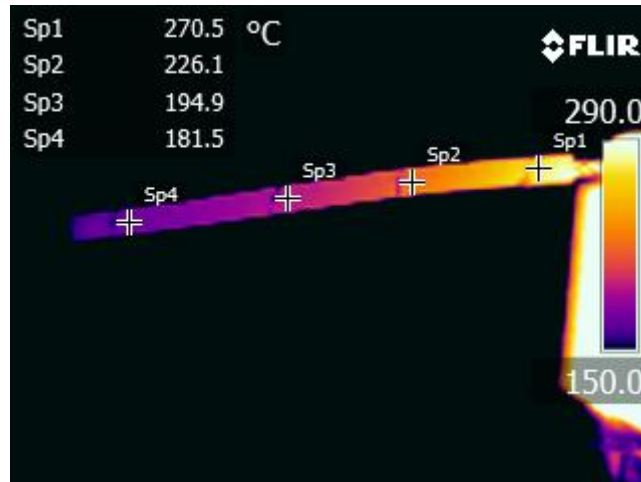


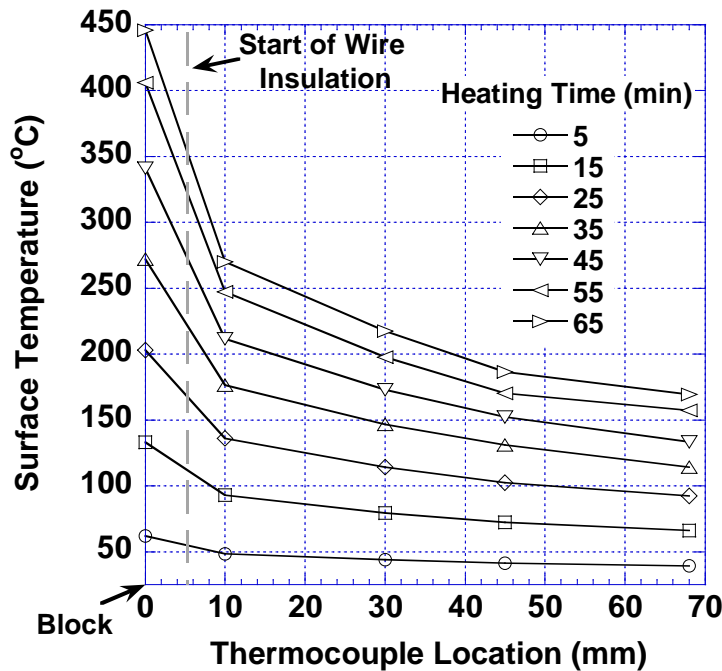
Figure 5-44. Heating profiles for 12 AWG XLPE wires at various times during the heating process. The temperature of the block can be seen in the top left corner in each image.



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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.



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

1 The temperature measurements suggest that the wire insulation closest to the bus bar
2 approaches temperatures close to the piloted ignition temperature. During the experimental
3 design, it was surmised that, given the final block temperature chosen, wire insulation would be
4 easily ignitable by the end of the test period and thus, poses an imminent fire hazard.
5 To support the assumption, ignitability experiments were conducted on the wire samples at
6 different times during the HRP, and at the end of test time. XPLE, PVC2, and CPSE wire
7 samples were attached to bus bars, and heated using the 16.3 minute HRP with the final set
8 point of 485 degrees C. A small flame was positioned under a wire sample for 5 seconds then
9 moved away. The time of persistent flame attachment after the pilot was moved was recorded.
10 The flame was from a horizontal 0.3 mm ID tube with a flow rate of 25 L/min of propane. The
11 end of the tube was 9.5 mm from the bus bar and the center of the tube was located 12.7 mm
12 below the wire sample. The tube was attached to a slide rail so it could be positioned under
13 heated wires rapidly. Figure 5-47 is a picture showing the bus bar mounted on its stand, two
14 wire samples, the ignition tube, and an enclosure located in a chemical hood. Each
15 experiment used two wire samples and was videotaped for subsequent timing analysis.
16 Figure 5-48 is a picture of the pilot flame before it was positioned under a wire sample.
17

18 Table 5-10 shows the results for the persistent burn time after the pilot flame was removed for
19 the four different pre-heat times. The nominal block temperature for the pre-heat times is also
20 indicated. After a heating period of 1,200 seconds and a block temperature of about
21 480 degrees C, the average persistent burn times were 5, 26, and 50 seconds for PVC2, XLPE
22 and CSPE, respectively. After pre-heating for 900 seconds and a block temperature of about
23 435 degrees C, XLPE and CSPE wires continued to burn for greater than 20 seconds on
24 average. After a heating period of 600 seconds and a nominal block temperature of about
25 300 degrees C, only the XLPE wire sustained flaming for longer than 1 second on average, with
26 an average persistent burn time of 14 seconds. After a heating period of 500 seconds and a
27 nominal block temperature of about 250 degrees C, none of the wire samples sustained flaming
28 for longer than 1 s. XLPE appears to be the easiest of the three wires to ignite, followed by
29 CPSE, then PVC2. The trend appears to be counter-intuitive, whereas thermoset insulation
30 materials, such as XLPE and CSPE, burned longer after pilot flame removal, compared to the
31 thermoplastic PVC. Possible factors affecting the ignitability here are possible flame retardant
32 additives, and differences in the wire conduction, which could lead to different temperature
33 profiles.
34



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Figure 5-47. Experimental setup



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Figure 5-48. Pilot flame

1 **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

2
3 Although these experiments do show that a small pilot flame can ignite pre-heated wires, it is
4 not unreasonable to expect that such pre-heated wire could ignite from a brief electric arc, or
5 glowing conductor, following an electrical failure; without sufficient pre-heating, ignition would
6 not occur.
7

8 **5.9 Evaluation of Test Results**

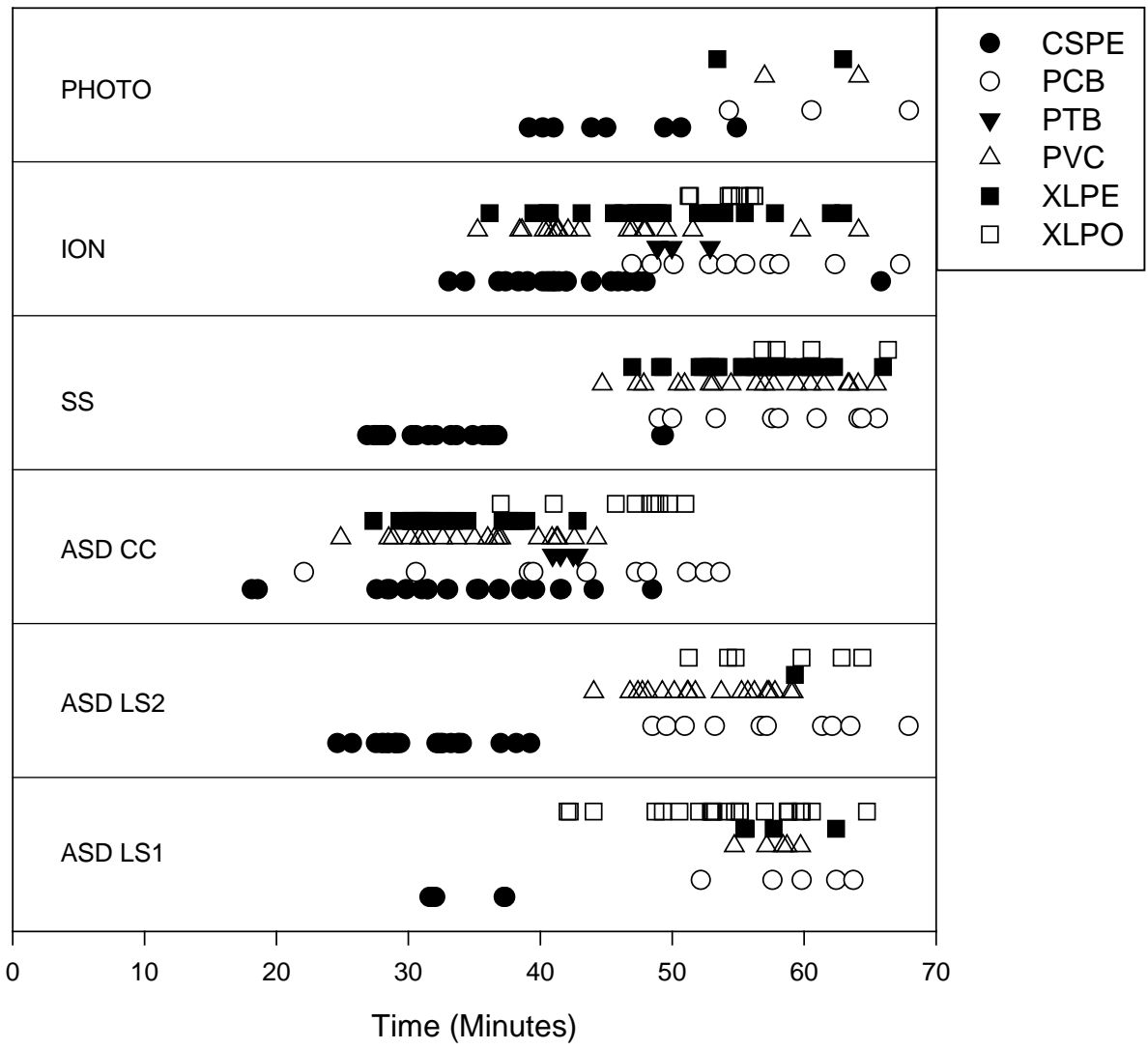
9
10 The results from testing provide information that supports several project objectives. This
11 section presents the test results specific to those objectives.
12

13 **5.9.1 System response to common products of combustion (Objective E)**

14
15 Detector response to smoke signature from materials included in the test program is presented
16 generically. The in-cabinet, naturally ventilated test data is used. This data set limits variability
17 of cabinet ventilation rate, and areawide detector-to-source location influences on detector
18 response. Figure 5-49 presents data from all one-hour HRP tests. The figure shows the
19 detection time for each detector type and material. The “alert” response is reported for the
20 VEWFD systems (SS, ASD CC, ASD LS1, ASD LS2) and the “alarm” response for the
21 conventional spots (PHOTO, ION). Note that the “alert” response is the 0.2 %/ft obscuration of
22 the laser based systems (ASD LS1, ASD LS2, and SS)¹⁰, while the “alert” response for the ASD
23 CC is the vendor recommended sensitivity. Since the latter doesn’t report in percent
24 obscuration per foot, comparisons between the ASD CC and other VEWFD systems *should not*
25 *be inferred* to be tested at equivalent sensitivity settings. Instances in which the detector did not
26 respond before the end of the test are *not shown*. Plots for the 15 minute and four-hour HRP
27 show similar responses and are presented in Appendix B.
28

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

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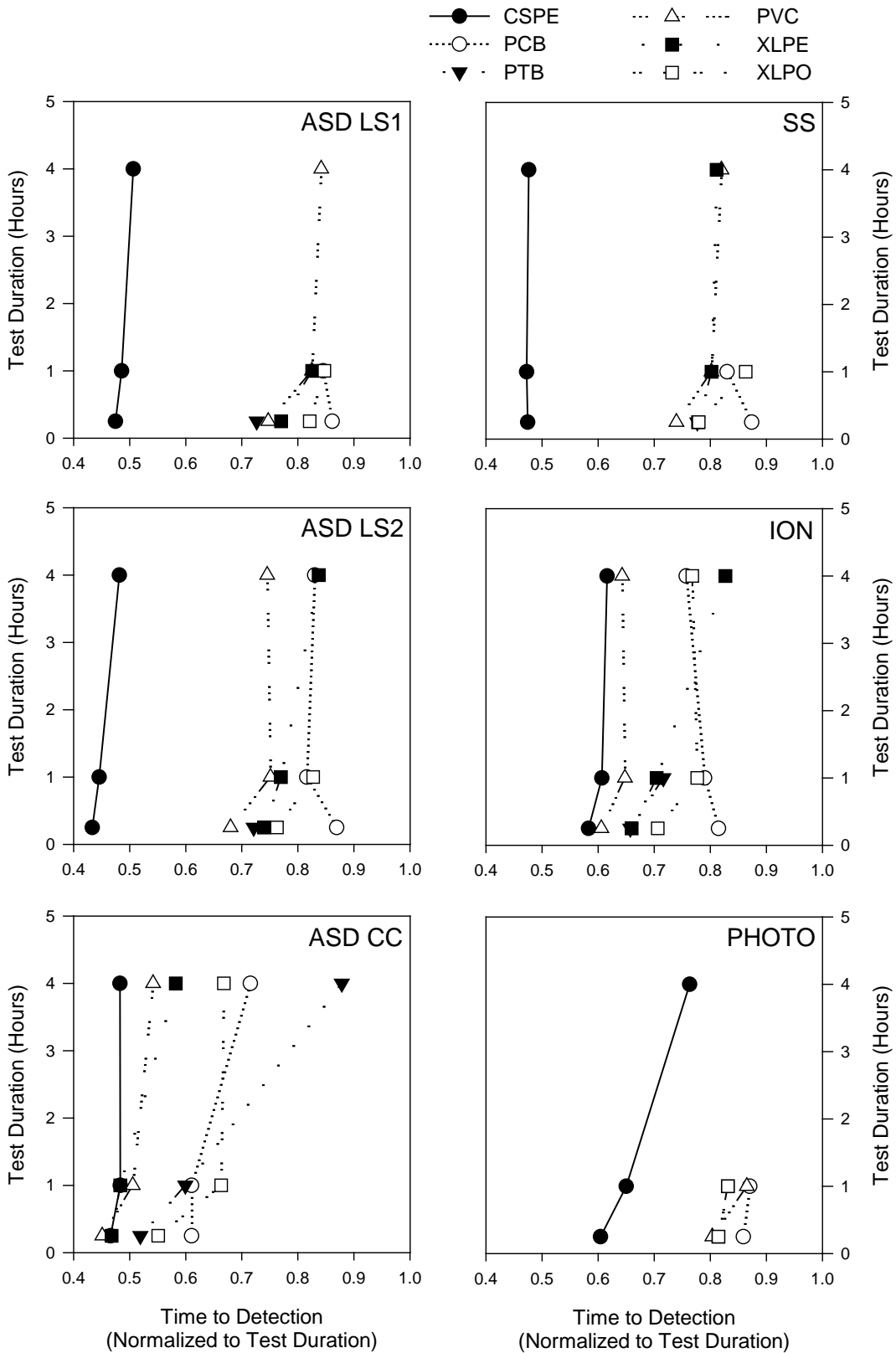
Figure 5-49. Detector response to selected materials (1-hour HRP)

4

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.

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Figure 5-50. Time to detection, by detector

1 The insights from this data indicate:
2

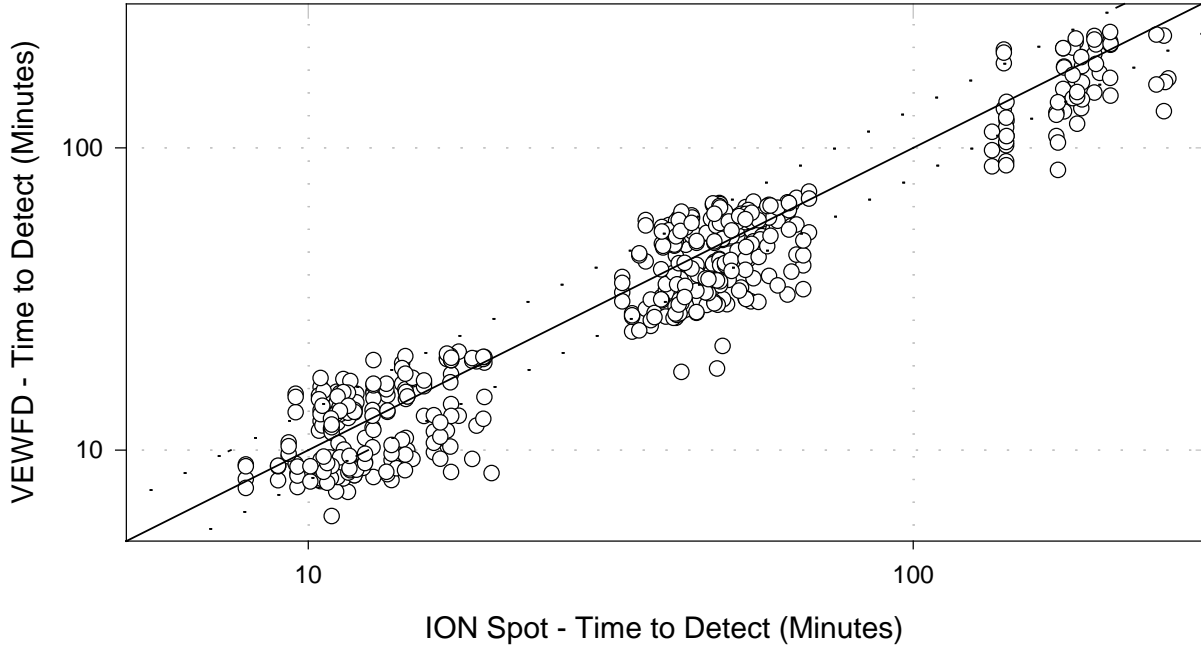
- 3 1. Based on the mean detection time normalized to the test duration, there is no apparent
4 trend for the mean time to detection and the HRP's used in testing. In general, the mean
5 time to detect increases with increasing HRP in a non-linear manner. This change
6 between the 15 minute and 1 hour HRP is more pronounced than the change between
7 the 1 hour and 4 hour HRP. This likely indicates the aerosol characteristics are
8 dependent on the rate of material heat up and aerosol generation.
9
- 10 2. The PHOTO spot-type detector only responded to the CSPE, PCB, PVC, and XLPE
11 materials. CSPE was the only material that the PHOTO consistently detected.
12
- 13 3. The CSPE material appears to be the easiest to detect. All detectors were effective at
14 detecting the CSPE. For VEWFD systems, including the sensitive spot detector, all
15 responded to the CSPE aerosol at approximately the same time, with ASD LS2
16 responding earliest (on average).
17
- 18 4. PTB, SR, and TEF are typically detected latest in the early fire stage and are the most
19 difficult to detect of the materials tested. The Silicone and Teflon conductor insulation
20 materials were only effectively detected by ASD CC and ION.
21
- 22 5. The printed circuit board data shows an opposite trend compared to the other materials,
23 in that the time to detect decreases with increased HRP from the 15-minute to 1-hr
24 HRP's.
25
- 26 6. With the exception of CSPE, the ASD CC and ION spot-type responded at an "alert" and
27 "alarm" setting, respectively, before either ASD LS1 or ASD LS2 "alert" response.
28

29 **5.9.2 Comparison between common detection systems and VEWFD systems** 30 **(Objective B)** 31

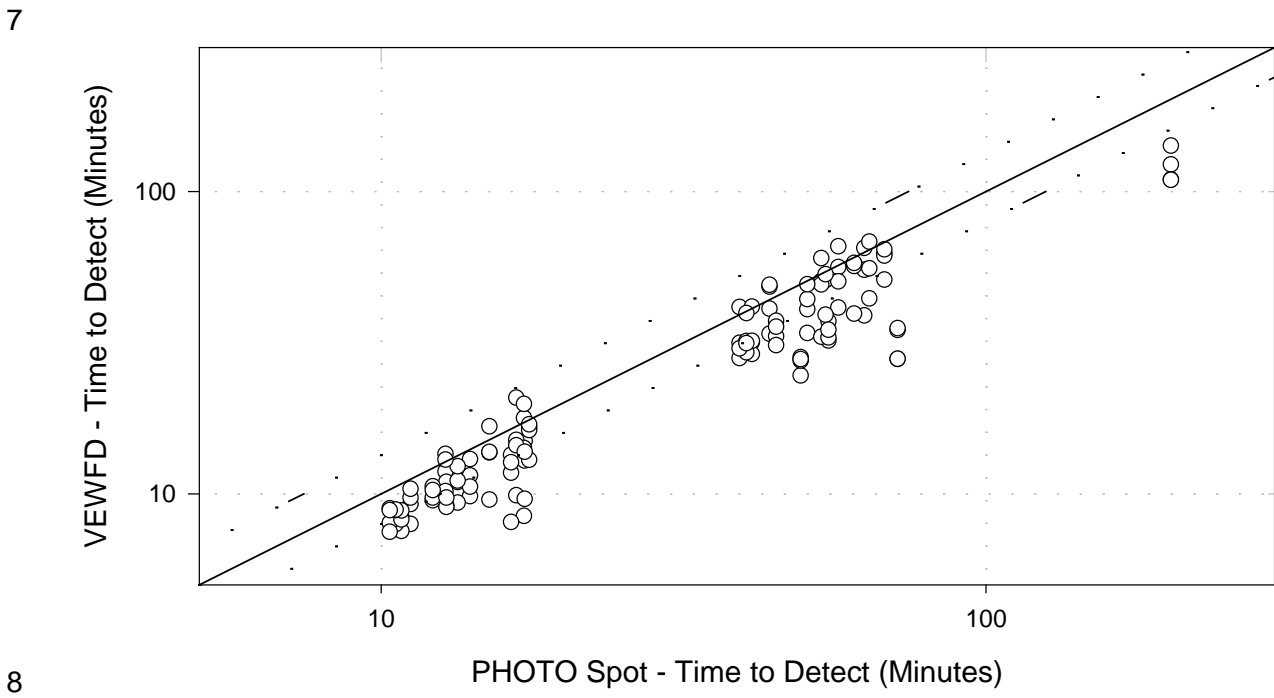
32 A comparison between the performance of conventional spot-type detectors (ION, PHOTO) and
33 VEWFD systems (ASDs and sensitive spot) is presented in summary plots. Each point on the
34 summary plots represents the time to detection within a single test. These plots present all
35 three HRP data on a single plot. The diagonal line represents equal performance. In Figure
36 5-51 and Figure 5-52, points below the diagonal line represent a test in which the VEWFD
37 system responded to an "alert" before the conventional detector "alarm." Points above the
38 diagonal line indicate the conventional spot-type detector responded with an "alarm" before the
39 VEWFD system "alert" response. The dashed diagonal lines represent two standard deviations
40 from the mean conventional detector response used for evaluations.
41

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

1 detectors show performance differences, even though both were set to the same port sensitivity
2 of 0.2 %/ft. obscuration.
3



4
5 **Figure 5-51. Summary plot – ION alarm versus VEWFD alert**
6 **(in-cabinet, natural ventilation)**



8
9 **Figure 5-52. Summary plot – PHOTO versus VEWFD (in-cabinet, natural ventilation)**

10

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

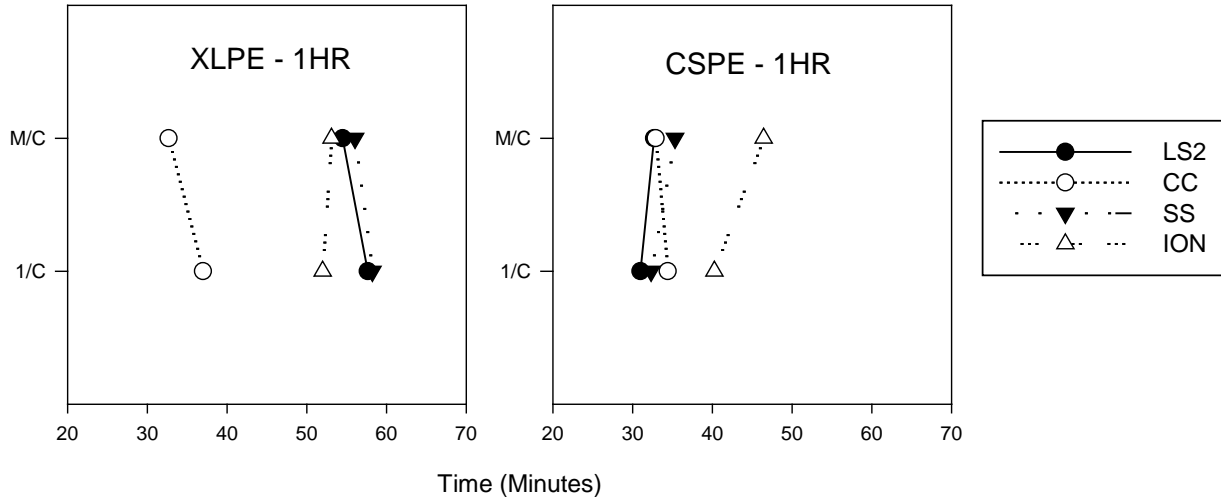
	ION		PHOTO	
	Mean	5 th /95 th Percentile	Mean	5 th /95 th Percentile
ALL VEWFD	2.9%	-39.8/38.0%	19.3%	-10.7/50.4%
ALL ASD	6.7%	-38.8/40.0%	20.6%	-10.5/50.6%
ASD LS1	-15.7%	-54.4/29.5%	12.1%	-18.7/45.7%
ASD LS2	-0.1%	-27.6/35.3%	23.6%	4.0/53.9%
ASD CC	23.5%	3.4/47.7%	25.9%	-7.6/50.8%
SS	-7.9%	41.1/30.0%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

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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.

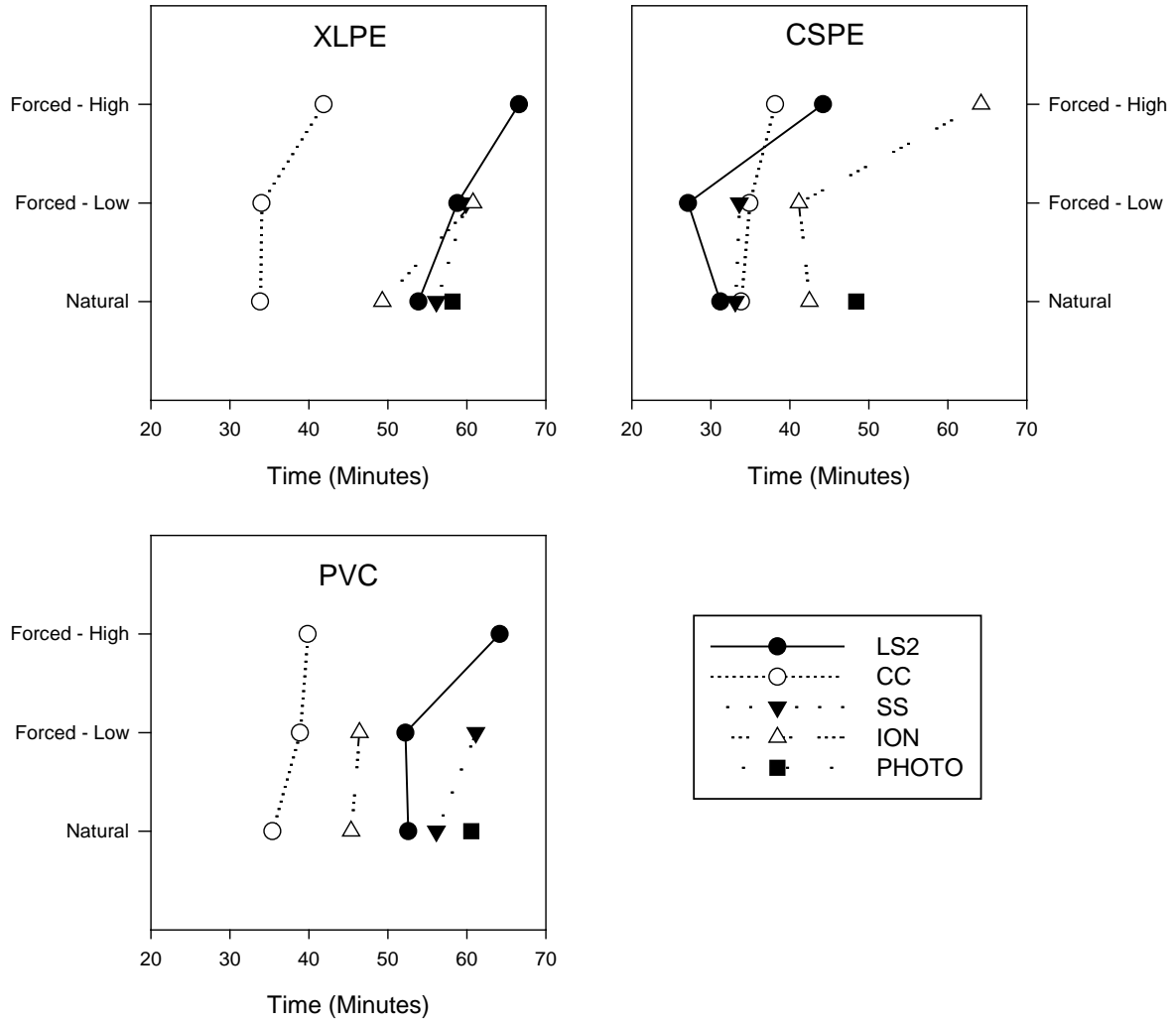
Figure 5-53 illustrates the responses of several detectors to two different material aerosols for different cabinet configurations. The “1/C” case represents a cabinet where a single sampling port is located. The “M/C” case represents a cabinet space where multiple sampling ports protect a section of 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.



1
 2 **Figure 5-53. Detector response versus number of sampling ports in cabinet space**

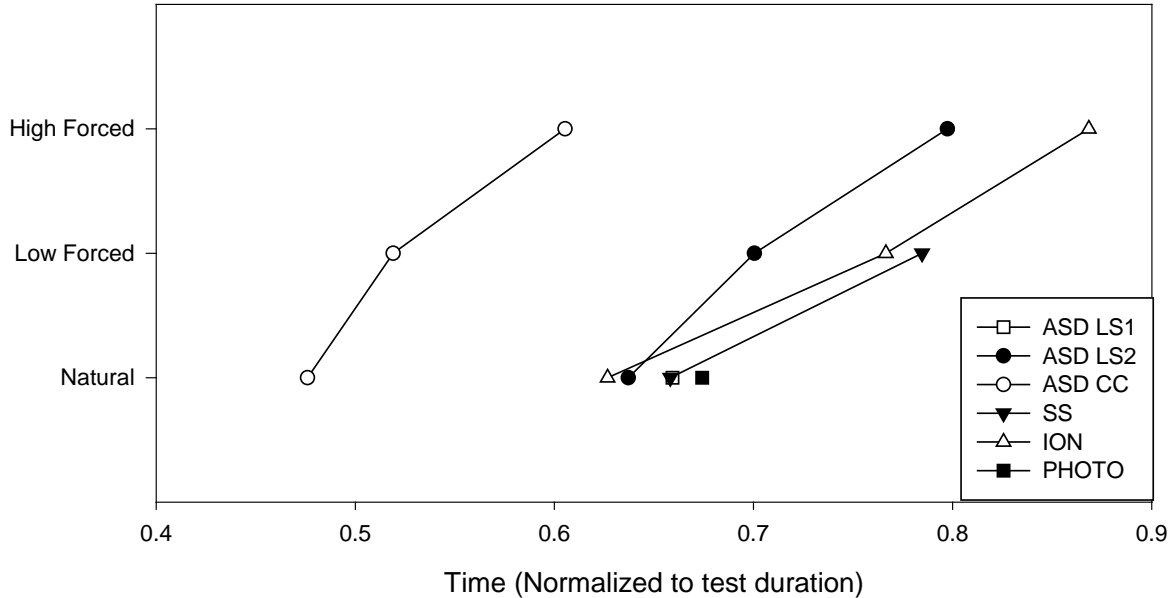
3
 4 Figure 5-54 present the effect cabinet ventilation configurations have on detector response.
 5 Three states of cabinet ventilation are shown. The “Natural” state represents tests where no
 6 mechanical ventilation was used. The “Forced – Low” state represents cases in the full scale
 7 testing where an 8.0 ACH cabinet ventilation rate was used. The “Forced – High” state
 8 represents the NPP cabinet tests where the ventilation rate was estimated at 300 ACH.
 9 In general, as cabinet ventilation rate is increased, the time to detection also increases. This
 10 general trend does not hold for the CSPE material where the ASD LS2 and ION spot-type
 11 detector responded sooner at the “Forced – Low” state than at the naturally ventilated condition.

12
 13 Figure 5-55 presents the results from in-cabinet detectors mean response time for all materials
 14 by cabinet ventilation conditions. From this graphic, it becomes apparent that the mean time for
 15 detector response increases with increasing cabinet ventilation conditions. It should also be
 16 noted that LS1 was only included in the naturally ventilated case and the PHOTO was no
 17 included in the high forced ventilation experiments.
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Figure 5-54. Effect of cabinet ventilation on in-cabinet detector response

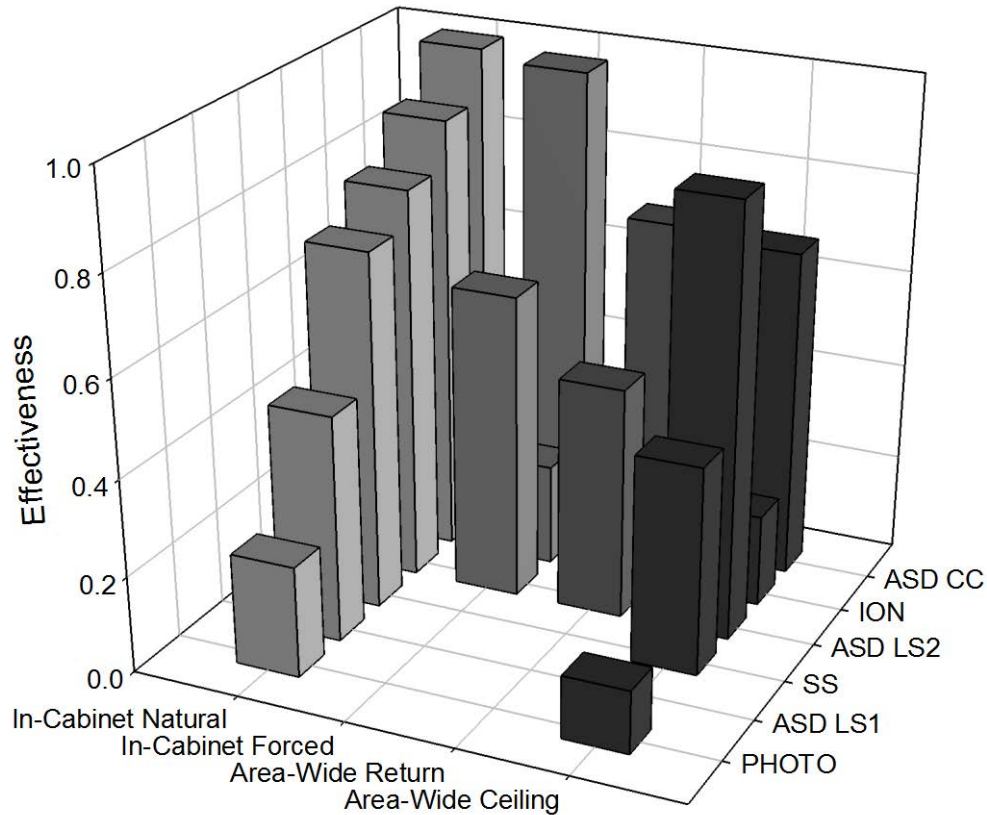


1
 2 **Figure 5-55. Effect of cabinet ventilation on in-cabinet detector response for all**
 3 **materials and all HRP.**

4
 5 **5.9.4 Effectiveness of in-cabinet and areawide VEWFD system applications,**
 6 **including an evaluation of system applicability for various NPP**
 7 **applications (Objective A)**

8
 9 System effectiveness is a measure of how well a design solution will perform or operate, given
 10 anticipated operational scenarios (Ref. 19). Effectiveness estimates for ASD VEWFD systems
 11 expected to operate during the pre-flaming (incipient) phase are based on the test data
 12 collected from the experiments conducted in this program. As indicated above, the source
 13 materials are heated to a temperature that can support flaming conditions. The effectiveness
 14 differs between in-cabinet and the two areawide configurations, primarily because of smoke
 15 dilution and stratification effects. Section 7.2 quantifies the effectiveness of the detection
 16 systems tested for use in the risk scoping study presented in Part II of this report. Figure 5-56
 17 present the mean effectiveness for the systems and applications tested. As shown in Figure
 18 5-55 and Figure 5-56, in-cabinet detection without forced ventilation provides the earliest and
 19 most effective application for detecting pre-flaming fire conditions.

20
 21 For the in-cabinet applications, the test data was initially analyzed for system effectiveness for
 22 two cases (i.e., naturally ventilated and forced ventilation conditions). However, the data
 23 showed a large discrepancy, an order of magnitude difference between the two cases. Further
 24 evaluation of the forced ventilation data indicated that the reactor protection system cabinet,
 25 taken out of a U.S. NPP had a much lower VEWFD system effectiveness compared to the
 26 mock-up cabinet used in the MCPTA tests, and the naturally ventilated case. Further evaluation
 27 of the differences between cabinet design and testing conditions identified several parameters
 28 that are likely influencing these results.



1
 2 **Figure 5-56. System effectiveness by detector and application**
 3 **(Note: no data for ION arewide return)**

4
 5 Cabinet Design Influence

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

20
 21 Ventilation rate

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

25

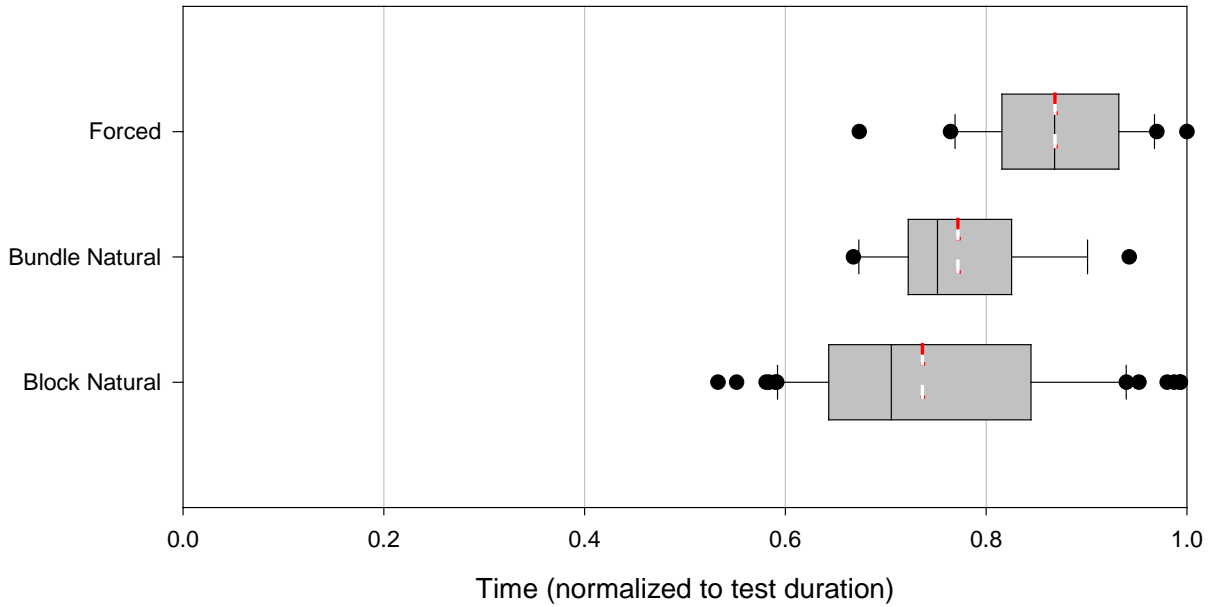
1 For in-cabinet applications, two parameters with an influence on system response were
2 identified: cabinet ventilation rates and cabinet internal obstructions, the latter being a
3 secondary or tertiary order effect. Three ventilation rates were available from the testing,
4 namely, naturally ventilated,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

12
13 Additionally, cabinet configurations such as fully louvered doors with internal heat loading and
14 room ventilation effects were not evaluated during this program; yet they could potentially have
15 an effect on the system performance, especially if sufficient thermal gradients are present within
16 the cabinet.

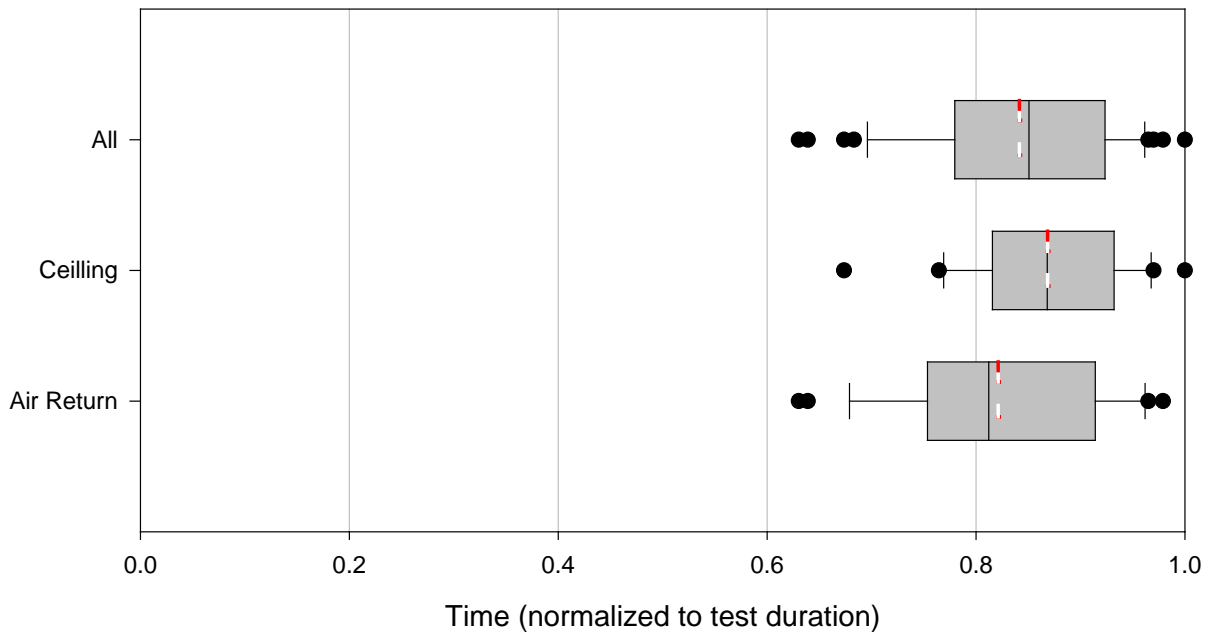
17
18 Cabinet internal component layout and ventilation configurations vary, and are likely to be an
19 important influencing parameter on the effectiveness of the system. Because of the limited
20 number of cabinets available for testing, the test data may not be representative of other
21 configurations. Several different estimates of system effectiveness are developed as shown in
22 Table 7-3. These estimates support the risk scoping study presented in Part II. The system
23 effectiveness estimates are all based on test data, either from this program or other publically
24 available test reports.

25 26 **5.9.5 Areawide ASD comparison**

27
28 The individual data sets were evaluated for the ability to be pooled into larger datasets using the
29 Kolmogorv-Smirnov (K-S) tests. For ceiling-mounted ASDs, VEWFD systems the data was able
30 to be pooled into the following three data sets: all tests using forced ventilation; naturally
31 ventilated cases using block smoke source; naturally ventilated case using bundle smoke
32 source. Figure 5-57 shows these data sets according to their time to detect the low energy
33 sources. A similar evaluation was conducted for the tests using forced ventilation with a
34 comparison between air return grill, and ceiling-mounted ASD performance. These results are
35 shown in Figure 5-58 and indicate that the air return grill and ceiling-mounted performance
36 results are similar enough to be pooled. From a practicality standpoint, given the fact that there
37 are a variety of source materials found in electrical enclosures and testing materials that
38 produce a range of aerosol characteristics representative of slow overheating conditions,
39 pooling of these data sets seems reasonable.



1
2 **Figure 5-57. ASD time to detect areawide ceiling configurations**



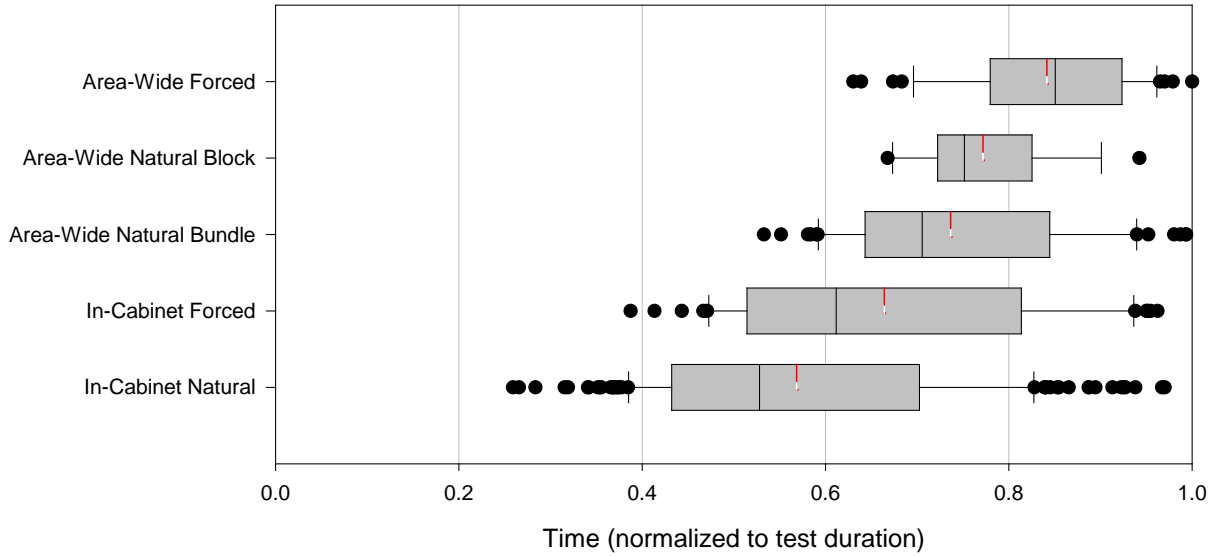
3
4
5 **Figure 5-58. ASD time to detect areawide forced ventilation air return and ceiling pooled**

6
7 The last comparison of the areawide data is to evaluate the effectiveness of the ASD system
8 tests. The effectiveness estimates are shown in Figure 5-58. These results indicate that for the
9 room air change rates tested, the air return grill application response sooner on average than
10 ceiling-mounted ASD systems. With the bundle tests producing more smoke than the block
11 tests, these results consistently show that either areawide application is better at detecting the
12 bundle source.

1
2
3
4
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10

5.9.6 ASD comparison: In-cabinet versus areawide

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



11
12
13
14

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

PART II

Smoke Detection Risk Scoping Study

1 **6. OVERVIEW OF QUANTIFICATION APPROACH**
 2

3 This section provides a high-level overview of the current fire probabilistic risk assessment
 4 (PRA) quantification method as described in NUREG/CR-6850; a summary of previous efforts; a
 5 discussion on possible approaches for quantifying smoke detector performance in fire PRA; and
 6 an overview of the method pursued under this research project.
 7

8 **6.1 Overview of Fire PRA Model**
 9

10 The fundamental concept of a fire PRA is to estimate the total core damage frequency (CDF)
 11 arising from fire initiators. The total CDF is the sum of the CDF contributions from individual
 12 fire-initiated scenarios. The CDF contribution from an individual fire scenario can be divided into
 13 three principal components (Ref. 35):
 14

- 15 1. frequency of the fire scenario
- 16 2. conditional probability of fire-induced damage to critical equipment given the fire
- 17 3. conditional probability of core damage given the specific equipment damage
 18

19 Mathematically, the total CDF is characterized as follows:
 20

21
$$CDF = \sum_i \lambda_i \left[\sum_j p_{ed,j|i} \left(\sum_k p_{CD,k|i,j} \right) \right] = \sum_i CDF_i$$

22
 23 Fire ignition frequency is defined as the occurrence rate of a *potentially challenging or greater*
 24 *fire* involving a specific component or specific compartment of the plant (Ref. 36).
 25

26 The individual fire scenario CDF is:
 27

28
$$CDF_i = \lambda_i \times p_{ed,j|i} \times p_{CD,k|i,j}$$

 29

- 30 Where
- 31 λ_i Frequency of fire scenario *i*
 - 32 $P_{ed,j|i}$ Conditional probability of damage to critical equipment set (“target set”) *j* given the occurrence of fire scenario *i*
 - 33 $P_{CD,k|i,j}$ Conditional probability of core damage caused by plant response
 34 scenario *k* given fire scenario *i* and damage target set *j*

35
 36 The probability of equipment damage is decomposed into two parts:
 37

38
$$P_{ed,j|i} = SF_i \times P_{ns,j|i}$$

 39

- 40 Where
- 41 SF_i severity factor for fire source *i*
 - 42 $P_{ns,j|i}$ probability of non-suppression before damage to target set *j* given
 43 ignition source *i*

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

48
49
$$CDF_i = \lambda_i \times SF_i \times P_{ns,j|i} \times p_{CD,k|i,j}$$

50

51 **6.2 Summary of Previous Quantification Efforts**

52
53 This section presents a summary of the previous approaches used to quantify the performance
54 of VEWFD system fire PRAs. This summary does not present any new information nor does it
55 evaluate the adequacy of previous approaches. It is suggested that the reader reference the
56 associated documents for a full understanding of the methods summarized herein.

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

58
59 NUREG/CR-6850 (EPRI 1011989), Appendix P, “Appendix for Chapter 11, Detection and
60 Suppression Analysis, (2005)” provides an approach for solving the Detection-Suppression
61 Event Tree to estimate a non-suppression probability. That event tree evaluates the prompt,
62 automatic, and manual detection and suppression capabilities. For in-cabinet smoke detection
63 devices, Appendix P provides the following information:

64
65 If in-cabinet smoke detection devices are installed in the electrical cabinet
66 postulated as the ignition source, the analyst should assume that the fire will be
67 detected in its incipient stage. The incipient stage is assumed to have a duration
68 of 5 minutes. To account for these 5 minutes, the analysts should add them to
69 the time to target damage (or, equivalently, add them to the time available for
70 suppression).

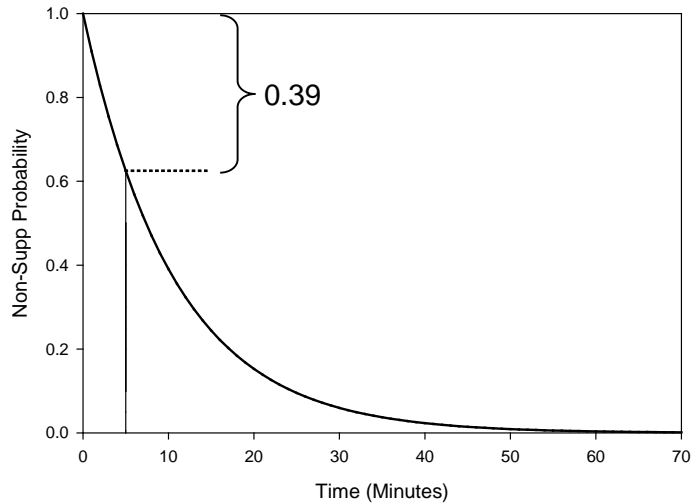
71
72 The non-suppression probability is calculated by the following equations:

73
74
$$\Pr(T > t) = e^{-\lambda t}$$

75
76 Where λ is the rate at which a fire is suppressed and t is the time available for suppression
77 before target damage calculated as follows:

78
79
$$t = t_{dam} - t_{fb} - t_{det}$$

80
81 where t_{dam} is the time to target damage, t_{fb} is the response time of the fire brigade, and t_{det} is the
82 time to detection. Given the information in NUREG/CR-6850 (EPRI 1011989), t_{det} can be set to
83 -5. As shown in Figure 6-1, adding 5 minutes to the time available for suppression results in a
84 reduction of 0.39 from the non-suppression probability, excluding the timing contributions from
85 the t_{dam} and t_{det} .



86

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

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

93

94 Supplement 1 to NUREG/CR-6850, Section 14, titled "Manual Nonsuppression Probability (FAQ
 95 08-0050)," presents clarifications on the use and updated to the non-suppression probabilities.
 96 The Supplement differs from NUREG/CR-6850 method in that the fire brigade response time is
 97 not directly used in the calculation of time available for suppression. Instead, an industry
 98 average is included in the non-suppression curves presented in the supplement. Thus
 99 Supplement 1 presents two approaches. The first approach assumes an industry-average fire
 100 brigade response. The time available for suppression is simply the difference between the time
 101 of detection and the time of damage. The second approach uses a correction factor for cases
 102 where it is judged that the scenario specific fire brigade response time distribution is significantly
 103 different from the underlying events reported in the EPRI Fire Events Database (the source of
 104 information used to develop the revised non-suppression probability curves). Under the
 105 scenario specific adjustment approach the non-suppression probability is calculated as;

106

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

107

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

109

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

110

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

113

114

115

116

117

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 ($\lambda\omega$) 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:

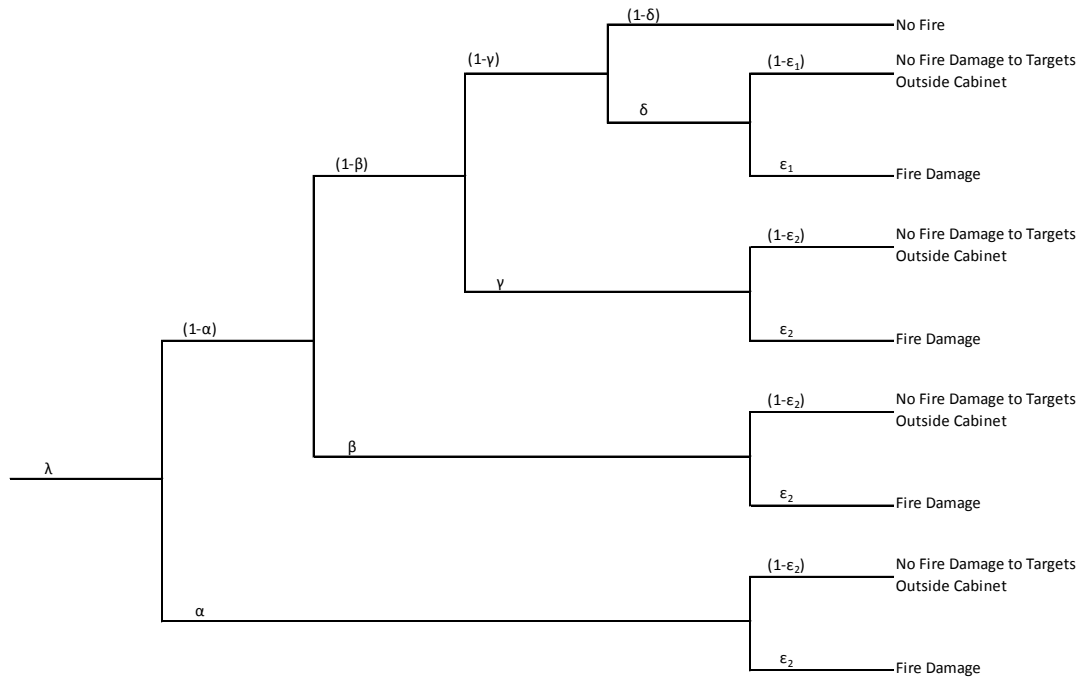
- VEWFD alarms will indicate incipient conditions approximately an hour or more before ignition occurs (based on manufacturers' claims, NFPA 76 objectives).
- Technicians respond within 15 minutes.
- Incipient condition will be identified and prevented from achieving ignition for approximately 99.9 percent 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.

Fire Initiating Event	Fration that have an Incipient Phase Detectable by System	Detector System Availability and Reliability	Successful Operator Response to Alert	Technician Successful in Preventing Fire in Incipient Stage	Fire Suppressed	End Point
-----------------------	---	--	---------------------------------------	---	-----------------	-----------



168

169 **Figure 6-2. FAQ 08-0046 proposed event tree for assessing fire risk for installed**
 170 **VEVFDS in-cabinet**

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

176

- 177 • electrolytic capacitors
- 178 • chart recording devices
- 179 • cooling fans
- 180 • mechanical timers driven by electric motors
- 181 • other components that may fail abruptly without a degradation phase detectable by an
 182 ASD VEVFDS

183

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

188

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

194 that the ASD VEWFS provides at least one hour of warning before the actual outbreak of an
195 open flaming fire.

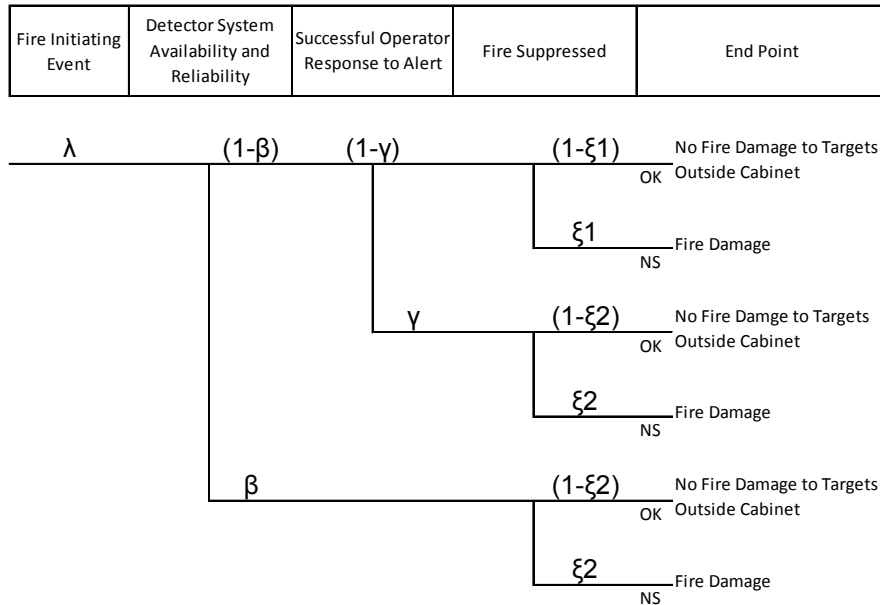
196
197 The next event represents the probability of failure to remove power from the device once it has
198 been located. The NRC staff determined that because of the complexity of identifying and
199 removing all power from the affected component, this parameters (δ) value should be set to 1
200 representing a zero probability of successfully removing power.

201
202 The last event "Fire Suppressed" has two parameters associated with it. ϵ_1 is the "enhanced"
203 non-suppression parameter, and represents the probability that, given the operator has
204 successfully responded to the alert ($1-\lambda$), the personnel staged at the cabinet associated with
205 the ASD VEWFS alert fails to promptly suppress the fire. Here, failure represents a scenario
206 in which the suppression activity is not performed quickly enough to prevent damage outside of
207 the protected cabinet, once the affected components' fire growth enters the flaming stage. The
208 NRC staff's interim position indicated that a value of 1×10^{-3} should be used for ϵ_1 .

209
210 The second suppression parameter, ϵ_2 the probability of "normal" non-suppression, addresses
211 cases in which the operator fails to properly respond to an alert, or cases in which the detector
212 fails to issue an alert (availability/reliability). The values used for ϵ_2 in this event tree should be
213 taken from the Detection Suppression Event Tree in NUREG/CR-6850, Appendix P, using the
214 electrical suppression curve for manual suppression, as appropriate. Additionally, FAQ 08-0050
215 in Supplement 1 to NUREG/CR-6850 provides updated information to Appendix P of
216 NUREG/CR-6850. Credit should be given as described in Appendix P for automatic detection
217 and suppression (normal spot detectors and automatic suppression in the area), as well as
218 delayed manual detection, manual actuation of fixed suppression, and manual suppression via
219 the fire brigade. Using the updated numerical results presented in Table 14-1 of Supplement 1
220 to NUREG/CR-6850 for Electrical Fires, making the assumption that the fire brigade has 5
221 minutes to suppress the fire, the non-suppression probability value of 0.602 should be used for
222 ϵ_2 .

223
224 Given the discussion provided in the FAQ, and summarized above, a simplified event tree can
225 be developed based on the fact that these systems can only be credited for protecting
226 equipment that exhibits an incipient stage detectable by the system (α set to 0) and no credit is
227 given for removing power from the component that caused the system alert (δ set to 1); this
228 simplified event tree is presented in Figure 6-3. Given this treatment, the simplified
229 FAQ 08-0046 event tree represents a reduction of 0.979 to 0.984 in the non-suppression
230 probability, dependent on addressability of the system and ignoring normal non-suppression
231 analysis.

232



233

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

236

237 **6.3 Approaches to Quantifying Smoke Detection Performance**

238

239 There are several methods that could be applied to evaluate the detection/suppression
 240 estimates associated with smoke detection systems. Examples include simulation, decision
 241 trees, and expert judgment. Some past quantification efforts¹¹ have used event trees to
 242 quantify risk improvements. This report also uses an event tree approach to estimate the
 243 probability of non-suppression for different smoke detector technologies. Event trees are
 244 models that group a broad range of possible scenarios into a small number of categories. For
 245 example, there is an infinite variety of pre-flaming scenarios; however, the event tree groups this
 246 infinite variety into two categories: slowly developing (where VEWFD might give substantial
 247 improvement over conventional), and rapidly developing (where VEWFD and conventional are
 248 likely to perform about the same).

249

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

253

254 **6.4 Event Trees and Definitions of Event Headings**

255

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

¹¹ See EPRI 1016735 and NRC FAQ 08-0046

262
263 The non-suppression probability event trees have three end states (1) no damage beyond
264 initiating component, (2) cabinet damage, and (3) fire damage outside cabinet. These end
265 states are defined as follows:
266
267 **No damage beyond initiating component** end state assumes that the degrading component
268 is damaged and incapable of performing its intended function. With a focus on electrical
269 cabinets, the initiation component can include, but not be limited to components such as relays,
270 coils, contactors, indication, circuit cards, terminal strips, cabinet ventilation blowers and other
271 similar component types.
272
273 **Cabinet damage** end state assumes that damage is not limited to the initiating component and
274 that other components within the cabinet are damaged. Suppression activities, regardless of
275 form are also assumed to damage the ability of components located within a cabinet to perform
276 their intended design function.
277
278 **Fire damage outside cabinet** assumes damage could not be limited to the initiating cabinet,
279 and target sets outside of the initiating cabinet may be damaged.
280
281 The event tree headings include estimation of fire phenomena, detector performance, human
282 performance measures, and fire suppression. The basis for the development of these estimates
283 is provided in the subsequent subsections.
284
285 The first event, "Fractions that have an incipient phase" [shown on the success branch (up)] is
286 separate from those that have shorter incipient stages. The next event "Detector System
287 Availability, Reliability" quantifies the systems operational performance. The failure branch
288 (down) represents the probability that a detection system will be unable to perform its function
289 because of system outage or hardware failure. The next branch "Effectiveness," evaluates the
290 system's ability to detect low-energy (pre-flaming) fires for a specific installed application. The
291 success branch represents a detection system's probability of effectively detecting a low energy
292 fire in its incipient stage. Success of the "MCR Response" event represents that the main
293 control room (MCR) operating crew has acknowledged a smoke detector alert or alarm and has
294 directed first level field response to the alerting/alarming fire location. Success in the "first Level
295 Field Response (Technician/Field Operator) Fire Watch Posted" represents the probability that
296 the field response plant personnel have arrived at the smoke detector alert/alarm location and
297 have successfully located the source of the alarm before flaming conditions. Success in the
298 enhanced suppression event represents the probability that any potential fire is suppressed
299 before fire damage to targets of concern. The last event "Conventional Detection/Suppression"
300 estimates the probability of successfully suppressing a fire given a failure of one of the earlier
301 events. To estimate the success of these branches, timing considerations such as operator or
302 fire brigade response, and time to target damage be estimated, and the suppression / detection
303 event tree from NUREG/CR-6850 (EPRI 1011989) can be solved.
304

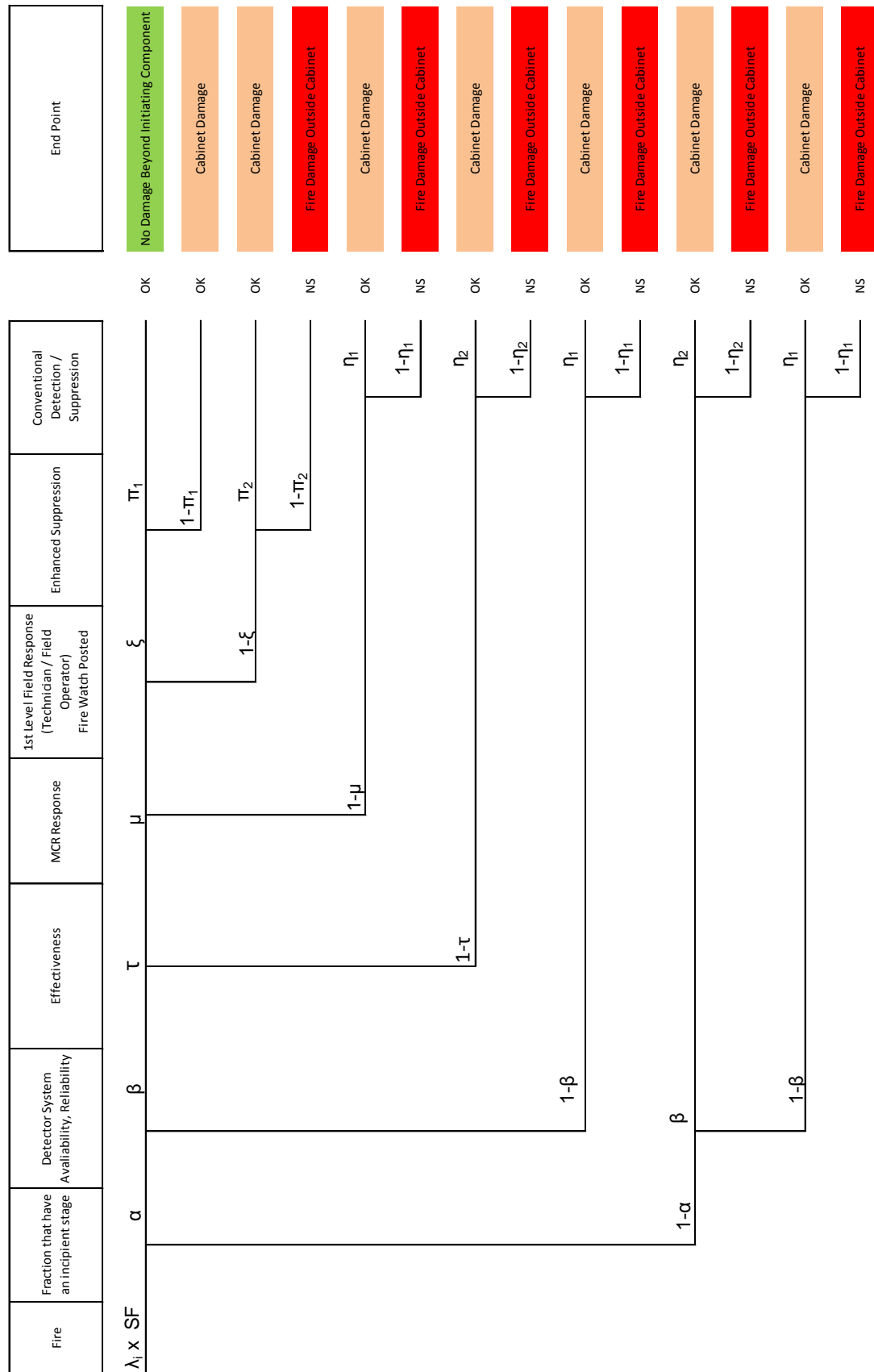


Figure 6-4. Basic event tree for in-cabinet smoke detection non-suppression probability estimation

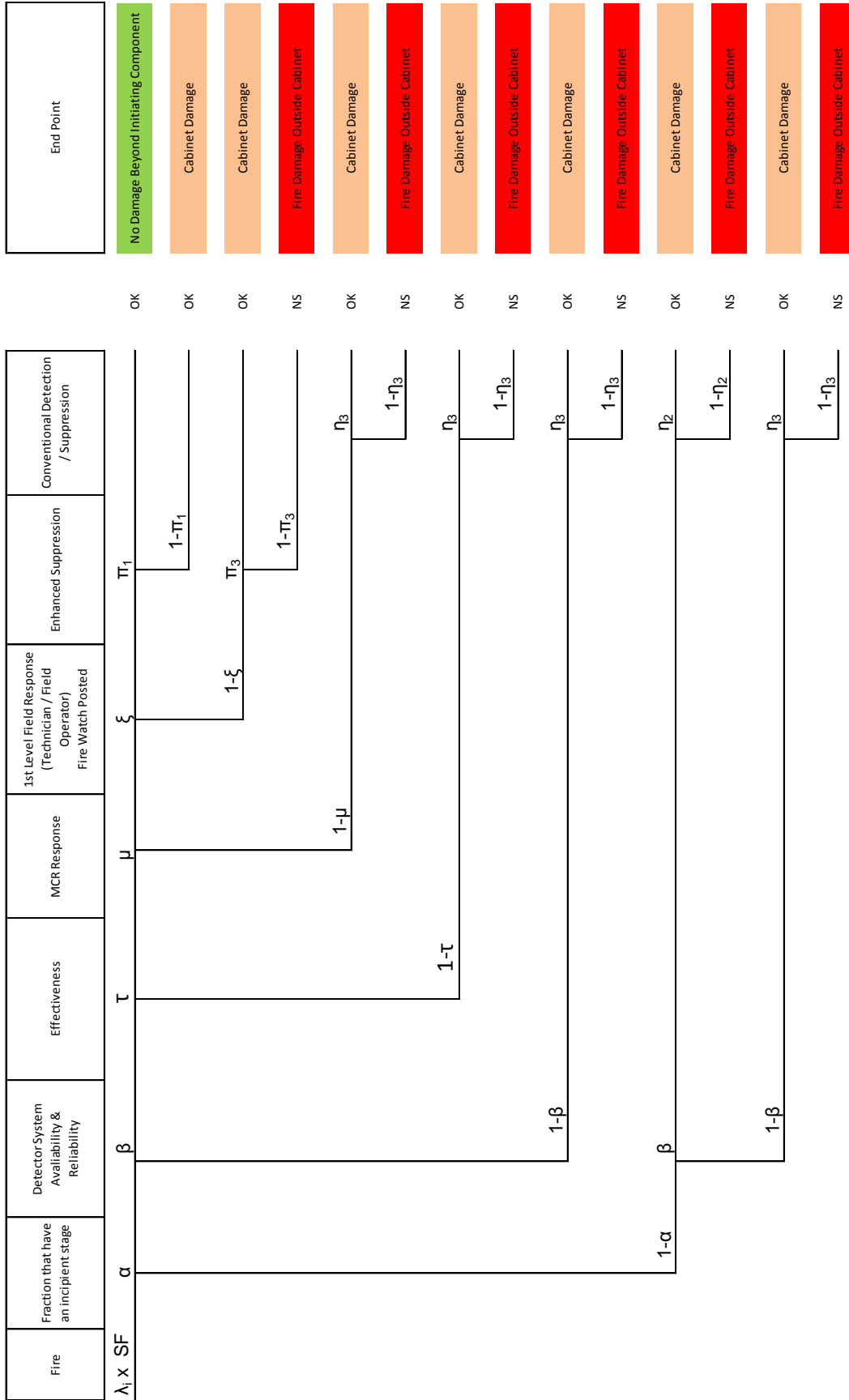


Figure 6-5. Basic event tree for areawide smoke detection non-suppression probability estimation

7. PARAMETER ESTIMATION BASED ON PART I

7.1 Fraction of Fires That Have an Incipient Stage

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

Operating experience has shown that many, but not all, electrical cabinet fires¹³ 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

¹² The basis for the 30 minutes criterion is presented later in this section.

¹³ Electrical cabinet fires are classified as Bin 15 in NUREG/CR-6850

1 NFPA 901, NFPA 921, and other NFPA standards and publications. These
2 definitions are provided in Appendix A [of EPRI 1025284] and were used as a
3 consistent means of classifying fire event information.
4

5 Thus, to understand the fraction of electrical panel fires that exhibit an incipient stage, the fire
6 events database was reviewed. Bin 15 “Electrical Cabinet” of the EPRI fire events database
7 was evaluated to inform the fraction of events, which exhibit an incipient stage of sufficient
8 duration, (greater than or equal to 30 minutes) such that detection and operator response could
9 enhance the suppression activities. All Bin 15 Electrical Cabinet events that contribute to fire
10 ignition frequency (i.e., Challenging, Potentially Challenging, and Undetermined) were reviewed.
11 Events classified as “non-challenging” were not evaluated because they do not contribute to the
12 fire frequency and are not considered important to plant risk. However, review of these “non-
13 challenging” events does indicate that the majority of these events exhibit failure mechanisms
14 for which an in-cabinet smoke detection system could provide enhanced warning. Nonetheless,
15 as they do not contribute to fire risk (as presented in Section 6.1), they are not examined further.
16

17 The results of this evaluation are documented in Appendix D. Determination of whether or not
18 an event has an incipient stage is subjective in nature, and highly dependent upon the amount
19 and quality of information available. As such, there were ‘rules’ developed to assist in making
20 this classification exercise practical, and as consistent as possible.
21

22 First, an attempt was made to make no assumptions regarding the event. If the necessary
23 information was not available, the reviewer ventured no guesses. In many events with limited
24 information, this rule likely directed the classification as being “Undetermined.” For example,
25 many events identify a breaker fault, but do not identify the component of the breaker which
26 failed. Since breakers have numerous failure modes that could result in a breaker fault, and
27 because the various failure modes may or may not exhibit an incipient stage, there was no
28 assumption made regarding any one particular failure mode; more-information was needed to
29 make such a determination possible.
30

31 Next qualitative definitions for “Yes,” “No,” and “Undetermined” were developed to support a
32 consistent classification of the events. The definitions used were as follows:
33

34 **Yes**, the description of the event provides sufficient detail to determine that slow component
35 degradation occurred. Additionally, if the description of the event doesn’t provide a direct
36 indication of slow component degradation, but can be inferred from the component which
37 failed, then it is still a ‘yes’.
38

39 An example of the latter circumstance would be a control power transformer (CPT)
40 within a motor control center (MCC) which fails due to internal winding failure, and not
41 from an over voltage condition on the primary side of the CPT.
42

43 **No**, description of event identifies rapid failure, failure during work activities (maintenance,
44 inspection, testing, cleaning, etc.), failure on demand, or the description of the event doesn’t
45 provide direct information regarding the time frame for component degradation but can be
46 inferred from other information presented.
47

48 **Undetermined**, event doesn’t provide sufficient details to determine that an incipient stage
49 occurred or did not occur.
50

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

13
 14 The results of this event review process are presented in Appendix D. Table 7-1 summarizes
 15 the results of this review for Bin 15 fires. Two of the events resulted in a differing classification
 16 among the two reviewers. In both cases one reviewer assigned an “undetermined”
 17 classification, while the other classified the event as having an incipient stage (“yes”
 18 classification). For these two events, a 0.75 weight was applied. The last column identifies the
 19 mean point estimate for “ α ” shown in bold font, with the 5th and 95th percentiles shown in
 20 bracket. These estimates are calculated excluding the “Undetermined” category and using a
 21 Jeffery’s non-informed method to estimate the uncertainty.
 22

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

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

25 [#] Power cabinets include electrical distribution electrical enclosures such as motor control centers, load centers,
 26 distribution panels, and switchgear.
 27

28 **7.1.1 Discussion of difference between this method and FAQ 08-0046**

29 This sub-section provides background information to support the approach described above as
 30 well as comparison to the interim staff position presented in Frequently Asked Questions
 31 (FAQ) 08-0046.
 32

33 The estimates developed above differ from the deterministic criteria presented in the U.S.
 34 Nuclear Regulatory Commission (NRC) interim staff position FAQ 08-0046. In that FAQ, the
 35 alpha term was estimated using a criteria of “fast acting components,” and a limitation on the
 36 maximum voltage of electrical cabinets (<250V).
 37

38 The FAQ 08-0046 defines “fast-acting components” as:
 39

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

5
6 Given these criteria are met, the FAQ presents a simplified model that assumes all fires have an
7 incipient stage of sufficient duration that an ASD VEWFD system installed in the electrical
8 enclosure containing the fire initiating component will provide at least one hour of advanced
9 warning.

10
11 Per the FAQ approach, for electrical cabinets that contain “fast acting” components, those
12 elements/parts are to be proportioned, and a fraction should be estimated as the (number of fast
13 acting components) / (total number of components within the cabinet). The FAQ does not
14 provide information on counting the number of components.

15
16 Although the intent of the FAQ approach was to eliminate those types of components that do
17 not have long incipient stages; review the FEDB, inspection reports and licensee event reports
18 (LERs); feedback received during site visits; and assess information from vendors (Ref. 20) it
19 could not be confirmed that this approach adequately dispositions equipment that does not
20 exhibit an incipient stage of sufficient duration to support enhanced suppression quantification.

21
22 Before the review of the EPRI Fire Events Database, the authors of this report were aware of at
23 least two events that conflicted with the FAQ 08-0046 interim staff position with regard to the
24 definition of fast acting components. The first event is documented in Inspection Report
25 05000348/364-11-012 and final significance determination process (SDP) (Refs. 38 and 39).
26 In this fire event, the mis-wiring of the 1A reactor coolant pump oil lift pump pressure switch
27 (cross-connection of 125 Vdc and 130 Vac circuit leads) caused a fire when the 1A RCP hand
28 switch was taken to start. Within seconds of operating the hand switch a fire was observed.
29 Given that the initiating component does not meet the definition of a fast-action component per
30 the FAQ and was determined to be potentially challenging based on the SDP, an extended
31 review of applicable operating experience was reviewed. The second event is documented in
32 licensee event report (LER) 96-005-00, dated May 20, 1996. In this event, a turbine lockout
33 relay failed when the turbine tripped on high vibration and resulted in a fire 3 minutes after the
34 relay failure (Ref. 40).

35
36 Other examples that conflict with the FAQ position include FEDB FID #30276, #30338. In the
37 first event, a malfunctioning charging circuit board caused a fire in a power transformer. The
38 location of the fire was on the power transformer and not the charging board. In the second
39 event, a panel blower (fan) failed because of accumulation of dust and dirt. The accumulation
40 occurred over a long period of time and the panel blower did not fail abruptly, but over some
41 period of time. During site visits (Section 3.1.1) an event was identified where VEWFD systems
42 were installed where failure of an AHU fan motor was detected by the VEWFD system; operator
43 actions were successful in responding to prevent a plant trip because of the unavailability of
44 required equipment.

45
46 Review of the applicable operating experience indicates that it does not support the use of
47 deterministic go/no-go criteria as presented in FAQ 08-0046. Although some of failure modes of
48 the “fast-acting components” do not involve an incipient stage (i.e., locked rotor) using these
49 deterministic criteria does not adequately represent the failure modes and associated length of
50 the component degradation phase. In addition, review of the operating experience has

1 demonstrated that use of VEWFD system to protect power cabinets is applicable for Bin 15 type
2 components as well as other types of components. However, the focus of this project is
3 exclusively Bin 15 type equipment.
4

5 There may be cases where the use of VEWFD systems combined with appropriate operator
6 actions may enhance the likelihood of preventing high-energy arc fault (HEAF) type events
7 (Ref. 41). There are also cases where use of these systems has not prevented HEAF events
8 (Ref. 42). Although the use of VEWFD systems to protect power distribution type equipment in
9 combination with adequate and prompt operator response could help reduce the likelihood of
10 HEAF (Bin 16) type event fires; it should not be considered a HEAF prevention system.
11 Evaluating the risk benefit from the use of these systems with regard to HEAF events is outside
12 the scope of this project.
13

14 **7.2 System Performance Measures (Availability, Reliability, 15 Effectiveness)** 16

17 The next events quantified in the event trees represent the smoke detection system
18 performance measures of availability, reliability, and effectiveness; system effectiveness (τ) is
19 represented separately. The parameter " β " represents the availability and reliability of a smoke
20 detection system to perform its intended design function. The success branch of " β " represents
21 the smoke detector being both available and reliable, calculated as the arithmetic sum of these
22 two estimates. The parameter " τ " represents the smoke detection system's effectiveness in
23 detecting pre-flaming (incipient) phase conditions. The success in this branch represents that
24 the smoke detection system has responded with an alert for the VEWFD system, or an alarm for
25 the conventional system during the incipient stage. Other system effectiveness measures such
26 as serviceability, maintainability, repairability, and operational readiness, although important to
27 consider during system selection, are not useful measures when quantifying the system's ability
28 to perform its intended function.
29

30 The availability and reliability of VEWFD systems are estimated generically below using
31 information collected during site visits (Section 3.1.1), vendor supplied information and
32 literature. The system effectiveness measure is also estimated below using available test data.
33 In addition to the operating experience reported, vendor literature has identified that the
34 following U.S. NPPs used ASD systems; Palo Verde, Calvert Cliffs, Nine Mile Point, Clinton
35 Generation Station, Seabrook, and Ft. Calhoun. Availability estimates with higher certainty
36 could be achieved if data from these sites could be collected and integrated into the assessment
37 presented here. For air return applications, the unavailability and unreliability of the HVAC
38 system must also be explained or justified.
39

40 **7.2.1 Estimate of generic system unavailability** 41

42 Availability is defined as the probability that a system is operating satisfactorily at any point in
43 time and considers only operating time and downtime (Ref. 21). Availability is a measure of the
44 ratio of the operating time of the system to the operating time plus downtime; its complement is
45 referred to as unavailability. Unavailability can be estimated by:
46

$$47 \quad U = \frac{t_d}{T_s}$$

1 Where t_d : system downtime for testing, preventative maintenance, and corrective
2 maintenance
3 T_s : the surveillance test interval
4

5 Operating experience data collected from site visits shows that there is a large variation in
6 system down time. The maximum likelihood estimate for an average annual system downtime
7 is 14.7 hours (hrs)/year/device. This results in a generic unavailability estimate of 1.70×10^{-3} .
8

9 For the air return application, the unavailability of the ventilation system should also be included
10 since the function of the ASD system in this application relies on the operation of the ventilation
11 system.
12

13 **7.2.2 Estimate of unreliability**

14
15 System reliability is the probability that an item (system) will perform its intended function for a
16 specified interval under stated conditions (Ref. 43). Its complement is referred to as
17 unreliability. The unreliability can be estimated by using the standby failure rate probability
18 model. This model assumes that the detector transitions to the failed state while the system is
19 in standby (i.e., period when no fire condition are present to detect). The transition to the failed
20 state is also assumed to occur at a random time with a constant transition rate. The latent failed
21 condition ensures that the detector will fail when it is next demanded, but the condition is not
22 discovered until the next inspection, test, or actual demand. This model will be used to
23 calculate smoke detector unreliability as:
24

$$25 \quad \underline{R} = \frac{E(\lambda)T_s}{2}$$

26
27 Where $E(\lambda)$: expected failure rate (per hour)
28 T_s : the surveillance test interval
29

30 The expected failure rate is

$$31 \quad E(\lambda) = \frac{k + 0.5}{T}$$

32
33 Where k : observed failures in T
34 T : total operating period (hours)
35

36 Several sources of information associated with ASD system reliability were identified. Each
37 source is explored individually and a generic unreliability estimate is provided based on the
38 average of the individual unreliability estimates.
39

40 Germany NPPs

41 Forell and Einarsson reported that three of the six German NPP units (2 PWR and 4 BWR)
42 investigated for fire protection systems and component reliability data included data on the
43 performance of ASD systems. Approximately 250 ASDs were included in the research, which
44 identified 5 failures in 12.19 million operating hours (Ref. 25). This operating experience results
45 in an expected failure rate of 4.5×10^{-7} /hr and an unreliability of 9.86×10^{-4} based on a semi-
46 annual surveillance.
47
48

1
2

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

Source	Technology (# Detectors)	Fire Events	System Failures	Total Operating Time (Years)	Down Time (hours)
TMI 1	Cloud Chamber (2)	2	PMT failure caused by improper maintenance	14.66 years per detector Total : 30 years	<u>Maintenance</u> 2-4hrs/qtr/device <u>Trouble Alarms</u> 4hrs/yr/device <u>Hot work</u> 20hrs/yr/device <u>Total</u> 12-20hrs/year/device
Robinson	Laser (1)	None	Power Supply 2002 (20day outage) Battery and Processor Replaced 2006 (27day outage)	Total : 17 years	<u>Maintenance</u> 24hrs/yr/device <u>Trouble Alarms</u> 2hrs/yr/device <u>Total</u> 26hrs/year
Harris	Cloud Chamber (10)	2	None identified	4 years per detector Total : 40 years	<u>Maintenance</u> 24hrs/yr/device <u>Trouble Alarms</u> 2hrs/yr/device <u>Total</u> 26hrs/year/device
Darlington	Laser (# not provided)	Machine belt smoke	None identified	8-9 years per detector	<u>Maintenance</u> Annual 1-2hrs/device
Pickering	Laser (# not provided)	Cork isolator overheating in air handling unit	None identified <u>Nuisance Alarms</u> 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	<u>Maintenance</u> Annual:2-3hrs/device Quarterly:3 hrs/device <u>Trouble Alarms</u> 1-2hrs/yr/device <u>Total</u> 15-17hrs/yr/device
NASA	Laser (>100)	Circuit board failure, ShopVac, fire in lab space	<u>Nuisance Alarms</u> Ventilation Changes	>300 years	<u>Maintenance</u> 1-3 hrs/yr/device

3
4

1 U.S. NPPs

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

6
7 ASD Vendors

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

11
12 Section 4.1 of UL 268 references a method for detector reliability prediction as follows (Ref. 44):

13
14 The maximum failure rate for a detector unit shall be 4.0 failures per million hours as
15 calculated by a full part stress analysis prediction as described in MIL-HDBK 217 or 3.5
16 failures per million hours as calculated by a simplified parts count reliability prediction as
17 described in MIL-HDBK 217, or equivalent, see Annex D. A "Ground Fixed" (GF)
18 environment is to be used for all calculations. When actual equivalent data is available
19 from the manufacturer, it is permissible that it be used in lieu of the projected data for the
20 purpose of determining reliability.

21
22 In addition, a component failure rate of not greater than 2.5 failures per million is referenced for
23 light emitting diode (LED) type smoke detectors using a photocell-light assembly. The same
24 component failure rate suggested for application specific integrated circuit (ASIC) employed in a
25 smoke detector unit.

26
27 Vendor 1: a. Per UL268 simplified parts count reliability analysis
28 3.5 failures per million hours
29 4×10^{-6} mean
30 Unreliability of 8.76×10^{-3}
31 b. Per UL268 full parts stress analysis
32 4 failures per million hours
33 4.5×10^{-6} mean
34 Unreliability of 9.86×10^{-3}
35

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

37
38 Vendor 2: Per MIL-HDBK-217 simplified parts count method
39 Overall MTBF = 6.09×10^6 hours
40 Overall FITS = 164.149
41 2.46×10^{-7} mean
42 Unreliability of 5.39×10^{-4}
43

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

45
46 Based on the information collected from Germany and U.S. NPP operating experience along
47 with the reliability estimates provide by the vendors (UL 268 or MIL-HDBK-217), the generic
48 unreliability of 4.5×10^{-3} is estimated based on a semi-annual surveillance period and equal
49 weighting of these four sources of data.

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

4
 5 **7.2.3 Estimate of generic system ineffectiveness**

6
 7 System effectiveness is a measure of how well a design solution will perform or operate given
 8 anticipated operational scenarios (Ref. 19). Effectiveness estimates for ASD VEWFD systems
 9 expected to operate during the pre-flaming (incipient) phase are based on the test data
 10 collected from the experiments conducted in this program. As indicated above, the source
 11 materials are heated to a temperature that can support flaming conditions. The effectiveness
 12 differs between in-cabinet, and the two areawide configurations, primarily because of smoke
 13 dilution and stratification effects. The effectiveness of these systems is determined generically
 14 using data collected during the NIST experiments, which applied a “one-stage” bayes approach
 15 (Jeffery’s non-informed). Only data from the 15, 60 and 240 minute HRP tests were used.
 16 Short tests such as resistor, capacitor, and shredded paper were not used.

17
 18 Several different estimates of system in-effectiveness are developed to support quantification of
 19 the event tree parameter τ , as shown in Table 7-3. The specific datasets used to develop these
 20 estimates are identified in Table 7-4.

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

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

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

1
2
3

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

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

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

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

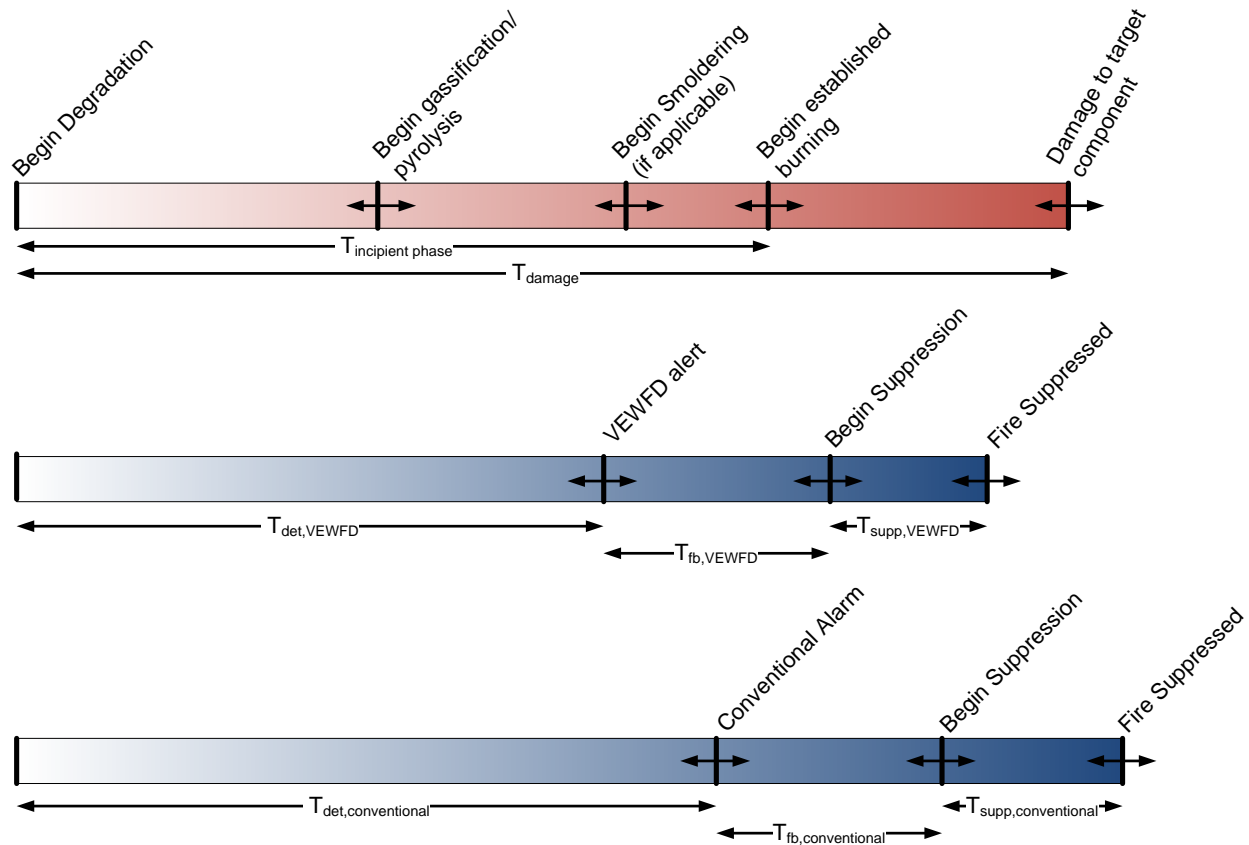
1

8. TIMING ANALYSIS

1
2
3 To determine the likelihood of success in suppressing a fire, timing information needs to be
4 provided such that operator failure rates and non-suppression probabilities can be estimated
5 and used in the event tree. The timing information that is directly applicable includes the time
6 frame that plant personnel have to respond to a smoke detection system alert, or alarm
7 notification before commencement of flaming conditions. Figure 2-2 provides a conceptual
8 illustration of the fire stages, showing the incipient, fire growth, steady state, and decay stages.
9

10 The flaming conditions' end point represents the demarcation between the event tree end
11 states, "No Damage Beyond Initiating Component" and "Cabinet Damage." Cabinet damage in
12 PRA terms refers to the point at which components other than the initiating component become
13 damaged, or when suppression activities are initiated. This approach assumes that once
14 flaming combustion commences, adjacent components to the initiating component are
15 damaged. A more detailed fire modeling approach could potentially provide for an additional
16 amount of time before other components within a cabinet being damaged, if initiating
17 component growth profiles, peak heat release rates, and component physical layout information
18 were known, along with the thermal failure threshold for the adjacent components. However, to
19 model all of the ignition sources within a cabinet and evaluate the time delay in damage to
20 adjacent components may provide too little additional benefit for the level of effort involved to be
21 worthwhile.
22

23 In addition to estimating the duration of an incipient stage for an electrical panel fire scenario,
24 the timing information of when the smoke detection system will respond with an alert or alarm
25 must also be known, such that the time available for operator response can be estimated.
26 Figure 8-1 presents timelines for the fire event for a generic fire scenario (top timeline), along
27 with timelines for very early warning fire detection (VEWFD) and conventional spot-type smoke
28 detection and operator response. Given the variability of the incipient stage duration, the start
29 of flaming combustion could begin before or after the operator response event. The analysis
30 assumes that since the fire probabilistic risk assessment (PRA) is quantifying the risk from
31 *potentially challenging or greater fires* that ignition can be expected to occur at some point if not
32 prevented/hampered by plant personnel, per the definition of fires characterized by the fire
33 ignition frequency.
34
35



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

6 To estimate the time available for operators to respond (i.e., time between VEWFD alert or
7 conventional alarm and flaming fire conditions), two approximations were actually needed:
8

- 9 • Timing of smoke detection systems response during an incipient fire phase
 - 10 – Results are presented in Section 8.1.1
 - 11
- 12 • Estimate of incipient stage duration for electrical panel equipment
 - 13 – Results are presented in Section 8.1.2
 - 14

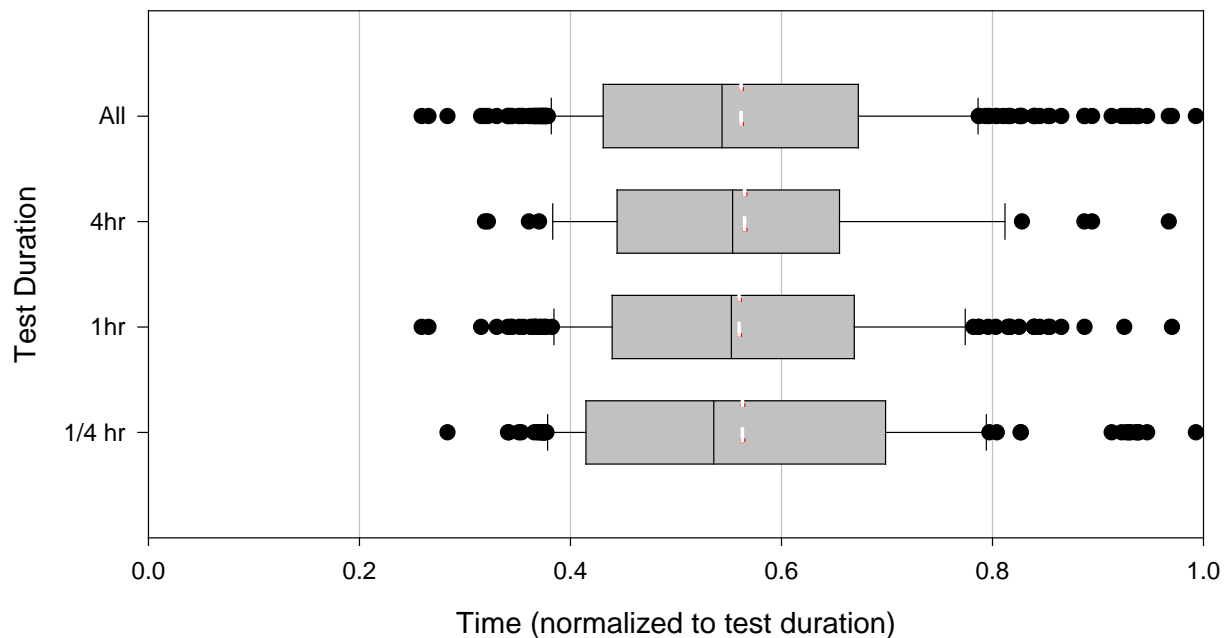
15 At some point following flaming combustion, if the “fire” is not precluded from manifestation as
16 such before the burning phase, the cabinet is damaged because of fire growth and if not
17 successfully suppressed, the fire may develop such that targets external to the cabinet become
18 damaged.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

21
22 The testing conducted as part of this program provides insights with regard to the amount of
23 time available from the time a VEWFD system alert is received to the point where flaming
24 combustion is assumed to occur (end of test). However, because the testing involved only three
25 different incipient fire durations, the data must be normalized to some baseline that represents

1 typical incipient event duration for the types of components found in the plants which these
2 systems are intended to protect. An analysis of available test data and operating experience
3 are used to develop these estimates as presented below and in Appendix D.
4

5 **8.1.1 Detector response time during the incipient stage**

6
7 This subsection evaluates the performance of VEWFD system response with regard to the time
8 of “alert” during an incipient stage. As discussed in Section 4, the copper block end point was
9 485 °C. This temperature is above the point in which piloted ignition of many polymer materials
10 occurs (Ref. 34). Thus, the end of the test (including hold time) will be used as the point where
11 the incipient stage ends. Figure 8-2 presents the test results showing the normalized time for
12 in-cabinet VEWFD system response with an “alert.” Statistical K-S tests were run between the
13 groups and found to be poolable. The pooled dataset is shown as “All” in Figure 8-2 and has a
14 median of 0.54 and mean of 0.56. These results support development of an estimate for
15 operator response time availability as discussed in the next section. A similar approach is used
16 for the conventional system evaluation. Those results are used in the following section.
17



18
19 **Figure 8-2. Summary of ASD VEWFD in-cabinet test results showing**
20 **normalized time of alert (box and whisker plot shows 10th, 25th, 50th**
21 **(median), 75th, and 90th percentiles with outliers shows as dots)**

22 **8.1.2 Estimating the duration of time available for operators to respond**

23 The incipient stage was described previously in Section 2.1 as the preheating, gasification, and
24 smoldering phases. Thus, the incipient stage includes everything from the start of component
25 degradation up to ignition, which is the point of self-sustained flaming combustion.
26
27

28
29 The duration of an electrical component incipient stage may vary from less than a second to
30 hours or days, and possibly even extended out to years; if age-related degradation mechanisms
31 are considered as the fire initiator. With this variability it becomes difficult to quantify, with any

1 certainty, the phenomena that effect the duration of the incipient stage; this is primarily because
2 of the sheer number of parameters affecting this data for many types of components, and the
3 many failure modes that prevent development of a precise characterization of this phenomenon.
4 This variability can be attributed to numerous factors, one being that, from a fire perspective,
5 component degradation does not equate to a functional failure of a component or system; it is
6 only (a breakdown) when the degradation progresses to a point where the thermal heat
7 dissipation (development of a fire or flaming conditions) and combustion byproduct cause
8 prompt or delayed component; or system functional failures. With no obvious failure, no action
9 can be taken; no one attempts to fix things that he/she does not know are broken. Another
10 related contributor is the lack of a detailed understanding of the failure mechanisms of electrical
11 components, with regard to the duration of the incipient stage; further, and more importantly,
12 there must be knowledge or understanding of the point during the incipient stage at which
13 sufficient concentrations of products of combustion are available at the smoke detector to
14 exceed a detector set point. The last point is particularly significant. In testing, a linear heating
15 ramp was used as an approximation of the incipient stage; however, in reality, the smoke
16 generation from degrading electrical equipment might not follow this approximation, but could
17 potentially follow a logarithmic or, exponential growth profile, or anyone in between. Therefore,
18 there is presently no agreed upon method to predict the time duration from when an electrical
19 component begins to degrade, and degrading components show smoke characteristics, to when
20 flaming combustion commences.

21
22 Although it can be said that most fires have an incipient stage, for a VEWFD system to be
23 modeled in the event tree above, the duration of an incipient stage must be sufficient to allow
24 the VEWFD system to respond to the products of combustion, *and* allow plant personnel
25 sufficient time to locate and either (1) “preclude” the “fire” from ever manifesting itself by snuffing
26 it out while still in the pre-fire stage (the “alpha” factor); or (2), if the “fire” cannot be precluded,
27 then providing some additional time for suppression activity once the fire manifests itself (for the
28 remaining [1- α] fires), translating into a reduction in the non-suppression probability. From a
29 safety standpoint, use of smoke detection systems becomes increasingly beneficial, as
30 additional time is available to respond to the particular event. Thus, the risk scoping study for
31 ASD VEWFD systems hinges on being able to determine the time available for operators to
32 respond to degrading conditions that have the potential to pose a *potentially challenging or*
33 *greater fire* threat. For fires that have a short incipient stage, there may not be sufficient time for
34 operators, technicians, or fire brigade to respond before fire damage occurring. For every
35 scenario, the personnel response time will be different, as will the duration of the incipient stage.
36 Thus, the variability of the response time and the incipient stage duration makes the
37 quantification of a successful response both uncertain and difficult to estimate. In addition,
38 although the incipient stage may last “x” minutes, the ASD VEWFD system (or spot-type
39 detector) will not provide advanced warning of “x” minutes but rather some “x-y” minutes, with
40 “y” not necessarily being less than “x”. That is, the VEWFD alert (spot-type alarm) threshold
41 may not occur before the development of a flame or flaming conditions, in which case the only
42 “benefit” may be additional time for suppression and a reduction in the non-suppression
43 probability.

44
45 With the lack of available information and the importance of understanding the duration of an
46 incipient stage, one approach could be to conduct a formal expert elicitation-type effort to
47 develop a consensus opinion. Unfortunately, the efficacy for such an effort was not realized
48 until late in this project, and as such, the needed resources, including budget and time, were not
49 available. Consequently, in an attempt to estimate the necessary information, a detailed
50 evaluation of the fire events database was conducted; the details of this research are

1 documented in Appendix D, identifying a limited number of cases to inform a duration estimate.
2 (Ref. 45, 46).

3
4 For the fire PRA quantification to be of use, what is being quantified as an incipient stage must
5 first be understood; then, using operational experience, test data, and judgment to develop an
6 estimate of the amount of time available for operators to respond. Therefore, in developing a
7 scenario that can quantify any potential risk enhancements from using these systems, several
8 simplifying assumptions are required, and they are noted herein.

9
10 Assumption #1: Incipient duration information is collected only for fires that exhibit incipient
11 stages of sufficient duration to allow for operator response before ignition.

12
13 Because each specific plant scenario will differ in the determination of the time to damage
14 and the specific target set, it would be unrealistic to use target damage as the end state of
15 the incipient duration. This assumption is also consistent with the definition of the incipient
16 stage provided in Section 2.1.

17
18 Assumption #2: Incipient duration information is collected only for electrical/electronic
19 component failures which are contained within an electrical enclosure (cabinet).

20
21 Interest in using ASD VEWFD systems in U.S. NPP applications has focused on electrical
22 enclosure fires. In the EPRI/NRC-RES Fire PRA Methodology, 37 different generic fire
23 frequency bins are identified. The fire frequency bin of most interest here is Bin 15,
24 "Electrical Cabinet."

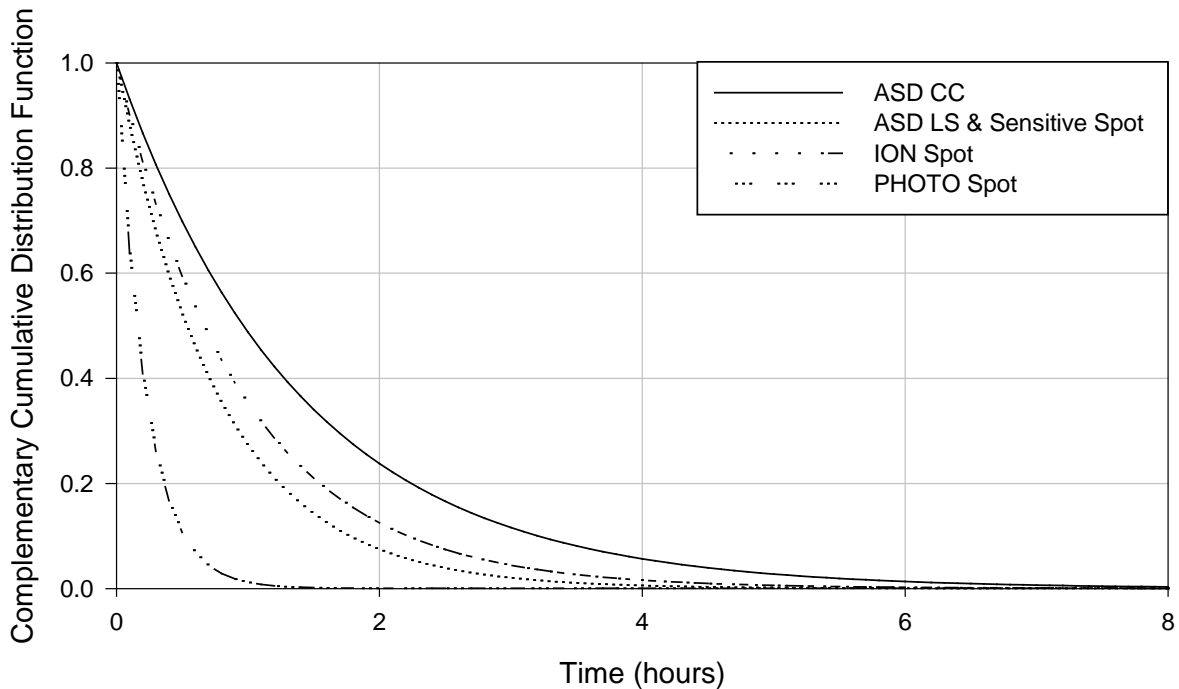
25
26 Although other types of components found in an NPP can, and will exhibit an incipient stage
27 of sufficient duration to allow enhanced suppression in applications in which VEWFD
28 systems are able to detect the products of combustion early on, the need for such
29 applications has not yet presented itself. However, a similar process could be followed to
30 develop such estimates.

31
32 Assumption #3: Use the experimental test results based on a linear heating ramp to estimate
33 the time available for operator response in instances in which the operating experience provides
34 information of the incipient stage duration.

35
36 In testing, a linear heating ramp was used as an approximation of the incipient stage. In
37 reality, the smoke generation from degrading electrical equipment might not follow this
38 approximation, but rather, could follow a logarithmic or exponential growth profile.
39 Therefore, there is presently no agreed upon method to predict the time duration from when
40 an electrical component begins to degrade, degrading component show smoke
41 characteristics, and when flaming combustion commences. Thus, the use of the test data
42 seems reasonable, but has inherent uncertainty associated with its ability to represent actual
43 electrical equipment failure modes.

44
45 Appendix D provides a detailed description of the research undertaken to identify operating
46 experience to support informing the duration of the available time for operator response. In
47 addition, recent operating experience with VEWFD systems in NPPs has provided several data
48 points on VEWFD system timing information. This information, along with the VEWFD system
49 performance as presented above, allows for the development of a distribution representing the
50 time available for operators to respond as shown in Figure 8-3. This time duration begins at
51 VEWFD system "alert" or conventional system "alarm" notification, and ends at the fire flaming

1 stage. However, it should be understood that the process followed contributes its own
 2 uncertainties, which may not be adequately quantified to represent an informed technical
 3 community's beliefs. The authors of this report suggest that a formal process (such as an
 4 expert elicitation) be followed if better resolution of this quantification is needed. It is also
 5 suggested that any such effort employ experts knowledgeable in electrical component design
 6 and failure characteristics, such as individuals from vendors of the equipment being protected
 7 (i.e., relays, transformers, power distribution equipment, etc.) or from industries with extensive
 8 operating experience and components similar to those found in NPPs.
 9



10
 11 **Figure 8-3. Distribution for duration of time available for plant personnel to respond to**
 12 **VEWFD system “alert” or conventional “alarm” notification of incipient fire**
 13 **conditions, for those fires, which exhibit an incipient stage for in-cabinet**
 14 **applications**

15 Figure 8-3 illustrates the exponential distribution representing the duration of time available for
 16 operator response before the onset of flaming conditions. These distributions were developed
 17 using available operating experience and information from interim staff position (Ref. 1). Where
 18 operating experience provided the duration of the incipient stage, that time was adjusted by
 19 using the normalized mean response time for the smoke detection system in-cabinet response
 20 from the test results. That is, if the incipient duration lasted 60 minutes and the normalized
 21 mean detection time for detector X was 0.5, then the time available estimate for that event and
 22 detector is 30 minutes. Three events having incipient stage durations of 0.5, 0.9, and 7 hours,
 23 respectively, were identified from the fire events database. Each of these values involved cases
 24 in which timing information regarding system start or change of stage was documented, and
 25 ended when the potentially challenging or greater fire event was identified. Thus, it is assumed
 26 that the incipient stage started when the equipment was turned on, which may or may not be
 27 true, and therefore, these values could be shorter in duration. Two of the events identified were
 28 from recent operating experience in which ASD VEWFD systems were present. In both cases,
 29 the ASD VEWFD systems were located in equipment other than the initiating equipment; thus

1 these two values could be longer in duration. Since the VEWFD detection type was known
2 (Cloud Chamber) the timing information from that event could be used directly for the cloud
3 chamber estimate. However, those two events timing information was adjusted for the other
4 detectors by using the normalized mean difference in performance. For instance, if a cloud
5 chamber event provided for 60 minutes of advanced warning from the VEWFD "alert," and
6 detector X provided half of the advanced warning as the cloud chamber (based on normalized
7 mean time to detection), then detector X would have allowed for 30 minutes of advanced
8 warning for that event. The last estimate was from the interim staff position, and since this
9 value was presented in both industry and NRC documents, it could be viewed as somewhat of a
10 consensus opinion. However, neither the industry nor the NRC document provided any
11 technical basis to support such an estimate. Review of operating experience has also
12 demonstrated that these assumptions are not bounding. Since the interim staff position does
13 not differentiate between detection technologies, the estimate is assumed to be applicable to all
14 VEWFD systems.

15
16 These distributions are developed to support human error probability quantification (see
17 Section 10.5) and to evaluate the varying performance of different smoke detectors,
18 distributions for time available for ASD CC, ASD LS, SS, PHOTO and ION detectors.
19 Appendix D.3 provides additional information on the events identified and the numerical
20 estimates.

21

9. HUMAN FACTORS ANALYSIS

The objective of the human factors (HF) analysis was to identify personnel tasks involved in the planned response to aspirating smoke detection (ASD) very early warning fire detection (VEWFD) alerts and alarms; and factors that may adversely affect personnel task performance (e.g., insufficient training, poor alarm design) during response operations.

The way in which an ASD VEWFD system is implemented (e.g., planned response, system design, application) determines how humans will interact with the system and, ultimately, may affect whether prevention or prompt suppression is achieved. As such, variations in implementation of an ASD VEWFD system can impact the system's effectiveness in the amount of advanced warning. Thus, the results of the human factors analysis are used primarily as input to the detailed human reliability analysis and, consequently, the risk scoping study presented in this report (Section 12). However, the HF analysis also serves to inform designers, reviewers and users about potential factors related to the way in which ASD VEWFD systems are implemented, that may adversely affect human performance.

Few licensees have implemented ASD VEWFD systems within the context of quantifying system performance in a fire probabilistic risk assessment (PRA). Therefore, information is limited regarding system implementation practices and effectiveness; thus, this HF analysis should be considered an early analysis. To supplement our knowledge of ASD VEWFD systems, in addition to the U.S. nuclear industry, we studied non-U.S. NPPs and non-nuclear facilities using these systems. It is recommended that this analysis be updated as more information becomes available regarding the usage of ASD VEWFD systems in the U.S. nuclear industry.

9.1 Information Gathering

To support the HF analysis, information about ASD VEWFD systems was gathered using various methods. Information gathering activities were strategic or resourceful in nature and yielded qualitative data. The following activities were conducted:

1. Document Review:
 - trip reports¹⁴ 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
 - ASD VEWFD alert and alarm response procedures at two U.S. NPPs
 - vendor documentation for special equipment (i.e., thermal imaging cameras and portable ASDs)
2. Expert consultation
 - developed and administered a set of questions regarding ASD VEWFD response operations to: 1) personnel at a licensee intending to use ASD VEWFD systems

¹⁴ The trips were conducted by the NRC team lead, Gabriel Taylor, and Tom Cleary from NIST. The HF and HRA NRC personnel (Amy D'Agostino and Susan Cooper) were not part of the team at this time and, thus, were not present during these trips.

1 to support its transition to NFPA 805 and 2) personnel at a licensee currently
2 using ASD VEWFD to support an approved NFPA 805 transition (See Appendix
3 C for questions and answers). One licensee provided written responses¹⁵ and
4 the other provided responses via teleconference. The following departments
5 were represented on the teleconference¹⁶:
6

- 7 • fire protection
- 8 • licensing
- 9 • instrumentation and controls (I&C) maintenance
- 10 • systems engineering
- 11 • corporate
- 12 • operations (a senior reactor operator (SRO))

13
14 3. Site Visit:

- 15 ○ trip to a licensee currently using an ASD VEWFD system as a surrogate to a
16 conventional spot-type smoke detector
 - 17 • plant tour focused on the ASD VEWFD system (e.g., ASD VEWFD alarm
18 display in MCR, local fire alarm control panel)
 - 19 • discussions with personnel regarding system implementation and
20 performance

21
22 **9.2 Human Factors Analysis of VEWFD System Response**
23 **Operations**
24

25 This section describes a two-step HF analysis of ASD VEWFD alert/alarm response operations.
26 The first step consisted of a tabletop analysis to identify the personnel tasks involved in the
27 response operations, captured in Section 9.2.1. The second step was an evaluation to identify
28 factors that may adversely affect task performance, captured in Section 9.2.2.
29

30 The HF analysis conducted was a generic analysis (i.e. not plant specific), which this was an
31 intentional choice by the project team. As there is no standardized way in which licensees must
32 implement these systems, a “generic analysis” allowed for exploration of various possible
33 implementations, while concurrently developing an understanding of the fundamental tasks
34 involved in response operations. The analysis identified the general structure of the human-
35 system and human-human interactions that are, likely, common to all licensees during ASD
36 VEWFD response operations. The analysis also highlighted variations in implementation
37 (e.g., alarm location) that are a product of licensee-preferred practices. Variations are of
38 interest because they can impact the efficacy of the human-machine system (i.e., interaction of
39 detection system and personnel response), such that they can either facilitate or deter fire
40 prevention or prompt suppression.
41

¹⁵ Positions and titles of the personnel that contributed to the written responses were not provided.

¹⁶ The staff members present for the teleconference were chosen by the licensee. The project team had no involvement in the selection process.

9.2.1 Step 1: Tabletop analysis

A tabletop task analysis is a technique that involves consulting with a group of experts who have an understanding of a system to define/assess particular aspects of that system. The discussions are typically directed around some basic framework (e.g., procedures). This technique can be used to “deepen task knowledge of a system ...[It] can create (on-line) detailed task information and/or can analyze that information in a problem-solving and explanatory way.” (Ref. 47)

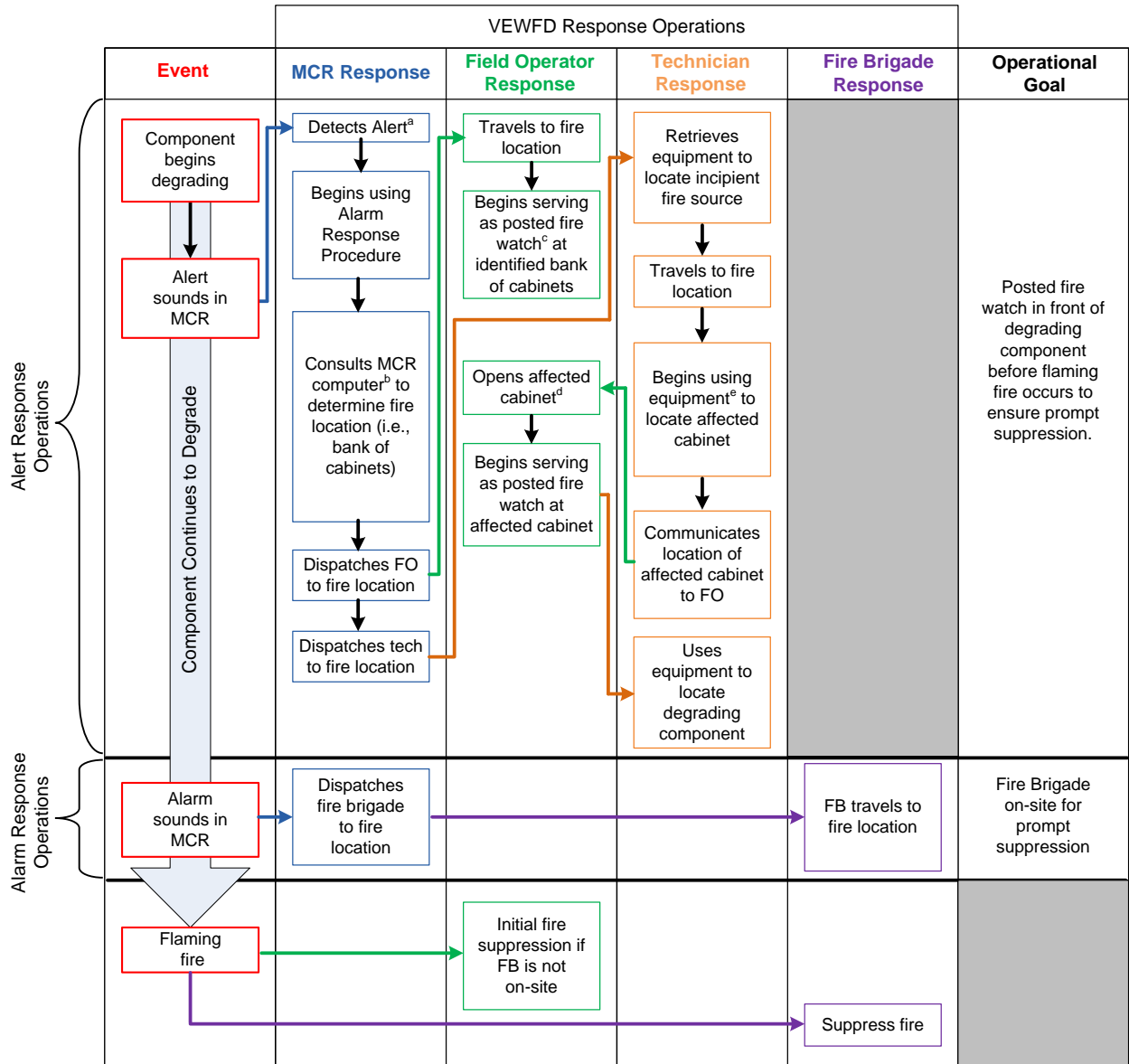
A tabletop analysis was conducted on ASD VEWFD response operations, which rely solely on human response. Before consulting experts, the project team gathered information via document review (described in 9.1) to gain a basic understanding of ASD VEWFD response operations (e.g., necessary tasks/equipment/personnel). Experts were then asked targeted questions aimed at validating our understanding of response operations, gathering missing information, identifying gaps, and gaining a deeper understanding of specific aspects of response operations.

The scope¹⁷ of the tabletop analysis was the personnel response to an ASD VEWFD alert followed by an alarm for an in-cabinet application. An alert occurs at 0.2 %/ft obscuration (effective sensitivity at each sampling port) and an alarm occurs at 1.0 %/ft obscuration (effective sensitivity at each sampling port). Plant personnel can take one of two strategies to respond to incipient fires, either a fire suppression strategy or a de-energizing strategy. A fire suppression strategy is one in which the end state is a posted fire watch at the affected cabinet and, thus, personnel are in position for prompt suppression. A de-energization strategy is one in which the end state is removing power from the affected cabinet (or part of the cabinet) and repairing the degraded component; this is a prevention strategy/approach.

The results of the tabletop analysis are depicted in Figure 9-1 and Figure 9-2. The figures are “generic” in the sense that they do not represent plant-specific response operations, but-, rather, depict an illustrative case. Figure 9-1 is a depiction of a fire suppression strategy and Figure 9-2 is a depiction of a de-energization strategy. Response operations primarily involve four types of personnel: 1) MCR operators 2) field operators 3) digital instrumentation and controls (DI&C) technicians and 4) fire brigade. MCR operators are responsible for detecting an alert, using the correct alarm response procedure (ARP), dispatching personnel to the fire location and, on alarm, activating the fire brigade. The field operator is responsible for serving as the initial fire watch (with suppression capabilities) and opening cabinets. The technician is responsible for gathering necessary equipment, traveling to the fire location, and using the equipment to find the incipient fire source. The fire brigade is responsible for suppression duties once they’ve arrived on the scene. Variations in system implementation and response operations that were observed during the information-gathering stage are noted by superscript letters in the figures and addressed further in Section 9.2.1.1.

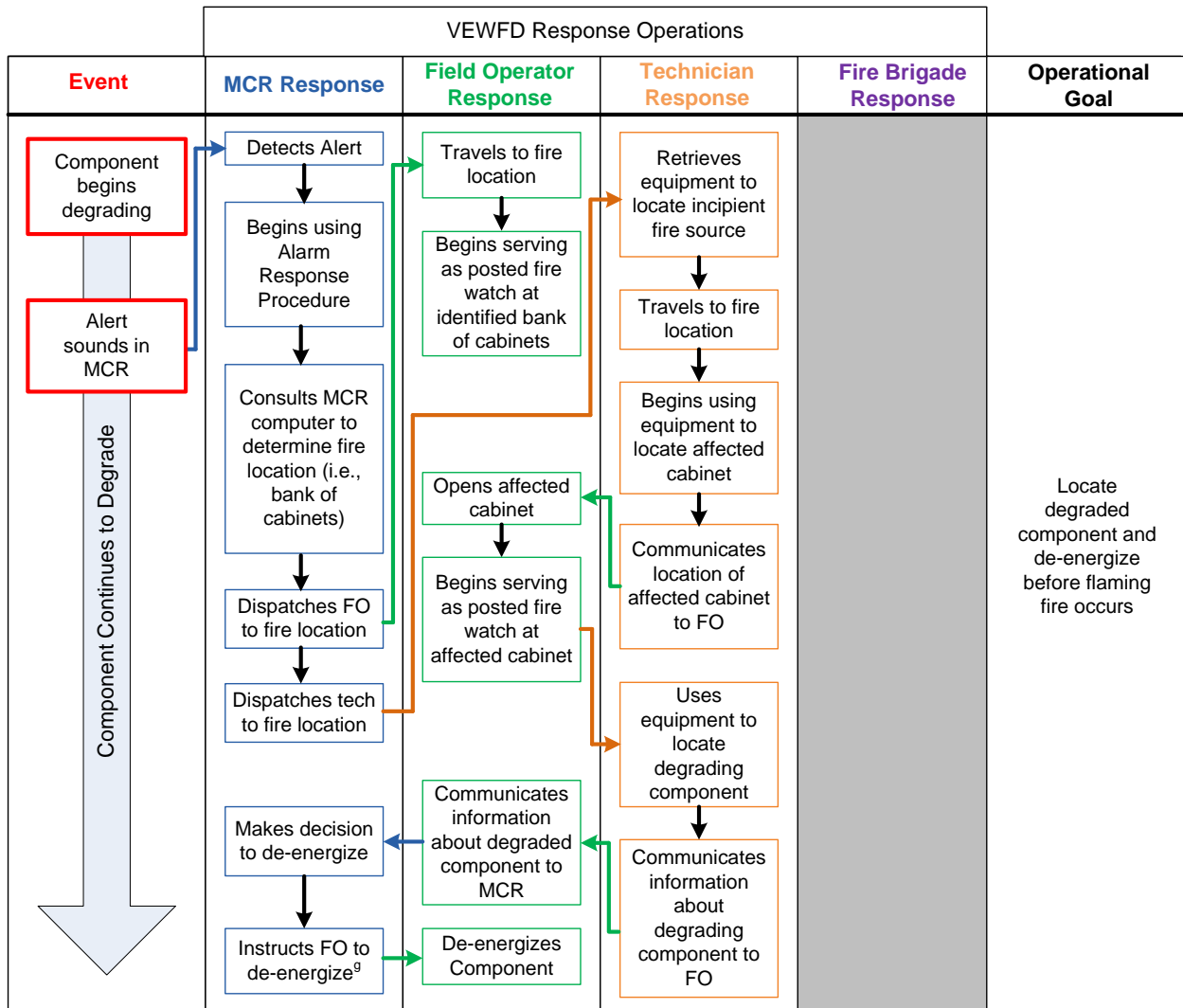
¹⁷ The scope of the analysis was determined by the information required to support the HRA (discussed in Section 10).

1



2

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



1
 2 **Figure 9-2. Generic depiction of operations in response to an in-cabinet ASD VEWFD**
 3 **alert followed by alarm where a de-energization strategy is being used**
 4

1 **9.2.1.1 Variations in ASD VEWFD system implementation and response operations**
2

3 Variations that were observed or discussed during the information-gathering stage and that
4 were noted in Figure 9-1 and Figure 9-2 are addressed further here:
5

- 6 • Alarm location varies. There are licensees that located the ASD VEWFD alarm display
7 on the front panel and others located it on a back panel. The implications of this
8 variation are discussed in Section 9.2.2.2.
9
- 10 • Licensees differ with regard to how personnel retrieve information regarding fire
11 location. At one licensee site, this information is provided via an MCR computer that
12 indicates the fire location/bank of cabinets in an alarm (represented in Figures 9-1 and
13 9-2). Others require operators to consult a main fire alarm control panel in or near the
14 MCR, which will indicate the room or area that is alarming; then, the field operator will
15 check a local fire alarm control panel and/or a local ASD VEWFD detector to get more
16 detailed location information (e.g., bank of cabinets). The more steps involved in
17 determining the fire location, the longer the overall response will be delayed, which may
18 decrease the probability of successful prevention or prompt suppression.
19
- 20 • The level and quality of training that fire-watch personnel receive varies. One licensee
21 reported that fire-watch personnel are trained in basic fire suppression using a fire
22 extinguisher and another reported that 95 percent of field operators are fire brigade
23 trained. The implications of this variation are discussed in Section 9.2.2.4.
24
- 25 • Cabinets at some sites require keys to be opened. The implications of this variation are
26 discussed further in Section 9.2.2.1.1.
27
- 28 • The type of equipment used to locate the degrading component varies. Some licensees
29 use portable ASDs, and others use thermal imaging cameras. The impact of equipment
30 type on response operations is discussed further in Sections 9.2.2.1.3 and 9.2.2.1.4.
31
- 32 • The personnel responsible (e.g., FO, MCR operator, another technician) for de-
33 energizing equipment varies based on the type of components/equipment being de-
34 energized. This variation may impact the necessary communications (e.g., the
35 operators may have to dispatch personnel who are not currently at the fire location).
36 This variation can affect the response timeline, and thus, impact the probability of
37 successful response operations. For example, if the equipment can be de-energized
38 from the MCR, this may shorten the timeline; however if other personnel have to be
39 dispatched to the fire location, this can extend the timeline.
40

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.

9.2.2.1.1 Keys

Keys may be required to access certain cabinets once the degrading component has been located. If all field operators do not routinely carry the keys to access locked cabinets, retrieving the keys will add time to the response operations timeline, and may decrease the probability of successful prevention or rapid suppression.

9.2.2.1.2 Personal protective equipment

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.

9.2.2.1.3 Portable ASDs

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

1 signature is not producing visible smoke to aid the responding field operators in locating the fire
2 source. These devices have the potential to locate the incipient fire before damage occurring to
3 other equipment. However, there are certain aspects related to the use of these systems that
4 affect their utility.

5
6 Differences in detection technologies (i.e., handheld and locally mounted ASD), should not be
7 mixed. For instance, if an electrical cabinet is protected by a cloud chamber based ASD, a
8 laser-based portable ASD is not suitable for use and vice-versa. This is because of the
9 differences in these two technologies' ability to detect different fire aerosol signatures (i.e., a
10 large number of small particles versus a small number of large particles). Therefore, there can
11 be instances where a handheld light-scattering based detector may not be effective at locating a
12 low energy fire source when a permanently mounted cloud chamber device is being used, and
13 vice versa.

14
15 Maintenance and testing are important to ensure the operability of these handheld systems.
16 The portable ASD systems are battery operated. Battery life typically varies from 2-3 hours.
17 As such, the battery should be properly maintained to vendor recommendations to ensure that
18 power is available when needed. Units based on cloud chamber technology require a suitable
19 water source to function. Thus, the supply should be routinely inspected and maintained to
20 ensure operability. Lastly, testing the units with the vendor-recommended frequency will ensure
21 that they are functioning properly, or that malfunctions are discovered and repaired in a timely
22 manner.

23 24 9.2.2.1.4 Thermal imaging cameras

25
26 A thermal imaging camera is a non-contact instrument which is able to quickly scan temperature
27 distribution of entire surfaces of machinery and electrical equipment and detect infrared
28 radiation (IR) emitted by objects. The amount of radiation emitted is dependent on the object's
29 temperature and emissivity properties. Emissivity is the efficiency with which an object emits
30 radiation and can range from 0 (not-emitting) to 1 (completely emitting). This is highly
31 dependent on material properties and also varies with temperature. In order for the thermal
32 imaging camera to read correct temperatures, emissivity must be taken into account. Most
33 thermal imaging cameras allow for emissivity as an input and use an algorithm to calculate the
34 temperature of a viewed object to most closely match the actual temperature. When using
35 thermal imaging cameras to survey the internals of electrical cabinets, it is important to select an
36 emissivity within an acceptable range.

37
38 The quality and effectiveness of thermal imaging cameras can vary with camera resolution,
39 thermal sensitivity and camera accuracy. Equipment should be chosen that is appropriate for
40 application in NPPs and is proven to be appropriately sensitive. Similar to portable ASDs,
41 thermal imaging cameras require periodic calibration, maintenance, and testing to ensure that
42 they are functioning properly.

43
44 When responding to a VEWFD "alert" or "alarm," the ability to use thermal imaging cameras to
45 locate the incipient source will vary. If thermal imaging cameras are used in conjunction with
46 portable ASDs, and a portable ASD is used to locate the affected cabinet, the thermal imaging
47 camera may support locating degrading components. In this scenario, the cabinet configuration
48 and thermal operating characteristics will affect the ability to locate the degrading
49 component. For instance, if the camera's view is clear and unobstructed, the ability to locate
50 degrading components should be enhanced. Conversely, if the cabinet has substantial
51 partitions and obstructions which do not allow for a direct line of sight for the camera to sense

1 an object emitted IR, the thermal imaging camera is less effective; and consequently, locating
2 the component may take substantially more time and the potential exists that the component
3 may not be located before flaming conditions.
4

5 The use of thermal imaging cameras requires the user to process the viewed image. Thus, it
6 may be beneficial to have accurate baseline images available and accessible. Baseline images
7 are images taken when equipment is at normal operating temperatures. Baseline images serve
8 as comparison data to assess whether or not acceptable temperatures have been surpassed,
9 and are commonly used as a periodic surveillance tool. Depending on how thermal images
10 must be processed, (e.g., operator compares current image to baseline, through the use of
11 software that processes images, etc.), the timeline for incipient fire identification should be
12 adjusted accordingly.

13 **9.2.2.2 Human-system interface**

14
15 A human-system interface (HSI) is the part of the system through which personnel interact to
16 perform their functions and tasks. The availability, functionality, and usability of human-system
17 interfaces can impact personnel performance. Guidance for the evaluation of HSIs is provided
18 in NUREG-0700, Revision 2, "Human-System Interface Design Review Guidelines" (Ref. 50).
19 HSIs that are poorly designed (e.g., poor labeling, subpar computer interfaces), have been
20 damaged, or are difficult to use, can negatively impact performance. Also, if the HSI does not
21 display required information, or if the information is inaccurate, performance can be adversely
22 affected. HSIs involved in ASD VEWFD alarm response operations include MCR HSIs, portable
23 equipment HSIs, and may include HSIs of local fire alarm control panels and local VEWFD
24 detectors.
25

26 **9.2.2.2.1 MCR HSI**

27
28 The value of the ASD VEWFD system is in creating the opportunity for fire prevention or prompt
29 suppression. As stated earlier, an effective response to a VEWFD signal relies on the actions of
30 NPP personnel. Thus, ASD VEWFD MCR alarm displays are aspects of the MCR HSI that
31 deserve consideration, as there can only be an effective operator response if the operator is
32 aware there is a problem. Broadly defined, alarms are signals/warnings that inform personnel
33 that a plant parameter, component, system, or function is currently in a state requiring the
34 attention of plant personnel. Both ASD VEWFD alerts and alarms that require personnel to
35 respond would fall under the broad definition of "alarm." This is pertinent because the
36 subsequent information in this section will discuss "alarm" characteristics, which, in the current
37 context, applies to both ASD VEWFD alerts and alarms that require personnel to respond.
38

39 As stated in NUREG-0700, Revision 2, "To be effective, an alarm system should attract
40 attention and help the operator focus attention on more-important rather than less-important
41 alarms." An alarm should be designed such that operators can reliably discern it. Alarms can be
42 made discernible through aspects such as signal level, visual coding, visual intensity, and
43 frequency of tonal signals. NUREG-0700, Revision 2, Section 4 provides detailed information
44 for alarm system design.
45

46 With regard to ASD VEWFD, there are several aspects of alarm design that should be
47 specifically noted:
48

- 49 • Signal level of alarms - NUREG-0700, Revision 2 states that the signal "should be such
50 that users can reliably discern the signal above the ambient control room noise."

1 Specifically, it advises that a signal approximately 10 decibels (dB) above average
2 ambient noise is adequate and that the sound intensity should be limited to a maximum
3 of 95 decibels in most circumstances. NFPA 72, states that the combination of ambient
4 noise and alarms “shall not exceed 110 dB at the minimum hearing distance” (Ref. 8). In
5 NPPs, there are a multitude of alarms. Although NFPA 72 states that fire alarms shall
6 not exceed 110 dB, caution should be taken to ensure that the ASD VEWFD alarms are
7 not “drowning out” reactor alarms (Ref. 8). This is possible if the reactor alarms are set
8 at 95 dB or less and the ASD VEWFD alarm at 110 dB.
9

- 10 • Alarm set-points - Nuisance alarms are alarms that have no operational significance to
11 current plant conditions. One type of nuisance alarm occurs when alarm set-points are
12 established so close to the normal operating value that many “false” alarms occur. If
13 nuisance alarms occur frequently, operators may become less likely to respond.
14 Operating experience indicates that VEWFD systems tend to alarm in response to
15 maintenance activities (e.g., welding/grinding activities) and “dirty” environmental
16 conditions (e.g., dust, charcoal in the air). Licensees have used several mitigating
17 strategies to reduce the amount of false alarms including disabling the system and
18 posting a fire watch during maintenance activities; and adjusting sensitivity settings that
19 account for environmental conditions.
20

21 Another variety of nuisance alarms is status indications or “messages that indicate the
22 status of plant systems but are not intended to alert the user to the need to take action.”
23 Status indications may increase the processing demand on operators and result in the
24 operator being unsure when a response is required and/or delay operator response.
25 ASD VEWFD systems offer users the capability to have multiple alert and alarm set-
26 points. If used, those alerts and alarms with no associated operator actions are
27 nuisance alarms. As suggested in Section 4.1.2-5 of NUREG-0700, Revision 2, status
28 indications should be segregated from alarms and should be presented to operators via
29 a non-alarm display unless there are unique aspects of the design that justify presenting
30 the information within the alarm display.
31

- 32 • Alarm Location - According to NUREG-0700, Revision 2, Section 4.6-5, alarm displays
33 and controls should be positioned such that responsible personnel can access the alarm
34 information with adequate time to respond. For example, if the VEWFD alarm is located
35 on the back panel in the MCR and only monitored periodically, it may take the MCR
36 operators longer to detect the alarm than if it were on the front panel, thus reducing the
37 time available to respond, and potentially decreasing the probability of fire prevention or
38 prompt suppression. Through site visits and expert consultation, it was determined that
39 there are licensee MCRs where the alarm is located on a front panel and others where it
40 is located on a back panel.
41

42 9.2.2.2.2 Local fire alarm control panels, local VEWFD detectors, and special equipment 43

44 ASD VEWFD response operations require technicians to interact with HSIs of special
45 equipment (portable ASDs/thermal imaging cameras) and may require field operators to interact
46 with the HSIs of local fire alarm control panels and/or ASD VEWFD systems. As explained in
47 NUREG-1921, MCR HSIs (including main fire alarm control panels) are subject to detailed
48 control room design reviews (DCRDRs) which has led to modification or elimination of many
49 problematic HSIs. However, local panels and special equipment have not received the same
50 level of regulatory review. HSIs of local fire alarm control panels, local detectors and special

1 equipment deserve consideration with regard to their potential impact on VEWFD response
2 operations.

3
4 Local fire alarm control panels and local detectors are akin to what NUREG/CR-6146, "Local
5 Control Stations: Human Engineering Issues and Insights," refers to as local control stations
6 (LCSs) (Ref. 51). LCSs are defined as "an operator interface related to process control that is
7 not located in the main control room. This includes multifunction panels, as well as single-
8 function LCSs, such as controls (e.g., valves, switches, and breakers) and displays (e.g.,
9 meters) that are operated or consulted during normal, abnormal, or emergency operations" (Ref.
10 50). Local fire alarm control panels and local VEWFD detectors are *displays* that are *consulted*
11 during *abnormal operations*, thus, meeting the aforementioned definition.

12
13 In NUREG/CR-6146, the results of a study to evaluate human engineering of LCSs in the U.S.
14 nuclear industry are captured. Approximately 3,000 LERs involving "poor ergonomics or human
15 environment" were reviewed and in-plant assessments of LCSs were conducted. Several items
16 of note resulted from this study: 1) many events were identified as having occurred as a result
17 of a specific human interface deficiency, 2) human engineering deficiencies at LCSs are quite
18 common across the industry and 3) human engineering deficiencies at LCSs can negatively
19 affect plant operation. Interestingly, while reviewing the LERs, it was noted that nearly half of
20 them involved equipment used for testing/calibration. Although testing/calibration equipment
21 events were not of interest in the study, the information is relevant for VEWFD response
22 operations. It suggests that special equipment HSIs may be less than ideal. Another
23 complicating factor for both LCSs and special equipment may be that, as opposed to MCR HSIs
24 that operators interact with frequently, personnel may rarely interact with LCSs and special
25 equipment. They must take action in much less familiar surroundings, using equipment with
26 less than ideal HSIs, potentially resulting in adverse effects on performance.

27
28 Project activities included one observation of a local fire alarm control panel and local VEWFD
29 system. Both appeared to be located in a readily accessible area and had readable and
30 understandable displays. Vendor documentation and videos were reviewed for thermal imaging
31 cameras and portable ASDs; however, the images of the equipment were not clear enough to
32 properly evaluate the quality of the HSIs. More research should be done to evaluate the quality
33 of the thermal imaging camera/portable ASD HSIs, and to explore personnel usage difficulties.

34
35 As stated in NUREG/CR-6146, "Like the workstations in the control room, LCSs are interfaces
36 between the operators and the plant, and the approach to their design should reflect the same
37 human engineering considerations given to the main control room..." (Ref. 51). High-level
38 guidance regarding design and evaluation of local control stations and portable diagnostic tools
39 (e.g., portable ASDs) is provided in Sections 12.2 and 13.8.3.2 of NUREG-0700 Revision 2.

40 41 **9.2.2.3 Procedures**

42
43 Procedures or instructions for performing actions, can impact human performance negatively or
44 positively depending on their availability, accessibility and quality. To create high-quality
45 procedures, they should be developed using accepted human factors engineering principles.
46 As stated in Section 9.2 of NUREG-0711, Revision 3, "Human Factors Engineering Program
47 Review Model," procedures should be "technically accurate, comprehensive, explicit, easy to
48 use, and validated" (Ref. 52).

1 Regarding ASD VEWFD response operations, MCR Alarm Response Procedures (ARPs) must
2 be available and accessible to guide the human response to a MCR alert or alarm. Personnel
3 should have immediate access to ARPs from the alarm location (Ref. 50). If procedures are not
4 readily available or accessible, it may negatively impact performance by increasing the time to
5 respond, thus decreasing the probability of fire prevention or prompt suppression.
6

7 Local actions (e.g., locating degrading components) are required in ASD VEWFD response
8 operations. Typically, there are procedures available for local actions; however, some tasks
9 may be considered “skill-of-the-craft”¹⁸ and, thus, are not proceduralized. Project research did
10 not yield information regarding the usage of procedures for local actions. If procedures are not
11 used, a strong case must be made for labeling a task “skill-of-the-craft” to provide reasonable
12 assurance of a safe operator response. Even when procedures do exist, it may not be practical
13 to page through a procedure while performing a task. For example, if a technician is using a
14 portable ASD to locate the degraded component, one hand would be used to hold the body of
15 the device and the other would hold the probe, thus making paging through a procedure
16 impractical. Thus, personnel must either be trained to perform the steps from memory or there
17 must be a contingency plan for providing the procedural steps (e.g., via portable radio).

18 **9.2.2.4 Training**

19
20 Nuclear power plant personnel must receive training in accordance with current regulations.
21 With regard to ASD VEWFD response operations, 10 CFR 50.120 applies to the non-licensed
22 operators (FOs) and I & C technicians and 10 CFR 55 applies to licensed operators. Both
23 regulations identify a systems approach as acceptable methodology for training nuclear power
24 plant personnel. A systems approach to training consists of the following five elements (10 CFR
25 55.4):
26

- 27 • systematic analysis of the jobs to be performed
- 28
- 29 • learning objectives derived from the analysis which describe desired performance after
30 training
- 31
- 32 • training design and implementation based on the learning objectives
- 33
- 34 • evaluation of trainee mastery of the objectives during training
- 35
- 36 • evaluation and revision of the training based on the performance of trained personnel in
37 the job setting
- 38

39 Ultimately, the training program must provide the instruction necessary to produce qualified
40 personnel to operate and maintain the facility in a safe manner. In general, training should
41 establish familiarity with procedures and operation of any special equipment; prepare personnel
42 to handle departures from the expected sequence of events; and provide opportunities to
43 practice the skills required to accomplish the task (Ref. 48).
44

45 Some of the training that may be necessary for ASD VEWFD response operations includes:
46

¹⁸ “Skill of the craft” is a term describing those tasks in which it is assumed that the workers know certain aspects of the job and need no written instructions (NUREG/CR-1278) (Ref. U).

- 1 • training for MCR operators on ASD VEWFD ARPs
- 2
- 3 • training for FOs and technicians on any applicable procedures
- 4
- 5 • training for technicians on the operation of thermal imaging cameras and/or portable
- 6 ASDs
- 7
- 8 • training for personnel who will serve as fire watch
- 9
- 10 • training for fire brigade personnel

11
12 Special equipment operation training may be especially important, as it is the key to locating the
13 degrading component. Portable ASDs have, more often, been used in other domains
14 (e.g., telecommunications); licensees should be cognizant that vendor training may have been
15 developed with domains other than nuclear in mind. Nuclear power plants may introduce
16 unique elements that warrant domain-specific training. Project research yielded limited
17 information with respect to the U.S. nuclear industry's current approach to special equipment
18 training. Personnel at one site receive initial training followed by retraining every 2 years for
19 portable ASDs. The training has classroom and practical aspects and lasts approximately
20 4 hours. The practical section consists of simulating a situation in which technician has to find a
21 degrading component by placing a "smoking" wire in a room beforehand that trainees must
22 locate. Another site reported that, although training has not yet been implemented, they expect
23 that all operators will have specific training in the use of portable ASDs, with a qualification
24 sign-off, as part of their basic operator training

25
26 Training is also an important consideration with respect to fire-watch and fire-suppression
27 activities. The level and quality of training that fire-watch personnel possess may vary. There
28 may be cases in which posted personnel are not qualified to suppress the fire, as they have only
29 been trained to detect visual signs of fire, and are required to report back to the MCR and wait
30 for the fire brigade. In other cases, the personnel may be trained in basic fire suppression using
31 a fire extinguisher or may have fire brigade level training¹⁹. If the fire watch personnel are not
32 trained to suppress the fire and must wait for the fire brigade, this will extend the response
33 timeline and may decrease the probability of prompt suppression.

34
35 One licensee reported that approximately 95 percent of its field operators are fire brigade
36 qualified, FOs are qualified as incipient fire watch, and personnel receive refresher training
37 yearly. Another licensee reported that all operators are trained in the proper use of fire
38 extinguishers. It follows that more confidence can be placed in those with more extensive
39 training to successfully suppress a fire.

40

41 **9.2.2.5 Staffing**

42

43 According to NUREG-0711, Revision 3, staffing levels are an important consideration when
44 plant modifications are undertaken. Plant modifications can impact important human actions,
45 thus, applicants should assess staffing needs to assure that required actions can be
46 successfully accomplished. Applicants should determine the following needs: 1) the type of

¹⁹ Fire brigade training acceptance criteria are laid out in the SRP section 13.2.2. Professional standards are further defined by NFPA 1081, "Standard for Industrial Fire Brigade Member Professional Qualifications."

1 staff (i.e., qualifications); 2) the number of staff and 3) the (required) availability of the staff.
2 Information about regulations and guidance regarding staffing is provided in NUREG-0800,
3 “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants:
4 LWR Edition,” Section 18 and NUREG-1764, “Guidance for the Review of Changes to Human
5 Actions” (Refs. 53 and 54).
6

7 The installation of an ASD VEWFD system is a plant modification; thus, staffing needs should
8 be assessed. ASD VEWFD response operations require both MCR and non-MCR staff.
9 According to NUREG-1792, “Good Practices for Implementing Human Reliability Analysis
10 (HRA),” “for control room actions, the availability of [MCR] staff is not a concern because plants
11 are required to maintain a minimum crew with qualified staff in or near the control room”
12 (Ref. 55). As a note of caution, applicants should ensure that MCR operators responsible for
13 control room actions do not have collateral duties that would threaten their availability in the
14 MCR. An operator who could be called upon to complete MCR actions should not, for example,
15 also be a member of the Fire Brigade for the same fire.
16

17 Non-MCR staff including an FO for initial fire watch duties, a DI&C technician to locate the
18 degraded component, and potentially, additional personnel for a long-term fire-watch, are also
19 needed for ASD VEWFD response operations. According to the distribution presented in
20 Section 8.1.2, Figure 8-3, the incipient stage duration distribution is not narrowly defined (i.e.,
21 ranges from four minutes to four hours). With a large amount of variability in the duration of the
22 incipient stage, it is a reasonable conclusion that personnel involved in response operations
23 need to be available on site to ensure a timely response. If a sufficient number of qualified
24 personnel is not available, the planned response should not be considered feasible²⁰. The
25 information gained from trip reports and expert consultation indicated that FOs and technicians
26 are available on site continuously. However, level of staffing may be of concern with regard to a
27 long-term fire-watch. The time between an incipient alarm and flaming conditions may be an
28 extended period of time (refer to Section 8 for timing estimates), hence necessitating that
29 licensees have personnel available for an extended fire-watch. Depending on staffing levels,
30 this may affect whether or not the fire watch is roaming or constant. A roaming watch is not
31 desirable as it could extend the timeline for detecting and suppressing a fire.

32 **9.2.2.6 Communications**

33
34 Much of the communication during ASD VEWFD response operations takes place between the
35 MCR and personnel outside the control room. The MCR must dispatch FOs, technicians and
36 the fire brigade. This communication is critical as the success of the alarm response operations
37 rests with the FO and technician arriving at the fire location and completing their tasks in a
38 timely manner. Communications equipment must be available, accessible and functional to
39 ensure communication can occur.
40

41 According to NUREG-0700, Revision 2, “Where communications are critical, users should not
42 be precluded from communicating with other plant personnel by the loss of one method” (Ref.
43 50). A complement of communications equipment for this context might include phone lines, the
44 intercom system, sound-powered phones and portable radios. Sound-powered telephone
45 systems do not require a separate electrical power supply to transmit signals; the force of the
46 user’s speech on the mouthpiece generates small electrical impulses, which are transmitted as

²⁰ Feasibility is defined as the ability to accomplish a task in the context within which it will be performed and there is adequate time available to perform the action, considering any adverse contextual or personnel factors that may delay or degrade performance. (Ref. 45, 46)

1 a signal. They are beneficial for situations in which electricity is not available; however, it should
2 be noted that training is required to operate them properly. Portable radio transceivers include
3 battery-powered communication devices that transmit messages through the airways rather
4 than through wires. However, there are places in the plant where radio usage is not permitted,
5 thus, strengthening the case for having several diverse methods of communication. This
6 complement to the communication equipment provides a variety of equipment that uses various
7 media for communication, and is a good example of establishing diverse communication
8 methods. Guidance for speech-based communications regarding topics such as sound quality
9 and area coverage is provided in NUREG-0700, "Human-System Interface Design Review
10 Guidelines," Revision 2, Section 10.2.

11 **9.2.2.7 Complexity**

12
13 Complexity refers to the ambiguity and mental effort associated with the situation to be
14 diagnosed, the decision to be made, or the action to be performed (Ref. 55). High levels of
15 complexity, particularly in the absence of training and practice, can negatively impact human
16 performance.

17
18 Sources of complexity that may affect task performance in VEWFD response operations
19 include:

- 20
- 21 • ambiguity from difficult-to-interpret cues and indications
- 22 • the need to consider multiple variables simultaneously
- 23 • the need to perform many unfamiliar steps in rapid succession
- 24

25 The *indications* from portable ASDs and thermal images may be *ambiguous or difficult to*
26 *interpret* because of the fact that, as stated previously, HSIs of special equipment often do not
27 receive the same level of review as MCR HSIs. The equipment HSIs may be less than ideal,
28 thus increasing the complexity of identifying the exact component that is degrading. Also, being
29 *unfamiliar* with the necessary equipment and procedures/task steps can make the task more
30 complex. If personnel use the portable equipment and perform the steps in VEWFD response
31 operations rarely, this may result in a situation in which personnel are performing many
32 *unfamiliar steps in rapid succession*. High-quality initial training and periodic refresher training
33 along with well-designed procedures and equipment can help to mitigate complexity.

34
35 The decision to de-energize the affected cabinet may also be a complex task. There are
36 *multiple variables* that personnel must take into consideration. First, personnel must have an
37 understanding of the contents of a particular cabinet to determine the effect that de-energizing
38 will have on the safe operation of the NPP. They must also consider the effort involved in the
39 task of de-energizing. According to experts (see section 9.1), de-energizing equipment can be
40 a very simple or a very involved and complex operation. For example, if an entire cabinet is
41 being de-energized, there are instances in which it can be de-energized from the MCR within
42 seconds. At one site, the logic for the cabinet power is laid out in MCR on control board,
43 making the de-energization process simple. Alternatively, if only one breaker is being de-
44 energized (partial cabinet), local action may be required, and the task would likely require
45 multiple steps. This is an important consideration because if the process takes an extended
46 amount of time, it may not be possible to complete it before the transition to a flaming
47 fire. Personnel must weigh the benefits of de-energizing to preserve equipment with the
48 ancillary effects on the rest of the plant. Some of the complexity associated with this task can
49 be mitigated by pre-planning the steps needed to de-energize the cabinets. One strategy would
50 be to "pre-locate" the isolation devices for all ignition sources within each cabinet in an effort to

1 speed up the process. This would include predetermining the isolation devices, conveniently
2 displaying that information for use in response to VEWFD alerts, training responders to rapidly
3 locate and operate the isolation device(s), and conducting drills to periodically demonstrate this
4 ability.
5

6 **9.2.2.8 Workload, pressure and stress**

7

8 Workload, pressure and stress, collectively, refer to the extent to which personnel experience
9 (time) pressure to perform an action, along with their overall sense of being threatened in some
10 way with respect to accomplishing their task. The emphasis for this factor is on the amount of
11 work that must be accomplished in the available time. If workload, pressure, and stress are too
12 high, they may adversely impact personnel performance.
13

14 For ASD VEWFD response operations, it appears on the surface, that there would be little time
15 pressure as this is *very early* warning fire detection. However, based on project research,
16 personnel are trained to handle incipient alerts and alarms with urgency, such that they are to
17 drop everything and respond. The value of these systems lies with the human reacting promptly
18 to prevent a fire, or quickly suppress it. Thus, creating some time pressure is an important
19 component of providing reasonable assurance of the feasibility and reliability of VEWFD
20 response operations. However, while some time pressure may help provide a feasible reliable
21 response, too much time pressure may result in degraded task performance (Ref. 56).
22

23 The fire itself can create time pressure because of the fact that the length of the incipient stage
24 of a fire can vary widely (see Figure 8-3); thus, the time available for personnel to respond will
25 also vary. It may be that being aware of the variability in the time available to respond, may
26 alone, create pressure and stress for personnel. Assessing the time available is further
27 complicated by the size of the zone in which the fire is located (e.g., 3 cabinets vs. 10 cabinets),
28 such that larger zones will require more time to identify the degrading component, likely creating
29 more workload pressure and stress.
30

31 Another source of stress during VEWFD response operations may be a concern for one's
32 personal safety. If a VEWFD detector is being used for power distribution equipment, there is
33 the potential for significant safety hazards (e.g., explosion upon opening a cabinet).
34

35 **9.3 Areawide Applications**

36

37 Areawide applications were not specifically addressed in the HF analysis. However, based on
38 discussions with plant personnel, it is expected that the personnel response to an areawide
39 incipient alert and alarm will be fundamentally the same as for in-cabinet applications. The only
40 difference is that the FO and technician will be sent to a room rather than a bank of cabinets,
41 after receipt of an "alert." The technician will need to locate the incipient fire source within that
42 room. The larger area that must be surveyed should be accounted for in the timing analysis.
43
44

10. HUMAN RELIABILITY ANALYSIS

10.1 Human Reliability Analysis (HRA) Approach

The objective of this section is to develop an improved, detailed HRA quantification to support a fire PRA quantification of VEWFD system performance. To accomplish this objective, existing HRA approaches will be used to the extent applicable to this particular context.

First, the HRA process (i.e., steps needed to perform HRA) used in this report is based on existing HRA processes. The Joint EPRI/NRC-RES Fire Human Reliability Analysis Guidelines (Ref. 49) and "A Technique for Human Event Analysis," (ATHEANA) (Refs. 57 and 58) describe two similar HRA processes. The HRA process given in NUREG-1921 is specific to a fire context. However, since the analysis in this report must address operator²¹ actions taken before or without a reactor trip, the NUREG-1921 process is not general enough to adequately address this context. Therefore, the HRA process used in this analysis is a combination of those in NUREG-1921 and ATHEANA. Namely, the first two steps in ATHEANA are added to the NUREG-1921 HRA process. As a result, the HRA process used in this report consists of the following steps:

1. define and interpret the issue
2. define the scope of analysis
3. perform qualitative analysis
4. identify and define human failure events (HFEs)
5. perform quantitative analysis to develop the human error probability (HEP) for each HFE
6. perform dependency analysis
7. perform recovery analysis
8. perform uncertainty analysis
9. complete documentation

Second, as will be discussed further in Section 12.5, HRA quantification will be based on existing HRA methods and their associated HEPs.

Each of the HRA process steps is addressed in the sections below. There is no explicit discussion for documentation as this section represents the results of this step.

10.2 Define Issues and Scope to Be Addressed

The issue to be addressed in this study, as described in Section 1.3, is to provide HRA input (both qualitative and quantitative) to support fire PRA for VEWFD applications.

²¹ For the application of incipient fire detectors discussed in this report, human actions and activities are required of: 1) MCR crew of operators and associated supervisor(s) 2) a field operator, 3) a technician (assumed to be an Instrument and Control technician), 4) the fire brigade, and 5) other plant personnel who may be needed for deenergization (e.g., electrical engineers, electricians). However, for simplicity, the authors describe the activities of all human activities (except the fire brigade) as "operator actions." Also, the failure probabilities associated with the fire brigade are quantified, as is described in NUREG/CR-6850 and elsewhere, using non-suppression curves that are supported by statistical data. The next section (i.e., Section 13) provides the quantification for suppression activities.

1 From the discussions in Section 9 regarding human factors analysis, it can be inferred that the
2 HRA task for supporting fire PRA for VEWFD applications will be different from that in traditional
3 HRA/PRA contexts.

4
5 Some of the key differences are as follows:

- 6
7 • **All operator actions are taken before (and, for success, without) a reactor trip, but**
8 **do occur after a signal in the main control room (MCR).** HRA/PRA traditionally only
9 addresses the time phase before reactor trip with operator actions that could result in
10 system or component unavailability. Consequently, the type of operator actions
11 associated with VEWFD installations has not been addressed in the development or
12 application of previous PRA studies²². In addition, all of these actions are directed at
13 prevention of a *potentially challenging or greater fire* (which would lead to a reactor trip).
14 While all of the actions addressed in this report occur before (or even without) a reactor
15 trip, in contrast, PRAs traditionally focus on operator actions in response to and after a
16 reactor trip²³. Some low power and shutdown (LP&S) PRAs include operator actions
17 that cause reactor trips (i.e., human-induced initiators), but these actions also differ from
18 the exact context of VEWFD applications in that they occur before or simultaneous with
19 reactor trip (rather than after); and they do not have as their goal to prevent a reactor trip
20 or other worsening condition.
21
- 22 • **There are no standard requirements for traditional job aids (e.g., procedures,**
23 **training, human-machine interface) supporting the operator actions of interest.**
24 While there are currently a few applications of VEWFD that are consistent with the
25 objectives of this report, the operator response and supporting job aids have not been
26 standardized either by regulation or common practice.
27
- 28 • **As discussed further in Section 10.5.1, the relevant success criteria, especially the**
29 **time available after which operator actions are not helpful, have been difficult to**
30 **establish.** Timing inputs are crucial to HRA. As discussed in NUREG-1921 (Ref. 49),
31 for successful performance, there must be more time available for the action than the
32 action requires; otherwise, the operator action is not feasible (i.e., guaranteed failure).
33 Development of both time available and time required have been difficult in this analysis
34 because of limited data.
35
- 36 • **In this analysis, a distribution for the time available for operator action has been**
37 **developed, rather than a single data point. To address this distribution, the HRA**
38 **has evaluated feasibility and quantified human failure probabilities for multiple**
39 **times available, each of which can have a different associated success criterion.**
40 As shown in the event tree for fire suppression strategy, in-cabinet installations (see
41 Figure 6-4), there are two event tree headings following the two operator responses: 1)

²² Initiating events for support system failures (e.g., loss of instrument air, loss of component cooling water) may involve control room alarms before reactor trip. However, as discussed later in this section, the time available for operator response to incipient fire detector alerts or alarms is limited, so operators must respond with some urgency. This is not typically the case for support system initiating events.

²³ Even those actions modeled in some fire PRAs that are preventive in nature, differ from those associated with incipient fire detector applications because, again, they occur following a reactor trip. Also, while some low power and shutdown (LP&S) PRAs include operator actions that cause reactor trips (i.e., human-induced initiators), these actions differ from the exact context of incipient fire detector applications in that: 1) they occur either before or simultaneously with reactor trip (rather than before) and 2) they do not have as their goal to prevent a reactor trip or other worsening condition.

1 enhanced suppression and 2) conventional detection/suppression. Also, each heading
2 for suppression has multiple factors to be evaluated (e.g., π_1 and π_2 for enhanced
3 suppression). As shown in Section 11, these factors are developed using non-
4 suppression curves, with the associated timing inputs linked to the success (or failure) of
5 field operator/technician response. Consequently, failure of the field operator/technician
6 response essentially represents a failure to effectively use the “extra time” provided by
7 the VEWFD system for fire suppression such that credit can be taken in the fire PRA.
8

9 These limitations indicate that a much more thorough qualitative HRA must be performed.
10 In particular, the human factor analysis described in Section 9 is an important input to
11 understanding the operational context (and potential variations with associated changes in
12 human performance). For example, the tabletop analysis²⁴ (and associated Figure 9-1)
13 described in Section 9.2.1 is an essential input to understanding what is required of operators
14 and technicians to successfully implement VEWFD for fire PRA. In modern day, at-power,
15 internal event Level 1 HRA/PRA studies, a formal task analysis is seldom required for any or all
16 of the following reasons:

- 17
- 18 • Task analyses have already been performed in the development of the control room
19 design and procedures (Ref. 59).
- 20 • Decades of simulator training and operating experience are available as inputs to the
21 HRA analyst to understand the role and responsibilities of operators that are relevant to
22 PRA.
- 23 • It is likely that a task analysis (probably something resembling a “cognitive task
24 analysis”) was performed as part of an earlier HRA/PRA study.

25

26 Overall, unlike the VEWFD application considered in this report, the HRA methods and
27 approaches for addressing at-power, internal events Level 1 HRA/PRA are mature and
28 supported with a wealth of relevant, realistic information.

29

30 Consequently, the development of an appropriate HRA approach for this study on VEWFD
31 applications must recognize the following:

- 32
- 33 • There is no “standard” or requirement for how VEWFD is implemented (and, therefore, it
34 resembles the equivalent of an “unconstrained, mathematical problem”)
- 35 • There is very limited information on existing VEWFD applications in NPPs
- 36 • HRA results must support VEWFD applications, in general, rather than a plant-specific
37 HRA of a VEWFD implementation (which is expected in HRA/PRA that follow the
38 ANS/ASME PRA Standard (Ref. 60))

39

²⁴ The “tabletop analysis” described in Section 9 is similar to a “task analysis” performed by HRA. However, “task analysis” is considered a more formal analysis by HF experts.

1 As a result, the HRA approach selected for this analysis relies on:

2

3 1. Whatever “real world” information is available, to the extent possible

4 2. Certain assumptions about performance shaping factors and other contextual factors
5 that, based on current information and the human factors analysis in Section 9, would
6 approximate:

- 7 • a “best case” implementation of VEWFD
- 8 • operator performance and response as modeled in at-power, internal events
9 Level 1 HRA/PRA

10

11 In addition, this analysis, like the human factors discussion in Section 9, focuses on in-cabinet
12 installations of VEWFD. Section 10.4 “Identification and Definition of HFES” discusses the
13 different types of installations and associated strategies for success.

14

15 **10.3 Qualitative HRA**

16

17 As is described in NUREG-1921 (Ref. 49), HRA qualitative analysis is a vital step in HRA that
18 provides the foundation for all other HRA products (i.e., identified and defined human failure
19 events, human error probabilities developed through application of HRA quantification tools).
20 Also, qualitative HRA is performed throughout the analysis, ending only when final
21 outcomes/output have been produced or claimed. Consequently, for this report, the qualitative
22 analysis step is listed ahead of all other purely technical tasks.

23

24 As noted above, one of the ways that this analysis is different from other HRAs is that it has not
25 been performed for a specific NPP installation of VEWFD. Without a plant-specific VEWFD
26 installation and its associated alert/alarm designs; response procedures; operator and fire
27 brigade training programs; control interfaces; conduct of operations (including protocols for
28 communications); and other aspects of an NPP that are typically investigated in an HRA
29 (through the collection and interpretation plant information, including a plant site visit), this
30 analysis has taken the approach of making assumptions about such contextual elements for
31 operator response, in place of the qualitative HRA traditionally performed.

32

33 The assumptions being used in place of the traditional qualitative HRA are that:

34

- 35 • To the extent possible, the data represent “real-world” information collected as part of
36 this project, coupled with a general understanding of NPP operations and operators.
- 37 • The data is representative of a “good” or “best case” operational context for supporting
38 successful and reliable operator performance for a VEWFD application.
- 39 • Based on the human factors analysis provided in Section 9 (especially, descriptions of
40 contextual factors that either are licensing requirements or are common to the at-power
41 internal events Level 1 PRA context).

- 42 • Based on the typical needs of HRA quantification tools.

43

1 The subsections below provide the assumptions for the MCR operator response and the
2 responses of the field operator and technician at the plant location where a VEWFD system has
3 detected a degrading component.

4
5 It should be noted that all of the assumptions below are intended to represent a fast response
6 from both MCR operators, as well as from field operators and technicians. As discussed in
7 Section 8.1.2, the currently available timing information indicates that the time available for
8 operator response (see Figure 8-3) can be quite short (i.e., 10 minutes or less), especially when
9 compared to timing information regarding the time required for combined operator response,
10 both in control room and ex-control room (see Section 10.5.1). Consequently, the assumptions
11 comprising the qualitative analysis below also attempt to capture those factors that support a
12 relatively fast operator response.

13 14 **10.3.1 Assumptions for MCR operator response**

15
16 For the MCR operator response to in-cabinet installations of VEWFD, the following assumptions
17 below are made, with the expectation that they collectively describe a “best case” context in
18 which timely, successful, and reliable operator performance can be expected, and which closely
19 resembles that for post-reactor trip MCR operator response for at-power, internal events Level 1
20 PRA:

- 21
22 • “MCR operator response” represents the collective effort of the MCR operating crew,
23 including the understanding that:
 - 24 ○ once an VEWFD system alert/alarm occurs, response to the VEWFD system
25 signal is the priority for all of the operating crew in the MCR
 - 26 ○ peer checking and other activities that support reliable response by the MCR
27 operators are used
 - 28 ○ formal, 3-way communication protocols are used within the crew as an additional
29 reliability measure to ensure accurate communication and to provide an
30 additional avenue for peer checking
- 31 • VEWFD system alert/alarm control panel(s) is/are located in the MCR on the front panel
32 (i.e., where operators are accustomed to seeing critical alarms).
- 33 • VEWFD system alert/alarm signals are audible, according to other MCR alarm standards
34 (see Section 9.2.2.2).
- 35 • There is a main fire alarm control panel²⁵ in the MCR, providing MCR operators with
36 quick and easy access to information on both the specific fire area or location of the
37 VEWFD system zone in “alert” or “alarm” condition and the specific cabinet or bank of
38 cabinets where the detector is installed.

²⁵ VEWFD system alarm control panels can be located in the MCR or in the plant. For one of the NPPs providing information for this project, a dedicated computer on the STA's desk provided all information collected by the VEWFD system. The authors have assumed an equivalent to this situation because: a) no additional time is required for a field operator to travel to a local fire alarm control panel and report back to the MCR, and b) the reliability of the MCR crew interpreting information from the main fire control alarm panel should be higher than that of a single field operator reading a local panel.

- 1 • Operators respond to VEWFD system alerts and alarms with urgency (that may be
2 inconsistent with other alarms that occur during normal operating conditions). This
3 sense of urgency is reinforced by training and procedures, and might be aided by
4 distinguishing tape or other markings for VEWFD system alarm panels. In particular,
5 MCR operators are trained to “**drop everything**” when a VEWFD system signals.²⁶
- 6 • Along with the previous bullet, the number of VEWFD system alert/alarms that require
7 such urgent response should be few as compared to other fire alarms, and measures
8 should be taken to avoid confusion of such alerts/alarms with other alarms that do not
9 require such urgency.
- 10 • Procedures (e.g., alarm response procedures (ARPs)) guide MCR response, including
11 consultation of the main fire alarm control panel and calls to the field operators,
12 technicians, and fire brigade. In addition, the instructions for VEWFD system response
13 are formatted and worded consistently with other instructions given in the ARPs.
- 14 • MCR operators expeditiously dispatch the field operator closest to the detector in “alert,”
15 providing essential location information.²⁷
- 16 • MCR operators use formal, three-way communication to describe the fire location to both
17 the field operator and technician to minimize the likelihood of miscommunication. Three-
18 way communication also can facilitate recoveries of miscommunication (e.g., repeat
19 back from field operator while looking at the main fire alarm control panel can serve as a
20 check, or other operators in the MCR who are also looking at the main fire alarm control
21 panel can serve as an independent check).
- 22 • MCR operators expeditiously dispatch a technician trained in portable ASD use,
23 providing essential location information.
- 24 • MCR operators expeditiously dispatch the fire brigade when the detector is in “alarm”
25 state, providing essential location information.
- 26 • False alarms for the VEWFD system are minimal (e.g., through appropriate initial testing
27 and appropriate set points), such that MCR operator response is not slowed or
28 questioned to be correct.
- 29 • There is normal staffing, such that there is no shortage of manpower.
- 30 • Accessibility is not a concern (as the VEWFD system in “alert” or “alarm” is outside the
31 MCR).

32
33 **10.3.2 Assumptions for field operator response**
34

35 For the field operator response, the following assumptions below are made, with the expectation
36 that they collectively describe a context in which timely, successful, and reliable operator
37 performance can be expected and which closely resembles that for post-reactor operator
38 response outside the MCR for at-power, internal events Level 1 PRA:

²⁶ This specific response was provided by one of the licensees that provided input to this project.

²⁷ Again, this is consistent with information provided by one of the NPPs consulted in this project.

- 1 • The field operator closest to the fire location is dispatched by the MCR operator.⁴
- 2 • VEWFD system response is the highest priority job for the field operator (upon receiving
- 3 dispatch from the MCR), such that no new activities will be started, and current, non-
- 4 critical activities will be suspended.
- 5 • Formal three-way communication is used between the MCR operator and field operator
- 6 so that the likelihood of miscommunication is very small.
- 7 • The field operator is trained to travel expeditiously to the low-energy (incipient) fire
- 8 location.
- 9 • The field operator is trained to suppress fires (e.g., fire brigade training).
- 10 • Required equipment (e.g., portable fire extinguisher) is available and accessible.
- 11 • There is normal staffing, such that there is no shortage of manpower.
- 12 • Accessibility is not a concern (since the field operator is fire brigade-trained).

13
 14 This last assumption is especially important. As discussed in Section 9.2.2.4, there are
 15 variations between plants on what, if any, fire training is provided to field operators. However,
 16 as will be discussed further in the context of the definition of a human failure event definition and
 17 associated success criteria, the time at which plant personnel having fire suppression capability
 18 arrive at the location of the VEWFD system in an “alert” or “alarm” will define operator “success”
 19 in the HRA/PRA quantification. Consistent with the general approach taken for this analysis, the
 20 “best case” (or case for which fire suppression capability arrives the fastest) is when field
 21 operators who may be dispatched have fire suppression training.

22 **10.3.3 Assumptions for technician response**

23
 24
 25 For the technician response, the following assumptions below are made, with the expectation
 26 that they collectively describe a context in which timely, successful, and reliable performance
 27 can be expected:

- 28
 29 • Formal three-way communication is used between the MCR operator and technician so
- 30 that the likelihood of miscommunication is very small.
- 31 • VEWFD system response is the highest priority job for the technician (upon receiving
- 32 dispatch from the MCR); such that no new activities will be started, and current, non-
- 33 critical activities will be suspended.
- 34 • The technician is trained to expeditiously collect necessary equipment and travel to the
- 35 low-energy (incipient) fire location.
- 36 • Required equipment is available and accessible.
- 37 • The technician is adequately trained in using special equipment for identifying low-
- 38 energy (incipient) fire conditions, including detection of both the relevant cabinet (if the

1 VEWFD installation is for a bank of cabinets) and the degrading component in the
2 cabinet.

- 3 • There is normal staffing, such that there is no shortage of manpower.
- 4 • Accessibility is not a concern (since the field operator, who is fire brigade-trained, is
5 responsible for operator response if the degraded conditions transition to a fire).

6

7 **10.4 Identification and Definition of Human Failure Events (HFEs)**

8

9 In traditional PRAs, operator actions that mitigate an accident or that worsen plant conditions
10 should be considered for representation in PRA models as human failure events (HFEs).
11 Consequently, this analysis considers only operator actions whose success would contribute to
12 preventing a “fire,” as defined by a fire PRA and associated success criteria.

13

14 NUREG/CR-6850, Supplement 1 (Ref. 61) identified two event tree headings associated with
15 human actions for determining fire PRA. While this earlier work was an important input to this
16 report, human failure events (HFEs) are identified herein by using the more thorough analysis of
17 human actions and associated performance provided by the human factors analysis discussed
18 in Section 9. In particular, the overall tabletop task analysis discussion and Figure 9-1 and
19 Figure 9-2 has been the basis for the identification and definition of HFEs. In addition, this
20 project included extensive coordination between the HRA team and the event tree developers
21 on the structure, headings and success criteria associated with the event trees shown in
22 Section 6.4.

23

24 In particular, three VEWFD installation types were identified as follows:

25

26 1. In-cabinet installations of VEWFD where the cabinet(s) are not targets of concern for the
27 fire PRA (i.e., “success” for the operator action is achieved when a field operator (or
28 other appropriately trained plant personnel) arrives at the fire location to provide
29 suppression capability **before** conditions transition from a low-energy (incipient) fire
30 condition to a flaming fire),

31

32 2. In-cabinet installations of VEWFD where the cabinet(s) **IS** a target of concern for the fire
33 PRA, i.e.,

34 a. “Success” can only be achieved by de-energizing the degraded component,
35 thereby preventing transition to a fire **before** transition from a low-energy
36 (incipient) fire condition to a flaming fire

37 b. De-energization cannot occur until:

38 i. an I&C technician (or other appropriately trained personnel) identifies
39 both the affected cabinet and the specific degraded component,

40 ii. MCR operators determine that the degraded component can be safely
41 de-energized without reactor trip, and

42 iii. Appropriate step-by-step instructions for de-energization are available.

- 1
2 3. Areawide installations of VEWFD (which, according to Section 9.3, are similar to the
3 other installation types, but require additional time needed for the I&C technician to
4 survey the entire room or fire area to identify the affected bank of cabinets or other
5 equipment, especially since in-cabinet installations can be addressable (i.e., the specific
6 alarming cabinet can be identified immediately if each cabinet is linked to its own
7 detector).

8
9 Each of these installations will have different success criteria and, again, there will also be
10 differences in the operator actions required. **The first type of installation is analyzed in**
11 **detail in the remainder of the HRA discussion.** For the other two installations, only some
12 HRA-related notes are provided (see Sections 10.5.4 and 10.5.5).

13
14 HRA tasks, including identification and definition of HFES, and coordination with event tree
15 development were iterative, rather than serial. However, for the purposes of this report, the
16 success criteria used to identify and define HFES, are presented first, immediately below,
17 followed by discussions of the HFES modeled in this analysis.

18 19 **10.4.1 Success criteria for in-cabinet, fire suppression strategy**

20
21 Success criteria must be defined for each event tree heading, including identified HFES. These
22 criteria are:

- 23
24 • **MCR response.** After the detector “alert” signals in the MCR, both the field operator
25 and technician must be dispatched to the correct location for the VEWFD system in
26 “alert” and this must be performed in a timely manner.
- 27 • **Field operator response.** Once the detector “alert” signals, this must result in the field
28 operator 1) arriving at the correct location for the VEWFD system in “alert,” 2) having the
29 ability to initiate suppression in the absence of the fire brigade, and 3) positioning himself
30 or herself, in a timely manner, in close proximity to the specific cabinet where a
31 degrading component is located.
- 32 • **Technician response.** The technician must 1) arrive at the correct location for the
33 VEWFD system in “alert” with the required equipment, and 2) correctly and timely
34 identify the specific cabinet where the degraded component is located, for cases in
35 which there is more than one cabinet associated with a detector. (Note that identification
36 of the specific degrading component within a cabinet is not required for this strategy.)

37 Timing inputs are almost always an important part of the success criteria defined for each
38 operator action. First, the operator actions must be feasible i.e., sufficient time available as
39 defined in NUREG-1921). Second, shortness of time to complete actions also can influence the
40 reliability (therefore, the failure probability) of operator actions. Usually, operator actions must
41 be completed before a worsened state occurs (e.g., equipment or plant damage).

42
43 In this analysis, success is defined as the field operator arriving before the start of flaming
44 conditions (or soon enough after that the fire can be controlled before targets outside of the
45 cabinet are damaged). Section 11 defines several cases for such “enhanced fire suppression”
46 (i.e., fire suppression sooner than would be possible using conventional fire alarms), each
47 corresponding with different arrival times for the field operator and different states of knowledge

1 with respect to the location of signaling VEWFD system. Consequently, critical timing inputs for
2 this analysis are as follows:

- 3
- 4 1. the total time available for operator actions measured as the time starting from the “alert”
5 to when the incipient stage ends and a fire begins (as discussed in Section 8), and
- 6 2. the total time required to complete all operator actions, ending with the field operator
7 positioned and ready to perform fire suppression activities.
- 8

9 Timing inputs are discussed further in the HRA quantification section (i.e., Section 10.5).

10 **10.4.2 HFEs for “fire suppression” strategy, in-cabinet installations**

11 The tabletop analysis provided in Section 9 describes in detail the operator and technician
12 actions that could be performed to prevent an in-cabinet fire (per definition by the fire PRA).
13 These actions are, in turn, aggregated or collected logically, then represented as human failure
14 events (HFEs) and, for this analysis, shown as top events in event trees.

15 Specifically, the operator activities for the in-cabinet, fire suppression VEWFD strategy that are
16 represented in event tree headings (see Section 6.4) are:

- 17
- 18 1. MCR operator response to VEWFD system signals
- 19
- 20 2. field operator and I&C technician response
- 21
- 22 3. fire suppression
- 23
- 24 a. “Enhanced” fire suppression (for cases in which fire suppression capability is
25 provided by the field operator (or other appropriately trained personnel) who is
26 **already at the fire location when the transition from low-energy (incipient)**
27 **fire to a flaming fire condition** occurs)
- 28
- 29 b. Conventional fire suppression (e.g., MCR operator response to VEWFD system
30 signal fails)

31 It is important to note that all of the suppression activities in the list above are not addressed
32 explicitly by HRA and are quantified using non-suppression curves as described in Section 11.
33 Further details on the definitions of these two HFEs are given below.

34 **10.4.2.1 HFE definition: MCR operator response (in-cabinet, fire suppression strategy)**

35 Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with
36 VEWFD installations, and the assumptions made in Section 10.3, the following are the key
37 events and responsibilities for the MCR operator once the VEWFD system signals “alert” in
38 MCR:
39
40
41

- 1 1. VEWFD system signals “alert” in MCR
- 2
- 3 2. MCR operators immediately note “alert” and switch focus on this signal²⁸
- 4
- 5 3. MCR operators find the appropriate alarm response procedure (ARP) for the VEWFD
- 6 system “alert”
- 7
- 8 4. MCR operators consult main fire alarm control panel in MCR to identify which detector is
- 9 signaling and the associated location, including specific cabinet or cabinet bank
- 10
- 11 5. MCR operators dispatch field operator²⁹ closest to the alerting detector, providing
- 12 location information
- 13
- 14 6. MCR operators dispatch technician to alerting detector
- 15
- 16 7. when VEWFD system signals “alarm,” MCR operators activate the fire brigade
- 17

18 For the fire suppression strategy addressed in this report, the seventh item above is not relevant
19 to the HRA.
20

21 **10.4.2.2 HFE definition: Field operator and technician response (in-cabinet, fire** 22 **suppression strategy)** 23

24 Based on the tabletop analysis in Section 9, interviews with plant personnel from two NPPs with
25 VEWFD installations, and the assumptions made in Section 10.3, the following are the key
26 events and responsibilities for the field operator and technician response in the fire suppression
27 strategy for in-cabinet VEWFD installations:
28

- 29 1. Upon dispatch, the field operator expeditiously travels to the fire location provided by the
30 MCR operator.
- 31 2. Upon dispatch, the technician expeditiously collects required equipment and travels to
32 the fire location provided by the MCR operator.
- 33 3. Upon arrival at the fire location, the field operator takes up the responsibility of fire watch
34 (with suppression capability). If there is only one cabinet served by the VEWFD system,
35 the field operator posts his watch directly in front of this cabinet.
- 36 4. Upon arrival at the fire location, the technician begins use of special equipment to
37 identify the affected cabinet.
- 38 5. The technician identifies the affected cabinet.

39 For this HRA, there are multiple end states modeled and these distinctions are related to the
40 field operators positioning with respect to the location of the degrading component and then
41 which fire non-suppression curves are appropriate to use for each of these end states. Some of

²⁸ Recall that no PRA credit for VEWFD system installations if a reactor trip or other similar higher priority event has occurred.

²⁹ Field operator is assumed to have fire brigade training.

1 these end states are shown in Figure 6-4, while others are related to the distribution of times
2 available from time of alert to flaming conditions (i.e., timing inputs discussed in Section 8).
3 Consequently, both qualitative and quantitative HRA inputs are important to the next heading in
4 event tree (i.e., for fire suppression).

5
6 For example, if the in-cabinet, VEWFD installation (fire suppression strategy) is for a single
7 cabinet, the field operator can immediately position himself/herself optimally³⁰ for fire
8 suppression without any input from the technician. The success of the field operator in this case
9 transfers to the event tree heading of “enhanced fire suppression.”

10
11 If, on the other hand, the VEWFD installation is for a bank of cabinets, the field operator can be
12 positioned to provide fire suppression capability, but cannot have the “optimal” position and
13 knowledge with respect to the location of the degraded component until the technician identifies,
14 first, the affected cabinet, and, then, the degraded component. This case also is treated as
15 “enhanced fire suppression” but uses a different non-suppression curve.

16
17 Section 10.5, immediately below, discusses these end states further and Section 11 continues
18 this discussion with respect to which non-suppression curves are appropriate.
19

20 **10.5 HRA Quantification**

21
22 Because HRA quantification methods and associated human error probabilities (HEPs) were
23 principally developed by and for post-initiator operator response, the overall strategy for
24 quantification of the operator actions in this report is to either describe or prescribe operational
25 conditions for the low-energy (incipient) fire response actions that are similar or parallel to the
26 more familiar post-initiator operator actions. Section 10.3 (HRA Qualitative Analysis) is the
27 starting point for the assumptions that will be used in HRA quantification to follow this strategy.
28

29 **10.5.1 Timing inputs to HRA**

30
31 HRA typically relies on inputs developed by and for other PRA tasks. While this research does
32 not involve a formal PRA study, it follows the traditional path in that several inputs to the HRA
33 are developed by other analysts. In particular, HRA-specific timing inputs were developed from
34 information collected through interviews of operations and fire protection personnel at NPPs that
35 have installed VEWFD.
36

37 It should be noted that, to the extent possible, the NUREG-1921 (Ref. 49) guidance on the
38 development of timing inputs and on feasibility assessment has been followed in this analysis.
39 For example, a feasibility assessment of the HFEs in this study (especially considering whether
40 there is sufficient time for operator response) is provided in Section 10.5.2. However, some of
41 the NUREG-1921 guidance could not be followed because of the lack of information. As
42 discussed below, the time required for field operator and technician response is based on
43 information provided by only two licensees. Also, in both cases, the timing information provided
44 was not based on walkdowns or demonstrations. In addition, the inputs provided for time
45 required (see Appendix C) were ranges with some recognition of variability in these times. The
46 HRA quantification below represents these variabilities, potentially resulting in higher HEPs that

³⁰ The only remaining distinction is whether the cabinet door is open or not. However, the best plan for field operator response would be for operators to know in advance (via procedures and/or training) if the cabinet can be opened and, if it cannot be opened, how fire suppression is to be accomplished.

1 what a plant-specific HRA for might produce for a location-specific VEWFD installation with an
2 associated narrower range of times required for operator actions.

3 **10.5.1.1 Time required for operator actions**
4

5 For this analysis, time required for operator actions is defined to be the time from when the
6 “alert” is received in the MCR until all operator actions, both those in the MCR and those taken
7 by the field operator and technician locally, are expected to be completed. The two most
8 essential HRA timing inputs are discussed below: 1) time required for operator action and 2)
9 time available for operator action.

10
11 The time required for each of the operator actions was developed from information collected
12 through interviews of plant personnel at two NPPs having VEWFD installations. (See
13 Appendix C for the details of these interviews.)
14

15 Table 10-1 below summarizes the HRA timing inputs developed. The ranges of times are either
16 directly provided by plant personnel or are interpretations of more informal estimates (e.g., a
17 “few” minutes can be translated into 3 or 4 minutes). Also, the durations of the field operator
18 response and technician response shown in Table 10-1 represent the range of time estimates
19 provided by both NPPs. For example, the duration of the field operator response (i.e., average
20 time between when the field operator receives dispatch call to arrival at the appropriate location)
21 was reported as 2 to 8 minutes for Plant X and 3 to 4 minutes for Plant Y, while Table 10-1 uses
22 the broader range of times provided by Plant X for this analysis. Although the information
23 sources for this timing data are limited, it was the only such information available when this
24 analysis was performed. As noted above, a plant-specific and location-specific analysis might
25 be able to produce a narrower range of times.
26

27 Cumulative times are total times from alert signal, with the travel times for the field operator and
28 technician being independent timelines. So, the range for cumulative time for completion of the
29 field operator response is determined by adding together the shortest duration times for both
30 MCR operator response and field operator response (i.e., 1 minute for MCR operator dispatch
31 of the field operator plus 1 minute for field operator travel to location) and adding together the
32 longest duration times for both (i.e., 2 minutes for MCR operator dispatch plus 8 minutes for
33 field operator travel time). Cumulative times for the technician are calculated in the same way,
34 with the shortest MCR response being 2 minutes (i.e., dispatch of the technician is performed
35 after the field operator is dispatched) and the shortest time for the technician to collect
36 necessary equipment and travel to the location.

37 **Table 10-1. Summary of Timing Inputs for Operator Actions After “Alert” Signal**

Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Cumulative Time from “Alert” (minutes)
Alert signal	MCR operator	Detect signal, use alarm response procedures, identify location of detector, and call to dispatch field operator	1-2	1-2
Alert signal	MCR operator	Dispatch technician to detector location	1	2-3

Table 10-1. Summary of Timing Inputs for Operator Actions After “Alert” Signal (Continued)				
Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Cumulative Time from “Alert” (minutes)
Call from MCR	Field operator in plant	Travel to location of VEVFD system in “alert”: standby as fire watch by cabinet(s)	2-8	3-10
Call from MCR	Technician	Obtain necessary equipment and travel to location of VEVFD system in “alert”	5-11	7-14
Arrival at location	Technician	Uses equipment to identify cabinet ³¹	1 cabinet: 0	7-14
			3 cabinets: 5	12-19
			6 cabinets: 10	17-24
			10 cabinets: 15	22-29
Cabinet identified	Technician	Uses equipment to identify degraded component in cabinet	3-4	1 cabinet: 10-18
				3 cabinets: 15-23
				6 cabinets: 20-28
				10 cabinets: 25-33

1
2 Note that from the discussion of success criteria in Section 10.4.1, “success” (i.e., the field
3 operator is positioned to immediately start suppression activities for the affected cabinet) can be
4 claimed for the following situations:

- 5
- 6 • single-cabinet installations, as soon as the field operator arrives at the fire location
 - 7 • three-cabinet installations, also as soon as the field operator arrives at the fire location³²
8 (with potential arguments that the same non-suppression curve can be used as for the
9 single cabinet case)
 - 10 • six-cabinet installations, after the field operator arrives AND the technician spends up to
11 approximately 25 minutes using a portable ASD to identify the affected cabinet
 - 12 • 10-cabinet installations, after the field operator arrives AND the technician spends up to
13 approximately 30 minutes using a portable ASD to identify the affected cabinet

14 In principle, the times by which the technician identifies the specific, degraded component within
15 the affected cabinet could be used to represent a different “success” state (with correspondingly
16 different non-suppression curves). However, as discussed in Section 11, this distinction is not
17 used in this analysis; yet, this timing information is used to discuss the de-energization strategy
18 in Section 10.5.4.

19

³¹ Estimated times are based on the use of the portable ASD without opening up the cabinet to determine which cabinet contains the degraded component.

³² This assumption can be made if the cabinets are not too large and the field operator is appropriately trained such that the field operator’s field of vision can encompass three cabinets in essentially the same way as for a single cabinet.

1 **10.5.1.2 Time available for operator actions for in-cabinet, fire suppression strategy**
2

3 In this analysis, time available for operator action is defined as the time from when an “alert”
4 signal from the VEWFD system is displayed in the MCR (i.e., when the cue for action is
5 received) until the incipient stage ends (e.g., a flaming conditions begin).
6

7 As discussed in Section 8, there is limited appropriate data for the duration of the incipient
8 stage, starting from “alert.” However, Figure 8-3 (and the associated raw data given in
9 Appendix D), shows probability distributions developed to represent the duration of the time
10 available from “alert” for four (4) fire detectors, including three (3) VEWFD systems and a
11 conventional fire detector; respectively, they are:
12

- 13 • air-aspirated (cloud chamber)
- 14 • air-aspirated (light-scattering) and sensitive spot (light-scattering)
- 15 • spot detector (ionization)
- 16 • spot detector (photoelectric)

17

18 Typically, a single value for time duration is developed for defining success criteria. Also,
19 usually when timing ranges or distributions are developed, the shape of the distribution
20 resembles either a normal distribution, or another distribution with small “tails” at the low and
21 high probability ends.
22

23 Based on the timing information developed in Section 8.1.2, neither of these typical conditions
24 applies to this research. Nevertheless, since Section 8.1.2 represents the time available for
25 operator actions as a probability distribution for each of the four detectors investigated in this
26 study, as opposed to one or more point values, the HRA task must sample these distributions
27 by selecting specific time points to perform the HRA quantification

28 For this analysis, the selection of time available points was driven by the need for the following:
29

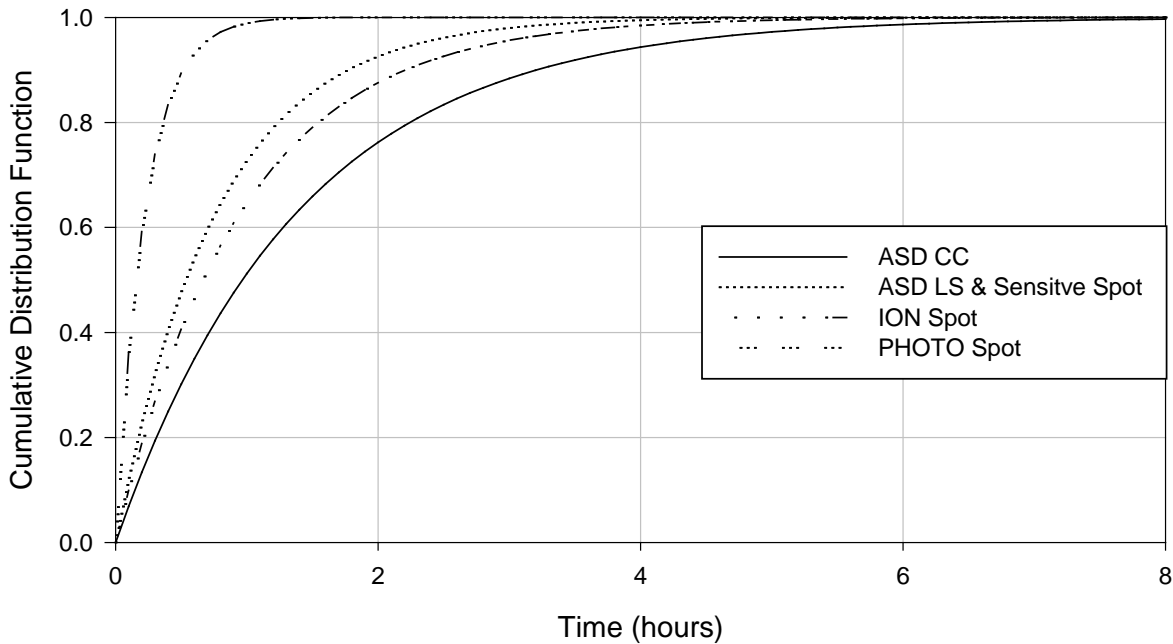
- 30 • representation of the “most likely” situation with respect to duration of the time available
31 for operator response following an VEWFD system “alert” signal
32
- 33 • representation of the situations in which all variations of in-cabinet, VEWFD installations
34 are feasible (i.e., the time available is equal to or less than the total time required for all
35 operator responses)
36
- 37 • representation of the median probability distribution and/or the approximately 1 hour time
38 available duration (which represents more time available than time required for all cases
39 of operator response)
40

41 Using both the time required information in Table 10-1 and the cumulative probability
42 distributions, the following cases were chosen with respect to the duration of the time available
43 (from “alert”):
44

- 45 • the time from “alert” that corresponds with a 90 percent likelihood that the transition to a
46 fire has **NOT** occurred
47
- 48 • 30 minutes after “alert” (which, from Table 10-1) is approximately the maximum amount
49 of time for the field operator to be positioned for immediate fire suppression
50

- 1 hour

The cumulative probability distributions for each of the four detectors investigated is shown in Figure 10-1 (These cumulative distributions are based on the same data and curves fit as the complimentary cumulative density functions are shown in Figure 8-3.) In addition, Appendix D provides minute-by-minute cumulative probabilities for each of the detectors. This information from Appendix D was used to information to develop Tables 10-2, 10-3, and 10-4 that display the fraction of the cumulative probability represented by each of these time points for the ASD VEWFD cloud chamber, ionization and VEWFD light-scattering (both ASD and SS) detectors, respectively. These fractions, in turn, can be are used as split fractions for the outcome of the HFE for “First Level Field Response.” In Section 10.5.3 and 10.5.4, human error probabilities are developed to be paired with each of these split fractions.



14

15 **Figure 10-1. Cumulative distribution function of time available for operator response by**
 16 **detection type**

17 The four sample points selected for this analysis are as follows:

18

- 19 • Sample 1: Incipient stage ends in only 10 percent of cases
- 20
- 21 • Sample 2: Incipient stage ends by 30 minutes after “alert” for VEWFD, “pre-alarm” for
 22 conventional ION
- 23
- 24 • Sample 3: Incipient stage ends after 30 minutes but before approximately 1 hour
- 25
- 26 • Sample 4: Incipient stage ends after approximately 1 hour
- 27

28 Note that, with these selections, the cumulative probability is fixed for one sample point
 29 (i.e., time available for operator response ends in 10 percent of cases) but the time from alert is
 30 not. All other sample points are associated with certain times and, therefore, the cumulative
 31 probabilities will be different for different detectors.

1 In the next section (Section 10.5), human error probabilities are developed for each of the four
 2 distribution sample points and their associated-split fractions.

3 **Table 10-2. Fraction of Probability Distributions for ASD VEWFD, Cloud Chamber**

Sample	Cumulative probability for incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-9 minutes*	0.10
2	0.30	>9 minutes AND <30 minutes**	0.20
3	0.51	> 30 minutes AND < ~1 hour**	0.21
4	1.0	> ~ 1 hour**	0.49

4 * From the text above, this is the definition of this sample point

5 ** From the text above, this is the result from the cumulative distribution function associated with the definition
 6 of this sample point

7 **Table 10-3. Fractions of Probability Distribution for Conventional Spot-Type,
 8 ION Detector**

Branch	Cumulative probability for incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-6 minutes*	0.10
2	0.41	> 6 minutes AND < 30 minutes**	0.31
3	0.65	> 30 minutes AND < ~1 hour**	0.24
4	1.0	> ~ 1 hour**	0.35

9 * From the text above, this is the result from the cumulative distribution function associated with the definition
 10 of this sample point

11 ** From the text above, this is the definition of this sample point

12 **Table 10-4. Fractions of Probability Distribution for VEWFD, Light-Scattering Detector**

Branch	Cumulative probability for incipient stage ended	Time from alert	Fraction of probability distribution (split fraction)
1	0.10	0-5 minutes*	0.10
2	0.48	> 5 minutes AND < 30 minutes**	0.38
3	0.73	> 30 minutes AND < ~1 hour**	0.25
4	1.0	> ~ 1 hour**	0.27

13 * From the text above, this is the result from the cumulative distribution function associated with the definition
 14 of this sample point

15 ** From the text above, this is the definition of this sample point

10.5.2 Feasibility assessment

Section 4.3.4 of NUREG-1921 (Ref. 49), identifies the following criteria for determining the feasibility of an operator action:

- sufficient time
- sufficient manpower
- primary cues available and sufficient
- proceduralized and trained actions
- accessible location
- equipment and tools available and accessible

NUREG-1921 further states that if an operator action is not feasible, it should be assigned a failure probability of 1.0.

As a result of the assumptions made in Section 10.3, all of the above criteria are met for MCR operator response and field operator/technician response, **except** sufficient time.

To determine the feasibility of overall operator response to in-cabinet, VEWFD installations for the fire suppression strategy, the time required for operator actions shown in Table 10-1 must be compared with the time available shown in Tables 10-2, 10-3, and 10-4 for the different detectors.

From Table 10-1, the total time required for operator success (i.e., MCR operator and field operator/technician success) is different depending on the VEWFD installations with respect to the number of cabinet:

- For one cabinet, success is achieved when the field operator arrives on location: 3 to 10 minutes.
- For 3 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 3 cabinets contains the degraded component: 12 to 19 minutes.
- For 6 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 6 cabinets contains the degraded component: 17 to 24 minutes.
- For 10 cabinets, success is achieved when both the field operator and technician arrive, AND the technician identifies which of the 10 cabinets contains the degraded component: 22 to 29 minutes.

These ranges for time required are compared to the available times (shown in Tables 10-2, 10-3 and 10-4) for each detector, with Sections 10.5.2.1, 10.5.2.2, 10.5.2.3, and 10.5.2.4 respectively, for each of the four sample points selected for this analysis, i.e.:

- Sample 1: Incipient stage ends in only 10 percent of cases
- Sample 2: Incipient stage ends by 30 minutes after “alert”

- 1 • Sample 3: Incipient stage ends after 30 minutes but before approximately 1 hour

2 **Sample 4: Incipient stage ends after approximately 1 hour**

3

4 **10.5.2.1 Sample 1: Feasibility assessment**

5

6 As defined above, Sample Point 1 corresponds with those cases in which the cumulative
7 probability distributions show that the likelihood of transition to fire conditions is 10 percent
8 (or less).

9

10 For the cloud chamber detector, Table 10-2 shows that there are 9 minutes of time available
11 when there is a 10 percent chance of the incipient phase ending. This time is approximately
12 equal to the time required for the one cabinet VEWFD installation. Because, in this case, the
13 longest time, in the range of required times, is only 1 minute greater than the time available.
14 This represents the situation discussed in NUREG-1921 regarding “tipping points” (i.e., a
15 significant change in HRA results with a small change in HRA inputs). Consequently, if this
16 analysis supported a plant-specific HRA/PRA, the recommended approach would be to collect
17 additional information on the time required (e.g., plant walkdowns or demonstrations) for a
18 location-specific VEWFD installation, with the expectation that the range of required times and
19 associated uncertainties would be reduced.³³ For the purposes of this analysis, the range of
20 required times is treated as being equal to the time required; therefore, the operator actions are
21 considered feasible for the cloud chamber, one-cabinet case.

22

23 For installations involving cloud chamber detectors and more than one cabinet, the time
24 required for MCR response, field operator/technician response is greater than the time
25 available. Consequently, these cases³⁴ are not feasible and should be assigned a failure
26 probability of 1.0.

27

28 Tables 10-3 and 10-4 for conventional spot-type ION and VEWFD light-scattering detectors
29 show that the time required for operator response is always greater than the time available for
30 this sample point. Therefore, all of these cases for these two detectors are not feasible for this
31 sample point and should be assigned a failure probability of 1.0.

32 **10.5.2.2 Sample 2: Feasibility assessment**

33

34 Sample Point 2 corresponds with cases in which the incipient stage ends sometime between
35 when 10 percent of incipient stages end and 30 minutes. As discussed earlier, the “10 percent
36 case” is different for each detector, namely:

37

- 38 • greater than 9 minutes to 30 minutes for ASD VEWFD cloud chamber
39 • greater than 6 minutes to 30 minutes for ION detectors
40 • greater than 5 minutes to 30 minutes for VEWFD light-scattering detectors

41

³³ Another way to reduce such uncertainties would be to establish a job performance measure (JPM) for these operator responses, especially that for the field operator.

³⁴ As is done later in Section 10.5, there might be legitimate arguments for treating the 3-cabinet and 1-cabinet cases in the same way so far as the time required for the field operator to be optimally positioned for fire suppression when the incipient phase ends.

1 Because the single-cabinet (and 3-cabinet), cloud chamber installation was feasible for the first
2 sample point, this case also is feasible for this sample point (and all other sample points to
3 follow).
4

5 For all other cabinet configurations of cloud chamber installations, the cloud chamber time
6 available range for this sample point is considered to be roughly equivalent to the ION and
7 VEWFD light-scattering detectors. So, for all detectors, comparison of the range of available
8 times with overall operator response times shown in Table 10-1 reveals the following with
9 respect to the “success” of operator actions (with the corresponding transfer to the “enhanced
10 fire suppression” event tree heading):
11

- 12 • For shorter times required, operator actions associated with the single cabinet and
13 three cabinet-per-bank installations are potentially feasible; however, since there is a
14 relatively small amount of overlap of the range of available times with the range of time
15 required, some adjustment to HEPs (e.g., multiplier of 3) would be appropriate

- 16 • The range of times required for operator actions associated with six cabinet-per-bank
17 installations (i.e., 17 to 24 minutes) is entirely within the range of available time for this
18 sample point; consequently, operator actions for this cabinet configuration are only
19 marginally feasible

- 20 • Operator actions associated with 10 cabinet-per-bank installations are not likely to be
21 feasible and should be assigned a failure probability of 1.0.

22

23 **10.5.2.3 Sample 3: Feasibility assessment**

24
25 Sample Point 3 corresponds with cases in which the incipient stage ends sometime between 30
26 minutes and 1 hour.
27

28 Comparison of this timing with overall operator response times shown in Table 10-1 reveals that
29 operator actions for all installations should be feasible. For 1- and 3-cabinet installations, this
30 represents expansive time available, compared to time required. Also, the HEP assignment for
31 10-cabinet-per-bank installation should be adjusted upward (as compared to the other cabinet-
32 per-bank installations) since the longest required times are essentially equal to the shortest time
33 available represented by this branch.
34

35 **10.5.2.4 Sample 4: Feasibility assessment**

36
37 Sample point 4 corresponds with cases in which the incipient stage ends sometime after 1 hour.
38

39 Comparison of this timing with the overall operator response times shown in Table 10-1 reveals
40 that operator actions for all detectors and cabinet configurations considered in this analysis
41 should be feasible. Furthermore, even for 10-cabinet-per-bank installations, the time available
42 represented by this branch is, at least, twice as long as the longest required times for overall
43 operator response
44

10.5.3 Basis for human error probabilities

Since the objective of the VEWFD installations for the scope of this analysis is to prevent a fire, by definition of a fire PRA, the context for operator response is very different than that traditionally modeled by HRA. Discussions given in Section 9 and earlier in this section have been aimed at describing such important differences.

However, since most HRA quantification methods, and their associated human error probabilities (HEPs), are intended for post-reactor trip response, the strategy for identifying appropriate HEPs for this fire prevention analysis using VEWFD installation is to: 1) identify or define similarities in the characteristics of the two contexts, and 2) use identified similarities in context to justify similar HEPs. In addition, the authors have chosen to analyze a “best case” set of conditions for HRA quantification, as illustrated below.

The HRA quantification approaches used in this comparison are not exhaustive. Methods included are:

1. technique for human error rate prediction (THERP) (Ref. 62)
2. EPRI's HRA Approach (Ref. 63), consisting of two methods addressing cognition:
 - a. cause-based decision tree method (CBDTM)
 - b. human cognitive reliability and operator reliability experiments (HCR/ORE) method
3. standardized plant analysis risk human reliability analysis (SPAR-H) (Ref. 64)
4. ATHEANA (Ref. 58)

10.5.3.1 HEP basis for MCR operator response (in-cabinet, fire suppression)

Combining and building on the descriptions of MCR operator response given in the success criteria and the HF analysis, respectively, the principal activities required for MCR operator response for the in-cabinet VEWFD installation and the suppression strategy are:

1. detection of the VEWFD system alert (and, later, alarm), and
2. use of alarm response procedures (ARPs) to:
 - a. identify the fire location and cabinet bank for VEWFD system in “alert,” and
 - b. make phone calls to dispatch to fire location:
 - i. first (on alert), a field operator
 - ii. next (on alert), to an I&C technician
 - iii. finally (on alarm), to the fire brigade response

In the context of post-reactor trip for at-power, internal events PRA, alarm detection and use of procedures to guide response are typical activities for MCR operator response. In general, these MCR operator activities comprise the cognitive (or diagnostic) portion of overall operator response. Communication between operators in the crew is most typical, but occasionally, emergency operating procedures (EOPs) will require MCR operators to make a phone call to a dispatch field operator. Explicit concerns for such communications to personnel outside the MCR have been more thoroughly considered in the context of fire PRA (e.g., NUREG-1921).

1 In the context of post-reactor trip MCR operator actions, there are many design requirements
2 and associated guidance for supporting such MCR operator actions (as discussed in Section 9).
3 This analysis assumes that these same requirements are used to support the pre-trip, “fire
4 prevention” MCR operator responses. As a result, failure modes associated with diagnosis or
5 cognition are expected to be the dominant contributor to these MCR operator activities.
6

7 THERP is not appropriate to use directly for this analysis (and, often, generally, for current NPP
8 designs) because it does not explicitly address cognition or diagnosis as most modern HRA
9 methods do; and it was developed before the Three Mile Island 2 accident (Ref. 59) and the
10 ensuing upgrades to NPP control room designs, operating procedures, operator licensing and
11 training programs. In addition, THERP’s “annunciator response model” does not appropriately
12 take into account the pattern-matching of annunciator tiles that modern NPP operators do when
13 responding to an event. Human error probabilities for THERP’s “annunciator response model”
14 (shown in Table 20-23 of NUREG/CR-1278) range from 1×10^{-4} to 2.5×10^{-1} .
15

16 The EPRI HRA approach includes two quantification methods that address cognitive failures.
17 EPRI HCR/ORE method is a time reliability correlation and typically used when available time is
18 relatively short. However, the HCR/ORE method should not be used for operator actions that
19 are extremely well-practiced or skill-based, such as manual reactor trip after trip signals and
20 alarms are received. The qualitative analysis in Section 10.3 is intended to describe a similar
21 operator response. Consequently, for this reason (and because of the HCR/ORE method
22 provides little insight on the potential causes of operator failure), EPRI’s CBDTM method is used
23 to calculate the cognitive contribution to operator failure.
24

25 EPRI’s CBDTM model consists of eight decision trees, four of which address failures in the plant
26 information-operator interface and another four that address failures in operator-procedure
27 interface. Both sets of these decision trees match well with the MCR operator actions described
28 above. The contextual factors assumed in Section 10.3 (as they relate to the VEWFD system
29 alarm in the MCR, the ARP used, the interface used to identify the fire and cabinet bank
30 location, and the phone calls made to the FO, I&C technician, and brigade) are used to apply
31 the CBDTM decision trees.
32

33 Table 10-5 summarizes these assessments and shows the resulting HEP assignments. For
34 instance, EPRI’s CBDTM assigns as “negligible” the contribution from all of the “data” decision
35 trees, and all but one of the “procedure” decision trees. The results in Table 10-5 also show
36 that the contribution from “procedures” for this HFE is the lowest possible HEP (i.e., $1E-3$ in
37 decision tree pc-e). If CBDTM recovery factors (e.g., self-recovery and other, or extra crew) are
38 applied, this HEP can be reduced to an HEP in the 1×10^{-4} range.
39

40 A similar analysis using SPAR-H for at-power contexts and the assumptions in Section 10.3
41 would result in the following assessments:

- 42 • available time is nominal
- 43 • stress of stressors is nominal
- 44 • with respect to complexity, it is an “obvious diagnosis” (i.e., better than nominal)
- 45 • experience and training are nominal
- 46 • procedures are diagnostic/symptom-oriented (i.e., better than nominal)
- 47 • ergonomics/HMI is good (i.e., better than nominal)
- 48 • fitness for duty is nominal
- 49 • work processes are good (i.e., better than nominal)

1 Using the worksheets in Appendix A of NUREG/CR-6883 with the information above, an HEP of
 2 2×10^{-4} is obtained.

3 **Table 10-5. MCR Operator Response Assessed with EPRI's CBDTM HRA Method**

Decision Tree Type	Decision Tree Branch	Decision Tree Branch Assessment	Associated HEP Assignment
Plant Information (regarding VEWFD system "alert" and "alarm")	Pc-a (Data not available)	<ul style="list-style-type: none"> is available in the MCR is accurate (e.g., no spurious signals or nuisance alarms) is trained upon 	negligible
	Pc-b (Data not attended to)	<ul style="list-style-type: none"> occurs during low workload conditions is a "check" (by virtue of this cue being an "alarm") is on the MCR front panel 	negligible
	Pc-c (Data misread or miscommunicated)	<ul style="list-style-type: none"> is easy to locate is a "good" indicator with respect to HSI concerns is communicated to the crew using formal, 3-way communications 	negligible
	Pc-d (Information missing)	<ul style="list-style-type: none"> cue is "as stated" 	negligible
Procedure	Pc-e (Relevant step in procedure missed)	<ul style="list-style-type: none"> is obvious (i.e., stand-alone step) is the only guidance being used at this time (i.e., no other procedures or activities are in play) is graphically distinct (e.g., typical HSI concerns with respect to procedure formatting have been addressed) is followed using place keeping aids 	1E-3
	Pc-f (Information misleading)	<ul style="list-style-type: none"> uses standard, unambiguous wording contains all required information 	negligible
	Pc-g (Error in interpreting logic)	<ul style="list-style-type: none"> does not contain "NOT" statements does not contain "and" or "or" statements does not contain both "and" and "or" statements 	negligible
	Pc-h (Deliberate violation)	<ul style="list-style-type: none"> is relevant for a practiced scenario is appropriate to the situation 	negligible

4

1 **10.5.3.2 HEP basis for field operator and technician response (in-cabinet, fire**
2 **suppression)**
3

4 As has already been discussed, the principal activities for the field operator are as follows:
5

- 6 • take call from MCR operator
7 • travel to low-energy (incipient) fire location
8 • position in close proximity to the affected cabinet (with or without input from the
9 technician following his/her use of a portable AS)
10 • stand at-ready for fire suppression³⁵

11
12 These activities are similar to those which might be modeled for an ex-control room action
13 modeled in an at-power, post-reactor trip Level 1 PRA, including some time urgency. However,
14 typically, such field operator activities also would involve some sort of equipment manipulation.
15 In this case, however, the only “execution” modeled for the field operator is the success or
16 failure of fire suppression (which is addressed in Section 11 with the assignment of appropriate
17 non-suppression curves). Therefore, the field operator activities modeled in this HRA represent
18 only part of what is typically modeled in HRA/PRA. Consequently, only the general HEP
19 guidance given in THERP or ATHEANA associated with “unlikely” or “very unlikely” failure
20 probabilities (i.e., 1×10^{-2} or 1×10^{-3} , respectively) is appropriate.
21

22 Similarly, for the technician, the principal activities are:
23

- 24 • take call from MCR operator
25 • gather necessary equipment
26 • travel to low-energy (incipient) fire location
27 • use portable ASD to identify affected cabinet (only needed for installations involving
28 more than three cabinets)

29
30 These activities are very different than those usually modeled in at-power, post-reactor trip
31 Level 1 HRA/PRA. Instead, these activities are similar to those modeled with pre-initiator HFEs
32 (e.g., test or maintenance activities), except these actions may be performed with some
33 urgency, and there is no opportunity to verify the actions. Consequently, an HEP (more) typical
34 of THERP or ASEP (Ref. 65) is the best fit (e.g., 1×10^{-3}).
35

36 **10.5.4 Results: HFE quantification for in-cabinet, fire suppression strategy**
37

38 This section presents the HRA quantification results for operator actions associated with the in-
39 cabinet, VEWFd system installations (ASD VEWFd cloud chamber, conventional spot-type
40 ionization, and VEWFd light-scattering detectors), using the fire suppression strategy.
41

42 HFE quantification results are obtained by using the following: 1) the assumptions discussed in
43 HRA qualitative analysis section, Section 10.3, 2) the timing inputs discussed in Section 10.5.1,
44 3) the feasibility assessments in Section 10.5.2, and 4) the basis for HEPs discussed in Section
45 10.5.3.
46

³⁵ This analysis that plant staff fire suppression capability will need to be present until either the incipient stage ends or the degraded component and/or cabinet is de-energized.

1 Tables provided in this section summarize the HRA results developed with the following
2 quantification steps:

- 3
4 1. Any cases where operator actions are not feasible are assigned a failure probability of
5 1.0.
- 6 2. Base HEPs are developed for HFEs representing both the MCR operator response and
7 the field operator/technician response:
 - 8 a. For the HFE representing the MCR operator response, Section 10.5.4.2
9 discusses the development of the base HEP which is used in all cases
10 (e.g., different durations of the time available for operator response)
 - 11 b. For the HFE representing the field operator/technician response, Section
12 10.5.4.3 discusses how base HEPs are developed for different sample points on
13 the probability distributions for the time available for operator action following
14 "alert." Differences between base HEPs for different times available is based on
15 comparisons between the time required with times available.
- 16 3. For the HFE representing the field operator/technician response, the base HEP is
17 multiplied by the associated split fraction for each sample point
- 18 4. The total HEP is determined as follows:
 - 19 a. For the HFE representing the MCR operator response, the total HEP is the same
20 as the base HEP
 - 21 b. For the HFE representing the field operator/technician response, the total HEP
22 equal to the sum of all sample point calculations of "Base HEP x Split Fraction"

23 Finally, the results for "total HEP" for each HFE (along with the results of Section 11) are used
24 to quantify the event trees shown in Section 6.4. More detailed discussions of how these HEPs
25 were developed are given in Sections 10.5.4.1 and 10.5.4.2 for MCR operator and field
26 operator/technician HFEs, respectively. In addition, the feasibility assessments given in Section
27 10.5.2 provide the basis for assessing field operator/technician failure probabilities with respect
28 the comparison of time required to time available, including considerations of HEP adjustments
29 with multipliers to address interim cases.

30
31 Tables 10-6, 10-7, and 10-8, respectively, summarize the HRA quantification results for both
32 HFEs, specifically for air-aspirated, cloud chamber detectors, configured for VEW, categorized
33 into the following groups:

- 34
- 35 • 1 and 3 cabinet-per-bank installations
- 36 • 6-cabinet-per-bank installations
- 37 • 10-cabinet-per-bank installations

38

1 **Table 10-6. HEPs for 1 and 3-Cabinet—ASD VEWFD Cloud Chamber Detectors**

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1E-02	0.10	1E-03	1.2E-3**
	2	1E-03	0.20	2E-04	
	3	1E-04	0.21	2.1E-05	
	4	1E-04	0.49	4.9E-05	

2 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

3 ** Only two significant digits shown for this calculated results.

4 **Table 10-7. HEPs for 6-Cabinet – ASD VEWFD Cloud Chamber Detectors**

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.1	0.12**
	2	0.1	0.20	2.0E-02	
	3	1E-02	0.21	2.1E-03	
	4	1E-04	0.49	4.9E-04	

5 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

6 ** Only two significant digits shown for this calculated results.

7

1 **Table 10-8. HEPs for 10-Cabinet—ASD VEWFD Cloud Chamber Detectors**

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-2	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.30**
	2	1.0	0.20	0.20	
	3	3E-02	0.21	6.3E-03	
	4	1E-04	0.49	4.9E-05	

2 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

3 ** Only two significant digits shown for this calculated results.

4
5 Similarly, Table 10-9 through 10-11, summarize the HRA quantification results for ionization
6 detectors:

- 7
8 • one and three cabinet-per-bank installations
9 • six-cabinet-per-bank installations
10 • 10-cabinet-per-bank installations

11 **Table 10-9. HEPs for 1 and 3-Cabinet - Ionization Detectors**

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.11**
	2	3E-02	0.31	9.3E-03	
	3	1E-04	0.24	2.4E-05	
	4	1E-04	0.35	3.5E-05	

12 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

13 ** Only two significant digits shown for this calculated results.

14

1

Table 10-10. HEPs for 6-Cabinet - Ionization Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.13**
	2	0.1	0.31	3.1E-02	
	3	1E-02	0.24	2.4E-03	
	4	1E-04	0.35	3.5E-05	

2 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

3 ** Only two significant digits shown for this calculated results.

4

Table 10-11. HEPs for 10-Cabinet - Ionization Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.41**
	2	1.0	0.31	0.31	
	3	3E-02	0.24	7.7E-03	
	4	1E-04	0.35	3.5E-05	

5 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

6 ** Only two significant digits shown for this calculated results.

7

8 Finally, Tables 10-12 through 10-14, respectively, summarize the HRA quantification results for
9 ASD VEWFD light-scattering detectors:

10

- 11 • one and three cabinet-per-bank installations
- 12 • six-cabinet-per-bank installations
- 13 • 10-cabinet-per-bank installations

14

1

Table 10-12. HEPs for 1 and 3-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.11**
	2	3E-02	0.38	1.1E-02	
	3	1E-04	0.25	2.5E-05	
	4	1E-04	0.27	2.7E-05	

2 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

3 ** Only two significant digits shown for this calculated results.

4

Table 10-13. HEPs for 6-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.1	0.14**
	2	0.1	0.38	3.8E-2	
	3	1E-2	0.25	2.5E-03	
	4	1E-04	0.27	2.7E-05	

5 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

6 ** Only two significant digits shown for this calculated results.

7

1

Table 10-14. HEPs for 10-Cabinet—Light-Scattering Detectors

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-4	Base HEP x Split Fraction	Total HEP*
MCR operator response (1- μ)	N/A	1E-04	N/A	N/A	1E-04
Field operator & technician response (1- ξ)	1	1.0	0.10	0.10	0.48**
	2	1.0	0.38	0.38	
	3	3E-2	0.25	7.5E-3	
	4	1E-04	0.27	2.7E-05	

2 * The total HEP is the sum of each split fraction multiplied by the associated base EHP for the sample point.

3 ** Only two significant digits shown for this calculated results.

4

5 Many spot-type smoke detectors (initiating devices) are capable of being installed as
 6 addressable devices. That is, an addressable smoke detector and associated system can have
 7 a discrete identification allowing for the ability of its status to be identified. For in-cabinet
 8 applications, addressability can allow for the identification of the specific cabinet where an
 9 addressable detector is located and alarming. As shown above, having an addressable ION
 10 detector (for example), would allow the use Table 10-9 and a total HEP of 0.11. Whereas, if the
 11 ION detector were not addressable to the specific cabinet, but to the bank of ten cabinets, then
 12 the total HEP increase to approximately 0.41. Based on these estimate, the ability to use
 13 addressable detectors to identify the cabinet of concern reduces the HEP by a factor of 4. If the
 14 detection system only identifies the fire area or room, then an even higher HEP should be
 15 expected such as in the case of an areawide system.

16

17 A similar approach could be used for ASD VEWFDF or spot-type VEWFDF systems where an
 18 individual zone was associated with a single cabinet. The ability of a detection system to
 19 identify the cabinet or location where abnormal conditions exist, should result in a shorter time
 20 to locate the potential fire source and allow for the use of a reduced HEP compared to a system
 21 that is not addressable to a specific cabinet.

22

23 **10.5.4.1 MCR operator response**

24

25 The state-of-practice in HRA currently is to treat each HFE, and its associated operator actions,
 26 holistically, rather than analyzing a breakdown of the various subtasks and individual influencing
 27 factors then “adding them up.” In particular, operator response in an existing U.S. NPP, in the
 28 MCR, following a reactor trip, and using the existing emergency operating procedures (EOPs),
 29 is understood to be supported by, for example (Note: this is not a complete or comprehensive
 30 list):

31

- 32 • a well-designed control room (including alarm panel placement and layout, clear
- 33 indication of different trains, appropriate lighting and ventilation)
- 34 • effective training and certifications

35

- 1 • job aids (such as procedures that follow human factors guidance with respect to content,
2 presentation and format)
- 3
- 4 • communication protocols
- 5
- 6 • a co-located crew and adequate and qualified staffing
- 7
- 8 • a strong safety culture
- 9

10 The combination of factors such as those given above may result in a certain expectation and
11 reliability of operator performance. Because of differences between NPPs and even operator
12 crews, there is no set combination of factors or features, or right or wrong implementation of job
13 aids or designs except that they must be demonstrated (via operating experience, namely);
14 each NPP's combination of job aids, influential factors and EOPs achieves the level of
15 performance expected. If a plant design (e.g., size of steam generators) is such that faster
16 response is required, then certain steps, training and procedures may be altered to compensate
17 for or address this need.

18
19 Consequently, the "right" set of design features, job aids, and so forth cannot be definitively
20 identified as it may come in a variety of forms. However, certain factors are expected to be
21 important to successful operator response (since they underlie operator response for post-
22 reactor trip events and using EOPs). For the purposes of this analysis, the assumptions
23 described in Section 10.3 are taken to be adequate to describe a context in which the MCR
24 operator response is similar to that for post-reactor trip response. Thus, under those conditions
25 described and assumed above, MCR operators are expected to act quickly, and with a reliability
26 consistent with alarm response and procedural use traditionally addressed by PRAs for post-
27 initiator actions.

28
29 Overall, with the assumptions made, and the implication that MCR operator response for the fire
30 suppression strategy of in-cabinet VEWFD installations, should mirror that for alarm response in
31 HRA:

- 32
- 33 • Does not consider any failure modes associated with detection.
- 34
- 35 • Considers only two potential failure modes for situation assessment (which are delays in
36 response and difficulties in identifying the specific cabinet(s) associated with the VEWFD
37 system signal, which is expected to be manifested as a delay also).
- 38
- 39 • Does not consider any failure modes associated with response planning.
- 40
- 41 • Considers only delays as potential modes associated with execution.
- 42

43 Based on this discussion, an HEP for this HFE is justified in being similar to those HEPs
44 developed in Section 10.4; namely, an HEP of 1×10^{-4} is assigned (which is independent of the
45 number of cabinets per bank in the installation and type of VEWFD system) for failure of MCR
46 response.

1 **10.5.4.2 Field operator and technician response**
2

3 The key to the success of this HFE is to locate the relevant cabinet so that the field operator can
4 be positioned to immediately suppress the fire when it starts. Consequently, the field operator
5 and technician are coupled in defining this HFE.
6

7 As summarized in the timing input tables and feasibility assessments (Sections 10.5.1 and
8 10.5.2, respectively), the assignment of HEPs for the combined field operator and technician
9 response is more complicated than that for the MCR operator response because of variations in
10 HRA inputs, namely:

- 11 • different times required, as a function of the number of cabinets per bank in the VEWF
12 installation
13
- 14 • different “branches” that represent different times available (i.e., durations of the time
15 available for operator response measured from “alert”), as a function of probability
16 distributions
17
- 18 • feasibility assessments for each combination of timing inputs
19
- 20 • differences in the sensitivity of detectors
21

22
23 Using the base HEP of 1×10^{-3} developed in Section 10.5.3, the following considerations were
24 used to develop the HEPs shown in Tables 10-6, 10-7, and 10-8:
25

- 26 • If the overall operator response is not feasible, then an HEP of 1.0 is assigned.
27
- 28 • If the range of times available overlaps the entire range of times required, an HEP of 0.1
29 is assigned.
30
- 31 • If the time available is just adequate compared to the time required, an HEP of 1×10^{-2} is
32 assigned.
33
- 34 • If the time available is significantly more than that required (but not more than twice as
35 much), then an HEP of 1×10^{-3} is assigned.
36
- 37 • If the time available is more than twice that required, an HEP of 1×10^{-4} is assigned.
38
- 39 • An HEP floor of 1×10^{-4} is used.
40

41 For example:
42

- 43 • an HEP of 0.1 (i.e., marginal feasibility) is assigned to:
 - 44 ○ six-cabinet configurations for both ion and light-scattering detectors, Sample
45 point #2 (i.e., time available ranges from 5 or 6 minutes to 30 minutes)
- 46 • an HEP of 1×10^{-2} (corresponding with “just enough time”) is assigned to:

- 1 ○ Sample point #1 for one- and three-cabinet configurations for cloud chamber
- 2 detectors
- 3 ○ Sample point #3 (i.e., time available 30 minutes to 1 hour) for six-cabinet
- 4 configurations of all detectors
- 5 • an HEP of 1×10^{-3} (i.e., significantly more time available than required is assigned to:
- 6 ○ Sample point #2 (i.e., time available from 9 to 30 minutes) for one- and three-
- 7 cabinet configurations of cloud detectors
- 8 • an HEP of 1×10^{-4} (representing “expansive time”) is assigned for:
- 9 ○ Sample point #4 (i.e., time available greater than 1 hour), for all detectors and
- 10 cabinet configurations
- 11 ○ Sample point #3 (i.e., time available between 30 minutes and 1 hour) for all one-
- 12 and three-cabinet configuration

13
 14 In a few instances, an interim multiplier has been used because the range of times available
 15 completely engulfs with the range of times required (see, for example, the feasibility assessment
 16 discussion for sample point #2 (i.e., Section 10.5.2.2). In such cases, the otherwise applicable
 17 HEP is multiplied by a factor of three (3). For example, an HEP of 3×10^{-2} is assigned to:

- 18
- 19 • Sample point #2 (up to 30 minutes time available) for one- and three-cabinet
- 20 configurations of ion and light-scattering detectors
- 21
- 22 • Sample point #3 (i.e., time available 30 minutes to 1 hour) for 10-cabinet configurations
- 23 of all detectors
- 24

25 Also, the following cases are not feasible (i.e., HEP of 1.0):

- 26
- 27 • Sample point #1:
- 28 ○ one- and three-cabinet configurations for ion and light-scattering detectors
- 29 ○ six-cabinet configurations for all detectors
- 30 ○ 10-cabinet configurations for all detectors
- 31
- 32 • Sample point #2, 10-cabinet configurations for all detectors

33 **10.5.4.3 Exploration of a variation in HRA quantification**

34
 35 From the discussion above, it is apparent that the HRA quantification results for the HFE
 36 representing the field operator and technician response are extremely sensitive to the
 37 comparison between the time required for operator actions, and the time available from VEWFD
 38 system “alert” to when the incipient stage ends. For this reason, this section explores how a
 39 variation in HRA timing inputs would influence HRA quantification results.

40
 41 For example, as shown in Table 10-1, the time required for the field operator to arrive at the
 42 location where the VEWFD system is in “alert” varies from 2 to 8 minutes. In addition, the
 43 answers to Question #14 in Section C.1.1 were:

- 1
2 • Plant X: varies but typically, 2 to 8 minutes
3 • Plant Y: 3 to 4 minutes
4

5 These variations in reported times could be explained by a variety of factors (principally related
6 to the field operator travel time), including:
7

- 8 • plant-to-plant differences in layout of fire areas
9
10 • for a specific plant, differences in field operator travel times, depending on the specific
11 location of the VEWFD system and where the field operator is located when the MCR
12 operator calls
13
14 • lack of operational experience with this field operator action
15

16 The qualitative analysis chapter in NUREG-1921 (Ref. 49) provides guidance on the
17 development of timing inputs for fire HRA, especially the discussions of sufficient time as a
18 feasibility assessment criterion (see Section 4.3.4.1 in NUREG-1921) and of timing as a
19 performance shaping factor (see Section 4.6.2 in NUREG-1921). This guidance, along with the
20 possible explanations for variations given above, points to a corresponding selection of ways to
21 explore variations in this timing input, such as:
22

- 23 1. The "Plant Y" data could be used as a plant-specific input (rather than a generic
24 representation of this input), or
25
26 2. uncertainty in the estimate of this timing input could have been reduced by either:
27 a) collecting a more robust set of operational experience that reduces such variations, or
28 b) establishing a job performance measure for this field operator action (or, even better,
29 for the integrated response of the MCR operators and the field operator) that requires
operator performance to meet certain targets (usually time required for performance).

30
31 Despite uncertainties regarding the time required for field operator actions, this analysis
32 explores the change in HRA quantification results if the time required for the field operator to
33 arrive on location is assumed to be four minutes. Investigating a single-cabinet installation of
34 an ION detector results in variations of time required (shown in Table 10-1 and Table 10-9) and
35 HRA quantification results (shown in Tables 10-15 and 10-16, respectively).
36

1 **Table 10-15. Variations in Timing Inputs for Field Operator Actions after “Alert” Signal**

Start of response	Who and Where?	Action(s) required for success	Duration (minutes)	Time from “Alert” (minutes)
Alert signal	MCR operator	Detect signal, use alarm response procedures, identify location of detector, and call to dispatch field operator	1-2	1-2
Call from MCR	Field operator in plant	Travel to location of VEWFD system in “alert”: standby as fire watch by cabinet(s)	4	5 - 6

2
 3 The revised time of 5-6 minutes required for a single-cabinet installation is now equivalent to
 4 (or maybe slightly less than) the 6 minutes that represents the shortest time available of the
 5 samples points for the probability distribution. Consequently, using the same considerations for
 6 developing HEPs that are described in Section 10.5.4.2, the results for the revised base HEPs
 7 and total HEP are shown in Table 10-16 below.

8 **Table 10-16. Variations on HEPs for Single-Cabinet—ION Detector**

HFE	Sample Point	Associated Base HEP	Associated Split Fraction from Table 10-3	Base HEP x Split Fraction	Total HEP*
MCR operator response	N/A	1E-4	N/A	N/A	1E-4
Field operator & technician response	1	1E-02	0.10	1E-03	1.3E-3**
	2	1E-03	0.31	3.1E-04	
	3	1E-04	0.24	2.4E-05	
	4	1E-04	0.35	3.5E-05	

9 * The total HEP is the sum of each split fraction multiplied by the associated base HEP for the sample point.

10 ** Only two significant digits shown for this calculated result.

11
 12 **10.5.5 HFE quantification notes for de-energization strategy**

13
 14 As described in the HF tabletop analysis (Section 9.2.1) and Section 10.4, in-cabinet
 15 installations of VEWFD that use a de-energization strategy will involve additional operator

1 actions and associated times (all of which must be performed before the incipient stage ends),
2 such as:

- 3
- 4 1. The technician must identify the degraded component first.
- 5
- 6 2. The field operator must communicate to the MCR operators what component is
7 degraded.
- 8
- 9 3. MCR operators must:
 - 10 a. Determine **if** the degraded component can be de-energized.
 - 11 b. Determine **how** (e.g., with what steps and by whom) the degraded component
12 can be safely de-energized (and without reactor trip).
- 13
- 14 4. The degraded component must be de-energized by plant personnel, such as:
 - 15 a. Electrical engineers or electricians (who may assist in developing the de-
16 energization strategy and in actually performing de-energization steps).
- 17
- 18 5. The field operator may assist in the de-energization.

19
20 Based on NPP interviews conducted for this project (see Appendix C), the complexity and
21 associated amount of time needed to de-energize can vary widely (e.g., from minutes to a
22 “research project” that takes days or more).

23
24 Similarly, the determination **of whether or not** a degraded component can be de-energized is
25 not always straightforward.

26
27 Consequently, given the varying times available (including some very short times), it is
28 recommended that pre-planning be done to:

- 29
- 30 • Identify which components within an in-cabinet, VEFWD installation **can** be de-
31 energized .
- 32
- 33 • Distinguish the specific steps needed for de-energization, to the extent possible.
- 34
- 35 • Determine how much time is needed to de-energize, to the extent possible.
- 36

37 38 **10.5.6 HFE quantification notes for areawide applications**

39
40 HRA for areawide applications of VEFWD would be similar to that for the in-cabinet,
41 de-energization strategy, except that even more time will be needed for field operator and
42 technician actions. A value of 1.0 was used to represent the HEP failure based on area wide
43 applications. That is, the timing information available for detecting fires before flaming
44 conditions will vary widely on a room by room basis. To inform HEP’s for area wide application
45 analysts should perform timing feasibility studies which take into account room factors such as;
46 area (i.e. size, ceiling height), contents of room (i.e. number of cabinets protected, alternative
47 fire sources), accessibility of room (i.e. ease of movement within the room, security, locked
48 doors, radiation areas etc.).
49

1 **10.6 HRA Dependency and Recovery Analysis**

2
3 Dependencies between HFEs addressed in this analysis have been treated directly through the
4 event tree representation.

5
6 Self- or within-crew recoveries have been addressed in the development of base HEPs (see
7 Section 10.5.3). Recoveries, as traditionally defined by PRA, are only addressed with respect to
8 fire suppression capability (i.e., “enhanced” versus “conventional”).
9

10 **10.7 HRA Uncertainty Analysis**

11
12 The uncertainty analysis guidance provided in Section 6.3 of NUREG-1921 (Ref. 49) is
13 appropriate for this study. However, because of the limitations in the information inputs for this
14 project, new uncertainty sources could not be identified (and uncertainty sources identified in
15 NUREG-1921 could not be proved as inapplicable).
16
17
18

11. FIRE SUPPRESSION

The objective of this section is to describe how the suppression events are modeled. Enhanced and conventional detection/suppression modeling is presented. The modeling of both events are adopted and modified as needed from the current suppression and detection analysis approach described in NUREG/CR-6850 and supplemental documents such as Supplement 1 and NUREG-2169. Reliance on current models allows for any future updates or advancements to be incorporated into this analysis. In other words, the suppression modeling presented in this section relies on current state-of-the-art methods and this dependence allows for the suppression portion of the event tree presented in Section 6.4 to be changed, as the state-of-the-art methods for suppression and detection analysis is advanced.

11.1 Enhanced Fire Suppression

Enhanced Fire Suppression is credited following the *success path* of the following branch points:

1. fraction of fires that have an incipient stage of sufficient duration (α)
2. very early warning fire detection (VEWFD) system availability, reliability, and effectiveness (β)
3. main control room (MCR) response (μ)

The “ π ” factor in the event tree represents the enhanced suppression probability. There are three cases for this factor which are dependent upon the success criteria provided in Section 10.4 for the “1st level field response (technician or field operator) fire watch posted (ξ)”.

The “ $1-\pi_1$ ” factor represents the probability that, given **success** of event ξ , the technician or field operator staged directly at the specific cabinet responsible for the VEWFD alert, fails to promptly suppress the fire quickly enough to prevent damage to targets outside the initiating component. That is, the fire has progressed past the incipient stage and has begun to damage additional targets within the cabinet before the field operator and technician can take action to prevent failure or promptly suppress a fire, if flaming does occur. “ $1-\pi_1$ ”, the probability of “enhanced” non-suppression, may be set to 1×10^{-3} . This is considered to be reasonable given that a trained field operator will be stationed at the initiating cabinet with the suppression equipment in the event that open flaming does occur.

The “ $1-\pi_2$ ” factor is applicable for the in-cabinet event tree and represents the probability that, given **failure** of event ξ , the technician or field operator in the area of the cabinet responsible for the VEWFD alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. This branch path takes into account that the field operator and technician have arrived at the bank of cabinets causing the VEWFD alert, but were unable to locate the cabinet causing the VEWFD system “alert” before the incipient fire progressed to a flaming condition. The MCR curve ($\lambda=0.324$) should be used for this case. This is considered to be reasonable representation given that a trained responder will be near the bank of cabinets where the VEWFD alert was initiated, actively searching for the source location of the alert.

The “ $1-\pi_3$ ” factor is applicable for the areawide event tree and represents the probability that, given **failure** of event ξ , the technician/field operator in the room responsible for the VEWFD

1 alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets
2 outside the cabinet. This branch path takes into account that the field operator/technician has
3 arrived at the room causing the VEWFDs alert, but was unable to locate the source of the
4 condition causing the VEWFD system “alert” before the low-energy (incipient) fire progresses to
5 a flaming condition. A newly developed non-suppression probability curve should be used with
6 $\lambda = 0.194$. This value is based upon an analysis of fire events from the Updated Fire Events
7 Database (Ref. 63). All fires in electrical cabinets were sampled for occurrences in which an
8 operator was present in the room of origin when a flaming condition began. The approximation
9 for the non-suppression value to be used was then evaluated against the MCR suppression
10 curve. Differences between the MCR and newly developed curve were sufficient to warrant a
11 new suppression curve for this application. This is considered to be reasonable representation
12 given that a trained responder will be in the room where the VEWFDs alert was initiated,
13 actively searching for the source location of the alert.

14
15 The probability that the fire brigade or other first responders will fail to suppress the fire
16 [$\Pr(T_{\text{supp}} \geq t)$] is estimated with suppression probability curves developed using the
17 suppression time data reported in FEDB. In EPRI 3002001989 (NUREG-2169), new non-
18 suppression probability estimates are provided. These new estimates are used in Section 12
19 “Illustrative examples.” These curves were developed using U.S. Fire Event Experience
20 through 2009 where manual suppression was involved and suppression time information was
21 available. Suppression time was defined as the time the fire was extinguished or the time the
22 fire was reported to have been under control by the fire brigade on scene (Ref. 45). Events
23 including self-extinguished fires, supervised burnouts, and fires extinguished with automatic fire
24 suppression systems were excluded from the curves. If the time from detection to suppression
25 was not known, but the duration of the fire event from start to suppression was known, then the
26 reported fire duration was used instead.

27
28 The mathematical model to derive $\Pr(T_{\text{supp}} \geq t)$ is described in NUREG/CR-6850 as follows:

29
30 *The data for analysis consists of reported fire durations in commercial*
31 *U.S. NPPs. These times are treated as being generated by an underlying*
32 *probabilistic model. The final output of interest is the suppression curve, which*
33 *gives the probability that a fire lasts longer than a specified time. If T is the*
34 *random variable describing when the fire is suppressed, and $\lambda(t)$ is the rate at*
35 *which the fire is suppressed (possibly time-dependent), this probability of non-*
36 *suppression is given by:*

$$\Pr(T > t) = e^{-\int_0^t \lambda(s) ds}$$

37
38
39
40 *In this equation, $\lambda(t)$ is a function of the parameters of the probabilistic model*
41 *chosen for T . The simplest model for T is the exponential distribution, whose*
42 *probability density function is:*

$$f(t) = \lambda e^{-\lambda t}$$

43
44
45
46 *In this model, λ is estimated directly and is not a function of time, giving*

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

1 The non-suppression probability is calculated using the above equation, usually
 2 selecting t as the time to target damage.

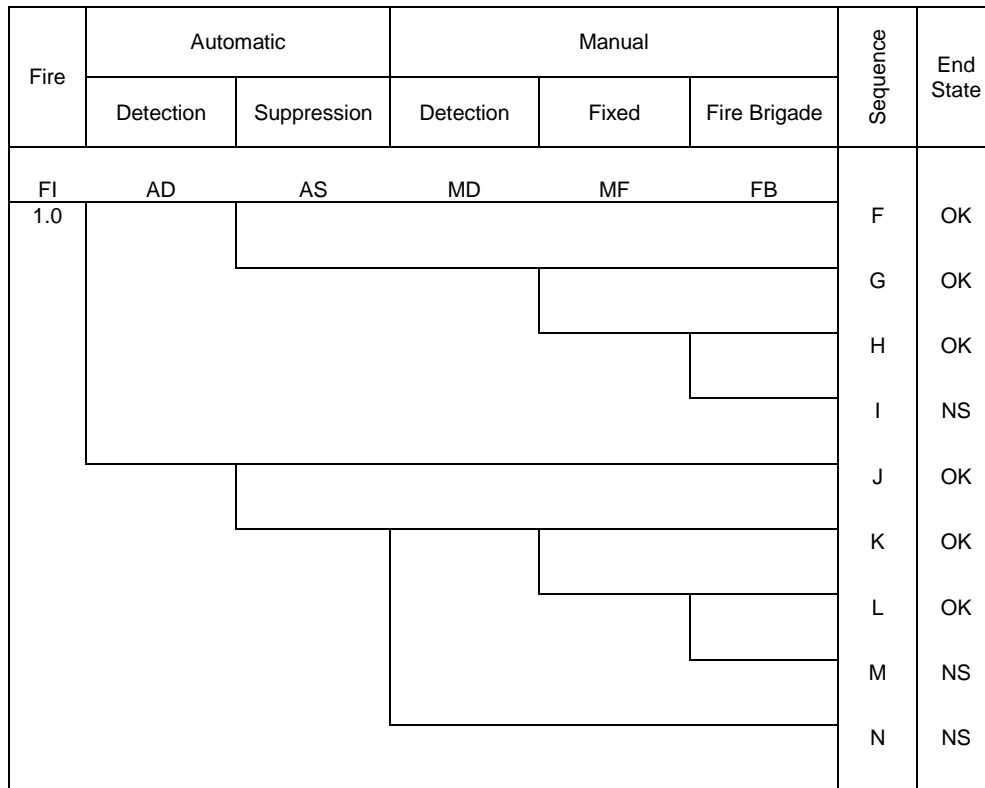
3
 4 The same mathematical model was used to derive the non-suppression probability curve related
 5 to “ $1-\pi_3$ ”.

6
 7 **11.2 Conventional Fire Suppression**

8
 9 Conventional detection/suppression is credited following the *failure path* of the following branch
 10 points:

- 11
 12 1. fraction that have an incipient stage of sufficient duration (α)
 13 2. detector system availability, reliability, and effectiveness (β_1 and β_1)
 14 3. MCR Response (μ)

15
 16 The “ η ” factor in the event tree represents the conventional suppression probability. There are
 17 three cases for this factor which are dependent upon the detection strategies used within the fire
 18 area. The probability of “normal” non-suppression should be taken from the Detection
 19 Suppression Event Tree in NUREG/CR-6850, Appendix P, using the electrical fire suppression
 20 curve for manual suppression as appropriate. The conventional detection suppression event
 21 tree is shown in Figure 11-1. The end points for conventional suppression are shown below in
 22 Table 11-1.



24 **Figure 11-1. Conventional detection suppression event tree**

25

1

Table 11-1. Conventional Detection Suppression Event Tree Outputs

Sequence	Detection	Suppression
F	Automatic detection by <ul style="list-style-type: none"> • Heat detectors • Smoke detectors 	Fire suppression by an automatically actuated fixed system
G		Fire suppression by a manually actuated fixed system
H		Fire suppression by the fire brigade
I		Fire damage to target items
J	Delayed detection by <ul style="list-style-type: none"> • Roving fire watch • Control room verification 	Fire suppression by an automatically actuated fixed system
K		Fire suppression by a manually actuated fixed system
L		Fire suppression by the fire brigade
M		Fire damage to target items
N	Fire damage to target items	

2

3 For **In-Cabinet** applications (Figure 6-4 only), in which redundant spot-type detection and
 4 automatic suppression systems are available in the area, “1- η_1 ” represents sequences F – N
 5 from Figure 11-1. That is, given a failure of the in-cabinet VEWFD system or MCR to respond,
 6 the room spot-type detection capability still exists within the room to detect the fire before
 7 delayed detection. From NUREG-6850, the probability of random failure of a conventional spot-
 8 type smoke detector system is assumed to be no larger than 0.05.

9

10 For **In-Cabinet** and **Areawide** applications (both Figures 6-4 and 6-5), “1- η_2 ” represents
 11 sequences F – N from Figure 11-1. That is, given a failure of the VEWFD system to provide
 12 sufficient advance warning, the VEWFD system will still perform normal automatic detection
 13 functions comparable to that of normal spot detection.

14

15 For **Areawide** applications (Figure 6-5 only), “1- η_3 ” represents only sequences J – N from
 16 Figure 11-1. That is, given a failure of the areawide VEWFD system there is no redundant
 17 normal detection capability within the room to detect the fire before manual delayed detection.
 18 Delayed detection is assumed 1.0 for cases in which no prompt or automatic detection is
 19 credited (or failed) if the estimated time for manual detection is less than the time to target
 20 damage.

21

22

23

12. QUANTIFICATION OF SMOKE DETECTION PERFORMANCE

The purpose of this section is to provide a description and evaluation of a method to estimate the non-suppression probability associated with using different types of smoke detectors in nuclear power plant (NPP) applications.

12.1 Illustrative Examples

This subsection provides illustrative examples of how the information developed in the report could be used in the detection/suppression analysis to estimate a probability of non-suppression for several smoke detection systems. For these examples, the same room will be used to evaluate different fire scenarios, smoke detection applications, and ventilation conditions. The room contains both control and power-type electrical enclosures. The examples evaluated include the following five cases:

- Case 1 Control cabinet ignition source, in-cabinet aspirating smoke detection (ASD) very early warning fire detection (VEWFD), bank of 10 cabinets that are naturally ventilated
- Case 2 Single partitioned control cabinet, in-cabinet ASD VEWFD, forced ventilation
- Case 3 Power cabinet ignition source, in-cabinet ASD VEWFD, bank of 10 partitioned cabinets that are naturally ventilated
- Case 4 Mix of control and power cabinets, areawide air return grill mounted ASD VEWFD
- Case 5 Mix of control and power cabinets, areawide air return grill mounted ASD VEWFD with room suppression system

All cases consist of an electrical cabinet fire (ignition source) affecting a cable tray containing a fire PRA target cable. In typical fire PRA analyses, the time to damage will vary depending on the cabinet configuration (associated heat release rate value from Table G-1 of NUREG/CR-6850), level of fire modeling (empirical, zone, CFD, THIEF, etc.), and the location of the cable tray. For these illustrative examples, it will be assumed that the time to damage this target cable is 10 minutes, regardless of the electrical cabinet fire hazard characteristics. This approach was chosen such that the resulting effects not associated with the suppression/detection aspects of the analysis are held constant, allowing for a direct comparison of the benefit from the use of ASD VEWFD among applications.

For each example, the results using the approach presented in this report will be shown, along with the results from using NUREG/CR-6850 Appendix P, and the FAQ 08-0046 simplified model approach on page 13-8 of NUREG/CR-6850, EPRI 1019259, Supplement 1.

12.1.1 Case 1: In-cabinet ASD VEWFD, bank of 10 control cabinets, natural ventilation

In this example, various in-cabinet smoke detection systems are evaluated for their ability to enhance the suppression capability for a potential fire hazard located in a bank of 10 low voltage control cabinets with natural ventilation. In addition, the room is also equipped with areawide conventional spot smoke detection mounted on the ceiling. The benefit from the use of ASD VEWFD systems will be evaluated for both cases where conventional detection is and is

1 not evaluated. Each in-cabinet smoke detection system will be evaluated separately. It is
 2 assumed that a single zone of the ASD protects the entire cabinet bank and the spot-type
 3 detectors are addressable to a single cabinet. The following information is necessary before
 4 proceeding with the analysis:

- 5
- 6 • Based on fire modeling analysis, the estimated time for conventional areawide smoke
 7 detection is 2 minutes, for this example.
- 8
- 9 • Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
- 10
- 11 • From fire drills records, the reasonable fire brigade response time is 10 minutes.
- 12

13 Based on the preceding information, the values presented in Table 12-1 are to be used in
 14 applying the incipient event tree approach; each parameter estimate is provided with source
 15 information as to where the particular estimate value can be located.

Table 12-1. Case 1 Input Parameters: Multi-Control Cabinet, In-Cabinet

Parameter	Estimate	Source
α	7.2E-01	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control Cabinet
$1-\beta$	6.2E-03 (ASD)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems
	5E-02 (Spot)	NUREG/CR-6850 – Appendix P
$1-\tau$	2.7E-03 : ASD CC 1.9 – 5.3E-01 : ASD LS 2.6E-01 : SS 1.0E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Natural Ventilation
$1-\mu$	1E-04	MCR operator response Section 10.5.4
$1-\xi$	0.30: ASD CC 0.48 : ASD LS 0.48 : SS 0.41 : ION	Field operator & technician response Table 10-8, 10-Cabinet – ASD VEWFD CC Table 10-14, 10-Cabinet – LS and SS Table 10-11, 10-Cabinet – Ionization
$1-\pi_1$	1.0E-03	Technician / Field operator staged <u>directly</u> at the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u> .
$1-\pi_2$	3.9E-02	See discussion below
$1-\eta_1$	4.8E-01	
$1-\eta_2$	4.6E-01	

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1 **Table 12-1. Case 1 Input Parameters: Multi-Control Cabinet, In-Cabinet (Continued)**

RESULT	With Conventional Detection	Without Conventional Detection (setting “η1” to 0)
	<u>Detection Type Pr_{n-s} (Factor)</u>	<u>Detection Type Pr_{n-s} (Factor)</u>
	ASD CC : 1.4E-01 (7.1)	ASD CC : 1.8E-01 (7.0)
	ASD LS : 2.0E-01 (4.9)	ASD LS : 2.4E-01 (4.8)
	3.1E-01 (3.2)	3.3E-01 (3.2)
	SS :2.4E-01 (4.2)	SS :2.6E-01 (3.8)
	ION : 1.9E-01 (5.4)	ION : 2.2E-01 (4.7)
	FAQ 08-0046 : 1.1E-02 (94.5)	FAQ 08-0046 : 1.0E-02 (47.9)
	NUREG/CR-6850 : 5.82E-01 (1.6)	NUREG/CR-6850 : 5.82E-01 (1.6)

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Figure 12-1, Figure 12-2, and Figure 12-3, illustrate the solution of the detection suppression event tree from NUREG/CR-6850 for the terms $1-\pi_2$, η_1 and η_2 respectively.

Figure 12-1 represents $1-\pi_2$, the probability that, given **failure** of event ξ , the technician/field operator in the area of the electrical cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. $1-\pi_2$ is calculated using the MCR curve. For this case, both the time to detection of the VEWFDS system and time to fire brigade response are set to 0 minutes, considering that the system has already gone into alarm and the technician/field operator is present in the room. The technician/field operator acts as the fire brigade as he/she has been trained to suppress fires (e.g., fire brigade training). The failure probability of the automatic detection, in this case, the VEWFDS system, is set to 0 as well. At this point in the event tree the system is assumed to have already operated successfully and the appropriate response is underway.

The probability of failure to extinguish the fire, once ignition has occurred, is calculated using the MCR curve ($\lambda = 0.324$) using a manual suppression time of $10-0-0 = 10$ minutes as:

$$e^{(-\lambda_{MCB} * 10)} = e^{(-0.324 * 10)} = 3.9E - 02$$

1

Fire	Automatic		Manual			Sequence	End State	Pr (non-suppression)
	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	AD	AS	MD	MF	FB			
1.0	1.0	0.0				F	OK	
		1.0		0.0		G	OK	
				1.0	9.6E-01	H	OK	
					3.9E-02	I	NS	3.9E-02
	0.0	0.0				J	OK	
		1.0	1.0	0.0		K	OK	
				1.0	0.0	L	OK	
					1.0	M	NS	0.000
			0.0			N	NS	0.000
						Total		3.9E-02

2

Figure 12-1. Case 1, detection suppression event tree (1-π₂)

3

Figure 12-2 represents (1-η₁), the presence of redundant conventional spot-type detection and automatic suppression systems available in the area. (1-η₁) is calculated through sequences F to N. Automatic conventional spot-type detection has a failure probability of 0.05 (Ref. 36). The probability of failure for the fire brigade is calculated using the electrical suppression curve using a manual suppression time of 10 - 2 = 8 minutes (t_{ms} = t_{dam} - t_{det}) as:

8

$$e^{(-\lambda_{electrical} * 8)} = e^{(-0.098 * 8)} = 0.457$$

10

11

If the automatic detection fails, delayed detection is credited. Sequences J to N refer to this situation. Assuming a time to delayed detection of 15 minutes, the fire brigade has no time to suppress the fire before target damage (i.e., 10-15-7 < 0 minutes).

14

15

Accordingly, the non-suppression probability is the sum of sequences I, M and N, which is 0.457+ 0.050+ 0.00 = 0.507.

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Fire	Automatic		Manual			Sequence	End State	Pr (non-suppression)
	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	AD	AS	MD	MF	FB			
1.0	0.95	0.0				F	OK	
		1.0		0.0		G	OK	
				1.0	0.543	H	OK	
					0.457	I	NS	0.434
	0.05	0.0				J	OK	
		1.0	1.0	0.0		K	OK	
				1.0	0.0	L	OK	
					1.0	M	NS	0.050
			0.0			N	NS	0.000
						Total		0.484

3 **Figure 12-2. Case 1, detection suppression tree for (1-η₁)**

4 Figure 12-3 represents (1-η₂), the presence of redundant conventional spot-type detection and
 5 VEWFDS systems. That is, given a failure of the in-cabinet ASD VEWFD system to provide
 6 sufficient advance warning, the VEWFD system will still perform normal automatic detection
 7 functions comparable to those of normal spot detection. For in-cabinet applications, the ASD
 8 VEWFD system time to detect is assumed to be 0 minutes. (1-η₂) is calculated through
 9 sequences F to N. Automatic conventional spot-type detection along with VEWFDS detection,
 10 has a failure probability of 6.2×10⁻³ per Section 7.2.2. The probability of failure for the fire
 11 brigade is calculated using the electrical suppression curve using a manual suppression time of
 12 10 - 2 = 8 minutes as:

13
 14
$$e^{(-\lambda_{electrical} * 8)} = e^{(-0.098 * 8)} = 0.457$$

15
 16 If the automatic detection fails, delayed detection is credited. Sequences J to N refer to this
 17 situation. Assuming a time to delayed detection of 15 minutes, since the time for manual
 18 suppression is less than zero, the fire brigade has no time to suppress the fire before target
 19 damage.

20
 21 Accordingly, the non-suppression probability is the sum of Sequences I, M and N, which is
 22 0.454+ 0.006+ 0.00 = 0.460

23

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Fire	Prompt		Automatic		Manual			Sequence	End State	Pr(non-suppression)
	Detection	Suppression	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	PD	PS	AD	AS	MD	MF	FB			
1.0	1.0		0.994	0.0				F	OK	
				1.0		0.0		G	OK	
						1.0	0.543	H	OK	
							0.457	I	NS	0.454
			0.006	0.0				J	OK	
				1.0	1.0	0.0		K	OK	
						1.0	0.0	L	OK	
							1.0	M	NS	0.006
					0.0			N	NS	0.000
								Total		0.460

3 **Figure 12-3. Case 1, detection suppression event tree (1- η_2)**

4
5 **12.1.2 Case 2: In-cabinet, single control cabinet, force ventilation high ACH**

6
7 In this example, various in-cabinet smoke detection systems are evaluated for their ability to
8 enhance the suppression capability for a potential fire hazard located in a single control cabinet
9 with a high rate of forced ventilation (approximately 300 cabinet ACH). In addition, the room is
10 also equipped with area wide conventional spot smoke detection mounted on the ceiling. Each
11 in-cabinet smoke detection system will be evaluated separately. The following information is
12 necessary before proceeding with the analysis.

- 13
14 • Based on fire modeling analysis, the estimated time for conventional area wide smoke
15 detection is 2 minute.
16
17 • Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
18
19 • From fire drills records, the brigade response time is 10 minutes.

20
21 Based on the above information the values presented in Table 12-2 are to be used in applying
22 the in-cabinet ASD VEWFD event tree approach;
23

1 **Table 12-2. Case 2, Input Parameters: Single Low Voltage Control Cabinet, In-Cabinet**

Parameter	Estimate	Source
α	7.2E-01	Fraction of fires that have an incipient phase Table 7-1, Low Voltage Control cabinet
1- β	6.2E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFDF systems NUREG/CR-6850 – Appendix P
1- τ	1.9E-02 : ASD CC 3.7E-01 : ASD LS 7.9E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Forced Ventilation
1- μ	1E-04	MCR operator response Section 10.5.4
1- ξ	1.2E-3 : ASD CC 0.11 : ASD LS 0.11 : ION	Field operator & technician response Table 10-6, 1&3-Cabinet – ASD VEWFDF CC Table 10-12, 1&3-Cabinet – LS and SS Table 10-9, 1&3-Cabinet – Ionization
1- π_1	1.0E-03	Technician / Field operator staged <u>directly</u> at the specific cabinet responsible for the VEWFDF alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u> .
1- π_2	3.9E-02	Same as Case 1
1- η_1	4.8E-01	
1- η_2	4.6E-01	
RESULT	With Conventional Detection	Without Conventional Detection (setting “ η_1 ” to 0)
	ASD CC : 1.4E-01 (7.3) ASD LS : 2.5E-01 (3.9) ION :4.0E-01 (2.5) FAQ 08-0046 : 8.2E-03(122.5) NUREG/CR-6850 : 5.82E-01 (1.6)	ASD CC : 1.4E-01 (7.1) ASD LS : 2.6E-01 (3.9) ION :4.2E-01 (2.4) FAQ 08-0046 : 1.6E-02 (62.8) NUREG/CR-6850 : 5.82E-01 (1.6)

2
3 For this case the solution of the conventional detection suppression event tree from
4 NUREG/CR-6850 for the terms 1- π_2 , η_1 and η_2 , are identical to Case 1 and will not be repeated
5 here.
6

7 **12.1.3 Case 3: In-cabinet ASD VEWFDF, power cabinet with 10 vertical sections,**
8 **natural ventilation**
9

10 In this example, various in-cabinet smoke detection systems are evaluated for their ability to
11 enhance the suppression capability for a potential fire hazard located in power cabinets (motor
12 control center with ten vertical sections) with natural ventilation. In addition, the room is also
13 equipped with area wide conventional spot smoke detection mounted on the ceiling. The
14 following information is necessary before proceeding with the analysis.
15

- 1 • Based on fire modeling analysis, the estimated time for conventional area wide smoke
2 detection is 2 minute.
- 3
- 4 • Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
- 5
- 6 • From fire drills records, the brigade response time is 10 minutes.
- 7

8 Based on the above information the values presented in Table 12-3 are used.

9 **Table 12-3. Case 3 Input Parameters: Multi-Power Cabinet, In-Cabinet**

Parameter	Estimate	Source
α	5.1E-01	Fraction of fires that have an incipient phase Table 7-1, Power Cabinets
1- β	6.2E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P
1- τ	2.7E-03 : ASD CC 1.9 – 5.3E-01 : ASD LS 2.6E-01 : SS 1.0E-01 : ION	System ineffectiveness Table 7-3, In-cabinet, Natural Ventilation
1- μ	1E-04	MCR operator response Section 10.5.4
1- ξ	0.30 : ASD CC 0.48 : ASD LS 0.48 : SS 0.41 : ION	Field operator & technician response Table 10-8, 10-Cabinet – ASD VEWFD CC Table 10-14, 10-Cabinet – LS and SS Table 10-11, 10-Cabinet – Ionization
1- π_1	1.0E-03	Technician / Field operator staged <u>directly</u> at the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u> .
1- π_2	3.9E-02	Same as Case 1
1- η_1	4.8E-01	
1- η_2	4.6E-01	
RESULT	With Conventional Detection	Without Conventional Detection (setting “ η_1 ” to 0)
	<u>Detection Type: Pr_{n-s} (Factor of credit)</u> ASD CC : 2.3E-01 (4.4) ASD LS : 2.8E-01 (3.6) 3.7E-01 (2.71) SS : 3.0E-01 (3.3) ION :2.7E-01 (3.7) FAQ 08-0046 : N/A NUREG/CR-6850 : 2.9E-01 (3.42)	<u>Detection Type: Pr_{n-s} (Factor of credit)</u> ASD CC : 2.3E-01 (4.3) ASD LS : 2.8E-01 (3.5) 3.6E-01 (2.8) SS : 3.2E-01 (3.0) ION :2.9E-01 (3.4) FAQ 08-0046 : N/A NUREG/CR-6850 : 2.9E-01 (3.42)

1 For this case the solution of the detection suppression event tree from NUREG/CR-6850 for the
 2 terms $1-\pi_2$, η_1 and η_2 , are identical to Case 1 and 2, and will not be repeated here.

3
 4 **12.1.4 Case 4: Areawide ASD VEWFD installed on air return grill, mix of control
 5 and power cabinets**

6 In this example, various room smoke detection systems are evaluated for their ability to
 7 enhance the suppression capability for a potential fire hazard located in a mix of power and
 8 control cabinets all. The room has an HVAC system. The following information is necessary
 9 before proceeding with the analysis.

- 10
- 11 • Based on fire modeling analysis, the estimated time for conventional area wide smoke
 12 detection is 2 minute.
- 13
- 14 • Based on fire modeling analysis, the estimated time to target damage is 10 minutes.
- 15
- 16 • From fire drills records, the brigade response time is 10 minutes.
- 17

18 Based on the above information the values presented in Table 12-4 are to be used in applying
 19 the incipient event tree approach;
 20

Table 12-4. Case 4 Input Parameters: Mixed Cabinet Type, Areawide

Parameter	Estimate	Source
α	5.4E-01	Fraction of fires that have an incipient phase Table 7-1, Bin 15 – All Cabinet Types
$1-\beta$	6.6E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P 4E-04 HVAC unreliability estimate used
$1-\tau$	<u>Ceiling</u> 3.2E-01 : ASD CC 1.1E-01 : ASD LS 5.7E-01 : SS 8.1E-01 : ION	System ineffectiveness Table 7-3, Areawide, Ceiling
	<u>Air Return</u> 3.0E-01 : ASD CC 5.2E-01 : ASD LS	System ineffectiveness Table 7-3, Areawide, Air Return Grill
$1-\mu$	1E-04	MCR operator response Section 10.5.4
$1-\xi$	1.0	Field operator & technician response Section 10.5.6
$1-\pi_1$	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFDS alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating</u> <u>component.</u>
$1-\pi_3$	1.4E-01	See discussion below
$1-\eta_2$	5.7E-01	
$1-\eta_3$	1.00	

RESULTS	Ceiling Detection		Air Return Detection	
	Detection Type	Pr _{n-s} (Factor)	Detection Type	Pr _{n-s} (Factor)
	ASD CC :	5.5E-01 (1.8)	ASD CC :	5.4E-01 (1.9)
	ASD LS :	4.1E-01 (2.4)	ASD LS :	6.8E-01 (1.5)
	SS :	7.7E-01 (1.4)	SS :	N/A
	ION :	8.8E-01 (1.1)	ION :	N/A
	FAQ 08-0046 :	N/A	FAQ 08-0046 :	N/A
	6850 :	1.0 (1.0)	6850 :	N/A

Figure 12-4, and Figure 12-5, illustrate the solution of the detection suppression event tree from NUREG/CR-6850 for the terms $1-\eta_2$ and $1-\eta_3$, respectively. The estimate for π_3 uses the non-suppression probability curves with $\lambda=0.194$.

$1-\pi_3$, the probability that, given **failure** of event ξ , the technician/field operator in the room responsible for the VEWFDs alert fails to promptly suppress the fire quickly enough to prevent damage to PRA targets outside the cabinet. $1-\pi_3$ is calculated using a suppression curve with $\lambda=0.194$. For this case both the time to detection of the VEWFDs system and time to fire brigade response are set to 0 minutes considering that the system has already gone into alarm and the technician/field operator is present within the room. The technician/field operator acts as the fire brigade as they have been trained to suppress fires (e.g., fire brigade training).

The probability of failure to extinguish the fire, once ignition has occurred, is calculated using the field operator detection curve ($\lambda = 0.194$) at time $10-0-0 = 10$ minutes as:

$$e^{(-\lambda_{area} * 10)} = e^{(-0.194 * 10)} = 0.144$$

Figure 12-4 represents $1-\eta_2$, the probability that the VEWFDs system will activate given a fire without an incipient stage. That is, given a failure of the VEWFD system to provide sufficient advance warning, the VEWFD system will still perform normal automatic detection functions comparable to that of normal spot detection. $1-\eta_2$ is calculated through sequences F to N with VEWFD system represented with a failure probability of 0.0 given that detector system availability, reliability, and effectiveness is accounted for with the β_4 branch point. The probability of failure for the fire brigade is calculated using the "All fires" suppression curve at time $10 - 2 = 8$ minutes as:

$$e^{(-0.070 * 8)} = 0.571$$

According to Section P.1.5, the non-suppression probability is the sum of Sequences I, M and N, which is $5.0 \times 10^{-1} + 0.0 + 0.0 = 6.1 \times 10^{-1}$

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Fire	Prompt		Automatic		Manual			Sequence	End State	Pr(non-suppression)
	Detection	Suppression	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	PD	PS	AD	AS	MD	MF	FB	F	OK	
1.0	1.0		1.0	0.0						
				1.0		0.0		G	OK	
						1.0	4.29E-01	H	OK	
							5.71E-01	I	NS	5.71E-01
			0.0	0.0				J	OK	
				1.0	1.0	0.0		K	OK	
						1.0	0.0	L	OK	
							1.0	M	NS	0.0
					0.0			N	NS	0.0
								Total		5.71E-01

3 **Figure 12-4. Case 4, conventional detection suppression tree for (1- η_2)**

4 Figure 12-5 represents η_3 , the probability that the ASD VEWFD system fails. That is, given a
 5 failure of the areawide VEWFDS system or main control room response to an ASD VEWFD
 6 response there is no redundant normal detection capability within the room to detect the fire
 7 before manual delayed detection. Delayed detection is assumed 1.0 for cases where no prompt
 8 or automatic detection is credited (or fails) if the estimated time for manual detection is less than
 9 the time to target damage. $1-\eta_3$ is calculated through sequences J – N. Assuming a time to
 10 delayed detection of 15 minutes, the fire brigade has no time to suppress the fire before target
 11 damage.

12
 13 Accordingly, the non-suppression probability is the sum of Sequences I, M and N, which is $0.0 +$
 14 $1.0 + 0.0 = 1.0$

15

1

Fire	Prompt		Automatic		Manual			Sequence	End State	Pr(non-suppression)
	Detection	Suppression	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	PD	PS	AD	AS	MD	MF	FB	F	OK	
1.0	1.0		0.0	0.0				G	OK	
				1.0		0.0		H	OK	
						1.0	0.0	I	NS	0.0
			1.0	0.0				J	OK	
				1.0	1.0	0.0		K	OK	
						1.0	0.0	L	OK	
							1.0	M	NS	1.0
					0.0			N	NS	0.0
								Total		1.0

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Figure 12-5. Case 4, conventional detection suppression tree for (1-η3)

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12.1.5 Case 5: Areawide ASD VEVFD installed on air return grill, mix of control and power cabinets, with room suppression

This example is identical to Case 4, with the exception that an automatic Halon suppression system is available in the room. The only event tree parameter that changes is $(1-\eta_2)$, as shown in Figure 12-6. Here the probability of the Halon system failure is 0.05 per NUREG/CR-6850 guidance in Appendix P.

Fire	Prompt		Automatic		Manual			Sequence	End State	Pr(non-suppression)
	Detection	Suppression	Detection	Suppression	Detection	Fixed	Fire Brigade			
FI	PD	PS	AD	AS	MD	MF	FB			
1.0	1.0		1.0	0.95				F	OK	
				0.05		0.0		G	OK	
						1.0	4.29E-01	H	OK	
							5.71E-01	I	NS	2.9E-02
			0.0	0.0				J	OK	
				1.0	1.0	0.0		K	OK	
						1.0	0.0	L	OK	
							1.0	M	NS	0.0
					0.0			N	NS	0.0
								Total		2.9E-02

11 **Figure 12-6. Case 5, conventional detection suppression tree for $(1-\eta_2)$**

12 Table 12-5 presents the results.

1

Table 12-5. Case 5 Input Parameters: Mixed Cabinet Type, Areawide with Halon

Parameter	Estimate	Source
α	5.4E-01	Fraction of fires that have an incipient phase Table 7-1, Bin 15 – All Cabinet Types
1- β	6.6E-03 (ASD) 5E-02 (Spot)	System availability and reliability Section 7.2 of this report for ASD VEWFD systems NUREG/CR-6850 – Appendix P 4E-04 HVAC unreliability estimate used
1- τ	<u>Ceiling</u> 3.2E-01 : ASD CC 1.1E-01 : ASD LS 5.7E-01 : SS 8.1E-01 : ION 8.7E-01 : PHOTO	System ineffectiveness Table 7-3, Areawide, Ceiling
	<u>Air Return</u> 3.0E-01 : ASD CC 5.2E-01 : ASD LS	System ineffectiveness Table 7-3, Areawide, Air Return Grill
1- μ	1E-04	MCR operator response Section 10.5.4
1- ξ	1.0	Field operator & technician response Section 10.5.6
1- π 1	1.0E-03	Technician / Field operator staged <u>directly at</u> the specific cabinet responsible for the VEWFD alert fails to promptly suppress the fire quickly enough to prevent damage to targets <u>outside the initiating component</u> .
1- π 3	1.4E-01	See discussion above
1- η 2	2.9E-02	
1- η 3	1.00	
RESULTS	Ceiling Detection <u>Detection Type Pr_{n-s} (Factor)</u> ASD CC : 3.8E-01 (2.6) ASD LS : 1.9E-01 (5.2) SS : 6.2E-01 (1.6) ION : 8.3E-01 (1.4) FAQ 08-0046 : N/A 6850 : 1.0 (1.0)	Air Return Detection <u>Detection Type Pr_{n-s} (Factor)</u> ASD CC : 4.0E-01 (2.06) ASD LS : 5.7E-01 (1.7) SS : N/A ION : N/A FAQ 08-0046 : N/A 6850 : N/A

2

12.2 Evaluation of the Event Tree Sensitivity

The in-cabinet event tree was evaluated for the “Fire Damage Outside Cabinet” damage state sensitivity to parameters. The conventional suppression was not modeled such that the results are applicable to the probability of non-suppression contributed to the use of in-cabinet VEWFD systems with appropriate operator response. Since conventional detection is set to fail (i.e., “ η ” set to 0), and the small HEP for MCR response “ $1-\mu$ ” 5×10^{-4} ; the only two parameters that affect the damage states are α and β . The results of the sensitivity are presented in Figure 12-7 showing the change in the factor of credit ($1/Pr_{\text{non-supp}}$).

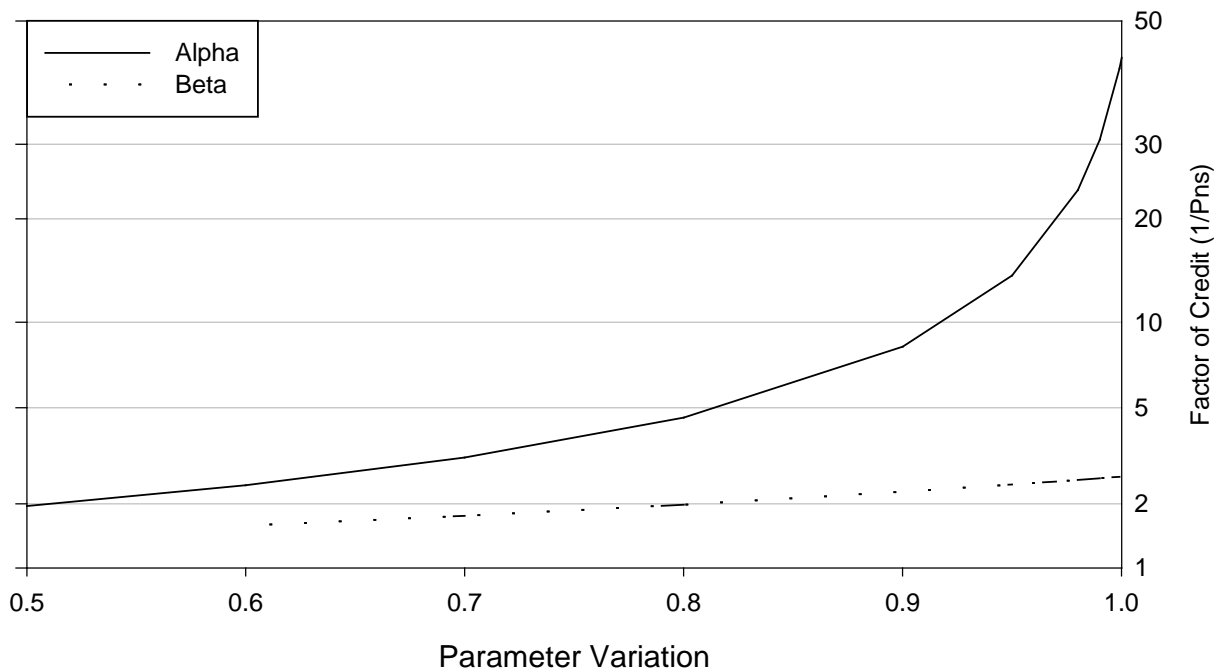


Figure 12-7. Probability of non-suppression sensitivity to α and β for ASD only (in-cabinet, conventional suppression not modeled).

12.3 Assumptions, and Limitations

The aforementioned quantification effort is based on the following assumptions and limitations:

1. System is designed and installed by trained and qualified technicians following appropriate vendor guidance. Any deviations between as-built and as-designed should be evaluated for effects on system performance
2. Systems are inspected, tested and maintained per vendor recommendations or applicable national consensus standards
3. Functionality testing via detector alarm response to smoke stimulus should be conducted following guidance in Annex A of NFPA 76 or vendor equivalent methods. Air flow through each sampling port credited for protection is verified.
4. Cabinet characteristics allow for the application of VEWFD systems, such that they are not tightly sealed.
5. The sensitivity settings of the VEWFD system is setup to meet or exceed (be more sensitive than) the NFPA 76 sensitivity requirements, namely

Light-scattering

- a. an *alert* is set to 0.2 %/ft obscuration at the sampling point above background, and
- b. an *alarm* is set to 1.0 %/ft obscuration at the sampling point above background

Cloud Chamber

- a. an *alert* is set to 1.0×10^6 particles/cm³ at the sampling point, based on tested configurations.
6. The sensitivity setting for the conventional system used for in-cabinet applications meet or exceed the sensitivities tested, namely;

ION Spot-type

- a. An *alarm* is set to 1.0 %/ft obscuration

PHOTO Spot-type

- b. An *alarm* is set to 2.0 %/ft obscuration

7. The VEWFD system *alert* corresponds to the field operator or technician response and a VEWFD *alarm* corresponds to an expeditious fire brigade response as described in Section 10.
 - a. When using a detection strategy with no ability to differentiate between the alert and alarm set points (i.e., in-cabinet ionization detectors with one setpoint), the alarm response should correspond to an expeditious fire brigade response as described in Section 10.

8. The approach presented is not applicable to main control room applications or other spaces that are continuously occupied. No human subject testing was performed to assess the performance of human senses to the response of smoke detection systems.
9. Compensatory measures are put in place whenever the VEWFD or conventional spot-type smoke detection system is unavailable.
10. Plant personnel responding to VEWFD or conventional spot-type systems are trained in the use of the systems, and any portable devices used to locate the degrading component.
11. The use of VEWFD or conventional spot-type systems does not replace the requirement to demonstrate the ability to meet the nuclear safety performance criteria for a fire scenario and its impact(s) on safe shutdown equipment.
12. Alarm response procedures are specific to VEWFD and training
13. Areawide HEP's are 1.0. The above examples do not include timing feasibility considerations as discussed in Section 10.5.6.

PART III

Conclusions and Perspectives

Definitions and References

13. REPORT SUMMARY AND CONCLUSIONS

This section summarizes the specific findings based on the analysis of the test data and review of the operating experience and literature related to the performance of very early warning fire detection systems, specifically aspirating smoke detection (ASD) configured as very early warning fire detection (VEWFD) systems. These findings are specific to the objectives outlined in Section 1.3

Operational experience and the tests performed under this program show that aspirated VEWFD systems, when designed, installed, and maintained are effective in detecting low-energy pre-flaming fire conditions. However, the testing has also shown that other forms of smoke detection such as conventional ION spot-type detectors perform equally well in naturally ventilated in-cabinet applications. The test results show that in-cabinet applications are the most effective use of smoke detection technologies in detecting low-energy incipient stage electrical cabinet fires as compared to areawide ceiling level detection. Areawide applications using an air return grill and those using ceiling-mounted air sampling port locations perform similarly. However, as ceiling height increases, ceiling areawide aspirated VEWFD applications will become less effective at detecting low-energy incipient fire sources, unless system sensitivities are increased or sampling port spacing is decreased.

VEWFD systems don't always provide enhanced warning over conventional spot-type detection during the low-energy incipient stage. The performance of either type of system (VEWFD or conventional spot-type) is dependent upon the material thermal decomposition rate, and aerosol characteristics. For in-cabinet applications, the cloud chamber ASD typically outperformed the other systems tested, followed by the ION spot-type detector which typically outperformed the light-scattering ASD and sensitive spot-type detectors. The PHOTO spot-type detector typically responded the slowest during the in-cabinet tests. The cloud chamber and ION in-cabinet performance is largely because of the aerosol characteristics at the early stage, which are typically spherical in nature; also the effects of aerosol aggregation and agglomeration have not developed to a point where light-scattering type detectors can be effective. However, the exception is CSPE material (or materials with similar aerosol characteristics), which had the largest partial size for the materials tests.

In areawide applications, the ASD and sensitive spot-type VEWFD systems typically performed better than the ION and PHOTO spot-type detectors. The ASD's ability to use cumulative sampling is largely the cause of the effect. ASD systems also have the added benefit of using filters to reduce nuisance alarm rates and can be designed to allow for more efficient inspection, maintenance, and testing. For fast-developing fires, the amount of additional warning between VEWFD and conventional systems is marginal at best.

With the exception of ASD systems designed to protect a single electrical cabinet, human interaction with equipment such as handheld thermal imaging cameras or portable ASDs will be needed to pin point the incipient fire. As part of the human factors analysis, a table top analysis of a generic plant personnel response to ASD VEWFD system alarms was conducted. The task analysis supports a human reliability analysis. Based on the expected operational response and timing estimate developed from operating experience and test results, a human reliability analysis was conducted based on the overall strategy that parallels post-initiator operator actions. The results of this HRA indicate that human error probabilities vary but combined with the suppression analysis, conclude that the trained human response is likely to succeed.

1
2 Review of operating experience, vendor supplied information, and literature has shown
3 agreement with the unreliability estimate provided in EPRI 1016735, "Fire PRA Methods
4 Enhancements: Additions, Clarification, and Refinements to EPRI 1019189." However, ASD
5 system unavailability differs from that report in the EPRI document, and is estimated at 1.7×10^{-3}
6 per detector unit per year, based on an average annual system down-time from plants where
7 information was collected. A wide variance of system downtime was observed from site visits
8 and literature. It was noted that system unavailability improved for facilities that had these
9 systems installed and operating for a number of years. Facilities which were using ASD
10 systems for the first time indicated longer system downtime, likely because of the lack of
11 understanding of the system maintenance requirements to ensure proper operation. For
12 areawide air return grill applications, the unreliability/unavailability of the ventilation system
13 should also be modeled, since the air return grill application requires forced ventilation to
14 perform as designed.

15
16 The experimental testing program has confirmed that cabinet design, fill/obstructions and
17 ventilation effects can influence the performance of VEWF systems. Forced cabinet
18 ventilation is a primary influence factor on detector response, especially with high rates of
19 cabinet air exchange. As cabinet ventilation rates increase, so does smoke dilution. For the
20 forced-ventilation rates used in this project's tests, the ASDs were slower to respond in force-
21 ventilated (high air exchange rate) cabinets than naturally ventilated cabinets. In addition the
22 ASDs were less effective in reaching an "alert" threshold in force-ventilated cabinet (high air
23 exchange rate) tests.

24
25 For in-cabinet applications, the presence of openings or lack of partitions between adjacent
26 cabinet sections having ASD sampling ports enhances the time to detection; this is because of
27 the cumulative effect of drawing samples from multiple sampling ports. For this effect to be
28 beneficial openings between cabinets would have to be sufficient in size to allow for the air
29 space communication between cabinet vertical sections.

30
31 Smoke source location also has an effect on VEWF response. The closer the source is to the
32 detector or sampling point, the more rapid the response. In the full-scale small room tests
33 where the source was elevated approximately two-thirds of the height of the cabinet off the
34 cabinet base; the ASDs responded approximately 9 percent faster than when the sources were
35 located on the base.

36
37 Other parameters not explicitly explored in this program's tests, but covered in the literature
38 relate to soot deposition and loss of aerosol thorough ventilation. Soot deposition internal to the
39 electrical cabinet will be influenced by the obstructions/fill (impaction), thermal gradients
40 (thermophoresis), and electric fields (electrophoresis). Cabinets with a large surface area of
41 ventilation, such as louvered vents compounded by thermophoresis, could result in a fraction of
42 aerosol being lost through these vents. These phenomena would cause less aerosol to be
43 transported to the ASD sampling ports located at the ceiling of the electrical cabinet resulting in
44 a delay in detection (compared to the data in this report), and a decrease in the effectiveness in
45 detection of low-energy fires during the incipient stage.

46
47 An evaluation of the non-suppression probability shows that the use of these systems can
48 reduce plant risk from the consequences of electrical cabinet fires. It has been shown that a
49 dominant contributor to the risk model is the estimation of the fraction of *potentially challenging*
50 *or greater fires* which exhibit an incipient fire stage of sufficient duration to allow for operator
51 response. Since fire PRAs only quantify those fires that initiate and can potentially grow to a

1 damaging state, the majority of smoking events are not modeled (included as a fire initiator).
2 The previous methods (EPRI 1011989 and FAQ 08-0046) used to estimate this characteristic
3 could not be confirmed based on the evaluation of the operating experience.
4

5 The risk benefit for using these systems varies by application with in-cabinet detection being the
6 best approach for detecting low-energy incipient sources early enough to allow for suppressing
7 before target damage to multiple components within or outside the electrical cabinet. Areawide
8 applications also provide some risk benefit; however, they are usually slower to detect low
9 energy fires because of a number of previously discussed contributing factors.
10

11 **13.1 Conclusions**

12
13 This confirmatory research program has shown that the performance of smoke detection to
14 detect low-energy pre-flaming conditions varies by detection technology, application, and
15 aerosol characteristics (dependent on material degradation characteristics).
16

17 For in-cabinet applications, the ASD cloud chamber VEWFD and ION spot-type detection
18 systems performed better than all light-scattering based technologies (three of the five ASD
19 VEWFD systems, sensitive spot VEWFD and PHOTO spot-type detector). This conclusion is
20 based on the systems response (ability to detect and mean time to detection) to the materials
21 and methods used in testing.
22

23 In areawide applications, the ASD systems outperformed the conventional spot-type detectors
24 (ION, PHOTO) for detecting low energy fire sources. This program has also confirmed that the
25 earliest and most effective method of detecting low energy fires is when the detector or
26 sampling port is located within the NPP electrical enclosure being protected.
27

28 This research has also provided a refined approach to quantify the performance of smoke
29 detection systems that could be used in fire PRA applications to estimate the non-suppression
30 probability. This refined approach uses operating experience, literature, test results, human
31 reliability methods, and the exponential suppression model to characterize the systems
32 performance. The approach relies more heavily on timing based information to characterize the
33 performance of the systems tested. Because of the uncertainty associated with characterizing
34 the duration and aerosol generation of the incipient stage for equipment commonly found in
35 nuclear power plant electrical enclosures, there are several parameters and assumptions that
36 could enhance the overall risk characterization. Most notably, the refined approach is sensitive
37 to the characterization of *Potentially Challenging or Greater Fires*³⁶ which exhibit an incipient
38 stage with a short duration and the timing associated with fires which do have a longer duration
39 incipient stage.
40

41 All methods currently available use some form of assumptions and limitations to bound the
42 evaluation. Validation of these assumptions and limitations could be better understood by
43 industry and regulatory support to facilitate collecting operating experience directly related to the
44 performance of these ASD VEWFD systems in NPP applications or within other industries with
45 similar components and equipment. Information such as nuisance alarm rate, scheduled and
46 unscheduled system down time, total number of operating detectors and years of operation for
47 each system would be useful in evaluating ASD performance. In addition, consistent and

³⁶ Potentially challenging or greater fires are classified as challenging, potentially challenging, or undetermined with regard to the fire severity classification documented in EPRI 1025284, "The Updated Fire Events Database: Description of Content and Fire Event Classification Guidance."

1 detailed reporting of instances where potential fires were caught in an incipient stage, how long
2 it took operators from time of VEWFD system alert to de-energize the equipment, instances
3 where flaming fires occurred and the associated time to suppress those fires that did occur
4 would help support any future risk quantification effort. Complete and consistent reporting could
5 be coordinated by a nuclear industry users group. General information on lessons learned from
6 the use of these systems in NPPs could be communicated via industry forums to benefit the use
7 of these systems such that an understanding of the performance of these systems could be
8 achieved.
9
10

14. RECOMMENDATIONS FOR FUTURE RESEARCH

This report has provided a consolidation of the best information to date related to aspirating smoke detection (ASD) system response to smoke sources typically found in U.S. nuclear power plant (NPP) electrical enclosures, along with a method for quantifying the performance of these systems in fire probabilistic risk assessment (PRA). In the process of quantifying these systems several assumptions had to be made. The most important quantity to define is the time duration distribution of the incipient stage. However, design fires typically do not model the incipient growth stage of fire. NUREG/CR-6850 (EPRI 1011989) models fires with a power law growth profile starting at time zero. Thus, following this model provides little to no incipient stage, depending on how you define the transition point of incipient to growth. Thus, for a more consistent application of this technology's potential advantages in performance-based applications, it would be desirable to develop scenario-specific (electrical enclosures, pump fires, transient fires, etc.) design fires that account for the incipient stage of burning. This is not to say that the incipient stage would exist in all scenarios, but development of a consensus definition of the incipient stage for various scenarios, and a consensus on how and when to model the incipient stage, could allow for greater certainty on the quantification of these systems in fire PRA.

With the limited knowledge of the incipient stage duration for *potentially challenging or greater fires* and the use of event trees to model risk, only a few conclusions can be drawn; the results of any research are only as good as the assumptions made. The human error probabilities (HEPs) were based on an estimate of time available for operator response developed from only a small sample of fire events in which sufficient information was available to quantify this duration; as such, this estimate is inherently uncertain. An alternative method to quantify this duration would be to conduct a formal elicitation process whereby a group of qualified experts with diverse backgrounds and knowledge provide professional judgment for use in quantifying the incipient stage duration. A panel constituted of NPP equipment manufacturing experts, fire PRA experts, and experts from other industries with fire response field experience, could develop a comprehensive view point to represent the scientific communities view.

A better measure of ASD very early warning fire detection VEWFD system performance may occur when sufficient operating experience in nuclear facilities is obtained and compared to similar applications lacking the use of this technology. Depending on the provenance of the use of this technology, operating experience gained over a period of 10 years, may provide a sufficient database to support such an evaluation. However, to make for a useful measure of system performance, it is recommended that a group associated with the nuclear industry's research arm, or operating experience, support a comprehensive and consistent reporting program. Such a program would provide useful information such as the number of detectors in use; nuisance alarm rate; availability estimates; reporting of operator response; including time to locate incipient source; number of cabinets being protected per detector zone; flaming fires that do occur in equipment protected by ASD VEWFD systems; and associated time to suppress such fires.

The testing program was limited by the availability of electrical enclosures to test. As such, the applicability of the test results for cabinets with louvered doors and/or back panels has not been determined. Additional data on cabinet ventilation configurations and a more rigorous evaluation of the effects of varying mechanical ventilation rates, would help support an evaluation of the performance of these systems.

1 As mentioned in the experimental approach section, an issue was identified concerning
2 sensitivity settings for the cloud chamber ASDs, which was not fully resolved. These ASDs do
3 not report detector sensitivity in terms of U.S. detection industry standard engineering units of
4 percentage of obscuration per foot, but in terms of numeric (dimensionless) settings. Although
5 the authors are not implying that the cloud chamber technology is deficient, guidance to support
6 the selection of set points to achieve the NFPA 76 sensitivity settings would be beneficial.

7
8 This report focused exclusively on the fire hazards associated with electrical enclosure fires.
9 Other types of equipment found in NPPs such as pumps, motors, air handling units, transient
10 combustibles, among others can exhibit an incipient stage and ASD VEWFD systems may
11 provide enhanced warning and a risk reduction. An evaluation similar to what was done in this
12 report would be beneficial. Follow-on work could catalog the types of smoke sources and
13 materials found in NPPs that contribute to the *potentially challenging or greater fires*
14 characterized by fire PRA.

15
16
17

15. DEFINITIONS

Acceptance test – The process wherein every sampling port is provided an appropriate stimulus that simulates the existence of the design fire, and the design sequence of operations of each system component in the entire system is verified and recorded in written form.^[1]

Alarm condition – An abnormal condition that poses an immediate threat to life, property, or mission.^[4]

Aspirating smoke detector (ASD) – A detector that consists of a piping or tubing distribution network that runs from the detector to the area(s) to be protected. An aspiration fan in the detector housing draws air from the protected area back to the detector through air sampling ports, piping, or tubing. At the detector, air is analyzed for fire products. This type of detector is also known as an *Air Sampling-Type Detector*.^[2]

Diffusion flame – A flame in which fuel and air mix or diffuse together at the region of combustion.^[4]

Early warning fire detection systems (EWFDS) – Systems that use smoke, heat, or flame detectors to detect fires before high heat conditions threaten human life or cause significant damage to telecommunications service.^[3]

Pre-alarm condition – An abnormal condition that poses a potential threat to life, property, or mission, and time is available for investigation.^[4]

Pyrolysis – A process in which material is decomposed or broken down, into simpler molecular compounds by the effects of heat alone; pyrolysis often precedes combustion.^[4]

Response time – The time between the generation of combustion aerosols at their source and the indication of their presences at the ASD. ^[5]

Sampling port – An orifice, through which air is drawn to an air sampling-type detector.^[3]

Sensitivity – Relative degree of response of a detector measured in percent per meter obscuration (%/ft obscuration). A higher sensitivity denotes response to a lower concentration of smoke than a low sensitivity, under identical smoke build-up conditions.^[6]

Sensitivity measurement – A quantitative measurement and recording of the stimulus necessary to achieve an alarm signal from an initiating device. A sensitivity measurement determines how large a stimulus is necessary to cause an alarm response. This measurement is to be compared to the value for the unit as shipped [as designed] to quantify any change in the performance one can anticipate from the unit. Thus, the sensitivity measurement is intended to assess the ability of the detector to perform its intended function when the design fire occurs. A sensitivity measurement differs from a test in that a test does not imply that the stimulus is of a similar magnitude to that obtained from the design fire.^[1]

- 1 **Smoke** - The airborne solid and liquid particulates and gases evolved when a material
2 undergoes pyrolysis or combustion, together with the quantity of air that is entrained or
3 otherwise missed into the mass.^[1]
4
- 5 **Smoke dilution** – A reduction in the quantity of smoke per unit of air volume of smoke reaching
6 the detector.^[2]
7
- 8 **Smoldering combustion** – A slow, low-temperature, flameless form of combustion, sustained
9 by the heat evolved when oxygen directly attacks the surface of a condensed-phase
10 fuel.^[7]
11
- 12 **Spot-type smoke detector** – A device whose detecting element is concentrated at a particular
13 location.^[6]
14
- 15 **Standard fire detection systems (SFDS)** – Systems that use fire detection-initiating devices to
16 achieve certain life-safety and property protection in accordance with applicable
17 standards.^[3]
18
- 19 **Stratification** – The phenomena whereby the upward movement of smoke and gases ceases
20 because of loss of buoyancy.^[2]
21
- 22 **Very early warning fire detection systems (VEWFD systems)** – Systems that detect
23 low-energy fires before the fire conditions threaten telecommunications service.^[3]
24

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- 44 64. NRC, "NUREG/CR-6883, The SPAR-H Reliability Analysis Method," August 2005.
- 45
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47 Analysis Procedure," 1987.
- 48
- 49

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APPENDIX A

VIEWGRAPHS FROM MEETING WITH ASD VENDORS

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A.1 Summary of Meeting

On May 16, 2013, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research conducted a meeting between the three aspirating smoke detection (ASD) vendors whose equipment was tested. Staff from NRC, National Institute of Standards and Technology (NIST), and at least one technical representative from each ASD vendor were present. The purpose of this meeting was to inform the vendors of how their systems were being setup and tested, present how their systems may be used in fire probabilistic risk assessment applications, and to elicit feedback from the vendors on specific engineering design guidance regarding ASD systems for nuclear power plant applications. Additionally, discussion on equipment listings and approvals occurred. The morning portion of the meeting consisted of presentations given by NRC and NIST staff; these presentations are located in the NRC Agencywide Document Access and Management System (ADAMS), under Accession No. ML14356A581. The afternoon portion of the meeting consisted of open discussions among all participants.

APPENDIX B

SUPPORTING EXPERIMENTAL DATA

B.1 Alarm Times and Experimental Conditions and Sample images

A file naming convention was followed to distinguish the various experiments, data files, and image files, and it is described in Table B1. An example of this naming convention is “A_XLPE_5_E_2.1” which represents an (A) areawide test, using XLPE source material located in a 5-cabinet configuration, with (E) cabinet ventilation, a 1-hour nominal heating ramp and this is the (.1) first test.

Table B-1. File name convention

Alarm configuration	C: In-Cabinet;	A: Areawide	M: Multi-zone
Material	PVC1: PVC wire (1) Teflon: PTFE wire XLPO1: XLPO wire (1) XLPE: XLPE wire 1XLPE : Single XLPE wire 2wire: Dual wire test Capacitor: 2 Capacitors Board PTB: Phenolic Terminal block	PVC2: PVC wire (2) Silicone: Silicone wire XLPO2: XLPO wire (2) CSPE: CSPE wire 1wire: Single wire test #Resistor: # of resistors PCB: Epoxy Printed Circuit Board	
Cabinet configuration	L: Laboratory Instrument cabinet 1: Single cabinet 3: Three cabinets configuration 4: Four cabinets configuration 5: Five cabinets configuration B: Laboratory Bellefonte cabinet O: Center of the Room C: Corner (Small Room) RL: Rear Left corner (Large Room) FR: Front right corner (Large Room)		
Test conditions	A: Top vents B: Side vents C: Room Ventilation D: Elevated Sample E: Cabinet Ventilation F: 7.4 ACH Room Ventilation G: 6.5 ACH Room Ventilation H: 14 ACH Room Ventilation		
Heating rate	0 : Single Wire test: 60 second charge Dual Wire test: 90 seconds charge 1: 15 min nominal heating ramp 2: 1 hour nominal heating ramp 3: 4 hours nominal heating ramp 4: 15 min nominal ramp with extended hold period.		
Test repeat #			

1 **B.1.1 Raw Data File Header Descriptions**

2

3 The following text describes the column header for the (raw) experimental data files for each set
4 of experiments conducted:

5

6 **Alarm Time Files—Laboratory Instrument and Large Cabinet Experiments**

7 Time - CPU time (Hour : Minute : Seconds)

8 Count - Loop time increment (s)

9 ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)

10 ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)

11 ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)

12 ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)

13 ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)

14 ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)

15 ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)

16 ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)

17 ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)

18 ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)

19 ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)

20 ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)

21 ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)

22 ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)

23 FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)

24 FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)

25 PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the
26 instrument cabinet .

27 PHOTO (1) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located outside the
28 instrument cabinet.

29 PHOTO (2) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
30 instrument cabinet.

31 PHOTO (2) C Alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
32 instrument cabinet.

33 SS (3) Pre-alert -SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument
34 cabinet.

35 SS (3) Pre-alert-SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument
36 cabinet.

37 ION (4) Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument
38 cabinet.

39 ION (4) C Alarm -ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the instrument
40 cabinet.

41 Temperature at Humidity Probe (oC) – The temperature (°C) at the location of the humidity
42 probe inside the instrument cabinet.

43 Relative humidity (%)– Relative humidity (%) inside the instrument cabinet.

44 Temperature, Top cabinet (°C) – Temperature (°C) measurement, at the base of the Instrument
45 cabinet.

46 Temperature, Bottom cabinet (°C) - Temperature (°C) measurement , at the ceiling of the
47 Instrument cabinet.

48

1 **Alarm Time Files – Small Room In-cabinet Experiments**

- 2 Time - CPU time (Hour : Minute : Seconds)
- 3 Count - Loop time increment (s)
- 4 ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
- 5 ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
- 6 ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
- 7 ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
- 8 ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
- 9 ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
- 10 ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
- 11 ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
- 12 ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
- 13 ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
- 14 ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
- 15 ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
- 16 ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
- 17 ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
- 18 FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
- 19 FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
- 20 PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
- 21 single cabinet.
- 22 PHOTO (1) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the single
- 23 cabinet.
- 24 ION (2) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the single
- 25 cabinet.
- 26 ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the single cabinet.
- 27 SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the single
- 28 cabinet.
- 29 SS (3) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the single cabinet.
- 30 PHOTO (4) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
- 31 four- cabinet configuration.
- 32 PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four-
- 33 cabinet configuration.
- 34 ION (5) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four-
- 35 cabinet configuration.
- 36 ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
- 37 configuration.
- 38 SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
- 39 configuration.
- 40 SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
- 41 configuration.
- 42 ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four-
- 43 cabinet configuration.
- 44 ION (7) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
- 45 configuration.
- 46 PHOTO (8) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the
- 47 four- cabinet configuration.
- 48 PHOTO (8) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON)) Located inside the four-
- 49 cabinet configuration.

- 1 SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
2 configuration.
- 3 SS (9) Alarm - SS spot detector alarm (0 : OFF, 1 : ON)) Located inside the four- cabinet
4 configuration.
- 5 ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
6 cabinet configuration.
- 7 ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
8 configuration.
- 9 SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
10 configuration.
- 11 SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
12 configuration.
- 13 PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
14 five - cabinet configuration.
- 15 PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
16 cabinet configuration.
- 17 ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
18 cabinet configuration.
- 19 ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
20 configuration.
- 21 PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
22 five - cabinet configuration.
- 23 PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
24 cabinet configuration.
- 25 SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
26 configuration.
- 27 SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
28 configuration.
- 29 PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
30 five - cabinet configuration.
- 31 PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
32 cabinet configuration.
- 33 ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
34 cabinet configuration.
- 35 ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
36 configuration.
- 37 SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
38 configuration.
- 39 SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
40 configuration.
- 41 Temperature at Humidity Probe (oC)– The temperature (°C) at the location of the humidity probe
42 inside the instrument cabinet.
- 43 Relative humidity (%) – Relative humidity (%) inside the test room.
- 44

45

1 Alarm Time Files – Small Room Areawide Experiments

- 2 Time - CPU time (Hour : Minute : Seconds)
- 3 Count - Loop time increment (s)
- 4 ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
- 5 ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
- 6 ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
- 7 ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
- 8 ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
- 9 ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
- 10 ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
- 11 ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
- 12 ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
- 13 ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
- 14 ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
- 15 ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
- 16 ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
- 17 ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
- 18 FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
- 19 FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
- 20 PHOTO (1) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
- 21 ceiling.
- 22 PHOTO (1) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 23 ION (2) Alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 24 ION (2) C Alarm - ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 25 SS (3) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 26 SS (3) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 27 PHOTO (4) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
- 28 ceiling.
- 29 PHOTO (4) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 30 ION (5) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 31 ION (5) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 32 SS (6) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 33 SS (6) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 34 ION (7) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 35 ION (7) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 36 PHOTO (8) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
- 37 ceiling.
- 38 PHOTO (8) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 39 SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 40 SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling.
- 41 ION (10) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
- 42 cabinet configuration.
- 43 ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
- 44 configuration.
- 45 SS (11) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
- 46 configuration.
- 47 SS (11) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
- 48 configuration.
- 49 PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
- 50 five - cabinet configuration.

- 1 PHOTO (12) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
2 cabinet configuration.
- 3 ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
4 cabinet configuration.
- 5 ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
6 configuration.
- 7 PHOTO (14) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
8 five - cabinet configuration.
- 9 PHOTO (14) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
10 cabinet configuration.
- 11 SS (15) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
12 configuration.
- 13 SS (15) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
14 configuration.
- 15 PHOTO (16) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the
16 five - cabinet configuration.
- 17 PHOTO (16) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located inside the five -
18 cabinet configuration.
- 19 ION (17) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five -
20 cabinet configuration.
- 21 ION (17) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
22 configuration.
- 23 SS (18) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
24 configuration.
- 25 SS (18) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located inside the five - cabinet
26 configuration.
- 27 Temperature at Humidity Probe (oC)– The temperature (°C) at the location of the humidity probe
28 inside the instrument cabinet.
- 29 Relative humidity (%)– Relative humidity (%) inside the test room.
- 30

31

1 Alarm Time Files – Large Room Single-zone Experiments

- 2 Time - CPU time (Hour : Minute : Seconds)
- 3 Count - Loop time increment (s)
- 4 ASD1 C Alarm - ASD 1 system C Alarm relay (0 : OFF, 1 : ON)
- 5 ASD1 Alarm - ASD 1 system Alarm relay (0 : OFF, 1 : ON)
- 6 ASD1 I2 - ASD 1 system I2 alarm relay (0 : OFF, 1 : ON)
- 7 ASD1 Alert - ASD 1 system Alert alarm relay (0 : OFF, 1 : ON)
- 8 ASD1 Pre-alert - ASD 1 system Pre-alert relay (0 : OFF, 1 : ON)
- 9 ASD1 Fault - ASD1 system Fault relay (0 : OFF, 1 : ON)
- 10 ASD2 Alarm- ASD 2 system Alarm relay (0 : OFF, 1 : ON)
- 11 ASD2 Alert- ASD 2 system Alert relay (0 : OFF, 1 : ON)
- 12 ASD2 I1- ASD 2 system I1 alarm relay (0 : OFF, 1 : ON)
- 13 ASD2 Pre-alert - ASD 2 system Pre-alert relay (0 : OFF, 1 : ON)
- 14 ASD2 Fault- ASD 2 system Fault relay (0 : OFF, 1 : ON)
- 15 ASD3 Alarm- ASD 3 system Alarm relay (0 : OFF, 1 : ON)
- 16 ASD3 Alert - ASD 3 system Alert relay (0 : OFF, 1 : ON)
- 17 ASD3 Fault/Pre-alert - ASD 3 system Fault/Pre-alert relay (0 : OFF, 1 : ON)
- 18 FACP Alarm - Fire alarm control panel Alarm relay (0 : OFF, 1 : ON)
- 19 FACP Trouble - Fire alarm control panel Trouble relay (0 : OFF, 1 : ON)
- 20 SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 21 front right corner of the room.
- 22 SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
- 23 right corner of the room.
- 24 ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 25 front right corner of the room.
- 26 ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
- 27 right corner of the room.
- 28 PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling
- 29 in the front right corner of the room.
- 30 PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 31 front right corner of the room.
- 32 ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 33 rear right corner of the room.
- 34 ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
- 35 right corner of the room.
- 36 SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
- 37 right corner of the room.
- 38 SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right
- 39 corner of the room.
- 40 PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
- 41 ceiling in the rear right corner of the room.
- 42 PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 43 rear right corner of the room.
- 44 PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
- 45 ceiling in the rear right corner of the room.
- 46 PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 47 rear left corner of the room.
- 48 ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
- 49 rear left corner of the room.

- 1 ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
2 left corner of the room.
- 3 SS (9) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
4 left corner of the room.
- 5 SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left
6 corner of the room.
- 7 ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
8 front left corner of the room.
- 9 ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
10 left corner of the room.
- 11 SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the
12 front left corner of the room.
- 13 SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left
14 corner of the room.
- 15 PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
16 ceiling in the front left corner of the room.
- 17 PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in
18 the front left corner of the room.
- 19 ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
20 configuration.
- 21 ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
22 configuration.
- 23 SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
24 configuration.
- 25 SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
26 configuration.
- 27 ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet
28 configuration.
- 29 ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet
30 configuration.
- 31 SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
32 configuration.
- 33 SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
34 configuration.
- 35 Temperature at Humidity Probe (oC) – The temperature (°C) at the location of the humidity
36 probe inside the instrument cabinet.
- 37 Relative humidity (%) – Relative humidity (%) inside the test room.
- 38 TC1 – Not used
- 39

40

1 **Alarm Time Files – Large Room Multi-zone Experiments**

2 Time - CPU time (Hour : Minute : Seconds)

3 Count - Loop time increment (s)

4 ASD4_Zone1_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 1.

5 ASD4_Zone1_Alert- ASD 4 system Alert relay (0 : OFF, 1 : ON) , located in zone 1.

6 ASD4_Zone1_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 1.

7 ASD4_Zone1_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON), located in zone 1.

8 ASD4_Zone2_Alarm- ASD 4 system Alarm relay (0 : OFF, 1 : ON), located in zone 2.

9 ASD4_Zone2_Alert- ASD 4 system Alarm relay (0 : OFF, 1 : ON) , located in zone 2.

10 ASD4_Zone2_I1- ASD 4 system I1 relay (0 : OFF, 1 : ON) , located in zone 2.

11 ASD4_Zone2_Pre-alert- ASD 4 system Pre-alert relay (0 : OFF, 1 : ON) , located in zone 2.

12

13 ASD4_Zone3_Alarm- ASD 4 system Fire 3 alarm relay (0 : OFF, 1 : ON), located in zone 3.

14 ASD4_Zone3_Alert- ASD 4 system Fire 2 alarm relay (0 : OFF, 1 : ON) , located in zone 3.

15

16 ASD4_Zone3_I1- ASD 4 system Fire 1 alarm relay (0 : OFF, 1 : ON) , located in zone 3.

17 ASD4_Zone3_Pre-alert- ASD 4 system Pre-alarm relay (0 : OFF, 1 : ON) , located in zone 3.

18

19 ASD4_Zone4_Alarm- Not used

20 ASD4_Zone4_Alert- Not used

21 ASD4_Zone4_I1- Not used

22 ASD4_Zone4_Pre-alert - Not used

23 ASD4_Fault - ASD 4 system Fault relay (0 : OFF, 1 : ON)

24 ASD5_Global_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), for all 3 zones (global.)

25

26 ASD5_Global_Alarm- ASD 5 system Fire 1 alarm relay (0 : OFF, 1 : ON), for all 3 zones
27 (global.)

28 ASD5_Global_C Alarm- ASD 5 system Fire 2 alarm relay (0 : OFF, 1 : ON), for all 3 zones
29 (global.)

30 ASD5_Zone2_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 2.

31 ASD5_Zone2_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

32

33 ASD5_Zone3_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 3.

34 ASD5_Zone3_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

35

36 ASD5_Zone1_Pre-alert- ASD 5 system Alert relay (0 : OFF, 1 : ON), located in zone 1.

37 ASD5_Zone1_Alert- ASD 5 system Action alarm relay (0 : OFF, 1 : ON), located in zone 2.

38

39 ASD5_Fault- ASD 5 system Fault relay (0 : OFF, 1 : ON)

40 FACP Alarm - Fire alarm control panel alarm relay (0 : OFF, 1 : ON)

41 FACP Trouble - Fire alarm control panel trouble relay (0 : OFF, 1 : ON)

42 SS (1) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
43 front right corner of the room.

44 SS (1) Alarm - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
45 right corner of the room.

46 ION (2) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
47 front right corner of the room.

48 ION (2) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
49 right corner of the room.

- 1 PHOTO (3) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling
2 in the front right corner of the room.
- 3 PHOTO (3) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
4 front right corner of the room.
- 5 ION (4) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
6 rear right corner of the room.
- 7 ION (4) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
8 right corner of the room.
- 9 SS (5) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
10 right corner of the room.
- 11 SS (5) Alarm - SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear right
12 corner of the room.
- 13 PHOTO (6) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
14 ceiling in the rear right corner of the room.
- 15 PHOTO (6) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
16 rear right corner of the room.
- 17 PHOTO (7) Pre-alarm - PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
18 ceiling in the rear right corner of the room.
- 19 PHOTO (7) C Alarm- PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the
20 rear left corner of the room.
- 21 ION (8) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
22 rear left corner of the room.
- 23 ION (8) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear
24 left corner of the room.
- 25 SS (9) Pre-alert - SS spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in
26 the rear left corner of the room.
- 27 SS (9) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the rear left
28 corner of the room.
- 29 ION (10) Pre-alarm - ION spot detector pre-alarm (0 : OFF, 1 : ON) Located on the ceiling in the
30 front left corner of the room.
- 31 ION (10) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front
32 left corner of the room.
- 33 SS (11) Pre-alert- SS spot detector pre- alarm (0 : OFF, 1 : ON) Located on the ceiling in the
34 front left corner of the room.
- 35 SS (11) Alarm- SS spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in the front left
36 corner of the room.
- 37 PHOTO (12) Pre-alarm- PHOTO spot detector pre-alarm (0 : OFF, 1 : ON) Located on the
38 ceiling in the front left corner of the room.
- 39 PHOTO (12) C Alarm - PHOTO spot detector alarm (0 : OFF, 1 : ON) Located on the ceiling in
40 the front left corner of the room.
- 41 ION (13) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
42 configuration.
- 43 ION (13) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
44 configuration.
- 45 SS (14) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
46 configuration.
- 47 SS (14) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
48 configuration.
- 49 ION (15) Pre-alarm- ION spot detector pre-alarm (0 : OFF, 1 : ON) Located in the single-cabinet
50 configuration.

- 1 ION (15) C Alarm- ION spot detector alarm (0 : OFF, 1 : ON) Located in the single-cabinet
- 2 configuration.
- 3 SS (16) Pre-alert- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
- 4 configuration.
- 5 SS (16) Alarm- SS spot detector pre-alarm (0 : OFF, 1 : ON) Located in the 3-cabinet
- 6 configuration.
- 7 Temperature at Humidity Probe (oC)– The temperature (°C) at the location of the humidity probe
- 8 inside the instrument cabinet.
- 9 Relative humidity (%) – Relative humidity (%) inside the test room.

10

11 **Bus Bar Heater File (Files ending with _T)**

- 12 Column 1 - CPU time (Hour : Minute : Seconds)
- 13 Column 2 - Counter (s)
- 14 Column 3 – Set point temperature (°C)
- 15 Column 4 – Actual Bus Bar temperature (°C)

16

17 **Room Temperature File (Files ending with _RT)**

- 18 Time - CPU time (Hour : Minute : Seconds)
- 19 Count - Loop time increment (s)
- 20 TC 1 - Temperature (°C) in the center of the room, 2.54 cm below the ceiling.
- 21 TC 2 - Temperature (°C) in the center of the room, 5.08 cm below the ceiling.
- 22 TC 3 - Temperature (°C) in the center of the room, 7.62 cm below the ceiling.
- 23 TC 4 - Temperature (°C) in the center of the room, 0.31 m below the ceiling.
- 24 TC 5 - Temperature (°C) in the center of the room, 0.61 m below the ceiling.
- 25 TC 6 - Temperature (°C) in the center of the room, 0.914 m below the ceiling.
- 26 TC 7 - Temperature (°C) in the center of the room, 2.13 m below the ceiling.
- 27 TC 8 - Ceiling temperature (°C) in the corner of the room.
- 28 TC 9 - Ceiling temperature (°C) in the corner of the room.
- 29 TC 10 - Ceiling temperature (°C) in the corner of the room.
- 30 TC 11 - Ceiling temperature (°C) in the corner of the room.
- 31 TC 12 - Room ventilation inlet temperature (°C).
- 32 TC 13 - Room ventilation outlet temperature (°C).

33

34 **Wire Thermocouples (Files ending with _WT)**

- 35 Time - CPU time (Hour : Minute : Seconds)
- 36 Count - Loop time increment (s)
- 37 TC 1 (X mm)- Thermocouple #1 located X mm form the bus bar.
- 38 TC 2 (X mm)- Thermocouple #2 located X mm form the bus bar.
- 39 TC 3(X mm)- Thermocouple #3 located X mm form the bus bar.
- 40 TC 4(X mm)- Thermocouple #4 located X mm form the bus bar.

41

42

43

1 **B.1.2 Sample before and after experiment images**
 2 Before and after sample images use the file naming convention appended with “Before” or
 3 “After”. Sequences of thermal images at fixed time intervals are given in folders labeled using
 4 the file naming convention appended with “TI”. The name of each thermal image corresponds
 5 to the time in minutes at which it was taken.

6 **Table B2. Exemplar image file names for materials tested.**

Material	Heating ramp	Before and after images	Thermal images folder
PVC wire (1)	15 min	N/A	C_PVC1_L_B_1.1_TI
	1 hour	C_PVC1_L_B_2.3_Before C_PVC1_L_B_2.3_After	C_PVC1_L_A_2.1_TI
PVC wire (2)	15 min	C_PVC2_L_A_1.2_Before C_PVC2_L_A_1.2_After	C_PVC2_L_B_1.1_TI
	1 hour	C_PVC2_L_B_2.2_Before C_PVC2_L_B_2.2_After	C_PVC2_L_A_2.1_TI
	4 hours	N/A	C_PVC2_L_B_3.1_TI
Silicone wire	15 min	C_Silicone_L_A_1.2_Before C_Silicone_L_A_1.2_After	C_Silicone_L_B_1.1_TI
	1 hour	C_Silicone_L_B_2.3_Before C_Silicone_L_B_2.3_After	C_Silicone_L_A_2.1_TI
PTFE wire	15 min	C_Teflon_L_A_1.2_Before C_Teflon_L_A_1.2_After	C_Teflon_L_B_1.1_TI
	1 hour	C_Teflon_L_B_2.2_Before C_Teflon_L_B_2.2_After	C_Teflon_L_A_2.1_TI
XLPO wire (1)	15 min	C_XLPO1_L_A_1.2_Before C_XLPO1_L_A_1.2_After	C_XLPO1_L_B_1.1_TI
	1 hour	C_XLPO1_L_B_2.2_Before C_XLPO1_L_B_2.2_After	C_XLPO1_L_A_2.1_TI
XLPO wire (2)	15 min	C_XLPO2_L_A_1.2_Before C_XLPO2_L_A_1.2_After	C_XLPO2_L_B_1.1_TI
	1 hour	C_XLPO2_L_B_2.2_Before C_XLPO2_L_B_2.2_After	C_XLPO2_L_A_2.1_TI
	4 hours	C_XLPO2_L_A_3.1_Before C_XLPO2_L_A_3.1_After	C_XLPO2_L_A_3.1_TI
XLPE wire	15 min	C_XLPE_L_A_1.3_After	C_XLPE_L_B_1.1_TI
	1 hour	C_XLPE_L_B_2.2_Before C_XLPE_L_B_2.2_After	C_XLPE_L_A_2.1_TI
	4 hours	N/A	C_XLPE1_L_B_3.1_TI
CSPE wire	15 min	C_CSPE_L_A_1.2_Before C_CSPE_L_A_1.2_After	C_CSPE_L_B_1.1_TI
	1 hour	C_CSPE_L_B_2.2_Before C_CSPE_L_B_2.2_After	C_CSPE_L_A_2.1_TI
Epoxy Printed Circuit Board	15 min	C_PCB_L_A_1.2_Before C_PCB_L_A_1.2_After	C_PCB_L_B_1.1_TI
	1 hour	C_PCB_L_A_2.2_Before C_PCB_L_A_2.2_After	C_PCB_L_A_2.1_TI
	4 hours	C_PCB_L_B_3.1_Before C_PCB_L_B_3.1_After	C_PCB_L_B_3.1_TI
Phenolic Terminal block	15 min	C_PTB_L_A_1.2_Before C_PTB_L_A_1.2_After	C_PTB_L_B_1.1_TI
	1 hour	C_PTB_L_B_2.2_Before C_PTB_L_B_2.2_After	C_PTB_L_A_2.1_TI
	4 hours	N/A	C_PTB_L_B_3.1_TI
Single XLPE wire	1 hour	N/A	C_1XLPE_L_A_2.1_TI

7
8

1 **B.2 Smoke Aerosol Measurements**

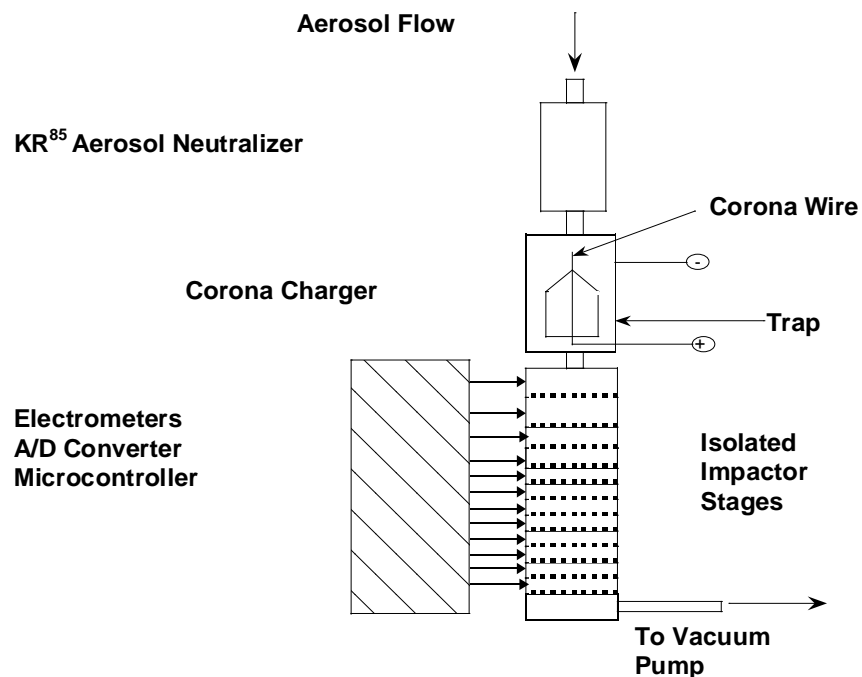
2 **Instrumentation descriptions**

3
4
5 Aerosol characterization equipment included an electrical low pressure impactor (ELPI) (Dekati,
6 ELPI) to record aerosol concentration and size distribution, a condensation particle counter
7 (CPC, TSI Model 3775) to provide the aerosol number concentration, an electrical aerosol
8 detector (EAD, TSI Model 3007) to provide a measure of the sum of particle diameters, and a
9 tapered element oscillating microbalance (R&P Inc. TEOM Model 1105) to record aerosol mass
10 concentration.

11
12 The ELPI consists of a 13-stage multi-orifice, low-pressure impactor that classifies particles
13 according to their aerodynamic size (equivalent diameter unit density sphere). A schematic
14 diagram of the instrument is shown in Figure B1. Beginning at the first stage, particles of a
15 narrow size range (defined by a cut-off size, $d_{50\%}$, where 50 percent of particles of a given size
16 are collected) impact on that stage's collection plate, while smaller particles move on to the next
17 stage. The process repeats itself until the last stage is reached. The particle concentration
18 below 0.03 μm is not measured, thus the size distribution is truncated. This may affect
19 concentration and average size measurements, and the instrument results are subject to this
20 bias.

21
22 The particles are separated according to their inertial properties, thus sizes are reported in
23 terms of the diameter of unit density spheres with the same inertial properties, termed the
24 aerodynamic diameter. The flow through the instrument is 10 l/min. Typically, cascade
25 impactors rely on a gravimetric determination of the number of particles collected on any stage,
26 thus the sampling time must be sufficient to gather a weighable amount of material on each
27 stage. This impactor is unique in that it detects particles that impact the different stages by
28 measuring the charge transferred to the stage from the elemental charges carried by the
29 particles. Aerosol particles will achieve a statistically average charge level based on particle
30 diameter, initial charge state, and exposure to charging mechanisms.

31
32 The ELPI conditions the aerosol to such a state by a two-step process. The initial charge state
33 is forced to an equilibrium, Boltzmann charge distribution by passing the aerosol through a
34 charge neutralizer (external to the ELPI). Then, a high-voltage corona wire unipolar charger
35 puts known excess charge on the aerosol particles based on their size and the residence time
36 the aerosol remains in the charging section. Excess ions and very small, charged particles are
37 removed by an ion trap just past the charger. Each impactor stage, (excluding the first, which
38 removes particles with aerodynamic diameters larger than 10 μm) is electrically isolated and
39 connected to an electrometer. As aerosol particles impact on the various stages, they transfer
40 their charges and a current is measured. Based on the current measurement, the impactor
41 stage cut-off sizes, flow through the instrument, and the relationship between the particle size
42 and average charge, the number of particles that impact each stage is computed and the
43 number size distribution is characterized. The number distribution can be converted into
44 diameter, surface area, or mass distribution, etc., and the total number, or mass (assuming
45 spherical unit density particles) can be computed.
46



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Figure B1. Schematic diagram of the electrical low pressure impactor

Table B3 shows the impactor stage cut-off sizes and the geometric mean of the size range of particles collected on a given stage, d_i , for standard impaction plates covered with aluminum foil.

Table B3. ELPI Impactor Plate Cutoff and Median Diameters

Impactor Stage	Standard Impactor Plates	
	Aerodynamic $d_{50\%}$ (μm)	Aerodynamic d_i (μm)
1	0.0280	0.0395
2	0.0557	0.0727
3	0.0948	0.122
4	0.157	0.203
5	0.263	0.317
6	0.383	0.485
7	0.615	0.764
8	0.950	1.23
9	1.60	1.96
10	2.40	3.10
11	4.00	5.18
12	6.70	8.16
13	9.93	-

9

1 If density is known, then the aerodynamic diameter can be replaced with the Stokes diameter,
2 defined as the diameter of a sphere with the same density and settling velocity of the particle.
3 The analysis of the ELPI data takes into account known aerosol particle densities. For the
4 unknown aerosol densities of the smoke generated from material degradation, a density of
5 1.00 g/cm³ is assumed, but this adds to the uncertainty of the results for the aerosol
6 concentrations and size distribution.

7
8 The CPC can detect and count particles 4 nm in diameter and larger up to number
9 concentrations of 1×10⁷ #/cm³. The CPC draws aerosols into a heated saturator where alcohol
10 vapor and the aerosol mix; this particle/vapor mixture then flows to a condensing section where
11 the vapor becomes superheated and condenses on the aerosol particles greater than 4 nm.
12 The particles grow rapidly to large individual particles that are counted optically. In that respect,
13 the detection principle of the CPC is similar to a cloud chamber aspirating smoke detector
14 (ASD). The CPC combined relative uncertainty is better than ±10 of the reading.

15
16 The EAD measures an aerosol concentration referred to as the total aerosol length, equal to the
17 sum of the diameter of all particles in a unit volume. This quantity is also referred to as the first
18 moment of the size distribution (the number concentration is the zero-th moment). In the EAD,
19 particles flow into a charging section where positive ions accumulate on particles to a net
20 charge state proportional to the particle diameter. An aerosol electrometer measures the net
21 charge, which is proportional to the total aerosol length. The combined relative uncertainty in
22 the EAD measurement is typically better than ±10 of the reading.

23
24 The TEOM is a direct measure of the mass concentration of an aerosol. The sampled aerosol
25 with a fixed volumetric flow is passed through a vibrating filter that accumulates the aerosol
26 particles. The vibration frequency is proportional to the mass of the filter. The frequency is
27 measured as a function of time, and with the volumetric flow rate, the mass concentration is
28 computed. The TEOM combined standard uncertainty is ±0.5 mg/m³.

29
30 Properties of the size distribution of interest include the first moment of the number distribution
31 with the mean size defined as the arithmetic mean diameter (AMD), given by

$$AMD = \frac{\sum(n_i \cdot d_i)}{N} \quad B-1$$

32
33
34 where n_i is the number of particles of size group d_i , and N is the total number of particles.
35 The first moment correlates with the response of the ionization chamber in smoke detectors.
36 Another property of interest is the mass (or volume) distribution, which is a better predictor of
37 the response of light-scattering, photoelectric alarms than the diameter distribution. The third
38 moment of the size distribution can be represented by the total mass, M (or volume) with a
39 mass mean diameter (d_{mm}), given by

$$d_{mm} = \frac{\sum(m_i \cdot d_i)}{M} \quad B-2$$

40
41
42 where m_i is the mass of particles of size group d_i , and M is the mass of all particles.
43 Comparing these two mean diameters gives a sense of the width of the size distribution. If both
44 AMD and d_{mm} are the same the particles are of a single size (monodisperse) while an
45 increasing difference between the two diameters indicates ever broadening distribution. For
46 log-normally distributed aerosols with an AMD of 0.100 μm and geometric standard deviations
47 (σ_g) of 1.30 and 1.70, the d_{mm} is 0.123 μm and 0.233 μm respectively.

1
2 The diameter of average mass can be computed if the mass and number concentration are
3 known using equation 3.

$$d_{am} = \left(\frac{6M}{\rho\pi N} \right)^{1/3} \quad \text{B-3}$$

4
5
6

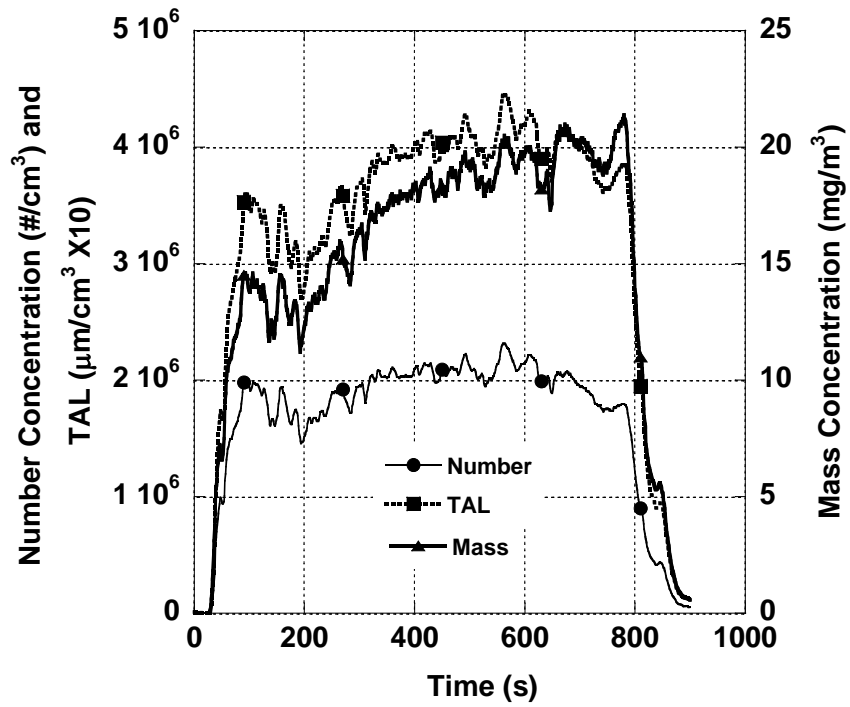
7 **B.2.1 Instrument Cabinet Experiments**

8 Experiments were conducted using a condensation mono-disperse aerosol generator (CMAG,
9 TSI Model 3475), an instrument that can produce high concentrations of narrow size distribution
10 aerosols from 0.1 μm up to 8 μm in diameter, and a Gemini smoke detector tester aerosol
11 generator, which produces aerosol designed to mimic smolder smokes. The CMAG produces
12 particles from Di-Ethyl-Hexyl-Sebacate (DEHS, density of 0.912 g/cm^3), while the smoke
13 detector tester produces particles from mineral oil (density of 0.85 g/cm^3).
14

15 Aerosols from the CMAG or smoke detector tester were introduced into the cabinet from a tube
16 located at the cabinet floor and pointing up. The aerosol was sampled from the ceiling of the
17 instrument cabinet and directed to the ELPI. Experiments were conducted with 9 different
18 settings on the CMAG, and one base setting on the smoke detector tester. Data for the
19 experiments are located in the spreadsheet files labeled {Instrument cabinet CMAG and Gemini
20 exps} and {Test_aerosol_ELPI}. The first file contains the ASD alarm times and the end of test
21 number and mass concentrations, and arithmetic mean diameter and diameter of average
22 mass, while the second file contains the number, total aerosol length, and mass concentrations,
23 along with the arithmetic mean diameter and diameter of average mass values as functions of
24 time.
25

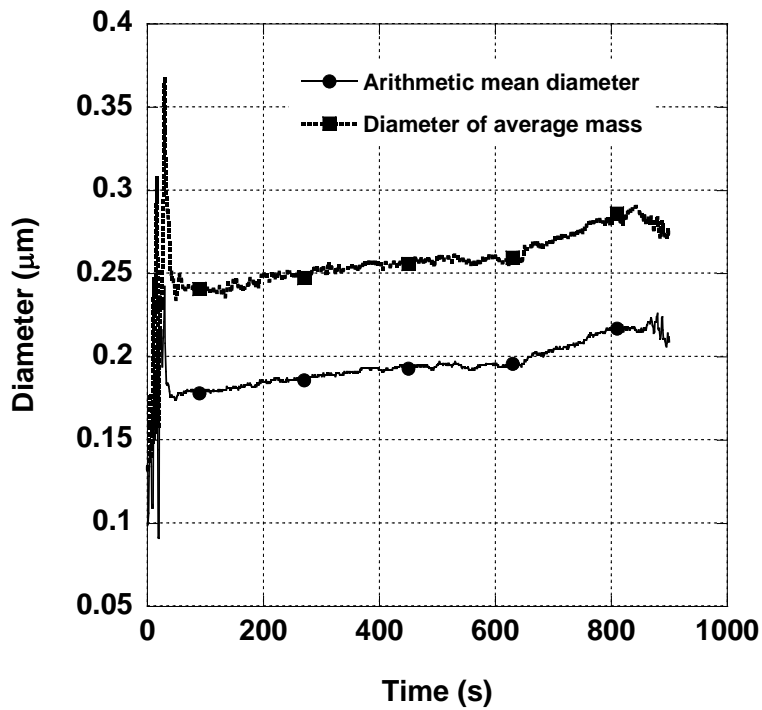
26 The arithmetic mean particle size at the end of the test for the CMAG experiments ranged from
27 0.12 μm to 0.82 μm , depending on the CMAG settings, and 0.33 μm for the smoke detector
28 tester aerosol. In only one CMAG setting did ASD2 (cloud chamber type) respond at alert or
29 alarm settings, and in fact, only pre-alerted in one other CMAG setting. The light-scattering
30 ASDs tended to respond at all CMAG settings. The smoke detector tester aerosol triggered all
31 light-scattering response levels, while the cloud chamber ASD responded at the level between
32 pre-alert and alert consistently. These results show the response to various concentrations of
33 given particle size distributions, but by themselves do not indicate effectiveness, nor
34 appropriateness for a given application.
35

36 An example of the ELPI data is shown below in Figures B2 and B3. The aerosol concentration
37 curves are proportional to each other since the size distribution of the CMAG aerosol does not
38 change much with time. The mean size fluctuates before the arrival of the CMAG aerosol at the
39 sampling port because of the low concentration background (room) aerosol. The mean
40 diameters show a slight growth trend over time, which may be caused by the aerosol generator,
41 or aging of the aerosol at the ceiling of the cabinet.
42



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Figure B2. ELPI aerosol concentrations for CMAG experiment 40.



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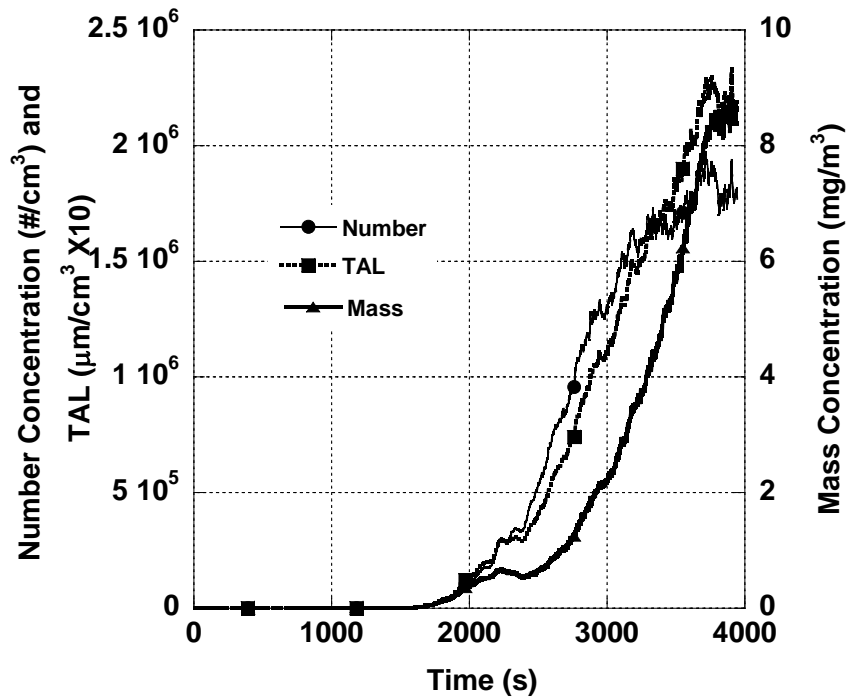
Figure B3. ELPI aerosol diameters for CMAG experiment 40.

1 **B.2.1.2 Degraded materials**

2
3 Almost all experiments conducted in the instrument cabinet with the degrading materials were
4 monitored with the ELPI. The spreadsheet labeled {Instrument_cabinet_ELPI} contains the
5 ELPI results number, total aerosol length, and mass concentrations, along with the arithmetic
6 mean diameter and diameter of average mass values as functions of time. Figures B4-B9 show
7 ELPI 60.0 min HRP results for XLPE, PVC(2), and CSPE samples.

8
9 Additional experiments were conducted in which the smoke sampled from the aerosol sampling
10 port was directed to the CPC, EAD and TEOM as alternate direct measurements of number
11 concentration, total aerosol length, and mass concentration. The materials examined were
12 limited to XPLE, PVC(2) and CSPE at HRP's of 15.0 min and 60.0 min, and overheated
13 resistors. The spreadsheet labeled {Instrument_cabinet_moments} contains the measurement
14 results and the bus bar heating measurements for those experiments.

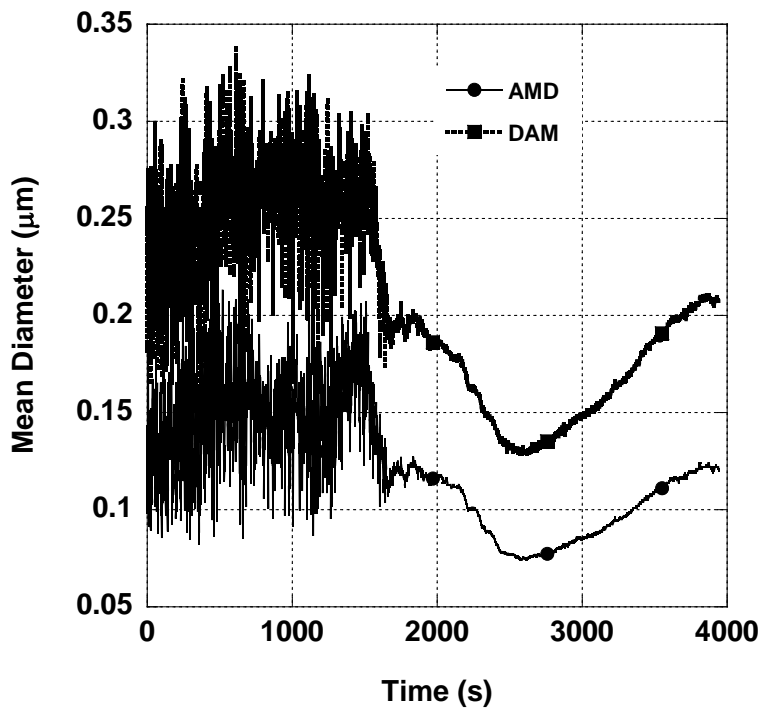
15



16

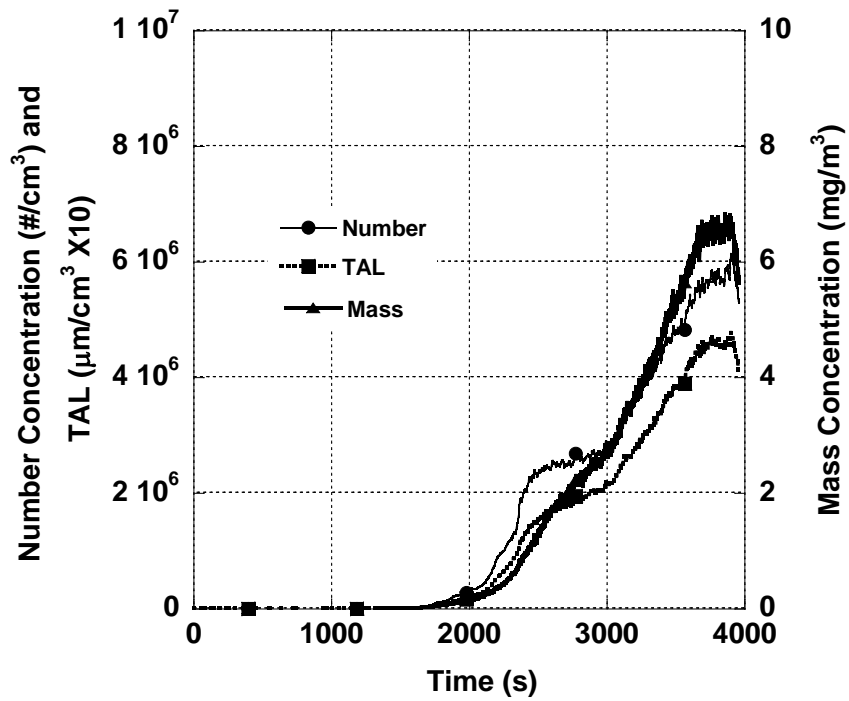
17 **Figure B4. ELPI aerosol concentration for XLPE and 60.0 minute HRP.**

18



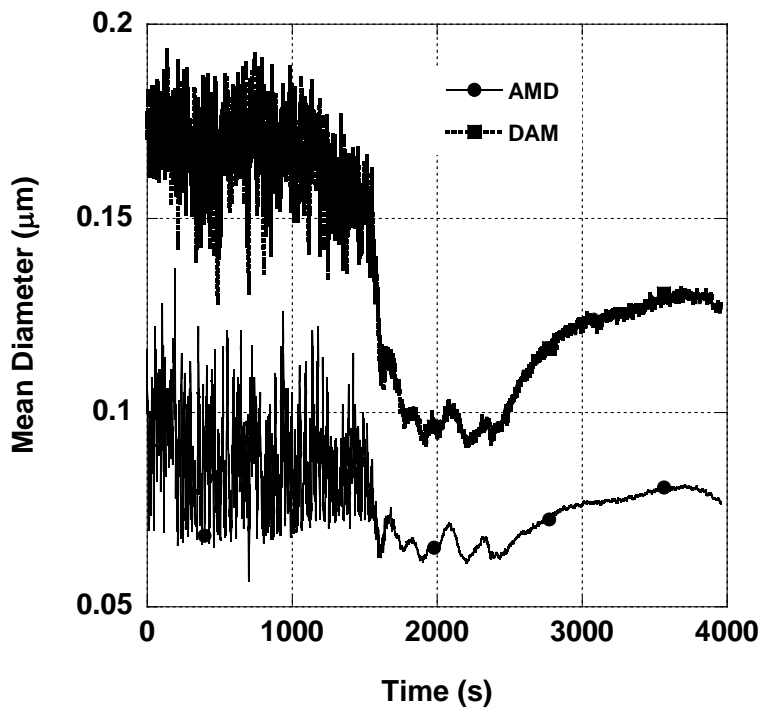
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Figure B5. ELPI mean particle diameters for XLPE and 60.0 minute HRP.



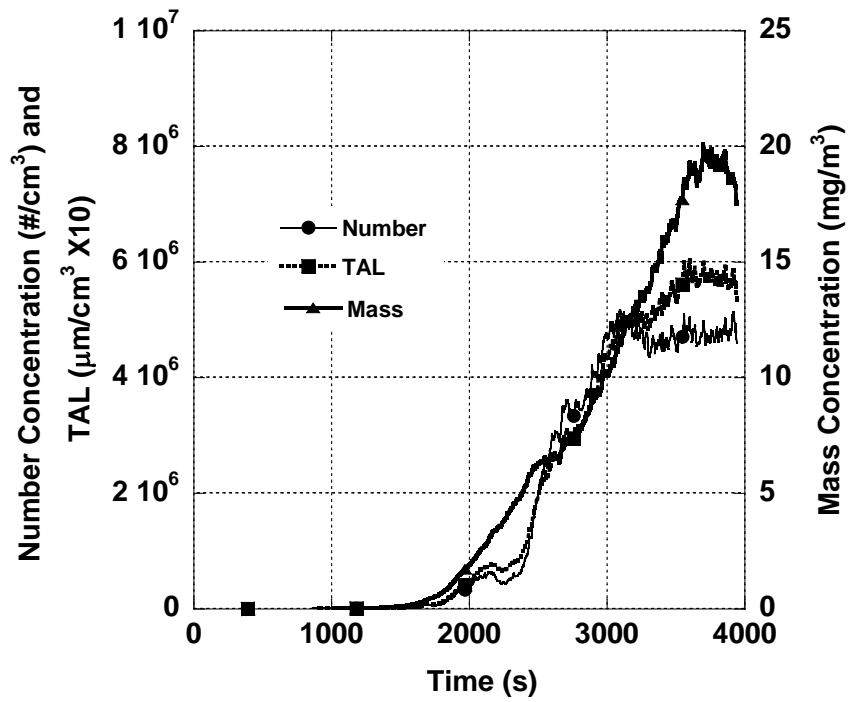
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Figure B6. ELPI aerosol concentration for PVC(2) and 60.0 minute HRP.



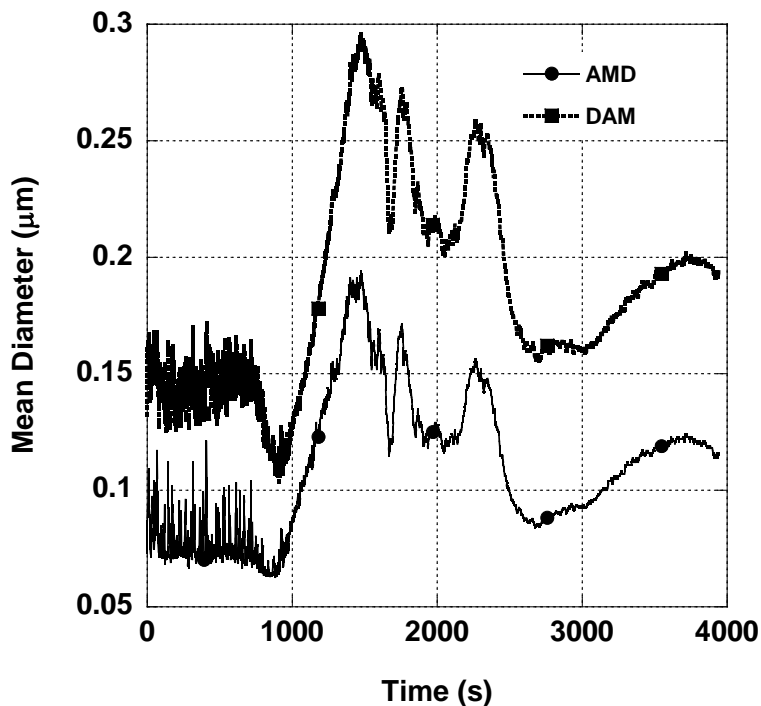
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3

Figure B7. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP



4
5

Figure B8. ELPI aerosol concentration for CSPE and 60.0 minute HRP.



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2

Figure B9. ELPI mean particle diameters for PVC(2) and 60.0 minute HRP

3

4 B.2.2 Large Cabinet

5

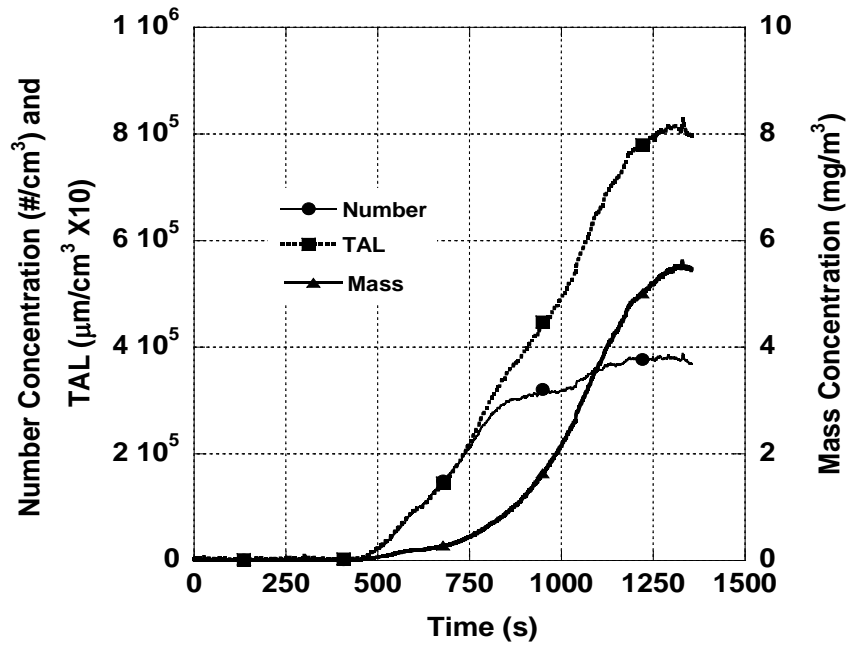
6 During the large cabinet experiments, smoke was sampled from the top of the cabinets and
 7 directed to the ELPI. Data was collected for the 16.3 and 65.0 minute HRP experiments for
 8 XLPE, PVC(2), CSPE, and PCB materials, and for 260 minute HRP experiments for XLPE and
 9 CSPE materials. Experiments were conducted with XLPE and CSPE samples in which the
 10 HRP was reduced to achieve a lower bus bar temperature, and the hold time was increased so
 11 the EOT times, 21.3 and 70 minutes, were the same. In addition, BS 6266 1 meter wire tests
 12 were conducted. The spreadsheet labeled {Large_cabinet_ELPI} contains the ELPI results
 13 number, total aerosol length, and mass concentrations, along with the arithmetic mean diameter
 14 and diameter of average mass values as functions of time.

15

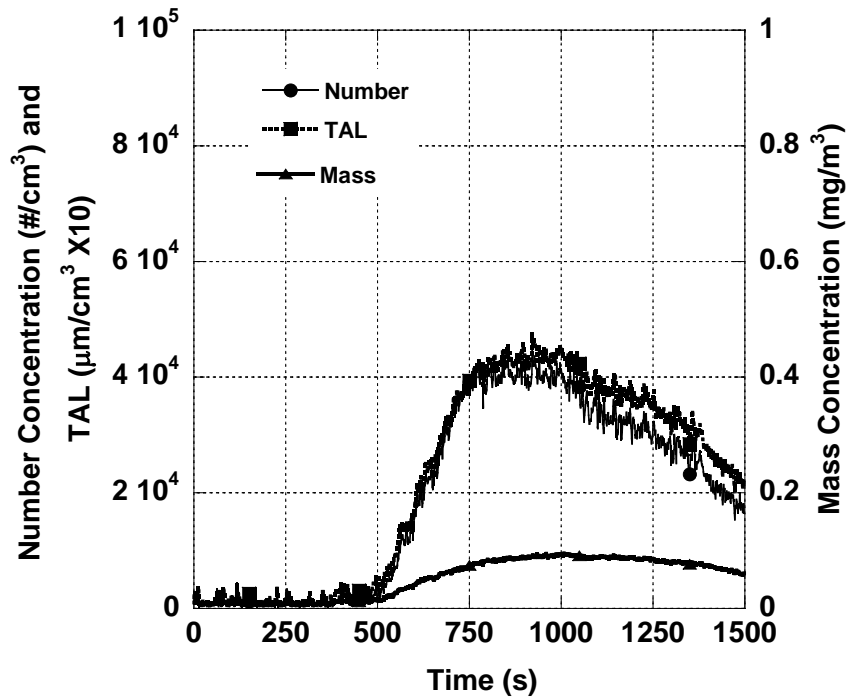
16 Figures B10 – B13 show the aerosol concentration results for naturally ventilated cabinets and
 17 XLPE and CSPE experiments, with the normal 16.3 minute HRP and shorter HRPs to set points
 18 of 325 degrees C and 225 degrees C, respectively.

19

20

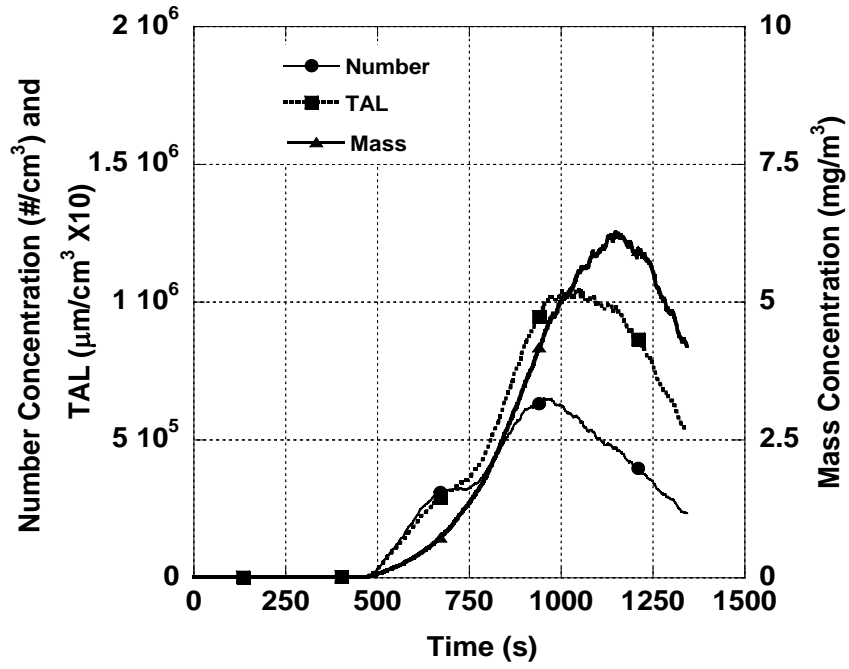


1
 2 **Figure B10.** Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and
 3 16.3 minute HRP.
 4



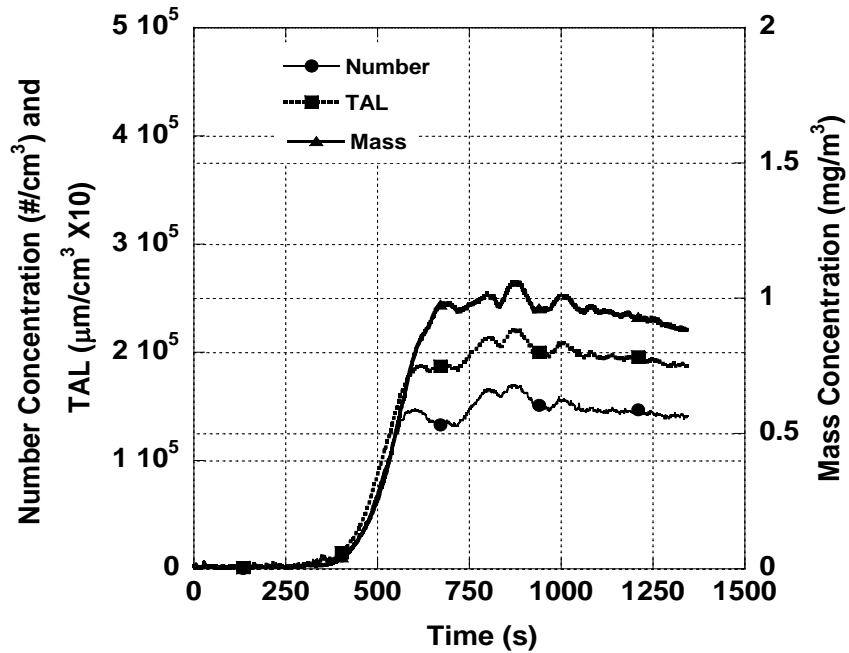
5
 6 **Figure B11.** Large, naturally ventilated cabinet ELPI aerosol concentration for XLPE and
 7 10.5 minute HRP to a set point of 325 °C and held until 21.3 min.

1



2

3 **Figure B12.** Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE
4 and 16.3 minute HRP.



5

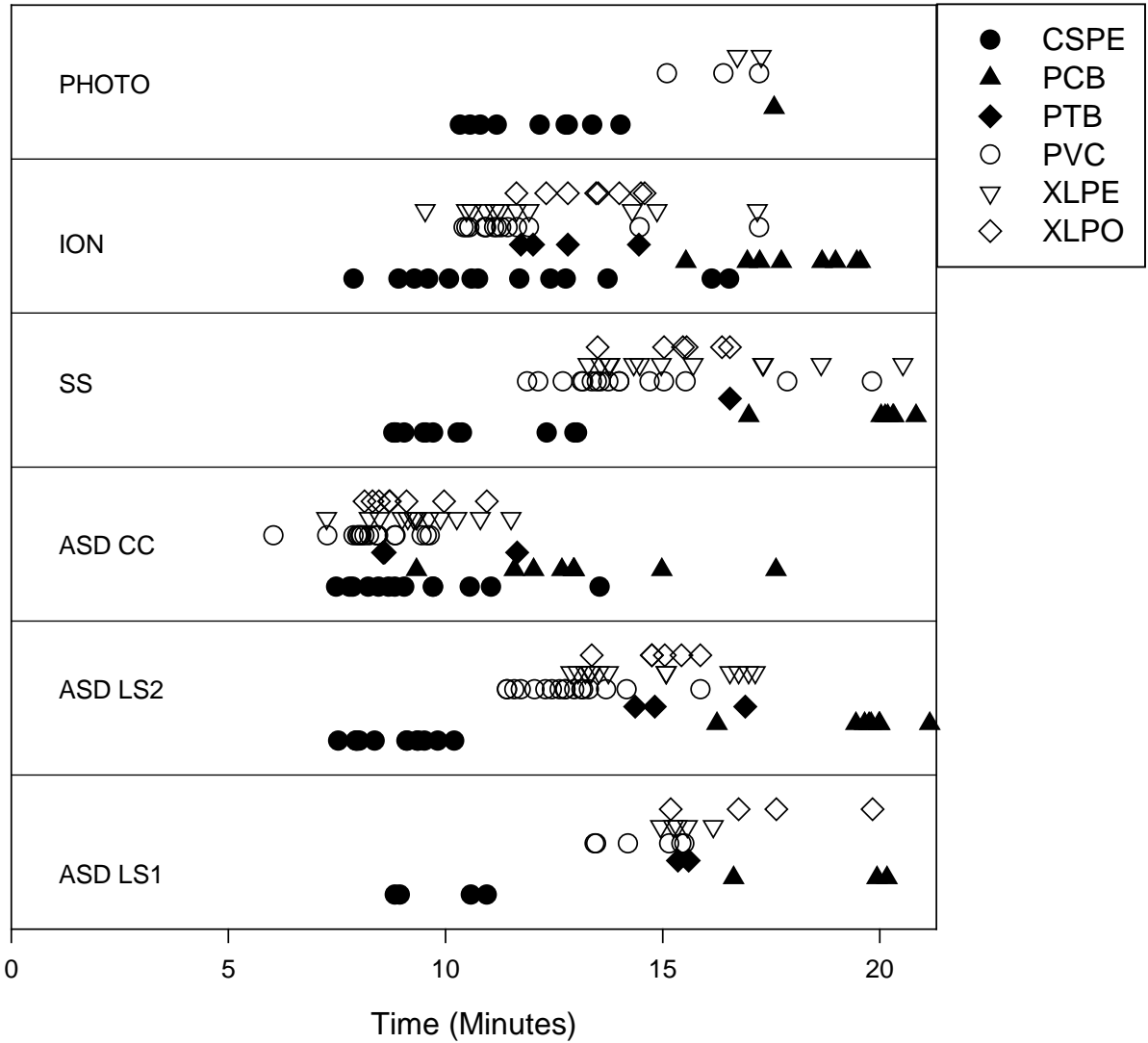
6 **Figure B13.** Large, naturally ventilated cabinet ELPI aerosol concentration for CSPE
7 and 7.9 minute HRP to a set point of 250 °C and held until 21.3 min.

8

1 **B.3 Supplemental Data Supporting Objective E**

2
 3 Figures B-14 and B-15 present the in-cabinet, naturally ventilated data for the 15 minute and
 4 4-hour HRP, respectively. These figures show the detectors' time of response ("alert" for
 5 VEWFD systems and "alarm" for conventional spots). This data shows trends similar to the
 6 data presented in Figure 5-49.

7

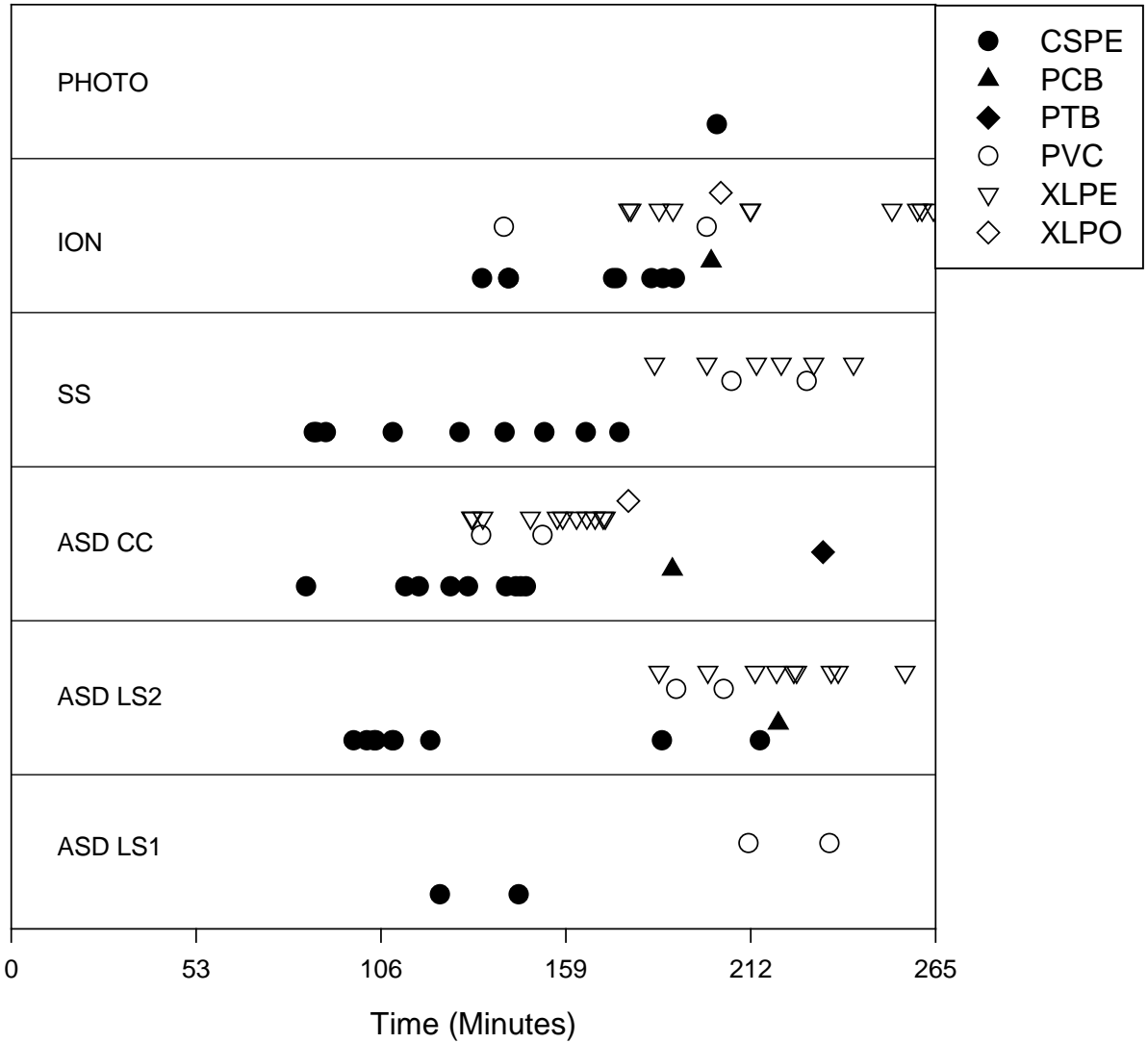


8

9

10

**Figure B-14. Detector response to selected materials (15 minute HRP)
 in-cabinet, natural cabinet ventilation**



1
2
3
4

Figure B-15. Detector response to selected materials (4-hour HRP) in-cabinet, natural cabinet ventilation

APPENDIX C

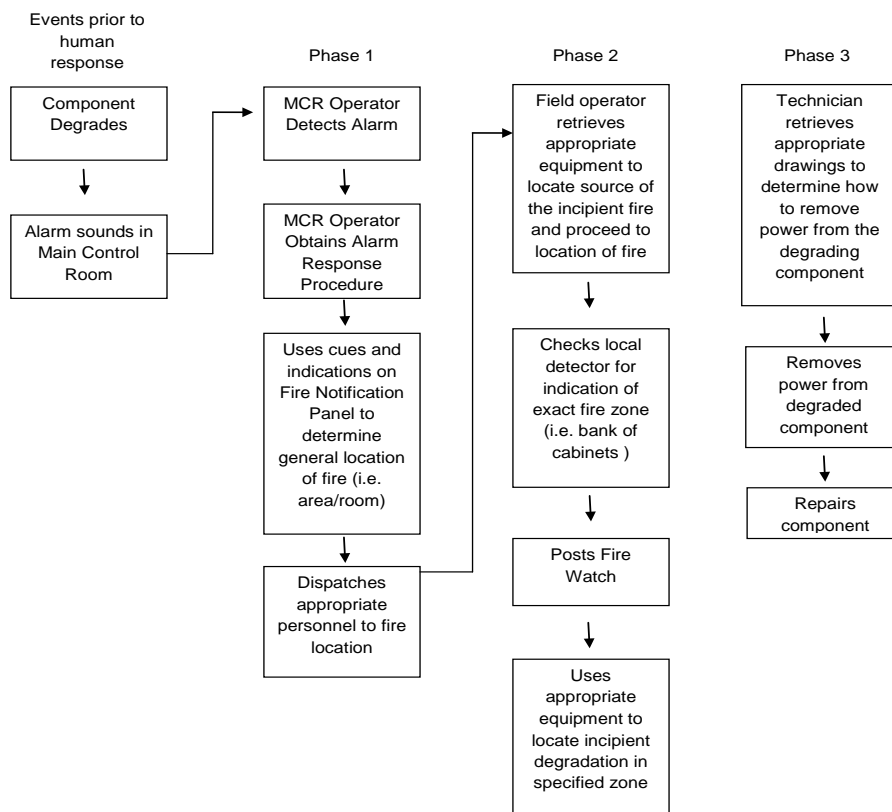
SUPPORTING INFORMATION FOR HUMAN PERFORMANCE EVALUATION

C.1 Human Factor/Human Reliability Analysis Evidence Database

This section provides documentation related to questions and answers received during the course of this project. After each entry, an application designator will appear, which are defined as follows:

IC – in-cabinet application
MCR – main control room application
AW – areawide application

C.1.1 Response Operations: Questions and Answers³⁷



³⁷ This set of questions was used to obtain information from 2 NPPs. One NPP provided written responses, the other through a teleconference.

1
2 The previous chart (in C.1.1.) depicts an in-cabinet very early warning fire detection system
3 (VEWFDS) alarm response operation. It is not specific to any one plant and represents a
4 generic case. The alarm response operations are represented here in three phases. The
5 authors categorized the responses into three different phases because each phase is
6 completed by different groups of personnel.
7

8 The authors recognize that there will be variations in alarm response operations. The aim is to
9 capture examples in which operations may vary from those depicted herein. In addition, some
10 specific questions regarding individual processes are noted below:
11

12 Operations Questions

13
14 1. Is there immediacy associated with VEWFDS alarm response? In other words, is the
15 alarm treated like any other fire alarm? If not, how is it different?

16 Plant X: Yes, if an alert comes in, an operator and instrumentation and control (I&C)
17 tech are sent. If an alarm, the operator and tech are sent along with the fire brigade. If a
18 system trouble annunciator comes in, an operator is sent out. Alarm does not
19 necessarily indicate a flaming fire. The response associated with an incipient alert/alarm
20 is the same as for spot detectors. First, the MCR dispatches an operator, not the fire
21 brigade, as in a VEWFDS alert. If additional signs/signals of fire are detected, then the
22 fire brigade is sent, similar to when a VEWFDS alarm comes in. Regarding immediacy,
23 fire alarms of any kind trump other activities, so a response from operators comes within
24 seconds. Only a reactor trip would trump a fire alarm. (IC)
25

26 Plant Y: Field operator dispatched immediately. (IC)
27

28 a. Are the VEWFDS systems set to have alerts and alarms? If so, how many of
29 each?

30 Plant X: Set to have one alert and one alarm (also real-time graphic read-out of
31 sampler) (IC)
32

33 Plant Y: Yes there is an alert and an alarm. Alerts are at 20 percent above
34 background and alarms at 50 percent above. (IC)
35

36 b. Are alerts, alarms and system trouble differentiated on the annunciator panel?

37 Plant X: Yes. (IC)
38

39 Plant Y: Yes, three annunciators on front panel. (IC)
40

41 c. If both alerts and alarms are used, how does the response differ?

42 Plant X: If an alert comes in an operator and I&C tech are sent. If an alarm, the
43 operator and tech are sent along with the fire brigade.
44

45 Plant Y: No difference in response, field operator will be immediately dispatched
46 to investigate either
47

- 1 2. Where is the alarm located in the control room (e.g. front panel/back panel)?
2 Plant X: All three annunciators are on the front panel.
3
4 Plant Y: Front panel.
5
6 3. Where is the fire notification panel located?
7 Plant X: A computer screen located on shift technical advisor (STA) desk. The screen
8 is separate from other screens and is dedicated to fire. A reactor operator (RO), senior
9 reactor operator (SRO), or STA can look at this. Either SRO will look or he or she will
10 assign someone to look (as STA will not be in MCR when this annunciator goes off).
11
12 Plant Y: Close to shift managers desk
13
14 4. What personnel are dispatched by MCR operators (e.g. just field operator, field operator
15 and digital instrumentation and controls (DI&C) technician)?
16 Plant X: Field operator and DI&C technician
17
18 Plant Y: Field operator only
19
20 a. Are the necessary staff available 24/7? If not, what are the contingency actions
21 (e.g., DI&C tech called in)? How do contingency actions affect the timing of the
22 response?
23 Plant X: Yes, including I&C tech. One is required at the plant at all times.
24 Probably more than one during the day shift.
25
26 Plant Y: Field operator available 24/7.
27
28 5. What equipment is used to locate source of incipient fire (e.g. sniffer, thermal imaging
29 camera)?
30 Plant X: Portable sniffer—tested weekly.
31
32 Plant Y: Portable sniffer.
33
34 a. If a thermal imaging camera is used, are baseline heat mappings of each cabinet
35 available to compare with current conditions? If so, is comparison done at the
36 scene of incipient fire or is additional analysis involved (e.g., software package
37 needed to compare conditions)?
38 Plant X: Thermal cameras are not used.
39
40 Plant Y: Not applicable.
41
42 b. What is the reliability and sensitivity of the sniffer technology?
43 Plant X: Tested weekly.
44

1 Plant Y: Not specifically known, but probably similar to fixed installation as it is
2 the same type of equipment.
3

4 6. How many cabinets are typically part of the same zone?

5 Plant X: It varies, from one to nine cabinets. There are typically sampling ports in each
6 cabinet. The cabinets are partitioned and sealed.
7

8 Plant Y: Between 5 and 15 cabinets
9

10 7. Is the posted fire watch a permanent or roaming fire watch? If it is roaming, how
11 frequently is the site observed?

12 Plant Y: Continuous fire watch until event is concluded. Fire watch personnel are
13 prevented from leaving the post; they cannot go through keycard door.
14

15 Plant X: Permanent fire watch following alert or alarm until situation resolved.
16

17 a. Is the dispatched field operator also considered the initial fire watch? If yes, what
18 training is required to qualify as a fire watch (e.g., ability to use fire extinguisher,
19 fire brigade training)?

20 Plant X: Yes. All (i.e., 100 percent) AO's have "fire watch incipient" training.
21 About 95 percent of FOs are fire brigade qualified. All FOs are qualified as
22 incipient fire watch; (this was added training, includes fire extinguisher use).
23

24 Plant Y: Yes. All operators trained in use of fire extinguishers, fire watch, and
25 most are fire brigade members.
26

27 8. What type of training is given to operators for using sniffers and thermal imaging
28 cameras?

29 Plant X: Training—initial, continuing training cycle every 2 years, sit down instructional
30 and practical at end, about 4-hour training. Practical training includes finding a
31 "smoking" wire; no timing data collected on this aspect of training.
32

33 Plant Y: Training not implemented as of yet, but expect that all operators will have
34 specific training (with qualification sign-off) in use of sniffers as part of basic operator
35 training.
36

37 9. Are cabinets opened when using the portable sensing equipment, or is it used with the
38 doors closed?

39 Plant X: It depends on the zone to which personnel are responding. If it is a
40 multi-cabinet zone, personnel start by sniffing the outside of cabinets to determine which
41 specific cabinet it is. The identified cabinet is then opened to find the component. If it is
42 a one-cabinet zone, the cabinet is opened. These actions are training-based.
43

44 Plant Y: Yes.
45

1 10. Is the stopping point for receiving credit at the point of posting a fire watch, at the point of
2 de-energizing the panel, or at time of repair?

3 Plant X: Assumption is made that 90 percent of incipient fires will be prevented and,
4 specifically, the fire watch will prevent the incipient fire from having an affect beyond the
5 ignition site.

6
7 Plant Y: National Fire Protection Association (NFPA) 805 Fire PRA credits incipient
8 detection as a means of detecting fire before propagation from cabinet. No credit is
9 taken for de-energizing or repairing affected component, or preventing loss of cabinet
10 function.

11
12 11. How often are VEWFDS down for service? How often are false alarms experienced?

13 Plant X: Annual maintenance requires system to be out-of-service for half a day.
14 Overall, Plant X is not seeing many unplanned shutdowns.

15
16 False alarms caused by ongoing work. Personnel usually know about this work and can
17 take detector out-of-service and post a fire watch. One detector alarms more often than
18 others; it is not necessarily false-alarm, but rather, a bit too sensitive. The alarm often
19 does not “lock in.” They are correcting this by changing the sensitivity settings. (IC)

20
21 Plant Y: No operating experience as yet.

22
23 Timing Questions

24
25 12. Do you have any information regarding timing from the VEWFDS alarm sounding to a
26 flaming fire?

27 Plant X: Yes, 2 hours and 42 minutes from alert to flaming fire on August 8, 2013.

28
29 Plant Y: No plant specific experience as yet.

30
31 13. What is the average time from the alarm sounding in the MCR to the dispatch of field
32 personnel?

33 Plant X: Immediately. The operator closest to location is dispatched.

34
35 Plant Y: Based on normal fire alarm response—Immediate

36
37 14. What is the average timing between the field operator receiving the dispatch call and
38 arriving at the fire location?

39 Plant X: Varies, but typically, 2 to 8 minutes. I&C tech are typically a few minutes
40 behind auxiliary operator (AO).

41
42 Plant Y: Usually 3 to 4 minutes for field operator; 15 minutes or less for brigade
43 response.

44

1 15. What is the average time for the field tech to locate the degraded component using the
2 portable equipment?

3 Plant X: No empirical information available. A single cabinet zone would require a few
4 minutes to narrow down which component.

5
6 a. How does the zone size affect this timing (three cabinet zone vs. 10 cabinet
7 zone)?

8 Plant Y: No experience as yet but would estimate 1 minute to sniff one cabinet.
9 Therefore time to identify specific cabinet could be 5 to 15 minutes.

10
11 b. If thermal imaging is used, how long does comparison between baseline and
12 current conditions take?

13 Plant X: Do not currently use thermal imaging.

14
15 Plant Y: Not applicable.

16
17 16. What is the average time to de-energize a degraded component?

18 Plant X: Quickly once the component is identified. If whole thing is on fire, they will
19 de-energize the entire cabinet, which takes seconds. It would take minutes for specific
20 breaker. One breaker requires a local action whereas the whole cabinet can be done
21 from the control room. The logic for the cabinet power is already laid out in MCR on
22 control board. No procedures for specific equipment de-energization; this activity is
23 directed by CR supervisor.

24
25 Plant Y: Do not anticipate de-energizing component as an immediate response unless
26 absolutely warranted because of the impact on plant operations

27
28 17. What is the average time to repair a component?

29 Plant X: Varies widely.

30
31 Plant Y: Long term.

32 33 **C.1.2 Information from Trip Reports**

34
35 1. How do operators respond to the various notifications, (e.g. pre-alarm and alarm)?

36
37 Response 1: They respond in accordance with APP-044-B39. If detector indicates
38 alarm, investigate for any indication of smoke, charring or overheating components. In
39 addition to visual inspection, other methods such as thermography can be used to locate
40 any overheating components. If an additional alarm on opposite train is received,
41 activate the fire brigade. (MCR)

42
43 Response 2: In a pre-alarm condition, operation attempts to clear the pre-alarm, if no
44 success, operation will initiate an operator alert and request ERT personnel
45 assistance. (AW)

46

1 Response 3: Pre-alarm: control room call responding organizations, shift emergency
2 response manager; someone checks the panel or visual size-up. Alarm: shift
3 manager. (AW)
4

5 2. Has the system false alarmed?
6

7 Response 1: Yes. During the initial installation of the VESDA system, multiple spurious
8 alarms were observed. Over the years, some alarm set points have been offset to
9 account for the environmental conditions, as a result, numbers of spurious alarms have
10 reduced. The cause of the spurious alarm ranges from unknown reasons, to airborne
11 charcoal dust from filters, to fumes from floor stripping, to dust bunnies. (AW)
12

13 Response 2: Yes. The most common cause is/was other work in protected areas (units
14 not bypassed). During the summers immediately following installation, there were some
15 issues caused by heavy smog or wildfires, causing high ambient background
16 conditions. (AW)
17

18 Response 3: Yes, from nitrogen purging, maintenance activities. Protocol to inform
19 CSNC, insurance company, (follow procedure for notification, SERM, duration time,
20 same notifications if it is a real fire. (AW)
21

22 Response 4: No. (MCR)
23

24 Response 5: Yes, from burning popcorn, hot work in the battery room, and a fan
25 failure. (AW)
26

27 3. How would an incipient fire be located and verified (equipment used, sequence of
28 actions taken)?
29

30 Response 1: Compensatory measures, thermal imaging (IR), only certified people can
31 use sniffers. (AW)
32

33 Response 2: Thermal imaging cameras are used to detect incipient fires. (AW)
34

35 Response 3: Cabinet doors would be opened, visual and smell senses would be used.
36 If necessary, a thermal imager would be used. (MCR)
37

38 Response 4: Human senses. (AW)
39

40 4. What kind of training has been provided to the operators, technicians and fire fighters on
41 the system?
42

43 Response 1: Control maintenance technicians were provided with a one week
44 comprehensive training on the EST 3 and the VESDA system at Edwards. They were
45 trained on the operation of the software and detection panel. (AW)
46

47 Response 2: Operations were provided with classroom and hands-on training for
48 operation of the Fireworks and Cirrus-Pro software. Operators were required to show
49 proficiency in Fireworks and Cirrus-Pro to gain qualification. Technicians were provided
50 initial classroom training on the Cirrus-Pro detectors and the FireWorks and Cirrus Pro
51 software which satisfied vendor qualification requirements for plant techs to work on the

1 Cirrus Pro detectors. A training aid that simulated the detector/fire panel/software
2 interconnection was provided to the training department for further instruction. (IC)

3
4 Response 3: No specific training implemented, the unit is straightforward. (MCR)

- 5
6 5. Are the operators trained on calibrating the system using proprietary software, if
7 applicable?

8
9 Response 1: The control maintenance technicians are trained on the manipulation of
10 the system and the use of the applicable software. Yes. Control Maintenance
11 technicians have been trained by the product vendor in the use of system configuration
12 software. This is required to enable the technicians to conduct proper maintenance,
13 testing and troubleshooting of devices. (AW)

14
15 Response 2: Operators are trained and qualified to use Fireworks and Cirrus-Pro
16 packages. (IC)

17
18 Response 3: No. (MCR)

- 19
20 6. Where is the detector located relative to the detection zone and why?

21
22 Response 1: The detector is located outside the RGTB cabinets, but approximately
23 5 feet from the nearest RGTB cabinet, because of space limitations. Tech manual
24 recommends locating the detector within the protected space. (MCR)

25
26 Response 2: Aspirating detector is located remote to the cabinets being monitored and
27 air sample is piped from the cabinets being monitored to the detectors. Each detector
28 has four zones. (IC)

29
30 Response 4: The detectors are typically located in the protected zone. This approach
31 acts to minimize any adverse effects caused by pressure differentials within different
32 areas of the station. It also serves to ensure that sampled air is discharged to the same
33 area from which it originated, eliminating opportunities for the spread of smoke or
34 airborne radioactive particles from one area to another (AW).

35
36 Response 5: In a different room. Both detectors are on the same wall next to each
37 other. (AW)

- 38
39 7. Are there any drawbacks specific to the VEWFDS?

40
41 Response 1: Maintenance requires quarterly and annual surveillance which is time
42 consuming and expensive. System is somewhat complicated, requiring a significant
43 vendor interface.

44
45 Response 2: A spare unit is recommended. (MCR)

- 46
47 8. What compensatory measures do you use when the system is out-of-service?

48
49 Response 1: Continuous fire watch. (AW)

50

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2
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14

Response 2: None. This detector is just one in a detection circuit made up of other spot detectors. The rest of the detector circuit remained operable. The detection circuit is located in the constantly manned control room. (MCR)

Response 3: Continuous fire watch. Also used when the fire source can't be located and alarm will not clear. (IC)

Response 4: Continuous fire watch, restricted work activities. (AW)

1
2
3
4

APPENDIX D

EVALUATION OF OPERATING EXPERIENCE DATA

5 **D.1 Evaluation of Fraction of Fire That Have Detectable Incipient**
6 **Stages**

7
8 This appendix documents the review of *potentially challenging or greater fires* from the fire
9 events database. The results are summarized in Table D-1, which contains several fields
10 described below.
11

Fire ID	Record number from EPRI Fire Events database
Fire Cause	Identifies apparent cause of event
Detected by	Identifies how the event was detected
Cabinet Type	Identifies the type of cabinet where the event occurred
Ignition Component	Identifies the component which ignited
Description	Provides summary of event
Incipient stage	Identifies if the event involved an incipient failure mode. Possible classifications are Yes, No, and Undetermined. Definitions are provided below.

12

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
29	Stab misalignment	Control Room instrumentation / annunciator	MCC	MCCB	Failure on demand. Following start of the main turbine turning gear motor a fire occurred in the 480V Engineered Safety Features (ESF) Motor Control Center (MCC) 2B64. Cause is attributed to design of breaker cubicle allowed misalignment when installing the breaker without providing a method of verifying proper breaker position.	PC	N	N
38	Run Contactor Short damaged CPT	Control Room instrumentation / annunciator	MG set Breaker	CPT	Failure During Test. During a bus undervoltage and ECSS integrated functional test for Units 2/3 Diesel Generator, a short in the run contactor coil to the 3A RPS MG Set Drive Motor Breaker caused excessive current flow through the control power transformer, which caught fire. This resulted in a loss of power on 3B RPS bus (because of the Reserve RPS Power Supply being out of service for a modification), a half scram and an unplanned Engineered Safety Feature (ESF) actuation.	CH	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
41	Stab misalignment	Fire Alarm	MCC	Breaker	Failure on demand. Immediately following start of the 'D' River Water Supply (RSW) pump, a fire alarm was received. Investigation identified fit between breaker primary disconnects and the associated breaker cubicle stabs was inadequate. Poor fit resulted in arcing in the breaker cubicle and subsequent fire. Breaker had been recently replaced as part of a design modification package and insufficient inhouse review of the breaker interface design specification is the apparent root cause.	PC	N	N
45	Undetermined	Control Room Instrumentation / Annunciator	MCC	MCC	Electrical fire in intake structure affecting 2 MCCs. Unite 1 Circ. Water MOVs and Lube Oil Cooling Water Pumps affected, and Unit 2 Circ. Water Pump Motor Bearings affected. Insufficient information to determine cause of failure or component that failed.	PC	U	U
69	Overheating wire	Control Room Instrumentation / Annunciator	Control Cabinet	Electrical cable insulation	Breaker self-closing caused by breakdown of insulation in breaker control cabinet. Breakdown caused by insulation contact with protruding tap of a wire wound power resistor, associated heat from resistor and deterioration caused by water intrusion (cabinet located in switchyard). Failure is a result of accumulated effects of 25 years of deterioration.	U (NC-PC)	Y	Y

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
83.1	Ground Fault	Plant Personnel	Power	Essential Lighting UPS / Distribution Panel	Smoke was discovered in the back boards area of the control room by a security officer performing an hourly fire watch tour. Smoke was emanating from the Emergency Lighting Uninterruptible Power Supply and the Essential Lighting Distribution Panel. Cause was short circuit current in plant ground system because of inadequate grounding procedures. Fire was self-extinguished by removal of power by opening AC breaker in ELDP.	PC	Y	Y
83.2	Ground Fault	Plant Personnel	Power	Essential Lighting Isolation Transformer	Following event 83.1, AO was surveying duty area and found smoke and fire in Train B DC equipment room (different room and elevation from event 83.1). Fire was contained to essential lighting isolation transformer. Fire required removal of 480V power from ELIT by manually opening circuit breaker, and application of carbon dioxide extinguisher by AO and Fire Brigade.	PC	Y	Y
89	CPT & Relay Failure	Unknown	MCC	CPT & HGA Relay	Internal short in the control power transformer, which caused the failure of the HGA control relay. Root cause of CPT failure not reported. Failure of these two components prohibited the proper operation and automatic transfer of the EDG room ventilation system from Unit 3 busses to Unit 2.	PC	Y	Y

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
98	Undetermined	Plant Personnel & Fire Alarm	Control Cabinet	Undetermined	During a 24-hr post-maintenance run of emergency diesel generator an operator noticed heavy smoke coming from the EDG control panel. Initiation component and cause of event was not identified.	PC	U	U
131	Undetermined	Plant Personnel	Undetermined	Undetermined	Non available, fire was in turbine building	CH	U	U
144	Stab Misalignment / Ground Fault	Control Room / Plant Personnel	MCC	Breaker stabs	Failure on Demand. Concurrent with attempted start of containment cooling fan (closing of breaker), supply circuit breakers for 480VAC MCC tripped as a result of a bus to ground electrical fault. Responding operators discovered a small fire in the MCC. Root cause identified inadequate design resulted in improper placement of circuit breaker in MCC. One stab didn't make up to its associated bus bar correctly, resulting in a high resistance connection.	PC	N	N
146	Breaker to Bus Stab High Resistance	Control Room / Plant Personnel	Load Center	Breaker stabs	Failure on demand. Breaker failure following placing breaker in-service after restoration steps from a test of the automatic start feature of an isophase bus cooling fan. Failure because of high resistance connection between bus bar stabs and breaker assembly.	PC	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
152	Breaker to Bus Stab High Resistance	Fire Alarm	MCC	Breaker stabs	Failure on demand following maintenance MCC failure concurrent with charging pump starting. Root cause identified high resistance connection at the stab/bus interface likely because of less than adequate preventative maintenance and original design inadequacy.	PC	N	N
161	Undetermined	Plant Personnel	MCC	Undetermined	'D' control rod drive mechanism (CRDM) fan (1-HV-F-37D) tripped. Approximately 30 minutes later operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed.	PC	Y	Y
175	Undetermined	Undetermined	7.2kV Switchgear	Undetermined	Fire in the non-safety 7.2kV switchgear room.	CH	U	U
187	Undetermined	Plant Personnel	Control Cabinet	Undetermined	Smoke from Unit 3 condensate demineralizer control panel. Power supply in the panel was unplugged to extinguish the fire.	PC	U	U
188	Lightning Strike	Plant Personnel	Power Control Cabinet	Undetermined	Lightning strike caused a fire in a power control center. De-energizing bus supplying power extinguished the fire in the power control center.	PC	N	N
203	Undetermined	Plant Personnel	MCC	Undetermined	Two MCCs burned	CH	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
206	Missing Component	Plant Personnel	Breaker	Breaker	Fire in recirculation motor generator field breaker caused by missing extension piece for the center phase shorting bus. This allowed the field to be continuously shorted during operation.	PC	U	U
211	Undetermined	Plant Personnel	MCC	CPT	Control Power Transformer failure in MCC	U (NC-PC)	Y	Y
219	Undetermined	Roving Fire Watch	MCC	CPT	Control Power Transformer failure in MCC	PC	Y	Y
224	Human Error	Plant Personnel	MCC	Undetermined	Electrical fault in 480V MCC cubicle caused by human error during maintenance/cleaning	U (NC-PC)	N	N
253	Breaker Failure	Plant Personnel	Switchgear	Trip Coil	Breaker failed to open causing excessive current in trip coil.	U (NC-PC)	N	N
254	Undetermined	Plant Personnel	MCC	Undetermined	MCC electrical overload	U (NC-PC)	U	U
303	High Resistance	Plant Personnel	Control Cabinet	Fuse Disconnect	Plant heater boiler control cabinet on fire caused by high resistance connection in the 60 amp fuse disconnect. Cabinet doors were found open with flames coming out of the cabinet and paint burning off of the top.	PC	Y	Y
320	Breaker Failure	Plant Personnel	MCC	Breaker	Feeder breaker tripped when operator attempted to start 'B' main chill water pump. Local breaker was observed to be on fire and had not tripped.	PC	N	N
381	Breaker cooling fan failure	Control room instrumentation / annunciator	MCC	Cooling fan	Aux cooling equipment fan motor shorted out with fan motor assembly on fire.	PC	U	U
411	Water intrusion	Plant personnel	Breaker box	Breaker	Breaker box failure caused by water intrusion	U (PC-CH)	N	N

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
517	Transformer fault	Control room annunciator & Smoke Alarm	UPS	Transformer	Fire in ERFDADS computer uninterruptable power supply. Apparent cause was a turn to turn fault in the top winding. Vibration, temperature, and age are contributing factors to this failure.	CH	Y	Y
520	Inverter fault	Control room annunciator & Smoke Alarm	UPS	Unknown	Fire in ERFDADS Inverter	PC	U	U
588	Ground fault	Control room annunciator & smoke alarm	Switchgear	Unknown	Ground fault on 480V SWGR	CH	U	U
10338	Breaker fault	Plant Personnel	MCC	Breaker	Failure on Demand. During start of pump, breaker flashed and resulted in small fire in cubicle with door forced open.	PC	U	Y
20264	MCC Coil fault	Plant personnel	MCC	Coil	Smoke observed coming out of MCC. Hold in coil overheated.	U (NC-PC)	U	U
20267	Breaker fault	Plant Personnel	MCC	Undetermined	Breaker malfunction	U (NC-PC)	U	U
20268	Overheated component	Plant Personnel	MCC	CPT	Control Power Transformer overheated	U (NC-PC)	Y	Y
20269	Undetermined	Plant Personnel	Electrical Lighting Panel	Undetermined	Electrical Lighting Panel Failure	U (NC-PC)	U	U
20270	Transformer Failure	Fire Watch	MCC	Transformer	MCC Breaker Transformer failure	U (NC-PC)	Y	Y
20272	Relay failure	Plant Personnel	Electrical Panel	Relay	Electrical Panel Relay	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
20273	Trip coil failure	Plant Personnel	Switch-gear	Breaker trip coil	Heavy smoke was observed in the Train 'A' switchgear room caused by a faulted trip coil.	U (NC-PC)	N	N
20275	Overheat	Plant Personnel	MCC	CPT	Control power transformer burned up causing the diesel generator lube oil heater MCC to smoke.	U (NC-PC)	Y	Y
20276	Breaker	Plant Personnel	Switch-gear	Undetermined	RCP breaker cubicle	U (PC-CH)	U	U
20282	Overheat	Plant Personnel	MCC	CPT	Operator saw smoke coming from an MCC for the MISV hydraulic pump; transformer fault.	U (NC-PC)	Y	Y
20287	Overheat	Roving Fire Watch	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20295	Overheat	Plant Personnel	MCC	CPT	Control power transformer overheat	U (NC-PC)	Y	Y
20302	Ground fault	Plant Personnel	MCC	Undetermined	Ground fault on main and/or reserve feed breakers cause fire	U (NC-PC)	U	U
20312	Switch	Smoke alarm	Switch-gear	Switch	EDG roto test switch damaged and failed causing a fire	U (NC-PC)	U	U
20325	Chemical Spill	Plant Personnel	Heat trace wiring	Heat trace wiring	Acid spill on heat trace wiring	U (NC-PC)	Y	Y
20328	Undetermined	Smoke alarm	Electrical Distribution	Undetermined	Sudden electrical distribution panel failure with smoke.	U (NC-PC)	U	U
20329	Relay fault	Plant personnel	Switch-gear	Relay	Relay stuck in intermediate position	U (NC-PC)	U	Y
20334	Breaker	Plant Personnel	MCC	Breaker	MCC Breaker	U (NC-PC)	U	U
20346	Breaker	Plant Personnel	MCC	Breaker	Breaker in 4kV room	CH	U	U
20356	Internal Short	Plant Personnel	MCC	Light bulb	Short in light bulb	U (NC-PC)	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
20357	Human Interaction, Improper Maintenance	Plant Personnel	MCC	MCC internals fell on power phase	Ground fault inside a nonsafety-related MCC caused by improperly equipment restored to service. Internal plane cover not properly secured and fell during investigations and caused ground fault.	U (PC-CH)	N	N
20362	High Resistance	Other Equipment Failure	MCC	Insulation / fuse block	Insulation burned off of one lead to motor starter contactor and fuse block severely melted. Termination screw loose on starting input terminals.	U (NC-PC)	Y	Y
20382	Undetermined	Plant Personnel	Switch-gear	Undetermined	Switchgear failure	U (NC-PC)	U	U
30276	PCB fault	Plant Personnel	Emergency Lighting	Power transformer	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell.	PC	N	N
30281	Procedure Error	Plant Personnel	Control Panel	Insulation	During testing of synch switches for Main Xfmr, Emergency Aux Xfmrs and Main generator, insulation failed because of excessive applied voltage (230,000volts applied to a 120V synch bus).	CH	N	N
30338	Inadequate PM	Control Room Instrumentation / Annunciation	Control Panel	Panel Blower	Panel blower (fan) failure. Blower found to be full of dust and dirt.	PC	Y	Y
30478	Relay failure	Plant Personnel	Control	Relay	Condensate demin panel fire and smoke from affected relays (3).	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
30513	Overheat	Fire Alarm	Control	CVT	Constant Voltage Transformer inside rod action control cabinet in back panels of MCR ignited combustible materials located inside transformer housing	PC	Y	Y
30522	Undetermined	Fire Alarm	Control	Undetermined	RBCCW cathodic protection cabinet fire.	PC	U	U
30578	Undetermined	Plant Personnel	Power Supply	Undetermined	Fire reported in electrical box associated with power supply for the cask handling crane. Damage limited to heat shrink tubing on a connector.	PC	U	U
50467	Breaker fault	Plant Personnel	Switch-gear	Closing Coil	Breaker found to be smoking. Breaker removed and found closing coil was frozen in the close position.	U (NC-PC)	N	N
50473	Water intrusion	Equipment trouble alarm	Electrical Panel	Relay	Small fire discovered in electrical panel while investigating burning odor while responding to alarm from same electrical panel. Flames and smoke were observed emanating from relay. Failure was a result of water intrusion from HVAC condensate drain line.	PC	Y	Y
50784	Relay misalignment	Plant Personnel	Control Cabinet	Relay	During relay testing, the relay began to smoke. During de-energization activates, the relay caught fire. Fuses were pulled and CO2 was used to extinguish. Suspected cause was a slight misalignment of the relay and contact structure.	PC	N	N
50811	Relay failure	Control Room Instrumentation / Annunciator	Control Cabinet	HFX relay	Received numerous alarms in control room related to FP filter low-flow alarm. Found FP pump tripped and pressure drop. Smoke observed in room. Investigation found HFX relay burning. Extinguished with portable.	PC	U	U

Table D-1. Evaluation and Description of Bin 15 Events							Incipient stage (Y/N/U)	
Fire ID	Fire Cause	Detected by	Cabinet Type	Ignition Component	Description	Severity Class	Reviewer 1	Reviewer 2
50874	Breaker failure	Plant personnel	Switchgear	Trip Coil	During shutdown of Recirc MG set the field breaker failed to open. Trip coil smoking and on fire. Fire extinguished and fuses pulled.	PC	N	N

D.2 Quantification of the Time Available for Operator Response

As shown in Figure 2-2, the fire growth profile is made up of several stages. Of importance is the early stage of the fire referred to as the “Incipient” stage. Although many fires exhibit this incipient stage, it is not typically modeled in performance-based design, primarily because of the variability of its duration. This variability is caused by several reasons; including deviations in material properties, ignition source, and configuration, just to name a few. Additionally, for fires which do display an incipient stage, testing has shown that aspirating smoke detecting systems configured to provide very early warning fire detection (VEWFD) do not detect the component degradation at its onset, but sometime after the first quartile. Thus, to quantify the time available for operator response, operating experience was reviewed to identify quantitative information to support a better understanding of either the incipient stage duration, or time available between ASD VEWFD alert and fire conditions. To focus this study, several assumptions must be made.

The assumptions used for the characterization of the available time estimates in this project are as follows:

1. Limited to electrical enclosures found in nuclear power plants
 - a. Excluded equipment includes components such as, motors, pumps, MG sets, diesel generators, air compressors.
 - i. These components are excluded, not because they do not have the potential to exhibit an incipient stage, but because of the limited scope and resources to develop an understanding of the failure modes and their associated duration, which can contribute to risk significant fire scenarios.
2. Limited to component fires that have a sufficiently long duration (incipient stage) such that operator response has the potential for enhanced warning and thus enhanced suppression capabilities.
 - a. The duration curve developed DOES NOT model the incipient duration for all fires, just those fires that exhibit an incipient duration greater than approximately 30 minutes³⁸.

It should be noted that the current state of knowledge related to understanding the duration of component degradation and associated fire signature from such degradation, is limited. One of the primary reasons for said limitation is because of the fact that, in many instances, the early degradation phases do not affect circuit or system functionality. As such, the early degradation conditions are not explicitly explored, with the exception of those plants that have a periodic inspection process which employs the use of thermal imaging cameras or similar technologies. Even so, these technologies and the frequency of inspection may not be completely successful in identifying these early degradations with such finality that corrective actions can be taken to remedy the potential failure of the component(s).

Given the assumptions and limitations, an attempt was made to quantify the duration of the incipient stage as discussed above. Because of the lack of information, it would have been ideal to conduct a formal expert elicitation process, where by a group of experienced experts

³⁸ The 30-minute minimum was chosen based on a factor of 2 based on the maximum use of 15 minutes for plant personnel (fire brigade) response to fire locations. The factor of 2 was based on the assumption that the incipient fire location may be more difficult to locate because of the nature of the fire signature exhibiting low amounts of smoke and possibly invisible smoke.

with diverse backgrounds and knowledge provides the expert judgment for use in quantifying the incipient stage duration. Unfortunately, this need was not identified in the initial project planning phase and so resources were not made available to support such an effort. Consequently, to acquire this type of information, an informal ad hoc approach was used in which several knowledgeable individuals from the NRC and Sandia National Laboratories were asked to quantify the incipient duration using available information.

Even with the pivotal role that quantifying the duration of the incipient stage plays with regard to determining successful operator action, limited responses were provided to the request. Thus, the estimate provided below represents an evaluation of available operating experience, and as such, likely does not represent the informed technical community's viewpoint. This evaluation is purely based on data, and no engineering judgment has been used to adjust the estimate.

Operating Experience

The Updated EPRI Fire Events Database was reviewed for Bin 15 "Electrical Cabinets" Fire Events. A summary of those events that contribute to the fire ignition frequency are presented above in Section D.1. Of those events, only a limited number are associated with low-voltage (<250V) equipment, with the majority of the events (approximately 80 percent) involving low-voltage switchgear, load control centers, or distribution panels, etc.

In reviewing all the low-voltage (<250V) Electrical Panel events classified as "Challenging," "Potentially Challenging," and for "Undetermined," zero events were identified as non-power distribution-type equipment in scenarios for which timing information associated with the duration of the incipient stage was provided.

When the review was expanded to include all Electrical Panel equipment types, which are classified as "Challenging," "Potentially Challenging," or "Undetermined," only one event was identified in which timing information associated with the duration of the incipient stage was presented. This event was FID 161 and indicated that approximately 30 minutes elapsed between time of breaker trip and operations finding a small flame within the enclosure. The event description is presented as follows:

'D' control rod drive mechanism (CRDM) fan tripped. Approximately 30 minutes later, operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed.

Although the event report is unclear regarding what caused the initial tripping of the CRDM fan and how long before the breaker trip the failing component had been degrading, it does suggest an approximately 30 minute reference point between an initiating event and detection (by plant personnel) of a small fire.

One event out of the ~70 events used to determine the fire ignition frequency for electrical panel provides a very weak basis with large uncertainty for quantifying the duration of the incipient stage generically for all of the varieties, vintages, and combinations of electrical components found in operating NPPs. Thus, in an attempt to develop a generic prediction of the duration of NPP electrical cabinets, other sources of information were sought.

The first source included reviewing the "Non-Challenging" events from the EPRI fire events database. Although use of this information is not ideal because these events are not used to

quantify risk, they may provide some insight into the quantification effort. Upon this review, two events were identified as having timing information associated with the duration of the incipient stage. The first “Non-Challenging” event was FID 10647, which indicated that a fire occurred in a control cabinet for a reactor building chiller that, because of high outside air temperature, ran under a full-load condition over the course of an afternoon. The following three apparent fire causes and contributing factors were identified:

- 1) Power cable was inadequately sized to 208 Amp service while the minimum electrical circuit load ampacity for this load was 403.2 Amp.
- 2) Breaker failed to trip during high current conditions
- 3) Experienced poor power-block phase connection (high resistance).

Although the event description does not provide a specific time frame during which the chiller unit was operating at full-load, or in excess of the ampacity limits of a 4/0 AWG power cable conductor, it did specify that the failure occurred over an afternoon. Webster’s Dictionary defines an afternoon as “the day from noon until sunset”(Webster’s II New College Dictionary, 3rd Ed., 2005). Thus, depending on the time of year and location within a time zone, the definition of an afternoon could vary from 5 to 9 hours. So, for this example, the average afternoon length was assumed to be 7 hours.

The second “Non-Challenging” event was FID 50836, and identified a computer inverter fire. In this event, detailed timing information was provided as follows. At 0500, the Unit 2 computer inverter was started up per operating procedures, with normal startup and loading indications. At 0555, a fire alarm was received. At 0558, the operator reported smoke and fire emitting from a U2 computer inverter. Loss of power to the computer bus resulted in the loss of most MCR U2 trending displays. Consequently, this event shows that in less than 58 minutes the equipment transitioned into flaming conditions.

The second source of information included the assumptions made in previous incipient fire detection risk quantification efforts, namely, the EPRI Fire PRA Enhancements and the NRC FAQ 08-0046 interim staff position. In EPRI Report 1016735, when determining the preemptive response effectiveness “P,” an assumption is made that “IFD systems will alarm up to an hour or more before ignition occurs (based on manufacturers’ claims, NFPA 76 objectives, and technical discussion in Appendix C of the EPRI report).” Although that report indicates that a technical discussion supporting the assumption is provided in Appendix C, a review of that appendix didn’t produce substantial evidence to support this estimate. In the published, final version of the NRC Staff interim position, the one-hour assumption was also made with little to no basis. Regardless of the validity of the one-hour estimate, it can be considered a quasi-consensus because numerous individuals were responsible for the development, review and approval of these documents. Hence, the one-hour time frame available following ASD VEWFD detection at an alert condition will be retained; however, it should be noted that this hour corresponds to the time from ASD detection to ignition, and not the start of component degradation to ignition.

The last source sought for insights was well-documented, recent U.S. NPP events in which ASD systems were in the area. These events, which occurred in 2013 and 2014, included ones captured in the fire events database.

2013 event: On August 7, 2013m, at 23:30, an operator was dispatched to Aux Bus E to

investigate an equipment trouble alarm. Four minutes later the operator identifies that there is a ground fault on the 6.9kV/480V Aux Bus E. At 23:38, an IFD zone located in an electrical cabinet 20 feet away notifies an alert condition. Two hours and forty-two minutes later an explosion occurs involving the Aux Bus 1E2. Therefore, the IFD provided 2.7 hours of advanced warning before ignition; in this case ignition is considered to be the occurrence of the explosion. Information from this event was taken from the following source, Beasley, K., 08-08-2012 HNP Fire Event on 1E2 Bus. Retrieved July 29, 2014 from Fire Protection Information Forum Archives: <http://www.nei.org/Conferences/Conference-Archives/Fire-Protection-Information-Forum-Archives>.

2014 event: The event occurred because of an internal fault in the 480V load center station service transformer 1D2. The event started at 07:51, with the MCR receiving electrical equipment trouble alarms associated with 1D2. At 08:32, it was confirmed that grounds were present on both sides of the transformer. At 09:00 a single zone of the IFD notified an alert condition, and at 09:02, the same IFD zone indicated an alarm condition. At 09:29, the resistor associated with the ground relay was glowing red, and at 09:31 it was determined to de-energize 1D2. At 10:07, local plant personnel identified smoke emanating from the 1D2 transformer cubicle and a determination was made to trip the reactor, which was at 75 percent power. At 10:24, a confirmation was made that no more smoke was emanating from the 1D2 transformer. Report never identified if flaming conditions occurred.

Regardless of the severity classification of this event, it provided timing information associated with the time between ASD response and fire, if it is assumed that when the plant was shut down a fire was eminent. Because of the limited amount of data, it was decided to keep this event data. So, given the IFD notified the MCR of an alert condition at 09:00, if we assume that ignition occurred at 10:07, there was approximately 1.12 hours of advanced warning before assumed flaming conditions.

This completes the available quantitative information regarding the length of the incipient stage for electrical components found in U.S. NPPs through operating experience. However, other sources of for timing information were sought, including NASA, Canada NPPs, National Laboratories, and the NAVY. One event was provided by a National Laboratory where resistors overheated in two isolation chassis drawers of a 125Vdc power supply rack for a Particle Beam Fusion Lab Z shot machine. The system uses software to control hardware (programmable logic controller). During an experiment in 2011, the shot was aborted, however an error in the software failed to shut down the power supply to two of the charging capacitor circuitry. This resulted in overheating of the resistor network to ground. From time of test abort to identification of overheating resistors was 59 minutes. Visible thermal damage was observed on the exterior of the electrical enclosure (discolored paint, soot deposits) and the resistor drawers were a complete loss.

Table D-2 provides a summary of this available operating experience duration information. The "Time Available" estimates are based off of the incipient stage operating experience and adjusted using the data from the NIST testing. The basis for this adjustment is presented in Section 8.1.2. The resulting exponential distribution fit to the "Time Available" data is shown in Figure D-1 and Table D-3.

Table D-2. Summary of Incipient Stage Duration and Time Available for Operator Response

Event	Incipient stage (Hours)	Time Available for Operator Response (Hours)			
		CC	LS-SS	ION	PHOTO
EPRI FEDB 161	0.5	0.26*	0.13*	0.17*	0.04*
EPRI FEDB 50836	0.9	0.47*	0.23*	0.31*	0.07*
SNL z-machine	0.98	0.51*	0.26*	0.33*	0.08*
EPRI / NRC FAQ		1.00	1.00	1.00 [†]	N/A
2014 Event		1.12	0.56*	0.73*	0.17*
2013 Event		2.75	1.38*	1.80*	0.42*
EPRI FEDB 10647	7	3.64*	1.82*	2.38*	0.56*
<i>Lambda</i>		0.7	1.3	1.0	4.5

* estimate based on operating experience adjusted with experimental results (mean time to detection) and assumption of linear component degradation

[†] used EPRI/NRC FAQ estimate for non-VEWFD system since data indicates that ION spot-type detectors performed equivalently or better than LS ASD VEWFD which those documents cover.

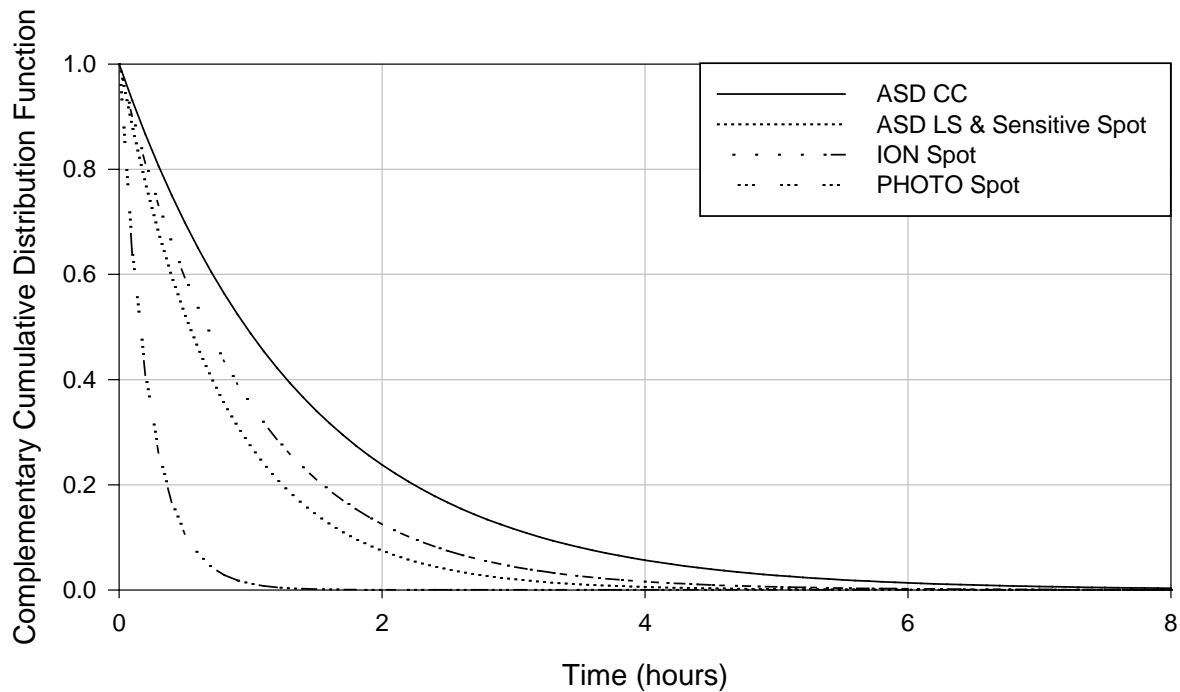


Figure D-1. Exponential distributions fit to data for the time available for operator response following an ASD alert for different detection technologies tested

Table D-3. Exponential Distribution Values for Time Available for Operator Response by Smoke Detection Systems

Time (Minutes)	Complementary Cumulative Distribution Function			
	ASD CC	ION Spot	ASD LS and SS	PHOTO Spot
0	1	1	1	1
1	0.99	0.98	0.98	0.93
2	0.98	0.97	0.96	0.86
3	0.96	0.95	0.94	0.80
4	0.95	0.93	0.92	0.74
5	0.94	0.92	0.90	0.69
6	0.93	0.90	0.88	0.64
7	0.92	0.89	0.86	0.59
8	0.91	0.87	0.84	0.55
9	0.90	0.86	0.82	0.51
10	0.89	0.84	0.81	0.47
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30	0.70	0.58	0.52	0.11
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60	0.49	0.35	0.27	0.01
Lambda	0.72	1.04	1.30	4.48

D.3 Evaluation of Enhanced Fire Suppression Fire Events

This section documents the review of fire events from the fire events database where an operator was present in the room of origin when a flaming condition began. These results were used to develop a new suppression curve. The results are summarized in Table D-3, which contains several fields described below.

- Fire ID Record number from EPRI Fire Events database
- Fire Cause Identifies apparent cause of event
- Detected by Identifies how the event was detected
- Cabinet Type Identifies the type of cabinet where the event occurred
- Description Provides summary of event

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
83.1	Ground Fault	Plant Personnel	Power	Smoke was discovered in the back boards area of the control room by a security officer performing an hourly fire watch tour. Smoke was emanating from the Emergency Lighting Uninterruptible Power Supply and the Essential Lighting Distribution Panel. Cause was short circuit current in plant ground system because of inadequate grounding procedures. Fire was self-extinguished by removal of power by opening AC breaker in ELDP.	9
161	Undetermined	Plant Personnel	MCC	'D' control rod drive mechanism (CRDM) fan (1-HV-F-37D) tripped. Approximately 30 minutes later operations locally opened the breaker after identifying a strong odor and that the breaker associated with CRDM fan was smoldering. Upon opening the cabinet a "6-inch flame" was observed. At the time of fire discovery the Operations fire brigade members were in the area. When the source was found the fire was immediately extinguished and reflash watch set	5

Table D-3. Evaluation of Enhanced Fire Suppression Fire Events

Fire ID	Fire Cause	Detected by	Cabinet Type	Description	Suppression Time (min)
253	Breaker Failure	Plant Personnel	Switchgear	Breaker failed to open causing excessive current in trip coil. Operations crew were present within room during failure.	10
20270	Transformer Failure	Fire Watch	MCC	MCC Breaker Transformer failure detected by fire watch	1
20272	Relay failure	Plant Personnel	Electrical Panel	Electrical panel relay fire. Detected by security guards within the fire area.	4
30276	PCB fault	Plant Personnel	Emergency Lighting	Emergency Lighting Battery Box Failed during annual inspections. Power transformer inside the box was observed to have sparked and caused a fire. Failure caused by bad charging board and one bad cell. An indication existed of the smell of smoke in the Control Room. Upon investigation found Emergency Lighting Battery Box # E7-12 on the East Wall of the Control Room, behind 1C614, with smoke coming out.	2

APPENDIX E

LITERATURE REVIEW

This appendix provides a summary of literature reviewed in support of this project. All summaries are from publically available documents. The literature is from a variety of sources, including the National Fire Protection Research Foundation, academia, vendors, conference proceedings, and journal articles. The summaries are provided in chronological order. At the end of this section, additional reading material that was reviewed is identified, but not summarized below.

- E.1 Custer, R.L.P., Bright, R.G., "Fire Detection: The State-of-the-Art," U.S. Department of Commerce, National Bureau of Standards, June 1974.

This report, although dated, provides a substantial amount of information related to fire detection technologies with consideration of fire signatures, detection modes, test methods, performance requirements, and code requirements. For those with limited-to-no knowledge of fire detection systems operations, review of the report is strongly recommended.

Important concepts gathered from this report, applicable to the current study include a description of submicrometer particle counting detectors; ambient condition effects on detector response; and an emphasis on the importance of detector maintenance. Relevant information is communicated in the main body of this report.

- E.2 Meacham, B.J., "Factors Affecting the Early Detection of Fire in Electronic Equipment and Cable Installations," May 1992.

This article provides an overview of the factors that influence fire detection, such as fuel characteristics; compartment configuration; environmental configurations; and maximum allowable fire size at time of detection; and guidance on selecting appropriate devices. The focus is on telecommunication facilities. The first factor discussed is the fuel and fire characteristics, which consist of circuit, component, or interconnecting wiring, which can produce considerable combustion products, but have a relatively low-energy output, and may never transition to a flaming fire. Loss history has shown that small, low-energy fires are a serious problem and make early detection difficult because of weak plume strength. Weak plumes and low ambient temperatures can cause insufficient smoke transport to the uppermost level of a ceiling-height enclosure.

- E.3 Gottuk, D.T., McKenna, L.A., "Response Time Comparison of Spot vs. Aspirated Laser Smoke Detection," September 1999.

Hughes Associates, Inc. performed 56 full-scale tests for Pittway Systems Technology Group, comparing the response time of laser-based Notifier VIEW spot detection systems to Vision Systems laser aspirating smoke detectors (ASDs), which were exposed to a variety of smoke sources and ventilation conditions within a telecommunications facility.

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An operating Bell Canada switch center was selected as the test site (100 ft. wide, 180 ft. long [18,000 sq.ft.], 15.5 ft. high. Five smoke sources were evaluated, including BSI 6266 wire; Bell Canada wire; BSI 6266 chemical smoke test; internal printed wire board; and conductive heating of EPDM cable insulation. The sources were evaluated at ten different locations with variable source heights and two different ventilation conditions. Normal ventilation conditions consisted of three recirculation air conditioning units, operating at a combined 25844 cubic feet per minute (cfm), serving the DMS switching center, and a general HVAC unit serving the larger toll/frame area at 12,618 cfm. Reduction ventilation conditions consisted of shutting down two of the three recirculation air conditioning units. Several variations of detector configuration were also used to evaluate any performance differences. The VIEW spot detectors were arranged in two redundant loops. One loop used detector spacing at 200 ft² while the other loop spaced the detectors at 400 ft². VIEW detectors were also placed on the return air grills, and detector-mounting angles were varied among tests to evaluate the effect on system response. Two laser ASDs were installed in the ceiling areawide configuration, and one laser ASD was installed on the return air grills of the recirculation system.

Several key insights were identified from this testing, namely the following:

- Comparable performance between the laser ASD and 200 ft² VIEW systems was demonstrated, while the 400 ft² VIEW system showed decreased performance compared to either the 200 ft² VIEW or laser ASD systems.
- Return air grill detection showed no clear difference between the laser ASD and the spot VIEW detectors. For the VIEW system, the return air grill configuration responded to fewer sources than the 200 ft² system and was slower to respond; however, the returns did detect 3 additional fires not detected by the areawide VIEW system.
- Considerable variability existed in the alarm times from a given detector system because of changes in source type and location. Even for tests in which conditions were the same, response time varied.
- ASD configured to both ceiling areawide and return air grills were unable to detect most of the BSI wire tests (13 of 19 tests undetected). Additionally, the majority of the Bell wire tests were undetectable by both ASD and VIEW systems.
- Air flow monitoring tests showed that the ASD system didn't issue a supervisory alarm until 66 percent to 76 percent of the sampling holes were blocked, while the vendor default settings for low airflow warning were determined or found to occur at 30 percent reduction in normal airflow. Thus, air flow reduction doesn't correlate to sampling hole blockage for the particular ASD system tested.

- 1 E.4 Geiman, J., Gottuk, D., "Alarm Thresholds for Smoke Detector Modeling," Fire Safety
2 Science Proceedings of the Seventh International Symposium, 2002.

3
4 This paper illustrates an evaluation of the use of smoke optical densities outside a
5 detector as a criterion for predicting smoke detector response. The Temperature
6 Rise Method was not evaluated because of the highly questionable accuracy. The
7 study applied three full-scale experimental data sets that used optical density meters
8 located in close proximity to some of the detectors (ion and photo). This paper
9 concludes that determining the precise alarm times is not currently possible with the
10 large number of variables that not only exist, but influence smoke detector response.
11 Using nominal detector sensitivities as an alarm threshold, leads to only about 20
12 percent of the alarm predictions corresponding to actual detector alarms. In most
13 cases, the use of the nominal sensitivity will result in predicting alarms before they
14 actually occur. One exception is ionization detector response to flaming fire
15 conditions, which corresponded with predicted alarm conditions 50 percent of the
16 time. Using an alarm threshold of 0.14OD/m (9.4 %/ft obscuration) provides a
17 relatively high level of confidence in predicting detector alarms, but will typically
18 predict alarm response times that are potentially longer than would actually occur.

- 19
20 E.5 Nicholson, J., "Looking Up: NFPA 805, Performance-Based Standard for Fire Protection
21 for Light Water Reactor Electric Generating Plants," NFPA Journal, May/June 2003.

22
23 This article provides a high-level overview of how performance-based fire protection
24 application of NFPA standards have improved safety at Canadian nuclear power
25 plants (NPPs). The use of performance-based, over prescriptive requirements,
26 facilitates the use of (their) equivalencies in making more realistic analyses of Bruce
27 Power Plants safe shutdown capability. The Bruce implementation of performance-
28 based initiatives was deemed to be equivalent to the Canadian Standards
29 Association N-293. As part of the plant upgrades, Vesda Air Aspiration Systems
30 were installed.

- 31
32 E.6 Tieppo, Eddie, "Very Early Warning Aspirated Smoke Detection in Nuclear Power
33 Facilities," October 2003.

34
35 This paper provides a high-level overview of design and benefits of VEWFD systems
36 over conventional spot-type detectors. Maintenance considerations for ASD systems
37 are also presented with discussion of detector unit, filter, and pipe network
38 maintenance concerns. This paper concludes with a discussion of several
39 applications used in Canadian NPPs in areas such as the main control room,
40 equipment rooms, cable tunnels, and generators halls.

- 41
42 E.7 Vision Systems, "White Paper: Using Air Sampling Smoke Detection to Protect Mission-
43 Critical Facilities from Fire," 2004.

44
45 This paper provides a high-level overview of the importance of protecting mission-
46 critical facilities, such as essential financial installations, from the effects of smoke
47 damage on their electronic computer systems. More and more, the risks associated
48 with data center fires are caused by increased energy consumption from modern
49 computers, and the need to use high-ventilation, flow rate air conditioning to cool the
50 computer electronics. Consequently, such high air flow environments, using
51 conventional spot-type detectors becomes ineffective. However, it is not only

1 potential fire damage from which the data centers need to be protected. Smoke
2 contamination of electronic equipment, even as small as 16 micrograms per square
3 centimeter, can cause corrosion and long term effects and 30 microgram per square
4 centimeter can result in short-term effects.

5
6 The paper also provides an overview of how ASD systems work; common
7 application in typical data center environments; ASD system design characteristics
8 that are important to consider in ensuring the EW or VEW detection; coverage area;
9 and sensitivities. The paper also establishes that in-cabinet and integrated-
10 equipment detection enable an excellent VEWFD solution for the following reasons:

- 11 1. Sampling is performed closest to the source.
- 12 2. Addressability is enhanced as compared to ceiling or air return type
13 detection.
- 14 3. Likelihood of smoke/fire damage to other equipment is minimized.
- 15 4. Background noise (dust/smoke) within enclosures is relatively consistent.
- 16 5. Numerous detector set points made a staged response replicable/possible.

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23
24 E.8 Vision Fire & Security, "Development of Performance Equivalency Methodology for
25 Detection and Suppression System Integration," 2006.

26
27 Vision Fire & Security Pty Ltd. developed a detection equivalency method, which
28 resulted in development of an "application tool" to allow ASD systems to be specified
29 as an alternative to the conventional spot-type detection design for applications in
30 which detection is used for suppression system actuation. The study focused on the
31 use of ASD systems in challenging environments, such as areas with high airflow,
32 very low or non-thermal energy fire hazards, and dense equipment layout as a
33 solution for risk management and business continuity. The Fire Dynamics Simulator
34 (FDS), a fire modeling computational fluid dynamic tool developed by NIST, was
35 used to determine the appropriate ASD alarm level to establish an equivalent or
36 better level of performance as compared to the benchmark for conventional
37 spot-detection.

38
39 This work identified that, for an equivalent performance, ASD requires higher
40 sensitivity settings in rooms where (1) the airflow is higher, (2) the room size is
41 increased, and (3) the ceiling height is increased. For the application using an ASD
42 system to supplement or replace conventional spot-type detectors, the report
43 concludes that with proper alarm settings (based on airflow characteristics and room
44 physical dimensions), detection performance can be enhanced, and more consistent
45 fire size at time of suppression can be achieved. The report doesn't appear to take
46 into consideration the uncertainty associated with the FDS modeling, nor does it
47 explicitly describe the basis equivalency calculation method.

48
49 E.9 Fabin, T.Z., Gandhi, P.D., "Smoke Characterization Project," April 2007.

1 The Fire Protection Research Foundation, along with the Underwriters Laboratories,
2 undertook a smoke characterization study to more fully characterize the products of
3 flaming and non-flaming combustion for materials found in common residential
4 settings. Small-scale cone calorimeter, intermediate scale calorimeter and UL
5 217/268-type fire room tests were conducted to evaluate smoke characteristics for
6 natural, synthetic, and multi-component materials in both flaming and non-flaming
7 combustion modes. Quantities such as mass-loss rates; heat and smoke release
8 rates; smoke particle size and count distribution; effluent gas composition;
9 combustion mode effects; smoke alarm response; and smoke stratification were
10 characterized. Although the report provides a thorough evaluation for the
11 combustion modes and materials tested, most of the materials are not commonly
12 found in NPP applications, making the application of these results uncertain.

13
14 E.10 Collier, P.C.R, Whiting, P.N., "Timeline for Incipient Fire Development: Study Report No.
15 194," 2008.

16
17 The Building Research Levy funded work to evaluate incipient fire development of
18 furniture fires with regard to the modeling of the incipient stage in performance-based
19 design fires. Using test data, and literature and statistical evaluations, the
20 researcher noted that the incipient fire development period is variable and its
21 duration was dependent on intensity and location of the ignition source. Because of
22 the variability in the incipient stage, the report recommends no allowance for incipient
23 fire development in performance-based applications. Although furniture fires are not
24 realistic surrogates for electrical cabinet fires, the variability of the duration of the
25 incipient stage is a characteristic likely applicable to electrical cabinet fires.

26
27 E.11 Milke, J.A., et al., "Validation of a Smoke Detection Performance Prediction
28 Methodology," Volumes 1-4, October 2008.

29
30 The Fire Protection Research Foundation sponsored a research project to evaluate
31 the current capabilities of the computational fluid dynamic (CFD) code FDS to predict
32 smoke detector activation in response to relatively low energy incipient fire sources.
33 This work was performed by the University of Maryland and Underwriter
34 Laboratories, and is documented in a four-volume report titled, "Validation of a
35 Smoke Detection Performance Prediction Methodology(Milke, Mowrer, Brookman, &
36 Gandhi, 2008)." Volume 1 documents the characterization of the heat and smoke
37 release of eight incipient fire sources that were selected for the project; Volume 2
38 provides a detailed description of the large-scale room fire tests. Volume 3
39 evaluates the smoke detector response, and Volume 4 compares the experimental
40 results with the predictions of FDS simulations.

41
42 Modeling of smoke detector response typically uses one of three methods, namely,
43 temperature rise, critical velocity, or optical density. However, these methods do not
44 address the operational principles of the detectors resulting in uncertainty in the
45 detector response modeling approximations. Eight smoke sources were
46 characterized by performing small-scale tests using the IMO intermediate scale
47 calorimeter at UL in Northbrook, IL. The smoke sources used include: shredded
48 office paper, polyurethane (PU) foam with micro-fiber fabric, printed circuit board,
49 and an ABS plastic computer case, which was used to create flaming smoke
50 sources, while PU foam with micro-fiber fabric, ponderosa pine sticks, cotton lined
51 fabric, and polyvinyl chloride (PVC)-insulated wire were used for smoldering smoke

1 sources. The primary smoke signature of interest was the obscuration of visible
 2 light, but particle count density, mean particle diameter, CO and CO₂ production
 3 data were also collected.
 4

5 The interesting results from this small-scale testing, as it relates to NPP smoke
 6 sources, are the characterization of the PVC-insulated wire test. The PVC test
 7 followed the procedure outlined in Annex B, "Performance Test Procedure for Very
 8 Early Warning and Early Warning Fire Detection Systems" of NFPA 76, using the
 9 North American Wire Test outlined in Table B.2.1 of that standard. However, the UL
 10 test deviated from the Annex procedure in that the test duration lasted 60 seconds,
 11 instead of the standard specified 30 second duration. The results indicated that the
 12 average maximum smoke release rate of 0.10 m²/s occurred just after 60 seconds;
 13 the maximum mean particle diameter of 0.135 micron occurred just before 120
 14 seconds; and the average maximum particle count density of 200,000/cc occurred at
 15 approximately the same time.
 16

17 The large-scale testing included unventilated and ventilated conditions. The 24
 18 unventilated tests were conducted in the UL 217/268 room, measuring 10.8 m by 6.6
 19 m and 3.0 m tall. The rooms were instrumented with photocell/lamp assemblies;
 20 measurement ionization chamber units; spot-type smoke detectors (both ionization
 21 and photoelectric types); thermocouples; thermocouple trees and velocity probes.
 22 The 64 ventilated large-scale tests were conducted in different room measuring
 23 7.2 m wide, 7.2 m long (51.8 m²) by 9.0 m high. This enclosure was equipped with
 24 an injection-type mechanical ventilation system, with two ceiling air injector diffusers,
 25 and four transfer grills providing air exhaust to the plenum space above the
 26 ventilated test room. The ventilated room experiments consisted of testing three
 27 ventilation rates, namely 0, 6, or 12 air changes per hour (ACH). The ventilated
 28 room tests included the same instrumentation as the unventilated tests, with the
 29 addition of three ASD single-zone systems, having three sampling ports per zone
 30 (two sampling ports within the test room, one port sampling from outside the test
 31 room). The intent of including the ADS systems was to collect information to
 32 evaluate the prediction capabilities of FDS. Unfortunately, the data files associated
 33 with the ASD system could not be synchronized with the other data files.
 34

35 Evaluation of the data/feedback indicates that the point type "smoke detector
 36 response(s) appear to be strongly dependent on the specific characteristics of the
 37 smoke and, in some cases, on the detector technology." The researchers then
 38 evaluated the detector response based on the 80th percentile values of obscuration
 39 and suggested nominal guidelines for detector response, depending upon the
 40 ventilation conditions, fire characteristics, (flaming vs. smoldering) and in some
 41 cases, detector technology.
 42

43 **Table E1. 80th Percentile Obscuration Level at Detector Response**
 44

Smoke Source	Ventilation	Detector Type	
		Photoelectric	Ionization
Flaming	With	5%/ft	8%/ft
	Without	8%/ft	
Non-Flaming	With	1 – 2.5%/ft	
	Without	10%/ft	12%/ft

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The report classified the smoke sources as “incipient fire sources,” considering that half the sources used produced their smoke signatures during flaming combustion; the basis for classifying these smoke sources as “incipient fire sources,” is questionable given that all were identified as either smoldering or flaming. In addition, no clear distinction was made as to the portion of the overall smoke release rate profile that corresponds to the incipient stage. Although these tests provided useful data for characterizing the effluent from the various fire sources and for evaluating the smoke prediction capabilities of FDS, because the results were not reported for the ASD system tested, little can be drawn from these results regarding the response of an ASD VEWFD system.

E.12 Xtralis, “IT/Server Room Fire Test Demonstrations – VESDA & photoelectric conventional point detectors, Technical Report,” October 2008.

Xtralis provides a case study from demonstration tests conducted at their Test Facility IT/Server room. Smoke tests were conducted in various locations within the room to demonstrate an ASD smoke detector’s early warning (EW) and very early warning fire detection (VEWFD) capability. The ASD applications tested included ceiling, return air grill, air duct, and cabinet configurations. The ASD system results were compared to conventional spot-type detectors that were included in the tests.

The test facility measured 11.0 m wide x 6.5 m deep x 3.0 m high for a total floor surface area of 71.5 m². The room ventilation conditions were representative of those found in telecommunication facilities, namely, clean, cool air is introduced through the floor, and exhaust via the air return grill located on a wall.

Individual Xtralis VLC detectors were used for cabinet, ceiling, air return grill and duct detection with conventional photoelectric spot-type detectors set to 1.4 %/m obscuration (Mode 1) located adjacent to the ASD sampling points, except for the cabinet applications. An alarm control panel was used to log all detectors’ alarm times. Fire/smoke tests included overheated PVC wire, overheated resistor, and smoldering smoke pellet tests were also conducted. The duration of the overheated cases did not exceed 10 seconds. Seven different locations throughout the facility were used to locate the fire/smoke generation specimens.

Results indicated that for the short-duration fire/smoke sources tested and the locations of the EW and VEWFD systems, performed better than the conventional spot-type detectors. These tests did not provide any information on system performance for slowly degrading electrical components or timing information for operator response to such incipient stages.

E.13 Xtralis, “Warehouse Fire Detection Test Results - ASD vs Point (spot-type) vs Beam Detectors, Case Study,” April 2008.

Case study presents results from a series of demonstration tests conducted in Victoria University’s Warehouse. Three small fire tests were conducted to illustrate the benefits of EW and VEW detection capabilities. Comparisons were drawn between ASD EW and ASD VEW, as well as conventional spot-type and beam detectors.

1 The warehouse was 43 m long, 12 m wide for a gross floor area of 516 m², and had
2 a ceiling height of 8.5 m at the central pitch. A single ASD pipe was installed along
3 the ceiling ventilated ridge and contained six sampling holes spaced 7.2 meters
4 apart. Several alarm thresholds were used for the ASD system, however only the
5 Alert (~0.1 %/ft obscuration [0.3 percent per meter obscuration]) and Fire 1 (~0.37
6 %/ft obscuration [1.2 percent per meter obscuration]) alarm times were reported.
7 Thus the Alert threshold was twice as sensitive and the Fire 1 threshold was almost
8 ½ as sensitive as the minimum sensitivity for an alert per NFPA 76. Six optical spot-
9 type detectors were also placed along the ceiling ridge vent adjacent to each ASD
10 sampling point. The spot-type detectors had a sensitivity of 1.4 %/m obscuration.
11 Smoke sources included liquid heptanes (100 ml), timber, and smoke pellets and
12 were all located in the same area under the center line of the sloped ceiling, between
13 the farthest two sampling points of the ASD system, and directly below the projected
14 beam detector line of sight; positioning of the warehouse rollup door(s) also varied.
15

16 The results indicated that the ASD system performed better than the conventional
17 and projected beam. For tests in which conventional spot-type detectors responded,
18 the ASD system responded on average 52.2 seconds before the spot-type detector.
19 Of the 21 tests conducted, the ASD systems responded with an alert 19 times, while
20 the spot-type responded only 4 times, and the beam detector only responded in one
21 test. The report concludes that the ASD system performed better than the other
22 systems compared and supports the use of ASD systems in challenging warehouse
23 type environments that promote smoke dilution because of high ceiling heights,
24 stratification and natural ventilation conditions. However, it should be noted that,
25 unless the report contains a typographical error, the 4.6 %/ft obscuration [1.4 %/ft
26 obscuration] sensitivity of the spot-type detector is outside the bounds of UL 268
27 (0.5-4.0 %/ft obscuration) and would not be cited on the listing.
28

29 E.14 Milke, J., et al., "Guidelines for Estimating Smoke Detector Response," Suppression and
30 Detection Research and Applications Symposium (SUPDET 2009), Orlando, FL
31

32 This paper summarizes the work completed in Volume 3 of the "Validation of a
33 Smoke Detection Performance Prediction Methodology," sponsored by The Fire
34 Protection Research Foundation. See Section E.11 for a full description of this work.
35

36 E.15 Miller, J., "Analyzing Photo-electric smoke detector response based on aspirated smoke
37 detector obscuration," Masters of Science Thesis, University of Maryland 2010.
38

39 Following the completion of the fire protection research foundation work, the data
40 was analyzed by a student at the University of Maryland to improve the obscuration-
41 level response accuracy of spot-type photoelectric smoke detectors. This work is
42 documented in a Master of Science thesis titled, "Analyzing Photo-Electric Smoke
43 Detector Response Based on Aspirated Smoke Detector Obscuration" (Miller, 2010).
44 In this work, the ASD data files were analyzed against the other light obscuration
45 measurements made during the testing, such that the data files could be
46 synchronized. Then, the spot-type detector response was compared to the
47 obscuration measurements made by the ASD system. The results concur with the
48 conclusions made in the original test program, with the exception of non-flaming fires
49 without ventilation; in this case, the student's analysis indicated that the photoelectric
50 detector performed better (responded at lower obscuration values) than the original
51 report suggested (range of 0.4 to 5 %/ft obscuration).

1
2 Although the results compare well with the conclusions from the original report,
3 uncertainties associated with averaging the ASD system response, unknown system
4 offset time, filter effects, and smoke transport lag, were not explicitly quantified, and
5 complicated the analysis. Even so, the results of this work parallel the conclusions
6 from the original report suggesting a relatively large deviation in the expected
7 obscuration level of 2.5 percent at photoelectric detector response. Unfortunately,
8 because the ASD system was used as a measurement device, rather than setup as
9 a detector, little can be drawn from this work regarding its performance. However,
10 the underlying conclusion re-enforces the basic fire detection principles that are
11 applicable to ASD detectors, which state that smoke characteristics, smoke
12 transport, and detector characteristics directly impact the performance of a detectors
13 response compared to its listing.
14

15 E.16 Zaworski, J., Laramée, S., O’Conner, D.J., “Comparative Testing of Various Detection
16 Technologies,” Schirmer Engineering Corporation, 2010.
17

18 Schirmer Engineering witnessed and reported the results of a series of fire tests
19 conducted in a warehouse environment for axonX. The work was commissioned by
20 axonX to evaluate the relative performance of their video image fire and smoke
21 detection (VID) against numerous flame and smoke detection technologies. The test
22 series consisted of 21 different fire scenarios which were repeated three times each
23 for a total of 63 tests using five technologies (ASDs, projected beam smoke
24 detection, spot-type ionization and photoelectric, and VID).
25

26 An ASD sampling pipe was located near the ceiling (~18ft) and ran the length of the
27 room with three sampling ports spaced approximately 20ft from each other. The
28 default ASD detector sensitivities were used with the “Fire 1” and “Fire 2” set points
29 used for comparison (~0.18 %/ft obscuration and 1.2 %/ft obscuration, respectively,
30 at each sampling point). Seven different fire sources ranging from smoldering to
31 flaming fires, were used. Of interest to the NRC/NIST project was the overheated
32 smoldering wire source, which consisted of a bundle of Type NM-B 14/3 cables
33 wrapped around a heating element energized for 20 minutes per test. The fire
34 sources were placed in three different locations within the room.
35

36 Results from this test series indicated that, in general, for warehouse type
37 applications, the VID response fastest from most fire sources typically followed by
38 the ASD and Ion spot detectors. For the low-energy overheated wire and smoldering
39 wood tests, the VID responded in the 298 – 455 second range, while the ASD, beam,
40 and Ion detectors responded in the 805 – 1016 second range. Given the sensitivity
41 settings for the ASD systems, physical arrangement, and fire source characteristics,
42 these results are reasonable.
43

44 E.17 Gottuk, D., et al., “Validation of Modeling Tools for Detection Design in High Air Flow
45 Environments, Final Phase I Report,” The Fire Protection Research Foundation, August
46 2012.
47

48 The Fire Protection Research Foundation sponsored an effort to examine the
49 applicability of using computer modeling tools for modeling smoke detection system
50 designs in high airflow rate environments. This report documents the identification of
51 modeling requirements, potential computer models, gaps in knowledge, and

1 development of a research program to address these gaps. Seventeen model
2 requirements and eight models were identified. The gap analysis identified the
3 following four gaps:
4

5 1) Specification of the fire and smoke input

6 Specification of the rate of smoke production for incipient fires and
7 the smoke production and heat release for flaming fires is
8 considered a modeling gap. Two aspects for this gap include
9 existence of applicable measured data, and the methodology for
10 specifying the inputs. The capability to predict the ignition and
11 growth of fires of real world objects remains the subject of academic
12 research.
13

14 2) Smoke transport

15 Soot deposition upon walls and equipment is a known challenge related
16 to smoke detection system design and modeling. Deposition of soot
17 reduces the concentration of soot in the air, and acts to delay detection
18 response. Soot deposition is primarily caused by thermophoresis
19 (thermal gradients), electrophoresis (electric fields), and impactation
20 (sharp turns in air streams near obstructions). This all suggests
21 deposition is more significant inside electrical equipment than outside.
22

23 3) Smoke detection performance

24 The ability to correlate conditions predicted by a model at a smoke
25 detector/ASD sampling port to an alarm condition within the detector is a
26 significant gap. There are no established correlations for predicting alarm
27 response for ASD systems at either low or high air flow environments.
28 ASD test data indicates that correlations will be highly dependent upon
29 the specific detector model.
30

31 4) Large-scale integral test data set

32 Limited data exists for HVAC flows and cooling effectiveness of
33 IT/telecom facilities. An IT/telecom facility-specific set of large-scale tests
34 would serve as a validation benchmark for determining the suitability of a
35 specific model.
36

37 In the development of a test plan to address these gaps in knowledge, the authors
38 identified the following issues, which are applicable to NPP fire scenarios in electrical
39 equipment enclosures:
40

- 41 • The duration and amount of smoke released from electrical equipment will be
42 dependent upon the size of the heat source, the orientation of the material
43 with respect to the heat source, and the amount of material exposed.
44
- 45 • Significant fire development occurs when pyrolysis/smoldering combustion
46 transitions to flaming. Although it is generally a goal to detect fires before
47 flaming conditions, there are practical issues that can prevent successful
48 intervention at the early stage. These include smoke levels not visible to site
49 personnel, resulting in a source being difficult to find, and fires that occur
50 because of energetic events, and result in relatively fast fire growth.

- 1 • Smoke production from an incipient circuit board fire may impact several
2 other circuit boards and pieces of electrical equipment, before being
3 enveloped into the primary air flow. In this scenario, soot deposition on the
4 impacted equipment may reduce the overall smoke concentration that is
5 transported to a detection site, compared to the same source in the open.
6
- 7 • Given the range of cabinet and ventilation configurations, it may be
8 necessary to evaluate several potential configurations with sources at
9 different locations within a cabinet. Total soot deposition may be significantly
10 different for source in the bottom of a cabinet that has continuous vertical
11 ventilation openings exposed to external ventilation conditions (smoke flows
12 out of the cabinet), compared to a source at the bottom of the cabinet with
13 exhaust openings at the top of the cabinet (smoke must flow up through the
14 cabinet).
15
- 16 • Several detection devices used complex algorithms that continuously monitor
17 ambient conditions and adjust detection levels accordingly.
18 An understanding of the operation of such software, the optional and default
19 settings, and the manufacturers recommendations are needed to ensure that
20 the device meets performance goals.
21

22
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NRC FORM 335 (12-2010) NRCMD 3.7	U.S. NUCLEAR REGULATORY COMMISSION BIBLIOGRAPHIC DATA SHEET <i>(See instructions on the reverse)</i>	1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.) NUREG-2180				
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10. SUPPLEMENTARY NOTES G. Taylor, NRC Project Manager						
11. ABSTRACT (200 words or less) Aspirated smoke detection (ASD) systems have been available on the commercial market for more than four decades as an alternative technology to spot-type smoke detection for detecting products of combustion. Recently, these systems have been installed as very early warning fire detection (VEWFD) systems to support licensees transitioning to a performance-based fire protection program. In many, but not all cases, the choice to install these systems is based on the expectation that these systems may reduce the estimated fire risk in a fire probabilistic risk assessment (PRA). The lack of data evaluating the performance of these systems has limited the acceptance of their use. This report documents research conducted by the Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), and the National Institute of Standards and Technology (NIST) to evaluate the performance of both ASD and conventional smoke detection systems in common nuclear power plant applications. A literature search, multiple scales of testing, and a risk-scoping study provide a comprehensive evaluation of the response of several smoke detection systems the incipient stage of fires.						
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